

# Special Technology Sessions

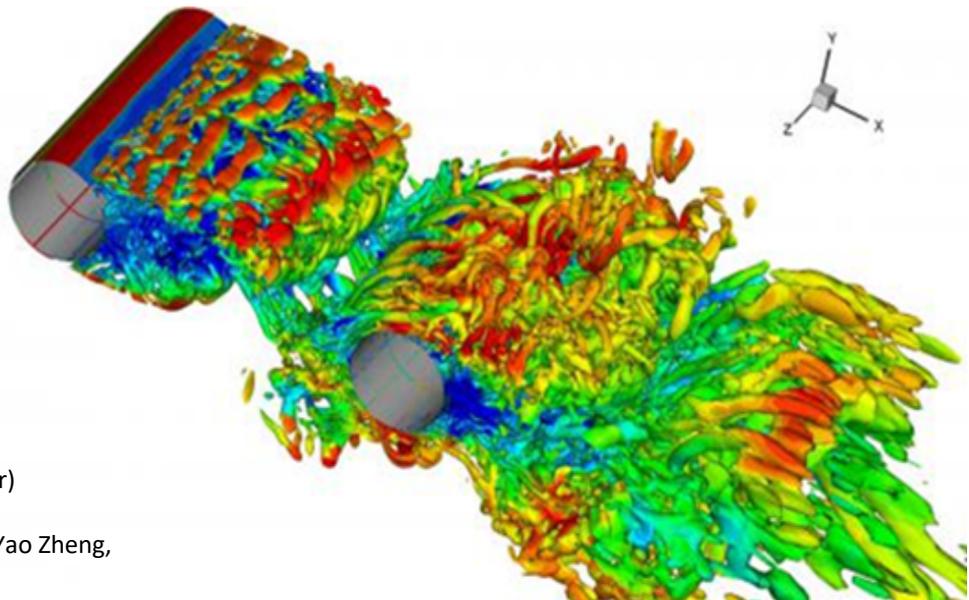
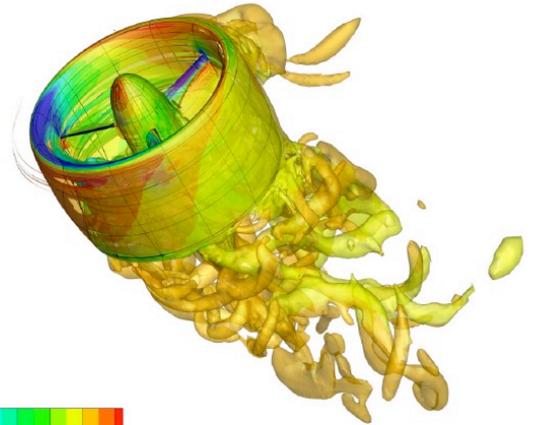
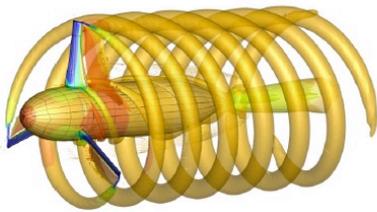
*8th European Congress on Computational Methods  
in Applied Science and Engineering (ECCOMAS 2020)*

*14th World Congress on Computational Mechanics (WCCM XIV)*

## Book of Abstracts

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(Editors)

ECCOMAS Industry Interest Group



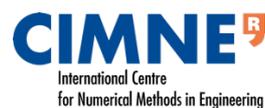
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Gabriel Bugada (Lower)

11 – 15 January 2021, Paris, France

A publication of:  
International Centre for Numerical Methods in Engineering (CIMNE) Barcelona, Spain  
First Edition: January 2021  
© The Authors  
Eds. Dietrich Knoerzer and Jacques Periaux and Tero Tuovinen  
ISBN: 978-84-121101-5-9



## Welcome Address of Professor Michal Kleiber, President of ECCOMAS

Thanks to hard work of our colleagues chairing the ECCOMAS Industry Interest Group (IIG) we have at our WCCM-ECCOMAS Congress 2020 numerous, competent and instructive contributions on innovative industrial applications of digital technology. The initiative to solicit these presentations is enormously important as the issues discussed form one of the main elements of the ECCOMAS mission. The ECCOMAS IIG made earlier a huge effort to organize numerous Special Technology Sessions at the Congress planned for July 2020. Since the difficult pandemic circumstances enforced the change of the Congress format to virtual some of the previously registered contributions have been included in the current on-line programme with their abstracts forming the content of this booklet.



No one today puts in question the importance of continuous interactions between research and industry as a crucial element of technology development, and as a consequence also of the fast and stable economy growth. The important elements in this context obviously are computational methods and the digital technology as a whole. Today the role of computer assisted methodologies is absolutely crucial for successful industrial implementations of innovative ideas and that is why this area of research and engineering applications is so actively supported by the European Commission through its research and innovation programmes and by the ECCOMAS through its variety of activities – organizing conferences and seminars as well as actively facilitating professional contacts between researchers and engineers.

An area which strongly relies on fast and continuous development of advanced computational methods, especially in fluid dynamics and structure mechanics, is no doubts aeronautics industry which long has already been a leader in the novel applications of numerical methods. It is therefore no surprise that the majority of paper presented in this booklet belong to this area of innovative industry.

On behalf of the whole ECCOMAS community of researchers and engineers I most cordially thank the colleagues for their unparalleled engagement in the preparation for our Congress of this very crucial part dealing with computational aspects of novel innovative technologies.

**Professor Michal Kleiber**  
ECCOMAS President

## Welcome Address of Dr. Andrea Gentili, European Commission.



I am delighted to welcome you all at this joint edition of the World Congress in Computational Mechanics and ECCOMAS Virtual Congress. Despite the current challenging circumstances due to the COVID-19 pandemic, it is my pleasure to see such enthusiastic response of all the research and innovation community, with more than 400 mini-symposia (MS) and more than 2500 papers accepted, along with an exceptional implication of the young community.

Research and Innovation, together with its intrinsic nature of sharing and discussing results for the ultimate benefit of the citizens, has not been stopped by the current crisis. By developing technologies that could make aviation more environmentally friendly, safer, and improve travellers' experience, research and innovation will make an important contribution to the EU's sustainability and transport policy goals.

I am sure that I do not need to remind you of the importance of reducing the risks of climate change and promote the digitalisation transformation of EU industry. That is why the EU, with the European Green Deal Communication, has made the greening and the digitalisation two of its outmost important priorities for the future EU.

Naturally, in aviation, safety must always remain paramount. Improving safety, as well as environmental protection and inter-modality, provides clear benefits to aeroplane passengers - but it also boosts the global competitiveness of the EU's aviation industry. This often leads also to sustainable job creation. Research in this field is not only producing excellent results, it is also strengthening the European aviation research community and fostering cooperation.

The focus for the next years in EU aviation R&I should be on developing and demonstrating solutions for decarbonisation and digitalisation of the aviation sector, and these can be a mix of basic research as well as of scaling up some of the quite developed solutions, including the ones from your own research, with the main aim of contributing to the zero emission objectives, and at the same time underpinning the sustainable global competitiveness of the European aviation sector, in line with the European Green Deal.

In conclusion, at the start of this exciting WCCM-ECCOMAS Virtual Congress, let me express two wishes:

- 1) I wish for all of us, in the private and public sectors, to continue working under such cooperative, constructive and stimulating circumstances as we have been doing until now, together with all the relevant stakeholders from industry, academia and research establishments.
- 2) I wish you all fruitful, constructive and exciting discussions for a successful event, despite its virtual dimension! Good luck!

**Dr. Andrea Gentili**

Acting Head of Unit RTD-D.3 'Low Emissions Future Industry'

## Introduction

The ECCOMAS and the aeronautics research have long traditional connections, as the aeronautics industry of Europe had and still has a need for advanced computational methods, especially in fluid dynamics and structure mechanics, where aeronautics was and still is a front runner in the application of innovative numerical methods. Already since the ECCOMAS Congress 1996 in Paris, Special Technology Sessions (STS) have been organised on technologies and research of industrial relevance mainly in the field of aeronautics, but also for research in renewable energy, information technology and other industries. Many papers of the STS present the achievements of research activities within the Research Framework Programmes of the European Union.

Within ECCOMAS, its Industry Interest Group (IIG) takes care for the link between research and industry and supports the organisation of STS. Since the ECCOMAS Congress 2016 in Crete, Greece, an STS book of abstracts has been produced to help conference participants in identifying the STS of their interest.

Senior experts of aeronautics and industrial technology areas organise the STS with selected specialists from industry, research institutions and universities. They all ensure the high scientific and technical quality of the STS.

The aim of the STS and their papers is to provide an overview on the state-of-the-art and future technologies in computational and digitalized methods and tools (modelling, simulation, optimisation and control, Artificial Intelligence (AI), etc.) for the application in aeronautics and other industries with related validations. The STS focus on industrial and disruptive technologies such as low-emission aircraft concepts and propulsion systems as well novel industrial production methods.

At the WCCM-ECCOMAS Virtual Congress in January 2021, 67 papers from 18 STS will be presented. Opposite to the physical conferences, the Virtual Congress allows all registered participants to view all paper presentations already at their convenience in the week before the official Congress. Instead of holding individual sessions, several STS will be clustered to thematic STS Discussion Sessions, which take place during the official Virtual Congress as live discussion panels with the STS chairpersons as the moderators.

### **The six STS Discussion Sessions will address the following topics:**

Session 1: "FreeFEM – the Open Source Multiphysics Toolbox"	(2500),
Session 2: "Industrial Methods"	(2400/2500),
Session 3: "Aeronautics – High-speed Transport"	(2200),
Session 4: "Aeronautics – Wing Aerodynamics"	(2300),
Session 5: "Aeronautics – Fluid Dynamics and Aero-acoustics"	(2300),
Session 6: "Aeronautics – Structures, Design and Optimisation Methods"	(2300).

The numbers indicate the thematic areas, as they are given on the Congress web-site:  
2200 = Aeronautics – Simulation and Validation,

2300 = Aeronautics – Design, Methods & Tools,  
2400 = Automotive, Mobility and Environment,  
2500 = Industry Applications.

In this Book of Abstract, each STS provides an abstract of its content and rationale followed by the abstracts of its papers. Most but not all papers that were planned for the cancelled Congress of July 2020 could be retained for this Virtual Congress. This Book of Abstracts contains only the papers presented at the Virtual Congress.

We thank particularly all STS chairpersons and their paper authors for their effort to setting up or contributing to attractive sessions. In particular by their effort, the STS provide an attractive contribution to the success of the WCCM-ECCOMAS Virtual Congress.

Finally, our sincere thanks go to the organisers of the WCCM-ECCOMAS Virtual Congress 2020, especially to Congress Chairmen Francisco Chinesta, Rémi Abgrall, Olivier Allix, Michael Kaliske and David Néron for their endorsement of the STS initiative as well as to Alessio Bazzanella with his team of the CIMNE Congress Bureau for the technical and logistic support, all under the difficult and uncertain constraints in the context of the COVID-19 pandemic.

Paris, December 2020,

Dietrich Knoerzer  
Jacques Periaux  
Tero Tuovinen

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## Time Schedule of the Live STS Discussion Sessions

during the WCCM-ECCOMAS Virtual Congress

**Monday, 11<sup>th</sup> January 2021, 16h35 – 17h35 (Paris Time):**

**Live STS Discussion Session 1: “FreeFEM – the Open Source Multiphysics Toolbox” (2500)**

**Participating STS:** STS-09 (5 papers), STS-10 (4 papers)

**Total:** 9 papers

**Moderators:** Frederic Hecht, Frederic Nataf

**Live STS Discussion Session 4: “Aeronautics - Wing Aerodynamics” (2300)**

**Participating STS:** STS-07 (4 papers), STS-17 (6 papers)

**Total:** 10 papers

**Moderators:** Jochen Wild, Marianna Braza

**Tuesday, 12<sup>th</sup> January 2021, 16h35 – 17h35 (Paris Time):**

**Live STS Discussion Session 2: “Industrial Methods” (2400/2500)**

**Participating STS:** STS-04 (2), STS-06 (4), STS-25 (4), STS-28 (3);

**Total:** 13 papers

**Moderators:** Nico Gauger, Tohru Hirano, Hiroshi Okada, Maurizio Maggiore

**Live STS Discussion Session 3: “Aeronautics - High-speed Transport” (2200)**

**Participating STS:** STS-14 (4 papers), STS-16 (5 papers)

**Total:** 9 papers

**Moderators:** Gérald Carrier, Normand Pierre-Elie, Marco Marini

**Wednesday, 13<sup>th</sup> January 2021, 16h35 – 17h35 (Paris Time):**

**Live STS Discussion Session 6:**

**“Aeronautics – Structures, Design and Optimisation Methods” (2300)**

**Participating STS:** STS-01 (4 papers), STS-11 (3), STS-13 (3), STS-18 (3)

**Total:** 13 papers

**Moderators:** Christophe Hermans, Jacques Periaux, Carlo Poloni, Dietrich Knoerzer

**Thursday, 14<sup>th</sup> January 2021, 16h35 – 17h35 (Paris Time):**

**Live STS Discussion Session 5: “Aeronautics – Fluid Dynamics and Aero-acoustics”**

**Participating STS:** STS-02 (2 papers), STS-20 (5), STS-22 (1), STS-26 (5) (2300)

**Total:** 13 papers

**Moderators:** Piotr Doerffer, Tatiana Kozubskaya, Leonidas Siozos-Rousoulis

## **STS Discussion Session 1: FreeFEM – the Open Source Multiphysics Toolbox**

**Moderators: Frederic Hecht, Frederic Nataf**

### **Participating STS:**

**STS-09            FreeFEM – the Open Source Multiphysics Toolbox (Part 1)**

*Chairs: Frédéric Hecht and Frédéric Nataf*

**STS-10            FreeFEM – the Open Source Multiphysics Toolbox (Part 2)**

*Chairs: Frédéric Hecht and Frédéric Nataf*

## STS-09 FreeFEM – the Open Source Multiphysics Toolbox (Part 1)

Chairs: Frédéric Hecht<sup>1</sup> and Frédéric Nataf<sup>2</sup>

Sorbonne Univ., Laboratory J. L. Lions and INRIA Team Alpines, Paris, France

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<sup>2</sup>frederic.nataf@sorbonne-universite.fr

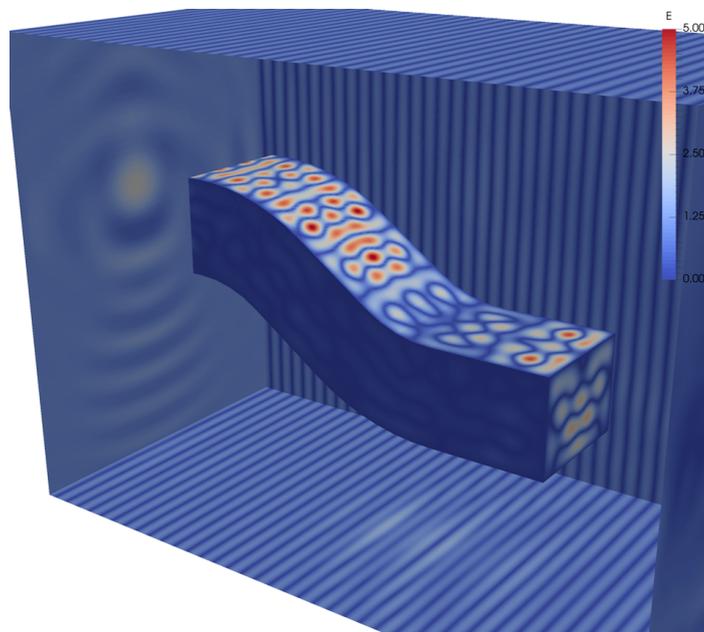
### Session Abstract

**Keywords:** *Multiphysics, Domain specific language, FreeFEM*

FreeFEM is a popular 2D and 3D partial differential equations (PDE) solver used by thousands of researchers across the world and by many companies. It allows you to easily implement your own physics modules using the provided FreeFEM language. Numerous physics are pre-built: Incompressible Navier-Stokes (using the P1-P2 Taylor Hood element), Lamé equations (linear elasticity), Neo-Hookean, Mooney-Rivlin (nonlinear elasticity), Thermal diffusion, Thermal convection, Thermal radiation, Magnetostatics, Electrostatics, Fluid-structure interaction (FSI), ... FreeFEM has its own internal mesher, called BAMG, and is compatible with the best open-source mesh and visualization software like Tetgen, Gmsh, Mmg and ParaView. It is interfaced with the state-of-the-art solvers: MUMPS, PETSc, PARADISO and HPDDM. FreeFem is also a language for the manipulation of data on multiple meshes. It allows rapid multiphysics prototyping and can be viewed as a kind of MATLAB for the finite element method. This software is based on an efficient DSL (Domain Specific Language) user language that allows you to define freely your simulation and the post processing analysis.

The papers of this STS will present industrial achievements of Multiphysics modeling using FreeFEM (fluid structure interaction, piezoelectric, thermodynamic energy storage, thermic analysis, glass modelling) as well as its availability on an energy efficient server platform.

**Figure 1: Electromagnetic scattering from COBRA cavity**



**List of session papers and speakers (Part 1):**

- **Free FEM – The Open Source Multiphysics Toolbox (*An introduction into the sessions*)**
  - Frédéric Hecht and Frédéric Nataf, Sorbonne Univ., Paris, France
  
- **Finite Element Solution of a Solder Filing Problem with Contact Angle and Volume Constraint**
  - Atsushi Suzuki, Cybermedia Center, Osaka University, Japan, atsushi.suzuki@cas.cmc.osaka-u.ac.jp
  - Hiroshi Ogawa, DENSO Corporation, Japan
  
- **Gob Forming: an Example of FreeFEM Use in Glass Industry**
  - Gérard Maes, ARC, Departm. Furnace Engineering, R&D Modelling and Simulation
  
- **Thermal Modelling of Injection Moulding of a PET Preform**
  - Marc Youcef, Husky Injection Molding Systems, Luxembourg
  
- **Surface Acoustic Waves Transducer Analysis with a Conventional P-Matrix Model Derived from Periodic FEM-BEM Using FreeFEM++**
  - Pascal Ventura, Université de Lorraine, Nancy, France, pascal.ventura@univ-lorraine.fr
  - Pierre Dufilié, Phonon Corporation, East Granby CT, USA
  - Frédéric Hecht, LJLL Sorbonne Université, Paris, France

## STS 09-1 Finite Element Solution of a Solder Filing Problem with Contact Angle and Volume Constraint

**Atsushi Suzuki<sup>1</sup>, Hiroshi Ogawa<sup>2</sup>**

<sup>1</sup> Cybermedia Center, Osaka University, Japan

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<sup>2</sup> DENSO Corporation, Japan

### Abstract

**Keywords:** *High-performance domain decomposition methods (HPDDM), Stationary state of liquid, Gradient flow solver, Diffusion equation*

A free boundary problem, which models stationary state of liquid between gaps of two solid metal materials, is considered. Here, the interface among air, liquid and the metal has contact angle less than 90 degree, which depends on physical characters of the liquid. An indicator function that distinguishes between liquid and air by its value as positive or negative is governed by a diffusion equation with a double-well potential that forces separation of the value of the indicator function as 1 or -1. In addition, the volume of the liquid is assumed to be a certain value.

We will present an algorithm combined with gradient flow solver and Newton iteration to find a solution of nonlinear diffusion interface equation with contact angle and volume constraint. Mesh refinement to capture the interface between liquid and air in the complicated shape of gaps defined by CAD software is performed by the 3D finite element mesh generator Gmsh and parallel computation is done by high-performance domain decomposition methods (HPDDM) in FreeFEM environment.

## STS 09-2 Gob Forming: an Example of FreeFem Use in Glass Industry

G rard Maes<sup>1</sup>

<sup>1</sup>ARC, Department: Furnace Engineering Team: R&D Modeling and Simulation

### Abstract

**Keywords:** *FreeFem use, Glass industry, Gob forming process, Modelling, Multi-physics problems*

In glass industry, a gob is an amount of molten glass intended to be mould and give a glass container or article. Because gob weight and shape are important characteristics, which should remain very accurate and steady during a production, the gob forming process has to be mastered with a correct setting.

However, the problem is the difficult conciliation between the great inertia attached to this process and the increasing needs to make the production more and more flexible. An original approach to fix the problem is to complete the process with a new degree of freedom (induction heating) working as a compensation system. Before investing in the making of a prototype, the solution has to be studied with modelling. To do modelling, FreeFem is chosen because of its various advantages compared to other codes, especially its high capacity to deal with strongly multi-physics problems with powerful tools acting on meshes such as cutting and isolating a gob numerically.

## **STS-09-3 Thermal Modelling of an Injection Molded PET Preform**

**Marc Youcef<sup>1</sup>**

<sup>1</sup> Husky Injection Molding Systems Ltd., Luxembourg

### **Abstract**

**Keywords:** *Injection molded PET preform, Part quality prediction, Thermal modelling*

A fully automated process is proposed for predicting the heat transfers into an injection molded PET preform. This analysis enables in return predicting the future quality of the PET preform part before manufacturing the related mold in production. On top of the part quality prediction, performance of the future system including mold and machine are estimated thanks to the heat transfer analysis.

## STS-09-4 Surface Acoustic Waves Transducer Analysis with a Conventional P-Matrix Model Derived from Periodic FEM-BEM Using FreeFem++

Pascal Ventura<sup>1</sup>, Pierre Dufilié<sup>2</sup>, Frédéric Hecht<sup>3</sup>

<sup>1</sup> LEM3, UMR CNRS 7239, Université de Lorraine, Metz, France, pascal.ventura@univ-lorraine.fr

<sup>2</sup> Microsemi Corporation, Simsbury, CT, USA, Pierre.dufilie@microchip.com

<sup>3</sup> Sorbonne Université, Université Paris-Diderot SPC, CNRS, INRIA, Laboratoire Jacques-Louis Lions, Alpines, F-75005 Paris, France, Frederic.hecht@sorbonne-universite.fr

### Abstract

**Keywords:** *Surface acoustic waves (SAW), transducer analysis, FreeFem++, Finite Element Method, Boundary Integral Formulation*

In order to solve the 2D physical simulation of surface acoustic waves (SAWs) transducer infinitely periodic in one direction, we proposed in 2013 [1] an original Variational Formulation (VF) which formally includes harmonic periodic boundary conditions, and, efficient boundary integral formulations allowing to account for the semi-infinite dielectric and piezoelectric spaces. In the case of the piezoelectric semi-space, the Green's functions are efficiently computed using Fahmy-Adler's method.

The numerical implementation has been done using the efficient FreeFem++ environment [2] able to deal very easily with the electro-acoustical VF.

On the other hand, the P-matrix model is a conventional tool used by SAW design engineers to simulate finite SAW Inter Digitated Transducers (IDT). Using the 2D periodic Finite Element Method / Boundary Integral Formulation (FEM/BIE) FreeFem++ tool, it is quite easy to derive the P-matrix coefficients of a single electro acoustical cell.

Numerical results will be given for various electro-acoustical cells including Hanma-Hunsinger cells.

### References

- [1] F. Hecht, P. Ventura, P. Dufilié, Original coupled FEM/BIE numerical model for analyzing infinite periodic surface acoustic waves transducers, *Journal of Computational Physics* 246 (2013) 265-274
- [2] Hecht, F. (2012), New development in FreeFem++. *Journal of numerical mathematics*, 20 (3-4), 251-266.

## STS-10 FreeFEM – the Open Source Multiphysics Toolbox (Part 2)

Chairs: Frédéric Hecht<sup>1</sup> and Frédéric Nataf<sup>2</sup>

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<sup>1</sup> Frederic.hecht@sorbonne-universite.fr

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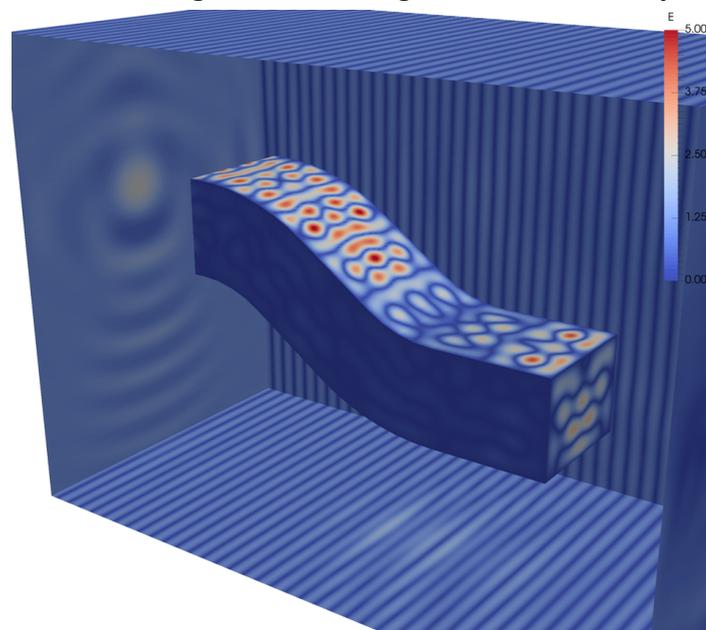
### Session Abstract

**Keywords:** *Multiphysics, Domain specific language*

FreeFEM is a popular 2D and 3D partial differential equations (PDE) solver used by thousands of researchers across the world and by many companies. It allows you to easily implement your own physics modules using the provided FreeFEM language. Numerous physics are pre-built: Incompressible Navier-Stokes (using the P1-P2 Taylor Hood element), Lamé equations (linear elasticity), Neo-Hookean, Mooney-Rivlin (nonlinear elasticity), Thermal diffusion, Thermal convection, Thermal radiation, Magnetostatics, Electrostatics, Fluid-structure interaction (FSI), ... FreeFEM has its own internal mesher, called BAMG, and is compatible with the best open-source mesh and visualization software like Tetgen, Gmsh, Mmg and ParaView. It is interfaced with the state-of-the-art solvers: MUMPS, PETSc, PARADISO and HPDDM. FreeFem is also a language for the manipulation of data on multiple meshes. It allows rapid multiphysics prototyping and can be viewed as a kind of MATLAB for the finite element method. This software is based on an efficient DSL (Domain Specific Language) user language that allows you to define freely your simulation and the post processing analysis.

The papers of this STS will present industrial achievements of Multiphysics modeling using FreeFEM (fluid structure interaction, piezoelectric, thermodynamic energy storage, thermic analysis, glass modelling) as well as its availability on an energy efficient server platform.

### Electromagnetic scattering from COBRA cavity



**List of session papers and speakers (Part 2):**

- **Data-Assimilation for Aerodynamic Using FreeFEM**
  - Olivier Marquet, DAAA-ONERA, Paris-Saclay University, Meudon, France, Olivier.Marquet@onera.fr
  - Pierre Jolivet, CNRS-IRIT, Toulouse, France
  - Vincent Mons, DAAA-ONERA, Paris-Saclay University, Meudon, France
  - Markus Zauner, DAAA-ONERA, Paris-Saclay University, Meudon, France
  
- **Running FreeFEM++ Payloads on Qarnot Green – Distributed Grid to Heat Buildings**
  - Rémi Bouzel, Qarnot Computing, Montrouge, France, remi.bouzel@qarnot-computing.com
  
- **Contact Problems in Industrial Applications Using FreeFEM**
  - Houssam Houssein, Airthium, Ecole Polytechnique, Palaiseau, France, houssein@ljll.math.upmc.fr
  - Simon Garnotel, Airthium, Ecole Polytechnique, Palaiseau, France
  - Frédéric Hecht, LJLL Sorbonne Université, Paris, France
  
- **Shape Optimization and Additive Manufacturing: The Dehomogenization Method**
  - Olivier Pantz, Laboratoire Jean-Alexandre Dieudonné, Université Côte d'Azur, Nice, France, olivier.pantz@univ-cotedazur.fr
  - Grégoire Allaire, Centre de Mathématiques Appliquées (CMAP), Ecole Polytechnique, Palaiseau, France
  - P. Geoffroy, Procédés et Ingénierie en Mécanique et Matériaux, CNAM, Paris, France

## STS-10-5 Data-Assimilation for Aerodynamic Using FreeFEM

**Olivier Marquet<sup>1</sup>, Pierre Jolivet<sup>2</sup>, Vincent Mons<sup>1</sup>, Markus Zauner<sup>1</sup>**

<sup>1</sup> DAAA-ONERA, Paris-Saclay University, Meudon, France

<sup>2</sup> CNRS-IRIT, Toulouse, France

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### Abstract

**Keywords:** *FreeFEM++ software, Unconventional partial differential equations, Aerodynamic flow solver, Large-scale eigenvalue problems*

The FreeFEM++ software is a convenient numerical tool to solve unconventional partial differential equations. It has been used in the Department of Aerodynamics, Aeroelasticity and Acoustics of ONERA to develop two research projects.

The first one, funded by the European Research Council, is concerned with the accurate mathematical description of linear instabilities developing when an incompressible flow interacts with a visco-elastic material. We will exemplify the implementation of the linearized Arbitrary Lagrangian Eulerian equations and the use of the PETSc/SLEPc interface for solving iteratively large-scale eigenvalue problems with efficient preconditioners.

Results will be briefly shown for a flexible plate interacting with the vortex-shedding in the wake of a cylinder and for a finite-length compliant-patch used to attenuate the Tollmien-Schlichting waves in a boundary-layer flow. The second research project is concerned with the assimilation of experimental or numerical data in aerodynamic flow solver. The variational approach of data-assimilation may be formulated as a constrained minimization problem, the functional measuring the difference between outputs of the numerical model and external data. We will show how unsteady adjoint equations have been implemented to provide the gradient of the functional required by a minimization algorithm such as I-BFGS.

Results of unsteady data-assimilation will be briefly shown for experimental PIV (Particle Image Velocimetry) data, aiming at improving their spatio-temporal resolution thank to the numerical model, and for numerical DNS (Direct Numerical Simulation) data, aiming at improving the accuracy of lower-fidelity numerical models.

## STS-10-6    **Running FreeFEM++ Payloads on Qarnot Green Distributed Grid to Heat Buildings**

**Rémi Bouzel<sup>1</sup>**

<sup>1</sup>Qarnot Computing, Montrouge, France, remi.bouzel@qarnot-computing.com

### **Abstract**

**Keywords:**    *Green HPC, Multiphysics, FreeFEM, Edge computing, Heating as a service, Job scheduler, Resource manager*

In this paper, we discuss a green and distributed type of data centers, implemented by Qarnot Computing. This approach promotes a new computing paradigm in which computers are considered as machines that produce both computation and heat, and are therefore able to reuse the waste heat generated. It is based on two main technologies: a new model of servers and a new distributed grid computing manager which encloses a heat aware job scheduler.

After introducing the different pieces of technology of the Qarnot green distributed grid, this paper will focus on how the FreeFEM++ payloads can be run efficiently on such a platform and how the server waste heat is reused.

## STS-10-7 Contact Problems in Industrial Applications Using FreeFEM

**Houssam Houssein<sup>1</sup>, Simon Garnotel<sup>1</sup>, Frédéric Hecht<sup>2</sup>**

<sup>1</sup> Airthium, Palaiseau, Ile-de-France, France,  
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<sup>2</sup> Laboratory J. L. Lions, Sorbonne Université, Paris, France,  
frederic.hecht@sorbonne-universite.fr

### Abstract

**Keywords:** *Mechanical contact, FreeFEM, Concept of master/slave, Constrained minimization problem*

The mechanical Contact between two bodies is one of the most difficult problem in solid mechanics, indeed the material non-linearity must be taken into account and the contact area is unknown. In the case of frictional contact, another non-linearity must be considered and makes the problem even more difficult. There exist several algorithms to solve the contact problems, most of them involve the concept of master/slave, which prevents the penetration of the slave body into the master one, which causes the non-symmetry of the algorithm.

In this work, the contact problem is formulated into a constrained minimization one. In the first part, we will present some algorithms, developed using FreeFEM, treating Signorini's problem (contact between a body and a rigid foundation). The Interior point optimizer (IPOPT) is used in order to solve the constrained minimization problem. In the second part an algorithm treating the contact between two bodies is presented, this algorithm uses the penalty method. One of the advantages of this algorithm is its symmetric behavior, in addition the geometries of the bodies can be chosen freely. Finally, in the case of Signorini's problem the resolution can be done in parallel using the solver TAO (PETSc).

The goal of our algorithm is to study the contact between an O-ring gasket and metallic parts of a pressurized machine.

## STS-10-8 Shape Optimization and Additive Manufacturing: The Dehomogenization Method

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### Abstract

**Keywords:** *Shape optimization, Design of mechanical structures, Dehomogenization method*

Shape optimization consists in automatizing the design of mechanical structures, whether it is a building, the wing of a plane or the piece of a car. Recent progress in additive manufacturing open new horizons. Firstly, this type of processes allows for creating pieces containing very fine details usually out of reach of classical methods. Secondly, it permits a customization of the design of a piece for the specific use it is intended to fill. Those characteristics call for the development of new optimization methods. Classical approaches could not fully exploit the potential of additive manufacturing. In this context, we present a new method called dehomogenization, which allows for a fine control of the complexity of a piece with respect to its optimality. Several examples will be presented in 2D and 3D.

A part of this work has been developed in collaboration with Safran.

## **STS Discussion Session 2: Industrial Methods**

**Moderators: Nico Gauger, Tohru Hirano, Hiroshi Okada, Maurizio Maggiore**

### **Participating STS:**

**STS-04           Advanced Modelling for Automotive Applications in Electric and Multi-Powertrain Vehicle Design**

*Chair: Maurizio Maggiore*

**STS-06           An Efficient Multidisciplinary Design Framework for Application in Industry**

*Chairs: Nicolas R. Gauger and Dietrich Knoerzer*

**STS-25           Japan Session 1 – Industrial Application of Extended CAE for the Implementation of Emerging Technologies**

*Chairs: Tohru Hirano and Genki Yagawa*

**STS-28           Japan Session 2 – Computational Mechanics for Integrity of Industrial Infrastructures**

*Chairs: Hiroshi Okada, Hiroshi Okada and Ryuji Shioya*

## STS-04      **Advanced Modelling for Automotive Applications in Electric and Multi-Powertrain Vehicle Design**

**Chair: Maurizio Maggiore<sup>1</sup>**

<sup>1</sup> European Commission, DG Research & Innovation, 1049 Brussels, Belgium  
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### **Session Abstract**

**Keywords:**      *Automotive, Modelling, Machine learning, Powertrain, Vehicles design, Simulation capabilities*

The introduction of new, greener powertrains in automotive applications has led to the need of developing new modelling tools and approaches both to the design of vehicles, which are moving towards a multi-powertrain approach, and individual components (magnetic modelling for electric motors, multilevel modelling for battery systems and cells, etc.). For electrochemical cells, in particular, improving simulation capabilities is key to catching up with current market leaders.

At the same time, approaches like machine learning, big data can deliver order of magnitude improvements in computing times and therefore time to market.

An EU-funded project working in these domains will present the advances and the future technology programmes.

**The following paper will be presented:**

- **Proper Generalized Decomposition (PGD) for Inertia Relief Problems and Parametric Modal Analysis (UPSCALE Project)**
  - Fabiola Cavaliere, Sergio Zlotnik, LaCaN, UPC Barcelona, [fabiola.cavaliere1@upc.edu](mailto:fabiola.cavaliere1@upc.edu), R. Sevilla, Swansea Univ., United Kingdom, Xabier Larrayoz, Centro Tecnico de SEAT, Martorell, Spain, Pedro Diez, UPC, Barcelona, Spain

## **STS-04-7 Application of Artificial Intelligence Enhanced CAE Tools in Vehicle Development (UPSCALE Project)**

**Enric Aramburu**

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### **Abstract**

**Keywords:** *Electrical vehicles, Artificial Intelligence (AI), Data analytics algorithms, Aerodynamic flow fields, Reynolds stresses*

The upcoming of electrical vehicles has posed new challenges to automotive engineers, such as battery modelling in crash simulations or quick and high fidelity aerodynamics assessment, which are deemed unfeasible with traditional CAE and Finite Element solvers. Artificial Intelligence (AI) algorithms have the potential to overcome this limitation thanks to its unbeaten calculation time; however, they open many questions about accuracy, simulation cost including the training efforts or its dependency on the training data and the universality of the solution.

The UPSCALE project is studying the feasibility of surrogating physics based solvers by data analytics algorithms for industrial applications. This paper shows the first conclusions of the usage of the “data based” solvers to compute aerodynamic flow fields and forces, Reynolds stresses in turbulent flows or the probability of shortcut in battery cells in crash events.

## STS-04-8 Proper Generalized Decomposition (PGD) for Inertia Relief Problems and Parametric Modal Analysis (UPSCALE Project)

Fabiola Cavaliere<sup>1</sup>, Sergio Zlotnik<sup>1</sup>, R. Sevilla<sup>2</sup>, Xabier Larrayoz<sup>3</sup> and Pedro Diez<sup>1</sup>

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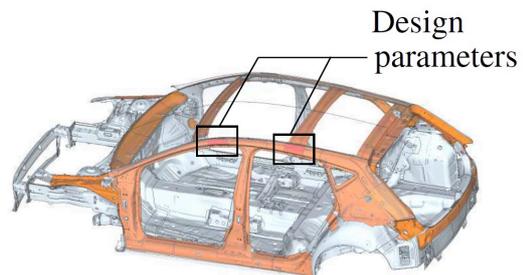
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### Abstract

**Keywords:** *Proper Generalized Decomposition (PGD), Algebraic PGD, Inertia Relief, Modal Analysis, Non-intrusive Design Parameters*

The final goal of this work is to develop a computational method able to optimize the car pre-design process with respect to the dynamic Noise, Vibration and Harshness (NVH) impact. A very crucial task during this phase is the design of components, which must be continuously re-adapted in order to meet all the established target specifications. Fig. 1 shows a typical body-car structure, where the geometrical sections of some components are the parameters of the problem. The ability to perform an accurate and fast evaluation of all possible configurations is still an open challenge, due to the high computational cost of each simulation involved and the number of configurations to be tested. A solution to decrease the numerical complexity of high-dimensional problems is to introduce reduced order models (ROMs) [1].



**Fig. 1:** *Body-in-White structure with parametric geometry*

In this work, the Encapsulated-PGD toolbox, based on the Proper Generalized Decomposition Least-Squares approximation [2], is proposed as a numerical tool able to provide an offline explicit separable solution in terms of an a-priori unknown number of parametric and mechanic modes. An equivalent static analysis of the originally dynamic problem is considered using the Inertia Relief method [3]. Then, the extension to a parametric modal analysis is explored in order to identify how a variation of user-defined parameters affects the dominant eigenmodes of the structure, thus its dynamic response. It will be shown how the method allows to deal with complex geometries and can interact with commercial software in a non-intrusive way. The ultimate goal is to produce a computational “vademecum” that could support the design engineers in the decision-making by evaluating in real time the impact of certain parameters on the global response of the structure.

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### References:

- [1] Chinesta, Francisco and Ladeveze, Pierre and Cueto, Elias, A short review on model order reduction based on proper generalized decomposition, Archives of Computational Methods in Engineering, Vol. 18, pp.395, Springer, (2011)
- [2] Diez, Pedro and Zlotnik, Sergio and Garcia-Gonzalez, Alberto and Huerta, Antonio., Encapsulated PGD Algebraic Toolbox Operating with High-Dimensional Data, Archives of Computational Methods in Engineering, doi: 10.1007/s11831-019-09378-0, (2019)
- [3] Barnett, Alan R. and Widrick, Timothy W. and Ludwiczak, Damian R., Closed-form static analysis with inertia relief and displacement-dependent loads using a MSC/NASTRAN DMAP Alter, (1995)

## STS-06      **An Efficient Multidisciplinary Design Framework for Application in Industry**

**Chairs: Nicolas R. Gauger<sup>1</sup> and Dietrich Knoerzer<sup>2</sup>**

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### **Session Abstract**

**Keywords:**      *Optimization methods, Adjoint solvers, Multidisciplinary case studies, Physical validation*

Optimization methods based on adjoint solvers have become an attractive tool in industrial research. From external aerodynamics to hydrodynamics, they are used to find new designs for the future that minimize energy losses and increase safety. For example, this has been very successful for airfoils, turbine blades or even boat hulls.

Besides their accuracy, adjoints can provide objective function gradients with respect to any design parameter at low computational cost. Over the last years, more and more multidisciplinary design problems, like fluid-structure interaction and conjugate heat transfer, had been approached via this technology.

However, many implementations suffer from being quite specific to a certain application or solver, which makes it hard to transfer them to industrial research departments. In a joint project funded by the Bayerische Forschungstiftung (Bavarian Research Foundation), three established open-source projects, KRATOS, SU2 and CoDiPack, are combined into a framework that is highly adaptable and that can be applied to engineering problems that are not yet known. In order to highlight some of its capabilities, this STS contains talks that present multidisciplinary case studies, physical validations via measurements and applications of the software at Bosch and Bosch Rexroth.

### **List of paper titles and speakers:**

- **Grid-based Shape Optimization to Reduce Pressure Loss under Stress Constraints in Structures with Internal Flow**
  - Daniel Baumgärtner, TU München, Munich, Germany, daniel.baumgaertner@tum.de
  - Kai-Uwe Bletzinger, TU München, Munich, Germany, kub@tum.de
- **Adjoint-based Free-shape Optimization of Pin-fin Heat-exchangers**
  - Tobias Kattmann, Bosch Corporate Research, Renningen, Germany, tobias.kattmann@de.bosch.com
  - Ole Burghardt, TU Kaiserslautern, Kaiserslautern, Germany, ole.burghardt@scicomp.uni-kl.de
- **Numerical and Experimental Validation of an Elbow Shape Optimized for Minimal Pressure Loss**
  - Eman Bagheri, bag@ipat.uni-erlangen.de
  - Stefan Becker, sb@ipat.fau.de
  - Friedrich-Alexander University Erlangen-Nürnberg, Erlangen, Germany,
  - Daniel Baumgärtner, TU München, Munich, Germany, daniel.baumgaertner@tum.de
- **Multidomain Adjoint Optimization Method for Pressure Loss and Lifetime**
  - Fabian Wörenkämper, Bosch Rexroth AG, Lohr am Main, Germany, fabian.woerenkaemper@boschrexroth.de

## STS-06-1    **Grid-based Shape Optimization to Reduce Pressure Loss under Stress Constraints in Structures with Internal Flow**

**Daniel Baumgärtner<sup>1</sup> and Kai-Uwe Bletzinger<sup>2</sup>**

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<sup>2</sup> Chair of Structural Analysis, Technical University of Munich, Germany, kub@tum.de

### **Abstract**

**Keywords:**    *Shape optimization, Vertex Morphing, Adjoint sensitivity analysis, Fluid-structure interaction, Multi-disciplinary analysis and design*

When optimizing structures with internal flow, a typical task is to modify the given shape such that the pressure loss in the flow is minimized, but stress constraints of the structure are satisfied. The task is challenging if the interaction between fluid and structure influences the stresses. We present a method, which solves this task by gradient-based shape optimization [1]. The method assumes a one-way fluid-structure interaction and relies on high-fidelity models. The critical ingredient is a grid-based parameterization of the shape using Vertex Morphing [2]. This parameterization enables a quick set-up of the optimization problem and provides high optimization potential. So far, Vertex Morphing has primarily been used in optimization problems that involve a single discipline. In this work, we extend Vertex Morphing for an application in multidisciplinary problems, e.g., to control several meshes simultaneously. It is shown that Vertex Morphing allows a consistent parameterization across multiple grids without extra modelling effort. We apply coupled adjoint sensitivity analysis to get the required gradients. A custom partitioned solution strategy is derived, which avoids the computation of cross-derivatives. Thus, one can employ given single-disciplinary adjoint solvers to compute the coupled gradients. The sensitivity analysis is verified with different examples. The overall method is demonstrated using a representative structure. The complete analysis and design process is realized using established open-source software [3], [4]. The results show that the method can find significantly improved shapes, despite strongly conflicting response functions.

### **References:**

- [1]    D. Baumgärtner, “On the grid-based shape optimization of structures with internal flow and the feedback of shape changes into a CAD model,” Dissertation [submitted], Technische Universität München, 2020.
- [2]    M. Hojjat, E. Stavropoulou, and K.-U. Bletzinger, “The Vertex Morphing method for node-based shape optimization,” *Comput. Methods Appl. Mech. Eng.*, vol. 268, pp. 494–513, 2014.
- [3]    T. A. Albring, M. Sagebaum, and N. R. Gauger, “Efficient Aerodynamic Design using the Discrete Adjoint Method in SU2,” in *17th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2016.
- [4]    Kratos Developer Community, “Kratos Multiphysics - a framework for building parallel multi-disciplinary simulation software,” 2019. [Online]. Available: <https://github.com/KratosMultiphysics>. [Accessed: 19-Jun-2019].

## STS-06      Adjoint-based Free-shape Optimization of Pin-fin Heat-exchangers

Tobias Kattmann<sup>1</sup> and Ole Burghardt<sup>2</sup>

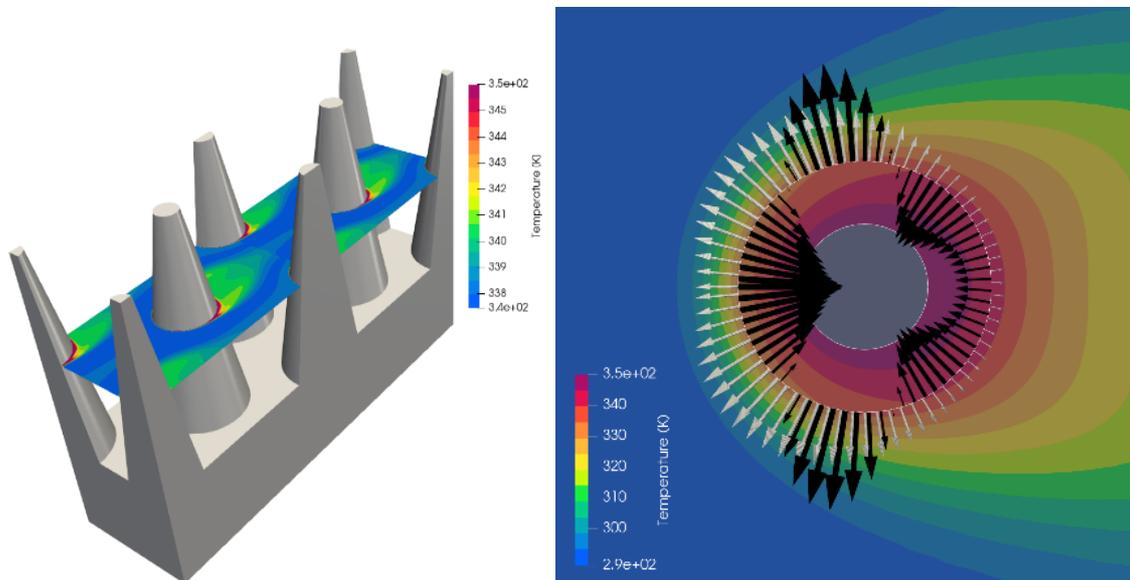
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<sup>2</sup> TU Kaiserslautern, Kaiserslautern, ole.burghardt@scicomp.uni-kl.de

### Abstract

**Keywords:**      *Adjoint optimization, Free-shape, CHT, Heat-exchanger, SU2*

Power electronics used e.g., in electric cars derates its performance above certain temperatures. A commonly used cooling strategy is liquid flow through a uniform pin-fin array attached to the power electronics device. In order to enhance the cooling performance, we use adjoint methods to optimize the pin shape in the array.



**Figure 1:** (left) Simplified simulation domain by using streamwise periodicity ;(right) Gradients of a 2D solid and fluid zone w.r.t. to heatflux over the zone boundary

The used discrete adjoint method using automatic differentiation [1] to compute gradients for generic multizone problems will be presented together with an efficient way to evaluate a pin-shape performance using streamwise periodic flow [2]. Simulation results, gradients and first optimizations will be shown. The implementations are available to the public via the open-source C++ code SU2 [3].

### References:

- [1] T. Albring, M. Sagebaum and N.R. Gauger. Efficient aerodynamic design using the discrete adjoint method in SU2. 17<sup>th</sup> AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference.
- [2] S.V. Patankar, C.H. Liu and E.M Sparrow. Fully developed flow and heat transfer in ducts having streamwise periodic variations of cross-sectional area. *Journal of Heat Transfer*, 99(2):180-186, 1977.
- [3] <https://github.com/su2code/su2>

## STS 06-3 Numerical and Experimental Validation of an Elbow Shape Optimized for Minimal Pressure Loss

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<sup>2</sup> Chair of Structural Analysis, Technical University of Munich, Germany, daniel.baumgaertner@tum.de

<sup>3</sup> Institute of Process Machinery and Systems Engineering, University of Erlangen-Nuremberg, Germany, sb@ipat.fau.de

### Abstract

**Keywords:** *Shape optimization, Pressure loss reduction, Relaminarization, Turbulence control*

Reducing the pumping power consumption in internal flows is directly linked to the minimization of pressure loss. This is especially important in the turbulent regime as the pressure loss scales quadratically with the Reynolds number. Thus, several studies have been conducted aiming at reducing the skin friction using passive methods such as introducing riblet and grooves as well as active approaches like surface heating or cooling.

In this study, we examine the capability of a discrete-adjoint shape optimization to minimize the pressure loss for turbulent flows in curved pipes. We have chosen the SST-RANS equations to model the turbulent flow. The corresponding adjoint equations are solved to compute the surface sensitivities necessary for shape optimization.

Our test-case exemplifies typical losses occurring in internal flows which can be categorized into direct dissipation induced by the mean flow and the turbulent dissipation due to velocity fluctuations. However, there are major uncertainties concerning the outcome of the optimization owing to the Boussinesq approximation at the core of all two-equation RANS models. The inability of the RANS equations in accurately predicting the separation point adds to this uncertainty even when the mean flow quantities such as the direct dissipation are of prime interest. The accuracy of the RANS models further declines in predicting the turbulent dissipation rate as the Reynolds stresses are entirely modelled. In our test-case, a laminar flow is an ideal solution to the pressure loss problem, hence the accurate prediction of the turbulent dissipation is the key for the relaminarization of the flow. This is because turbulence can be entirely suppressed if, and only if the turbulent dissipation at the wall vanishes [1].

To cast light on these uncertainties and to validate the outcome of the optimization, we have conducted experimental studies as well as direct numerical simulations (DNS) of the baseline and the optimized geometries. Both the experiment and the DNS results confirm the reliability of the optimization in reducing a significant portion of the pressure loss. More importantly, the DNS result shows a drastic reduction in the turbulent dissipation rate at the wall downstream of the bend. Consequently, the reduction of the turbulent dissipation rate and the increase in the anisotropy of the Reynolds stresses drive the flow towards relaminarization and a laminar velocity profile starts to appear.

### References:

[1] V. Krieger, R. Perić, J. Jovanović, H. Lienhart and A. Delgado, *Toward design of the antiturbulence surface exhibiting maximum drag reduction effect*, Journal of Fluid Mechanics, Vol. 850, 2018

[2] J. Kühnen, B. Song, D. Scarselli, N. B. Budanur, A.P. Willis, M. Avila and B. Hof, *Destabilizing turbulence in pipe flow*. Nat. Phys., doi: 10.1038/s41567-017-0018-3, 2018

## STS-06-4 Multidomain Adjoint Optimization Method for Pressure Loss and Lifetime

Fabian Wörenkämper<sup>1</sup>

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### Abstract

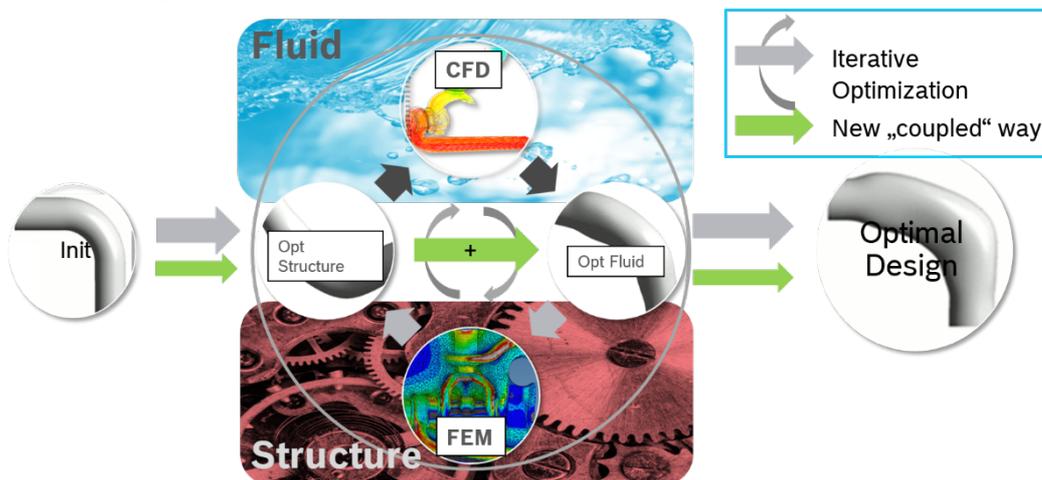
**Keywords:** MDO, Shape optimization, Valve housings, Adjoints

The need for robust and efficient (shape-) optimization strategies has been growing up over the last years. Since the possibilities for creating unusual geometries are increasing due to flexible 3D-printing methods, adjoint optimization techniques becomes a very interesting method since the number of design variables (FE-mesh) does not affect computational time.

For Bosch Rexroth there is a special focus on the shape optimization of valves and valve housings which need to be optimized for fluid- and structural mechanics objectives: pressure losses which result from the fluid flow through the housing channels or from bigger circulation flows shall be decreased while the lifetime of the housings shall be increased or at least kept at the same level. High pulsating pressures in the channels can lead to fatigue failure of the housing after a period with a high number of load changes.

For this an efficient workflow will be introduced where both domains are optimized simultaneously in contrast to the iterative and time-consuming state-of-the-art process where each domain is optimized separately. As this work is embedded in a public research project, a handful of open-source tools are used. The OS – fluid mechanics solver SU2 is used for computations on the fluid mechanics side while structural tasks are solved with Kratos (OS-Software of TUM).

Besides these two ready-to-use tools a self-developed tool is used to compute lifetime analogue to the commercial tool FEMFAT. This code is differentiated by the Tool CoDiPack from University of Kaiserslautern to gain the sensitivities which are needed for the shape optimization process.



## STS-25 Japan Session 1 – Industrial Application of Extended CAE for the Implementation of Emerging Technologies

Chairs: Tohru Hirano<sup>1</sup> and Genki Yagawa<sup>2</sup>

<sup>1</sup> Daikin Information Systems Co. Ltd., Osaka, Japan, tohru.hirano@daikin.co.jp

<sup>2</sup> University of Tokyo and Toyo University, Saitama, Japan, yagawag@gmail.com

### Session Abstract

**Keywords:** CAE, Internet of Things (IoT), Artificial Intelligence (AI), Cyber Physical System (CPS), Digital Twin, Environmental protection, Transportation

Recently, many new innovative technologies such as Internet of Things (IoT), Artificial Intelligence (AI), 5G, Cyber Physical System (CPS) are emerging, and manufacturing industries are facing with the disruptive change for their business paradigm. Moreover, modern manufacturing industries are also confronting with strong consciousness on contributing to the environmental protection of the world.

In the last WCCM XIII Mini-symposium MS1314, we have defined Extended CAE [1] to include not only the design synthesis and optimization but also the IoT and AI technology. Also, in the last 15th USNCCM Mini-symposium MS704, we have discussed on the real-world modelling [2] (Digital Twin) on the Cyber Physical System for the realization of Society5.0 [3]. In this WCCM XIV, we will have Mini-symposium MS196 on 'Leveraging Extended CAE Technology Toward the Realization of Human-Centred Society 5.0'.

In this Japan-STS Industrial Session, we would like to introduce several activities of Japanese Enterprises on the implementation of those emerging technologies into the products, processes and services. Especially concerning to the implementation of those new technologies into the new products and the manufacturing processes, the methodology changes for the realization of the products and processes are required, which sometimes invokes the material change and also structural optimization. Another application of emerging technology are introduced for the development of the new thermo-electric materials in view of the collaboration between AI and materials scientists.

As the keynote speech, the implementation of Statistical Mathematics and Machine Learning technology for Digital Twin in the automobile safety designs will be also discussed. This industrial session will cover those widespread modelling and application technologies, which will integrate computational engineering and information engineering with the help of extended CAE technology.

### References:

- [1] T. Hirano, "Defining Extended CAE Technology toward the Integration of CAE and AI", WCCM XIII, MS1314, July 24, (2018)
- [2] T. Hirano, "Integration of CAE and AI on the Cyber Physical Systems for the Foundation of Society5.0", 15th USNCCM, MS704, July 28 - August 1, (2019)
- [3] [https://www8.cao.go.jp/cstp/english/society5\\_0/index.html](https://www8.cao.go.jp/cstp/english/society5_0/index.html)

**List of paper titles and speakers of STS-25:**

Speech 1 (15 min.)

- **Introduction: Integration of Statistical Mathematics and Machine Learning with CAE Expands the New Digital World for Manufacturing Industries**
  - Tohru Hirano, Daikin Information Systems Co. Ltd., tohru.hirano@daikin.co.jp

Speech 2 (30 min.)

- **Shape Optimization of Catalyst Pellets for the Improvement of Synthesizing Process of Environmentally Friendly Refrigerants**
  - Jihong Liu, Technology and Innovation Center, Daikin Industries Ltd., jihong.liu@daikin.co.jp
  - Daisuke Karube, Chemicals Division, Daikin Industries Ltd., daisuke.karube@daikin.co.jp

Speech 3 (30 min.)

- **Development of New Thermoelectric Material through Collaboration between AI and Materials Scientists**
  - Masahiko Ishida, NEC Corporation, ishida@ah.jp.nec.com

Speech 4 (Keynote, 45 min.)

- **Parametric Model Reduction and Surrogate Modelling of Structural Deformations from Full Model Car Crash Analyses**
  - Tsuyoshi Yasuki, TOYOTA Motor Corporation, tsuyoshi\_yasuki@mail.toyota.co.jp

## STS 25-1 Introduction: Integration of Statistical Mathematics and Machine Learning with CAE Expands the New Digital World for Manufacturing Industries

Tohru Hirano <sup>1</sup>

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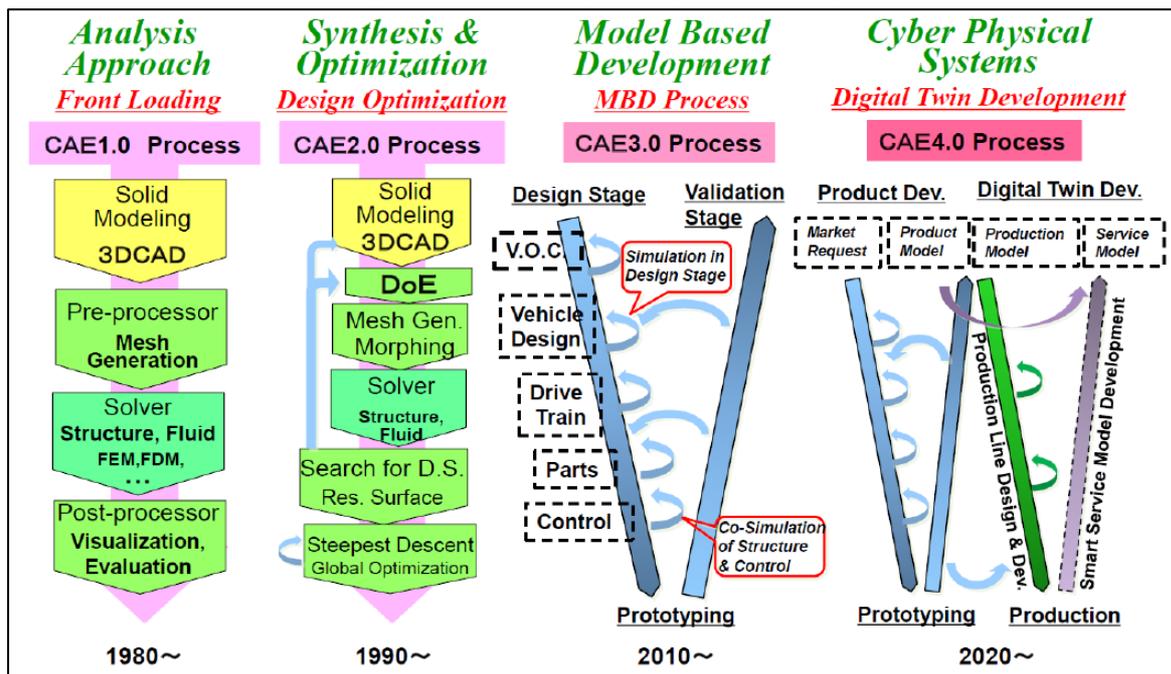
### Abstract

**Keywords:** CAE, Internet of Things (IoT), Artificial Intelligence (AI), Cyber-Physical Systems (CPS), Model Based Development (MBD), Digital Twin Development, Surrogate Modelling

Recently, many new innovative technologies such as Internet of Things (IoT), Artificial Intelligence (AI), 5G and Cyber-Physical Systems (CPS) are emerging, and manufacturing industries are facing with the disruptive change for their business paradigm.

We have defined Extended CAE Technology [1] so as to integrate the Synthesis & Optimization Approach with the IoT & AI Technology in the innovative design process for new products. We have also defined CAE4.0 as the extension of Model Based Development, which will integrate products and Digital Twins on Cyber Physical System and create Digital Twin models for the products, the production lines and the smart services [2] as depicted in the following picture.

We will introduce the new approach to implement those emerging technologies into the products, processes and services with Digital Twins utilizing surrogate modelling.



### References:

- [1] T. Hirano, "Defining Extended CAE Technology toward the Integration of CAE and AI", WCCM XIII, MS1314, July 24, (2018)
- [2] T. Hirano, Integration of CAE and AI on the Cyber Physical Systems for the Foundation of Society5.0, 15th USNCCM, MS704, July 28 - August 1, 2019

## STS-25-2 Shape Optimization of Catalyst Pellets for the Improvement of Synthesizing Process of Environmentally Friendly Refrigerants

**Jihong Liu<sup>1</sup> and Daisuke Karube<sup>2</sup>**

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### Abstract

**Keywords:** *Catalyst Pellet Shape, Reactor, Bulk Density, Stress Distribution, Simulation*

The production technology of fluorocarbon gases by vapour phase reaction is frequently used to produce environmentally friendly HFC (hydrofluorocarbon) and HFO (hydrofluoroolefin) refrigerants that do not destroy the ozone layer and have low global warming potential.

In order to maximize gas production efficiency, it is important to determine the shape and size of catalyst pellets which have been determined based on empirical rules and experiments. This is because the shape and size of the catalyst pellets affect its filling state in a reactor, and the filling state has a great influence on the vapour phase reaction. For example, if the filling state is too dense, the gas cannot pass through catalyst layer efficiently and the reactivity is deteriorated, and if the filling state is too sparse, the gas does not contact the catalyst layer efficiently. In addition, the filling state also affects the stress distribution of the catalyst pellets, and the catalyst pellets in the lower part of the reactor may be crushed by the weight of the upper ones. This may increase pressure loss of the reactor and the catalyst pellets at the lower part of the reactor may become difficult to be used during gas reaction anymore.

In this paper, we proposed a simulation approach based on the dynamic explicit finite element method to evaluate the filling state of catalyst pellets in a reactor [1, 2]. Using the simulation method, we clarified that the shape of catalyst pellet had an influence on its bulk density and stress distribution and found an optimal shape of catalyst pellet that can reduce stress and increase bulk density in a reactor. Moreover, we also revealed for the first time that compared to an optimum cylindrical shape, an elliptical cylinder-shaped catalyst pellet with a major axis to minor axis ratio of 1.5 can further reduce stress by 2% and further increase bulk density by 2%. The optimally shaped catalyst pellet is expected to improve its filling state in the reactor, extend the durability of the catalyst pellet and increase the efficiency of environmentally friendly refrigerants production. At the same time, the simulation method can contribute to speeding up production equipment development and improving its completeness.

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## STS-25-3 Development of New Thermoelectric Material through Collaboration between Artificial Intelligence (AI) and Materials Scientists

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### Abstract

**Keywords:** *Artificial Intelligence (AI), Combinatorial experimentation, Piecewise linear regression*

Recently, spin-driven thermoelectric effects (STEs), including the spin-Seebeck effect (Fig. 1(a)) and anomalous Nernst effect (Fig.2 (b)), has received much attention as a promising path towards low cost and versatile thermoelectric technology with easily scalable manufacturing. However, progress in development of STEs materials is hindered by their very complicated fundamental physics (spincaloritronics, which describes the spin-heat-charge relationship). In such cutting edge of scientific field, data-driven approaches relying on statistics and machine learning, instead of more traditional modeling methods, can exhibit their full potential.

We used machine learning modeling to establish the key physical parameters controlling STEs. Visualization of the machine learning models give us valuable inputs and impetus to understand the STEs phenomena. Guided by the models, we have carried out actual material synthesis which led to the identification of a new STE material with large thermopower.

In the session, we will introduce our combinatorial experimentation methods for materials synthesis and characterization, a machine learning technique based on the piecewise linear sparse regression to obtain models in a multi-dimensional STEs property space [1] and automated first-principle simulation for physical property optimization using a Bayesian game tree search algorithm [2].

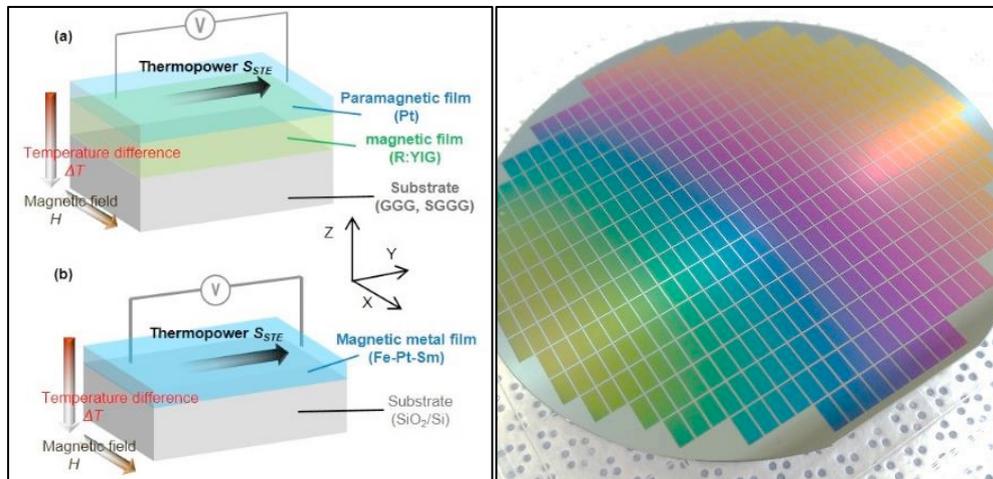


Figure 1: Schematics of the spin Seebeck and anomalous Nernst device structures.

Figure 2: Combinatorial composition spread samples.

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This work was supported by JST-PRESTO (Grant No. JPMJPR17N4), JST-ERATO (Grant No. JPMJER1402).

## STS-25-4 Parametric Model Reduction and Surrogate Modelling of Structural Deformations from Full Model Car Crash Analyses

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### Abstract

**Keywords:** *Collision safety, CAE, Surrogate modelling, Proper orthogonal decomposition*

Full model car crash analyses are common tools for car development in automotive industries. Elapse time of them is around one day, and optimization of performance of collision safety by these analyses are time consuming.

Surrogate model of structural deformations from full model car crash analyses in side impact was generated by using proper orthogonal decomposition (POD) [1]. The surrogate model was a parametric model reduction and could estimate structural deformation of full model car crash analyses in real time changing parameters in the reduced model.

Surrogate model of structural deformations from full model car crash analyses in frontal impact was generated by same way. However, the surrogate model could not accurately estimate structural deformation of full model car crash analyses changing parameters in the reduced model [2]. Bifurcation of deformed shape of front side rail in full model car crash analyses were categorized in to three groups by referring Euclidean distances of the rail, and surrogate model was generated again for each group. These surrogate models could estimate structural deformation of full model car crash analyses accurately in real time changing parameters in the reduced model.

Real time simulation by surrogate model can contribute to reduction of time for optimizing performance of collision safety.

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## STS-28 Japan Session 2 – Computational Mechanics for Integrity of Industrial Infrastructures

Chairs: **Hiroshi Okada<sup>1</sup>, Hiroshi Okuda<sup>2</sup> and Ryuji Shioya<sup>3</sup>**

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### Session Abstract

**Keywords:** *Elastic-plastic problems, Damage mechanics, Advanced particle methods, Isogeometric analysis, Computational fracture/damage mechanics*

In the Special Technology Session (STS) “Computational mechanics for integrity of industrial infrastructures”, we discuss about the most advanced computational methods, which aim at the “integrity of “industrial infrastructures”. The industrial infrastructures include civil engineering structures such as bridges, buildings, highway and railroad structures, aircrafts, ships, power plants, manufacturing facilities, etc. The integrities of such structures are very important issues to assure our safe and sustainable society. The computational methodologies are the tools for us to maintain the integrities of industrial infrastructures. Typical computational mechanics related topics that will be covered in this STS include:

- Advanced Constitutive Models for Elastic-Plastic Problems and Damage Mechanics,
- Large Scale/ High Performance computing,
- New Computational Methodologies, such as Advanced Particle Methods, Isogeometric Analysis, X-FEM, etc.,
- Computational Fracture/Damage Mechanics.

There will be three presentations, one presentation will be given by researchers from industries and the other two will be delivered from researchers in academia.

### **List of paper titles and speakers:**

- **Artificial Intelligence Simulation to Predict of Liver Lipid Levels**
  - Ryuji Shioya, [shioya@toyo.jp](mailto:shioya@toyo.jp)
  - Hongjie Zheng
  - Toyo University, Saitama, Japan,
- **Simulation of Fatigue-Crack Propagation Observed in Mechanical Components in Industry**
  - Koki Tazoe, YANMAR CO. Ltd, Maibara, Shiga, Japan, [koki\\_tazoe@yanmar.com](mailto:koki_tazoe@yanmar.com)
  - Genki Yagawa, Emeritus Professor, Univ. of Tokyo and Toyo University, Japan, [yagawag@gmail.com](mailto:yagawag@gmail.com)
- **On Collaborative Computational Fracture Mechanics Research between the Academic and Industrial Sectors**
  - Hiroshi Okada, Tokyo University of Science, Japan, [hiroshi.okada@rs.tus.ac.jp](mailto:hiroshi.okada@rs.tus.ac.jp)

## STS-28-1 Artificial Intelligence Simulation to Predict of Liver Lipid Levels

Ryuji Shioya<sup>1</sup> and Hongjie Zheng<sup>1</sup>

<sup>1</sup> Toyo University, Saitama, Japan, shioya@toyo.jp

### Abstract

**Keywords:** *Fatty liver, Deep learning, Convolutional neural networks, Transfer learning.*

In recent years, AI technology, especially image recognition technology, has been applied to various fields. In deep learning, a convolutional neural network (CNN) is applied to image classification [1], medical image analysis [2], and so on. In this paper, we apply the CNN image recognition technology to the livestock industries.

In the livestock industry area, the lipid content in meat is an important factor that determines the value of livestock products in general [3]. For example, the abundance of intramuscular fat (IMF) in beef is a significant determinant for grade value. Foie gras known as fatty liver produced from geese or duck is a highly valuable meat-derived product. Chicken livers with high lipid can give us a rich foie gras taste on a budget and is popular for costumers as chicken by-products. In general, the liver lipid grade is largely determined by the subjective experience of graders, therefore inconsistencies and errors in judgment are unavoidable. It is necessary to an objective, quick and simple measure of liver lipid grade.

In this paper, we propose a neural network-based approach to liver lipid level assessment in the image. The dataset is collected from four farms. The liver images and liver lipid values are used for regression and classification. In the regression model, the liver lipid value is predicted directly from the liver image. In the classification models, the liver lipid value is split into two types (normal liver or fat liver). The results show that the model trained using transfer learning achieved high accuracy.

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### Acknowledgements:

This research was supported by grants from the Project of the NARO Bio-oriented Technology Research Advancement Institution (R&D matching funds on the field for Knowledge Integration and innovation).

## STS-28-4 Simulation of Fatigue-Crack Propagation Observed in Mechanical Components in Industry

Koki Tazoe<sup>1</sup> and Genki Yagawa<sup>2</sup>

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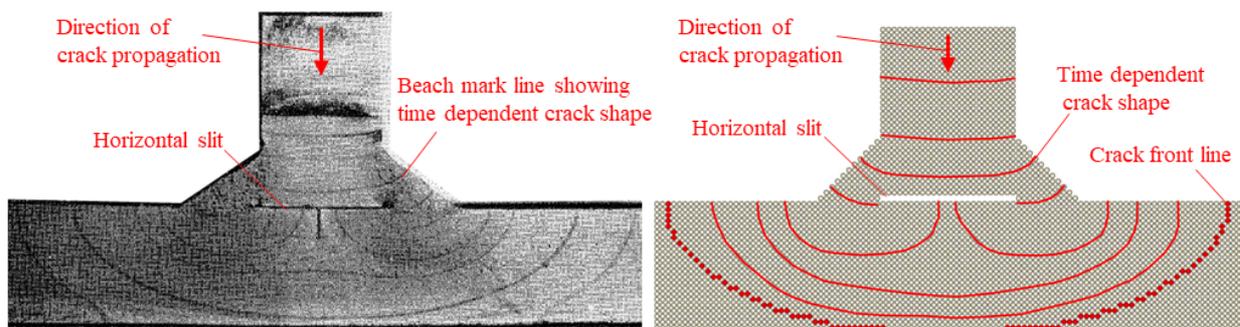
### Abstract

**Keywords:** *Fatigue, Crack propagation analysis, Welded joint, Smoothed particle hydrodynamics method*

The fatigue crack propagation observed in real mechanical structures often involves crack separation and merging. For example, that in a welded T-joint with an embedded horizontal slit, Fig. 1(a), shows the crack separation at the edge of the slit and the merging at the other side of it [1].

To solve such complex situations, we proposed a new approach by using the smoothed particle hydrodynamics method named as “SPH-Fatigue” [2], where the fatigue crack virtually propagates through the crack front particles and the crack front line is given the feature of changing its shape naturally as a chained crack front line based on the experimental observation [2].

In the present study, we apply the SPH-Fatigue to some industrial problems with fatigue crack propagation and the analysed results are compared with experimental results. For example, Fig. 1(b) shows the analysed result of the T-joint structure by the SPH-Fatigue. It is noted that the analysed history of crack shape is almost the same as that of the experiment [1].



(a) Experimental result [1]

(b) Computed result by SPH-Fatigue

**Figure 1:** *Fatigue crack propagation in welded T-joint with an embedded slit*

### References:

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## STS-28-5 On Collaborative Computational Fracture Mechanics Research between the Academic and Industrial Sectors

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### Abstract

**Keywords:** *Flight tests, Fatigue, Multi-axial fatigue, Ductile fracture, Low-cycle-fatigue*

For a number of years, collaborative programs on fundamental and applied fracture mechanics researches have been carried out in subcommittees, which were set by the Atomic Energy Research Committee of JWES (Japan Welding Engineering Society) [1]. The research subcommittees were consisting of expert researchers and engineers from industries and academia. The major target of the researches has been in the enhancement of fracture assessment methodologies for nuclear vessels, pipings and other structures, adding new knowledges and technologies to design and maintenance code for nuclear structures such as Fitness-for-Service for Nuclear Power Plants of JSME (Japan Society of Mechanical Engineers) [2]. The titles of the research programs, their abbreviations and their periods are (1) Research on Fatigue Properties under Multi-Axial State of Stress, its phase 2 and 3 (MF, FY 2001-2003, MF-II, FY 2004-2006 and MF-III, FY 2007-2009), (2) Research on Ductile Fracture under Multi-Axial State of Stress for Component and Structure of Light Water Reactor (MDF, FY 2010-2013, activities halted during FY 2011), (3) Survey on Important knowledge of Multi-Axial Fatigue and Ductile fracture for Component and Structure of Light Water Reactor (MFD, FY 2015-2016), (4) Low Cycle Fatigue and Ductile Fracture under Cyclic Loading (FDF-I, FY 2017-2018) and (7) Low Cycle Fatigue and Ductile Fracture under Cyclic Loading-Phase II (FDF-II, FY 2019-Present). The author has been involved in all the programs, as an active member.

MF, MF-II and MF-III conducted experimental and numerical studies on fatigue problems under multi-axial stress states. In MDF, the researches were extended to the low-cycle fatigue problems under multi-axial stress states. Experimental and numerical studies were conducted. In MFD, the researches continued based on the experimental data which were accumulated in MDF research activities. MF, MF-II, MF-III and MDF programs were sponsored by the group of electric power company headed by the Tokyo Electric Power Company (TEPCO). The researches on the low-cycle fatigue problems have continued in FDF and FDF-II. The outcomes of the researches are open to the research and engineering communities through the web page of JWES [3].

In WCCM-STs, selected research outcomes which were accomplished by the author will be presented based on the information open to the public through the JWES web page [3].

### References:

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## **STS Discussion Session 3: Aeronautics - High-speed Transport**

**Moderators: Gérald Carrier, Normand Pierre-Elie, Marco Marini**

### **Participating STS:**

**STS-14 Sonic Boom Prediction: Near-field Simulation, Far-field Pressure Signature Evaluation, Structural Transmission and Low Boom Design**

Chairs: Gérald Carrier and Pierre-Elie Normand

**STS-16 Hypersonic Flight Technology Developments for Civil Air Transport in Europe**

Chair: Marco Marini

## **STS-14      Sonic Boom Prediction: Near-field Simulation, Far-field Pressure Signature Evaluation, Structural Transmission and Low Boom Design**

**Chairs: Gérald Carrier<sup>1</sup> and Pierre-Elie Normand<sup>2</sup>**

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### **Session Abstract**

**Keywords:** *Supersonic, Near-field pressure field, Far-field pressure signature, Sound metrics, Structural transmission modelling, Low boom design, Prediction capabilities*

Since the retirement of Concorde, many ambitious industrial projects have emerged to be its worthy successor. However current regulations prohibit anyone from operating a civil aircraft at supersonic cruise over land. The reason being the sonic boom felt and heard on ground over the flight path of the supersonic aircraft.

Many researches have showed the way to a design that can diminish the perceived sound level on the ground. The Quiet Super Sonic Technology Demonstrator [1] will provide input concerning the feasibility of low sonic boom design in terms of measures and community response. JAXA intends to demonstrate and validate its "low sonic boom design concept" through flight tests [2]. As for the European side, the project RUMBLE [3] provides sonic boom prediction methodology, sleep studies and structural transmission analysis.

In this context this technical session will focus on the recent international work concerning:

- Near field CFD computation, code-to-code comparison and best practices
- Far field propagation: code-to-code comparison, atmospheric sensitivity, topology effects, earth's boundary layer's turbulence effects and best practices
- Structural transmission analysis
- Low boom design

### **References**

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**The following papers and authors are foreseen in STS-14:**

- **Sonic Boom Prediction Capabilities: Overview of the Project RUMBLE Work Package 2**
  - Gérald Carrier, gerald.carrier@onera.fr, Olivier Atinault, Patrice Malbequi, Aurelia Cartieri, P. Taravel, ONERA, Meudon, F-92190, France,
  - Pierre-Elie Normand, Dassault Aviation, St Cloud, France,
  - Didier Dagna, Sébastien Ollivier, Ecole Centrale de Lyon, Ecully, France,
  - Regis Marchiano, Sorbonne Université, Paris, France,
  - Stephen Rolston, Airbus, Filton, United Kingdom,
  - Jochen Kirz, DLR, Braunschweig, Germany,
  - and Finn Løvholt, NGI - Norges Geotekniske Institutt, Oslo, Norway
  
- **Numerical Modelling Study of Sonic-Boom-Induced Structure Vibration**
  - Joonsang Park, Joonsang.Park@ngi.no,
  - Finn Løvholt, Finn.Lovholt@ngi.no,
  - Karin Norén-Cosgriff, karin.noren-cosgriff@ngi.no,
  - Jörgen Johansson, Jorgen.Johansson@ngi.no, NGI - Norwegian Geotechnical Institute, Oslo, Norway
  
- **Resolution of the Euler Equations in Curvilinear Coordinates for Sonic Boom Propagation**
  - Ariane Emmanuelli, ariane.emmanuelli@ec-lyon.fr
  - Thomas Lechat, thomas.lechat@ec-lyon.fr,
  - Didier Dagna, didier.dagna@ec-lyon.fr,
  - Sébastien Ollivier, sebastien.ollivier@ec-lyon.fr,
  - Philippe Blanc-Benon, philippe.blanc-benon@ec-lyon.fr, École Centrale de Lyon, Écully, France
  
- **Quantification of the Turbulence Effects on Classical and Low Booms**
  - Roman Leconte, roman.leconte@dalembert.upmc.fr,
  - Régis Marchiano, regis.marchiano@sorbonne-universite.fr,
  - Jean-Camille Chassaing, jean-camille.chassaing@sorbonne-universite.fr,
  - François Coulouvrat, francois.coulouvrat@upmc.fr, Sorbonne Université, Paris, France
  
- **Sensitivity Propagation Analysis of a Supersonic Aircraft Low Boom Signal through Different Atmospheres**
  - Pierre-Elie Normand, Dassault-Aviation, St. Cloud, France, pierre-elie.normand@dassault-aviation.com,
  - Gérald Carrier, gerald.carrier@onera.fr,
  - Patrice Malbequi, patrice.malbequi@onera.fr ONERA, France

## STS-14-1 Sensitivity Propagation Analysis of a Supersonic Aircraft Low Boom Signal through Different Atmospheres

Pierre-Elie Normand<sup>1</sup>, Patrice Malbequi<sup>2</sup>, Arthur Schady<sup>3</sup> and Gerald Carrier<sup>4</sup>

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### Abstract

**Keywords:** *Meteorology, Far-field propagation, Statistical analysis, Low boom signal*

The RUMBLE (RegULATION and norM for low sonic Boom LEVELs) project, funded by European Commission, aims through Work Package 2 at validating numerical methods for far field prediction. It also aims, through Work Package 4 at providing inputs to the SuperSonic Task Group within ICAO/CAEP to determine a way of assessing a reference day standard and evaluating maximum sonic boom levels.

The supersonic flight being constrained by regulation authorities, the assessment of an acceptable sound level of sonic booms is required. The level on the ground depends on the nearfield signature of the aircraft and the propagation in a heterogenous atmosphere.

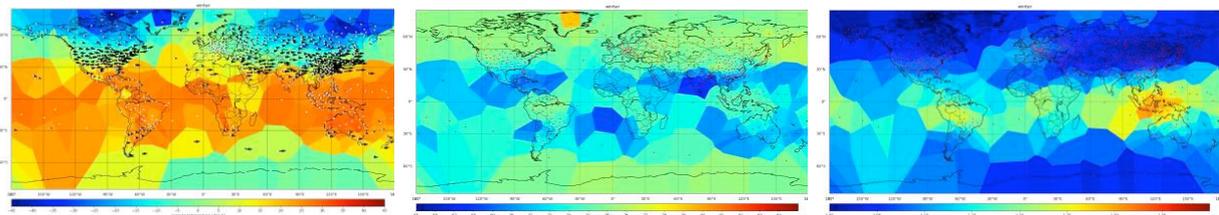
Within the RUMBLE consortium, two propagation codes based on classical ray-tracing [3][4] are available. For both, the propagation from the nearfield to the ground is predicted with the eikonal equation and a sound absorption model.

We first present a comparison of the two codes done by evaluating results on a database consisting of 1100 atmospheres extracted from the Integrated Global Radiosonde Archive (IGRA) database [2] and using a low boom signature based on the NASA C25 low boom concept. Next, in order to conduct a sensitivity analysis of sonic boom propagation two sources were chosen to extract worldwide realistic atmospheres:

- IGRA database [2]
- ERA5 database [1].

For 2017, 666 locations were chosen from the IGRA database and more than 350000 atmospheres were extracted. As for the ERA5 database around 950000 atmospheres were extracted at the same locations.

**Figure 1:** Left: Average temperature at ground level and average wind at 10000m; Center: Average PLdB levels; Right: Mach cut-off evaluation



A statistical comparison is lead to evaluate the sonic boom levels on ground resulting from the far-field propagation as well as Mach cut-off values.

## References

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## STS-14-2 Quantification of the Turbulence Effects on Classical and Low Booms

**Roman Leconte<sup>1</sup>, Regis Marchiano<sup>2</sup>, Jean-Camille Chassaing<sup>3</sup> and Francois Coulouvrat<sup>4</sup>**

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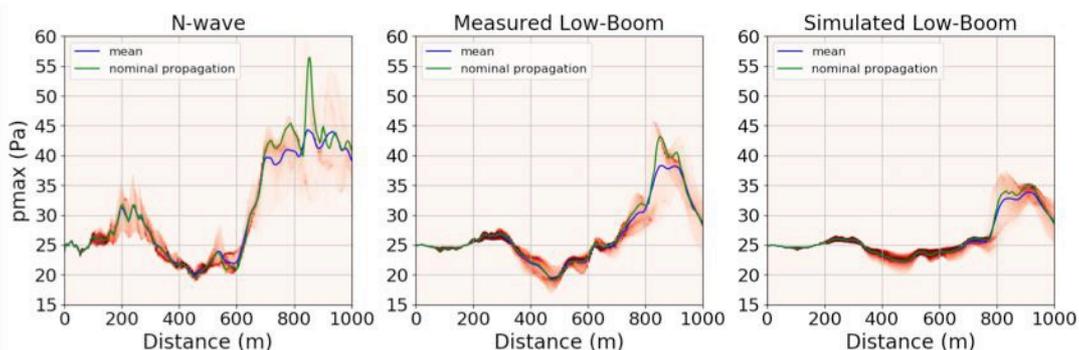
<sup>3</sup> Inst. J. R. d'Alembert, Sorbonne Université, Paris, jean-camille.chassaing@sorbonne-universite.fr

<sup>4</sup> Inst. J. R. d'Alembert, CNRS, Paris, francois.coulouvrat@sorbonne-universite.fr

### Abstract

**Keywords:** *Aeroacoustics, Low-boom, Stochastic study, Turbulent atmosphere*

The renewal of civil supersonic aviation requires to study the propagation of sonic boom in the turbulent atmosphere to quantify the noise perceived on the ground. Indeed, turbulence in the planetary boundary layer is known for long to play a major effect on the shape, amplitude and sound level of the sonic boom, and tools are needed to predict and understand this influence. Here, an isotropic and homogeneous atmospheric turbulence is assumed with a von Kármán spectrum of wind velocity fluctuations. Both classical (N-wave like) booms and low-booms are propagated in the turbulent layer by means of a recently developed 3D propagation code, assuming a wide-angle, one-way nonlinear propagation over a rigid ground in an absorbing atmosphere [1]. A stochastic study is then performed using the generalized polynomial chaos method (gPC) [2] with the von Kármán spectrum parameters as stochastic variables. For one study, a fixed random matrix is used to take into account the inherent randomness of the atmospheric parameters. Such study is then repeated with 50 different realisations of the random matrix, to obtain statistically meaningful observations. The statistical properties of the peak pressure and relevant sound level metrics (A-SEL, B-SEL, C-SEL, D-SEL, and PLdB) are examined with propagation distance, and differences between the propagation of a classical N-wave and a low-boom are observed (figure 1): the classical N-wave shows higher peak pressures and larger variations than the low-boom signal. The sensitivity of the propagation to the turbulence parameters is studied, and a predominance of the intensity of turbulence is observed. Finally, the variance of the metrics as function of the propagation distance shows globally a linear increase with the distance, with a larger slope for the classical N-wave. This study paves the way for a better understanding of the influence of turbulence parameters on sonic boom [Study realised as part of project Rumble - Grant Agreement 769896].



**Figure 1:** Probability density (red), mean value (blue) and nominal value (green) of the ground peak pressure with propagation distance for 3 booms and 1 random realisation matrix atmosphere.

### References

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## STS-14-3 Sonic Boom Prediction Capabilities: Overview of the Project RUMBLE Work Package 2

Gerald Carrier<sup>1</sup>, Olivier Atinault<sup>1</sup>, Patrice Malbequi<sup>1</sup>, Aurelia Cartieri<sup>1</sup>, P. Taravel<sup>1</sup>, Pierre-Elie Normand<sup>2</sup>, Didier Dragna<sup>3</sup>, Sébastien Ollivier<sup>3</sup>, Regis Marchiano<sup>4</sup>, Stephen Rolston<sup>5</sup>, Jochen Kirz<sup>6</sup> and Finn Løvholt<sup>7</sup>

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### Abstract

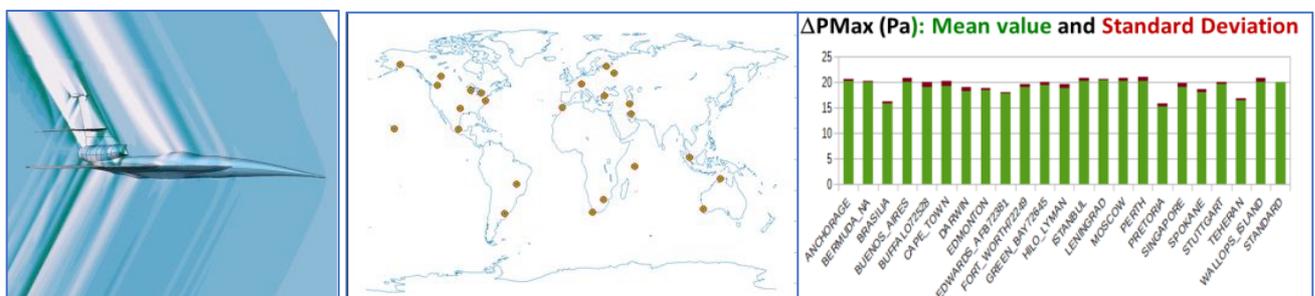
**Keywords:** *Sonic boom, Euler equations, Curvilinear coordinates, Ground effects*

The RUMBLE (RegUlation and norM for low sonic Boom LEvels) project, partially funded by European Commission, is a collaborative research effort between EU and Russia intended to improve knowledge and models, develop numerical and experimental methods and validate simulation codes related to sonic boom. The overall objective of the project is to contribute through scientific data to the international efforts to prepare and propose future regulations for an acceptable low sonic boom supersonic transport. One of the six work-packages composing the RUMBLE project (WP2) is dedicated to the validation of Sonic Boom prediction capabilities, involves seven European partners and targets the following objectives:

- to validate numerical methods for nearfield and farfield predictions of sonic boom;
- to validate wind-tunnel technique for nearfield measurement in cruise conditions;
- to develop and validate models for indoor sonic boom prediction, including building response
- to design the aerodynamic shape of a low boom demonstrator;
- to provide recommendations on sonic boom prediction complying with certification procedures.

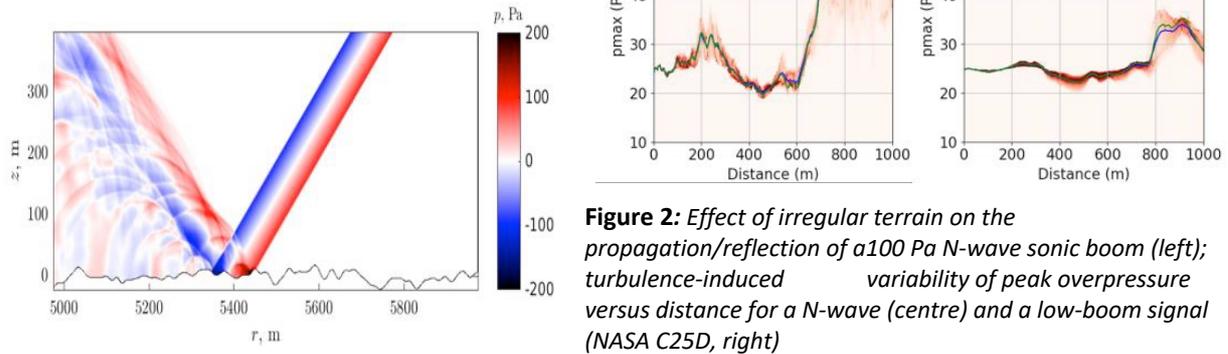
The activities of this second work-package are organized in two main tasks: the first one is devoted to the validation of numerical prediction capabilities of the sonic boom ground signatures produced by representative low-boom aircraft; the second one develops aerodynamic shapes of a representative low-boom demonstrator that will later be tested in a supersonic wind-tunnel.

**Figure 1:** Near field prediction of NASA C25D low-boom geometry by CFD (left) and far-field propagation validation through various realistic atmospheres representative of 24 locations in the world (centre/ right)



In the first task, validations of near-field prediction capabilities by CFD are first performed using the existing low-boom aircraft geometries issued from AIAA Sonic Boom Prediction Workshop 2 (NASA C25D). Investigations of the effect of mesh characteristics and flow-modelling (Euler and RANS) are

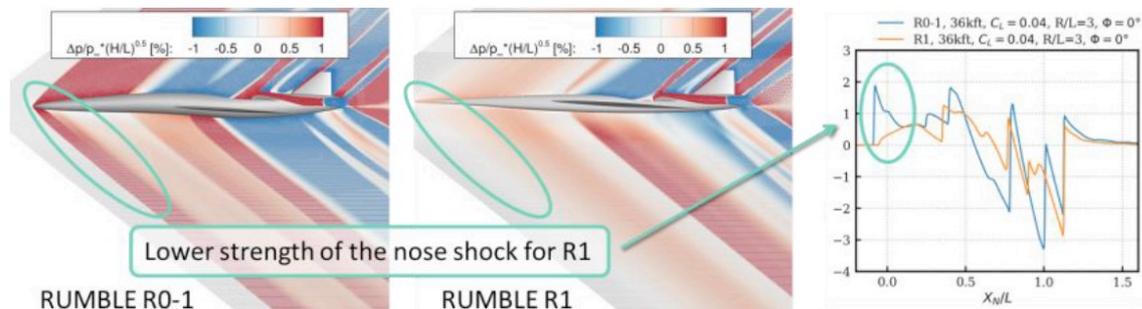
conducted to derive good practices (Figure 1, left). Then prediction of far-field propagation capabilities is evaluated: two propagation codes based on classical ray-tracing [1][2] are verified through extensive code-to-code comparisons on a wide basis of test cases of real atmosphere profiles representative of 24 worldwide locations (Figure 1, right). More complex phenomena impacting the sonic boom, topography (Figure 2, left) and planetary boundary layer turbulence (Figure 2, right), are also investigated using more advanced propagation simulation techniques [1][3].



**Figure 2:** Effect of irregular terrain on the propagation/reflection of a 100 Pa N-wave sonic boom (left); turbulence-induced variability of peak overpressure versus distance for a N-wave (centre) and a low-boom signal (NASA C25D, right)

Finally, an indoor sonic boom prediction methodology has been developed and applied to account for multistorey large building dynamics. It is based on a characterization of building responses in frequency domain using numerical multiphysics simulations accounting for admittance and transmission losses.

In the second task, inspired from previous studies ([4][5][6][7]), an iterative CFD-based manual design process is currently applied to design the aerodynamic shapes of a representative low-boom demonstrator (Figure 3). These shapes will be tested in 2020 in the ONERA S2MA supersonic wind tunnel to validate the low-boom design work and provide new near-field data to validate CFD predictive capabilities.



**Figure 3:** RUMBLE low-boom aerodynamic shape design

In the complete version of the paper, a more detailed descriptions of these different activities conducted in this work-package of the RUMBLE project will be presented.

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## STS-14-4 Numerical Modelling Study of Sonic-Boom-Induced Structure Vibration

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### Abstract

**Keywords:** *Sonic-boom-induced, Structure vibration, Finite element simulation*

Sonic boom induces energetic low-frequency sound and vibration in buildings, which may potentially cause human annoyance. In order to mitigate such undesired impacts, we need to understand quantitatively how sonic boom interacts with typical structures and is transmitted indoor. To achieve this goal, the current study deploys an advanced numerical simulation approach that is based on finite elements (FE) and considers fully-coupled interactions between sound, structure, and ground. The FE method is well suited here, because it enables to incorporate a range of complex building composition, including windows, glasses, wooden stud, coupling between structural elements, etc. in addition to integrating fully between sound pressure and structure vibration for arbitrary geometry (Løvholt et al., 2017).

The primary outcome from numerical simulation is to estimate building vibration, indoor sound pressure as well as their frequency and temporal characteristics. For this purpose, we first select typical sizes for walls and floors in Europe building types, with some detail such as window types, glass thickness, window opening, etc. Then, we calculate various effects on the transmission loss and vibration admittance (i.e. ratio between sound pressure and vibration) by varying wall-floor types, room sizes, number of windows, glass thickness, gaps in window, etc. The building response is highly dependent on the construction type and the above parameters. Furthermore, the simulations show that in many situations, vibrations could be sufficiently large to potentially cause annoyance to people. In particular, openings, poor window quality, and soft floors may lead to such situations. Therefore, it is critical to take into account all the details of different types of construction available for the numerical analysis. The second part of the study is to look into the dynamics of a whole building structure (e.g. multi-storey buildings) due to sonic boom. In this part, the horizontal motion of the building is the main focus. The vibration response is dominated by the lowest natural frequency of the building, typically below 3-4 Hz. We use laboratory data and full-scale field test data from sound sources such as blasts, loudspeakers, and subsonic aircrafts to calibrate the model simulations. In addition, we analyse and use new sound and vibration field data from supersonic flight tests conducted in Russia in 2019.

This work is conducted within the EU Horizon 2020 project RUMBLE and has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the grant agreement No 769896.

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## STS 14-5 Low Sonic Boom Design in RUMBLE Project: Progress and Challenges

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### Abstract

**Keywords:** *Supersonic, Sonic boom, Ground noise, Aerodynamic design, Optimization*

A transport aircraft flying at supersonic cruise speed generates shock waves that hit the ground, producing a typical bang noise. Several studies demonstrate that this sonic boom can be mitigated to acceptable levels thanks to a dedicated aerodynamic shaping ([1] to [4]).

The EU funded RUMBLE project (RegULATION and norM for low sonic Boom LEVELs) is a collaborative project dedicated to the production of the scientific evidence requested by international regulation authorities to determine the acceptable level of overland sonic booms and the appropriate ways to comply with it. Within RUMBLE, the authors collaborate to design a low boom demonstrator concept. Most of the work relies on iterative design loops using CAD design and CFD computations (inviscid and viscous flows), while fulfilling the constraints of integrating the engine, the cockpit, the landing gears and other devices.

Starting from a reference R0 geometry corresponding to a single pilot, one engine configuration of a supersonic concept flying at Mach = 1.6 at 36 000 ft, the collaborative work first focused on the nose aerodynamic shaping and wing design, using iterative design loops. The resulting R1 shape was then optimized to improve the nose aero shaping, which plays a major role in sonic boom reduction. Wing dihedral together with an apex were added in order to smooth the area rule of the configuration; leading to the R2 geometry. Assessing the pressure levels in the near field, 3 to 5 body lengths away from the aircraft, and propagating these signals with numerical far-field propagation tools show that all those efforts lead to a true improvement of the sonic boom levels.

Shaping the configuration from nose to tail, the design now focuses on the air intake integration, which strongly couples with the upper wing flow, and the horizontal tail plane and nozzle shielding that drive the tail shock waves. The remaining work represents an exciting challenge given the high interdependency of aircraft components and their contribution to the sonic boom perception on ground. The final R3 configuration will be evaluated at several flight conditions in order to assess the robustness of the design in terms of sonic boom reduction.

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## STS-14-6 Resolution of the Euler Equations in Curvilinear Coordinates for Sonic Boom Propagation

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### Abstract

**Keywords:** *Sonic boom, Euler equations, Curvilinear coordinates, Ground effects*

Sonic boom prediction is tackled within the EU project RUMBLE, which aims at providing expertise to support the definition of new regulations regarding low-level sonic boom. The impact of atmospheric turbulence, temperature gradients and ground effects on sonic boom propagation are notably investigated.

In the present work, sonic boom propagation is simulated by solving the 2D non-linear Euler equations in the time domain. Adiabatic flow is assumed, with ideal and calorifically perfect fluid. With the current prediction schemes, the ground is usually assumed flat and perfectly reflecting and the amplitude of the reflected boom is obtained by multiplying the one of the incident boom by a constant factor. With this code, ground elevation variations can be taken into account thanks to a curvilinear coordinate system. It allows to adjust the mesh to a varying topography at ground level. The use of the Euler equations allows to account for diffracted waves generated by ground elevation gradients without any approximation, unlike parabolic methods or ray-tracing. The code is based on finite difference, using high-order schemes to capture the propagation of acoustic waves accurately [1]. An optimised fourth-order scheme using an eleven point stencil is chosen in space along with a selective filter, and an optimised fourth-order six-step Runge-Kutta scheme is used in time. The equations are solved in a supersonic moving frame, so that non-reflective acoustic boundary conditions are not required.

Both elevation and meteorological effects on sonic boom can be investigated using this method. The impact of different types of ground elevation is analysed for incident boom signatures typical of a classical N-wave and of a low boom. Investigations are focused on waveform variability but also on modifications of the noise perceived at ground level using metrics sensitive to different frequency content.

### Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N769896 (RUMBLE). In addition, this work is supported by RSF-17-72-10277 and by the Labex CeLyA of Université de Lyon, operated by the French National Research Agency (ANR-10-LABX-0060/ANR-11-IDEX-0007).

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## STS-16 Hypersonic Flight Technology Developments for Civil Air Transport in Europe

Chair: Marco Marini<sup>1</sup>

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### Session Abstract

**Keywords:** *Hypersonic flight, Stratospheric altitude, Liquid hydrogen*

Since fifteen years, the European Commission has been funding projects devoted to civil high-speed air transport at stratospheric altitudes, with the final goal to reduce the duration of antipodal flights to 2-4 hours. These vehicles take off and land as conventional aircraft. They are equipped by propulsive systems using liquid hydrogen as fuel and are able to accelerate up to Mach 5-8 at typical cruise altitudes of 25-35km. Studies have demonstrated the technical and economic feasibility of hypersonic flight, also highlighting that various misconceptions or prejudices exist resulting in the formulation of particular paradoxes and paradigms.

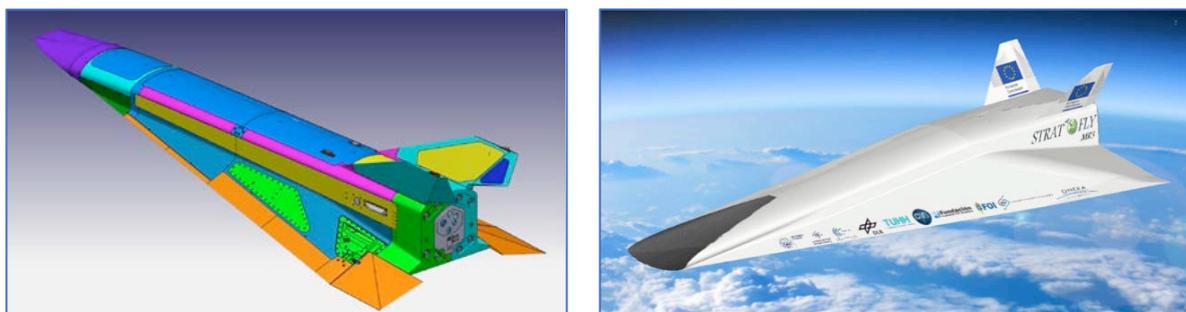
Many technological aspects have been deepened, when developing complex systems as cruise vehicles and flight demonstrators, by exploiting latest developments in computational mechanics and applied mathematics, including experimental campaigns for validation: i) aerodynamics and aerothermodynamics; ii) air breathing propulsion (precooled turbojets, air turbo rockets, dual-mode ramjets/ scramjets); iii) air-hydrogen combustion; iv) NO<sub>x</sub> emission reduction and jet noise abatement; v) flight mechanics, trajectory optimization and GN&C; vi) avionics, on-board instrumentation, flight control system; vii) structural airframe, materials layout, thermal protection system, thermal control system, thermo-structural analysis.

The modelling approach has ranged from engineering tools used in preliminary stages of the projects to high-fidelity properly validated simulation tools for detailed design phase, requiring without doubt a multi-disciplinary approach that needs flight data for its validation.

This STS will present the status of technology developments in European research institutions, university and industries, showing some key achievements that are contributing to enhance the accuracy and fidelity of design tools to be used for future high-speed passenger aircraft.



**Figure 1:** LAPCAT-II A2 cruiser (left) and LAPCAT-II MR2.4 vehicle (right)



**Figure 2:** HEXAFLY-INT EFTV glider (left) and STRATOFly MR3 vehicle (right)

**List of paper titles and speakers of STS-16:**

- **High-Speed Transportation: Challenges, Paradigms and Paradoxes**
  - Johan Steelant, ESA-ESTEC, Noordwijk, The Netherlands, Johan.Steelant@esa.int
  
- **HEXAFLY-INT: Design of the Experimental Flight Test Vehicle**
  - Sara Di Benedetto, CIRA, Capua, Italy, s.dibenedetto@cira.it
  
- **Main Challenges of the Concept of Operations of Future High-Speed Aircraft: The Case of STRATOFly MR3**
  - Nicole Viola, Politecnico di Torino, Turin, Italy, nicole.viola@polito.it
  
- **Combined Cycle Propulsion System Design and Challenges for STRATOFly MR3 Power Plant**
  - Bayindir H. Saracoglu, VKI - von Karman Institute for Fluid Dynamics, Rhode-Saint-Genese, Belgium, saracog@vki.ac.be
  
- **The SABRE Hypersonic Test Bed (HTB) – A European Hypersonic Flight Research Vehicle**
  - Richard Varvill, Reaction Engines Ltd., Culham Science Centre, Abingdon, Oxon, U.K., Richard.Varvill@reactionengines.co.uk

## STS 16-1 High-Speed Transportation: Challenges, Paradigms and Paradoxes

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### Abstract

**Keywords:** *Hypersonics, Flight test, Vehicle design, High Speed Transportation*

In line with the long-term vision of the European Commissions' FP6 and FP7 framework programmes, several complementary activities on civil high-speed transportation were initiated as from 2005. These provided the European industries, research institutions and academia a unique opportunity to elaborate various technologies and to work out vehicle concepts covering a wide scope of speed, fuel and range. The focus was both on the development of needed technologies and the technical feasibility of high-speed vehicle concepts for civil long-haul transportation. The various disciplines covered throughout the last 15 years permitted an evolutionary technology development and provided with modest budgets sufficient background to evolve towards an international experimental flight platform for high-speed transportation.

Civil high-speed transportation has always been hampered by the lack of range potential or too high fuel consumption stemming from a too low cruise efficiency. During the ATLLAS I/II and LAPCAT I/II projects, radical new vehicle concepts were proposed and conceived having a strong potential to alter this trend. This innovative approach is based upon a well elaborated integration of a highly efficient propulsion unit into a high-lifting vehicle airframe. The realization of a combined high propulsive and aerodynamic efficiency is based upon the minimization of kinetic jet losses while striving to the most uniform yet minimal induced velocity for lift creation.

ATLLAS and LAPCAT aimed investigating basic phenomena such as high-speed aerodynamics (transition, SWBLI, FSI...) and airbreathing propulsion (intakes, scramjets....), environmental impact (emissions, sonic boom...), numerical multi-disciplinary tool development and validation, economics.... Additional projects such as HIKARI and FAST20XX extended the scope towards market response, thermal-energy management, flight control, suborbital flights, legal and medical aspects, safety... The more general outcomes and observations accumulated over the last 15 years can be grouped as follows:

1. High-Speed Transportation Paradigm: high-speed transportation is technically and economically viable.
2. Thermal Paradox: the faster one flies for a given range, the lower the on-board absorbed heat.
3. Structural paradox: the faster one flies, the more flight cycles the materials can sustain.
4. Environmental paradigm: the faster one flies, the higher the cruising altitude with a potentially lower impact on the climate.

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## STS 16-2      HEXAFly-INT: Design of the Experimental Flight Test Vehicle

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### Abstract

**Keywords:**      *Hypersonics, Flight test, Vehicle design, High Speed Transportation.*

The HEXAFly-INT Experimental Flight Test Vehicle (EFTV) has been designed to perform an unpowered controlled flight test at hypersonic speed, demonstrating the capability of performing manoeuvres and carrying breakthrough technologies on-board.

The payload will be launched by a sounding rocket (the Brazilian VS50 launcher based upon a 12-ton solid rocket motor) in a suborbital trajectory having an apogee at about 100 km. During the early phase of its descent flight segment, the EFTV will be docked to the Experimental Support Module (ESM) which has the aim of controlling the vehicle attitude by means of Cold Gas reaction control System thrusters (CGS). After the separation from the ESM, a pull-out manoeuvre will bring the EFTV to level flight condition at a target altitude of 32km at approximately Mach 7 (experimental phase). The EFTV will be equipped with an avionic system composed of an inertial measurement unit, a GPS, two servo-actuators for the ailerons, and a flight control computer, which will ensure the on-board mission management. The vehicle will also be equipped with an in-flight measurement system acquiring pressure, temperature and acceleration data sensors for the sake of post flight analysis and simulation tools validation. The on-board avionics will also include a downlink telemetry system (i.e. with antennas) which will transmit all mission data to the Ground Control Station at the launch site.

The vehicle design, manufacturing, assembly and verification are the main drivers and challenges in the project. A multidisciplinary approach has been adopted for designing the EFTV [1]; a view of the main activities and their integrations will be given.

A synthesis of the relevant aspects concerning the EFTV Aero-Database will be provided. It relies on a massive number of Navier-Stokes CFD computations; an extensive comparison between numerical and experimental results was also performed [2]. This approach allowed to validate the CFD results in representative conditions, and define a suitable uncertainty model that was provided to Flight Mechanics team along with the nominal coefficients. Then, a Monte Carlo simulation campaign was carried out accepting AoA and bank angle as external inputs with mission objectives clearly driving the definition of cost functions and constraints [3].

As a low-cost demonstrator, the main structure of the EFTV vehicle is mostly metallic. The chosen material is a Russian variant of titanium alloy, named BT-20. A high emissivity paint ( $\epsilon > 0.8$ ) is used for maintaining the temperature of the fuselage panels below 700°C.; at stagnation regions additional protection by ZrO<sub>2</sub> is needed. Ceramic Matrix Composite material is adopted for the hot structures (wing leading edges and ailerons). Finally, the internal equipments are protected from the thermal radiation coming from the panels of the structure by means of an internal thermal protection system based on a light flexible microporous insulator named Aeroguard® provided by PROMAT firm in Belgium. The materials configuration was mainly defined by means of a coupling between results from CFD in terms of heat flux convective coefficient and thermal FEM analyses [4].

The combination of thermal loads with the other loads the vehicle is subjected to during the flight manoeuvres (inertial and pressure loads) provides the table of load cases used for structural analysis and safety assessment during the descent part of the trajectory, whereas during ascent the main contribution to structural loads is given by the loads at take-off. For these latter, the equivalent quasi-static loads (combination of static and dynamic loads) at the centre of gravity of the vehicle were computed.

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## STS 16-3 Future Aerospace Transport & High-Speed Vehicles: Combining Aeronautic & Space Technologies

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### Abstract

**Keywords:** *Space transportation, Innovative aerospace vehicles, Numerical solutions*

ArianeGroup industrial view on far future space transportation is calling for a vehicle which enables regular flight from Earth to space low orbit, and back, also capable to transport passengers: this is the concept of an “orbital spaceplane”.

This step is far from reach with today's technologies, and ArianeGroup, at that time Astrium then Airbus-DS, did look for an intermediate technological advanced concept motivated by the opportunity of the emerging market related to human access to sub-orbital space (pioneered by USA companies Virgin Galactic, X-Cor and Blue Origin at that time).

The concept study was indeed combining aeronautics and space technologies for such innovative vehicle that a sub-orbital spaceplane is. Critical technologies validation through R&T effort proved that such choice was sound. Then AG developed a vision of aerospace future transport vehicle enabling, along successive technological and vehicle system incremental steps and related applications, to serve both the space and the aeronautic markets for transportation of goods and passengers, opening as well the path to passengers high-speed (hypersonic) / long range transport in civil-aeronautic-like safe conditions.

The paper will summarize this vision, and introduce the high-speed passenger long-range transport aerospace vehicles that ArianeGroup, in its former status and today, conceptually studied.

Two emblematic vehicles, in ArianeGroup referential, are introduced: on the air-breathing hypersonic transport side, the aerospace-plane ZEHST concept was established at time of Astrium with Airbus Innovation Work, capitalizing on the sub-orbital Astrium Spaceplane results, with the target of using matured propulsion technologies and introducing a particular flight path for minimizing some environmental impacts.

At the other end of the studied concepts, the X-Hyp is a point-to-point spaceplane, injected at high speed and flying to destination in hypersonic gliding, currently under study. Its flight path brings it at edge of space but it is managed for being much more effective (lighter vehicle) than a ballistic vehicle for the same range. The design is made for Zero Carbon Emission, and quasi-zero sonic boom impact, fulfilling the societal expectations of today.

Finally, those innovative aerospace vehicles require advanced computing capabilities and numerical solutions, as they drive the engineering teams to enter somehow new aerodynamic, aerothermal/thermal and thermodynamic domains, due to the new operational use (aerodynamics, propulsion) and higher stress combinations on materials.

## STS 16-4 Main Challenges of the Concept of Operations of Future Highspeed Aircraft: The Case of STRATOFly MR3

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### Abstract

**Keywords:** *High Speed Transportation, Mission analysis, Emissions, Noise*

The worldwide incentive to reconsider commercial high-speed transport urges Europe to quantitatively assess the potential of civil high-speed aviation with respect to technical, environmental and economic viability. High-speed commercial flights could be significantly beneficial for long-haul routes to virtually shrink the globe and shorten the time of flight of one order of magnitude for antipodal destinations, thus revolutionizing the present idea of business trips and touristic travels.

The fulfilment of this need can however be seriously hampered by the goal of reaching complete decarbonisation in aviation by 2050, unless innovative technological solutions are investigated, developed and eventually integrated and validated in operative aircraft. Different enabling technologies at subsystems level and different aircraft configurations are likely to be sought for the various ranges (short, medium and long) to comply with the requirement of zero carbon dioxide emissions.

The concept of high-speed aircraft makes sense only for long-haul routes with ranges up to antipodal destinations because long-haul routes maximize the benefits of a hypersonic cruise, while medium-haul routes suffer from shorter cruise phases. Therefore, for long-haul high-speed routes liquid hydrogen can be considered as not drop-in fuel to allow for zero carbon dioxide emissions. Thanks to its higher specific energy, liquid hydrogen is crucial for long range missions, which do also benefit from higher aerodynamic and propulsive efficiency. However, to reach the goal of green aviation, the target of zero carbon dioxide emissions is not enough. In fact, nitrogen oxide emissions have also to be kept as low as possible to control air quality and water vapour has to be minimized to control the balance of green-house gases. In the next future aviation shall be green and shall be quieter. The latter issue, noise, becomes extremely important when it comes to high-speed aircraft.

Within this context, the H2020 STRATOFly Project aims at assessing the potential of a high-speed transport vehicle to reach TRL6 by 2035, with respect to key technological, societal and economical aspects. STRATOFly builds on the heritage of past European projects, taking as reference the mission and the aircraft configuration of LAPCAT II project. On this basis, the design of the vehicle, STRATOFly MR3, and its mission are assessed further.

After a brief introduction about the Horizon 2020 STRATOFly project, the paper focuses on the analysis of the reference mission of STRATOFly MR3 and on additional feasible missions connecting more city-pairs. Aircraft performance are evaluated all along the trajectory. Nitrogen oxide and water vapor emissions are calculated for all flight phases, on the basis of low-fidelity and high-fidelity models, and their effects on climate impact are analyzed, taking also into account possible variations of cruise altitude without affecting the propulsive performance. In addition, noise is estimated for the LTO (landing and take-off) cycles.

As high-speed aircraft, suited for long-haul routes, STRATOFly MR3 is compared with its main competitors which exploit hydrocarbon or liquid hydrogen as fuel. Eventually main conclusions are drawn.

## STS-16-5 Combined Cycle Propulsion System Design and Challenges for STRATOFly MR3 Power Plant

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### Abstract

**Keywords:** *Hypersonic propulsion, Combined-cycle propulsion, Scramjet, Air-turbo rocket.*

The current aviation ecosystem and society pushes the industry to develop new airplanes which fly faster, cleaner and higher efficiency than the industry standards of today. In this regard, hypersonic aviation can address such needs by significantly reducing the flight time for the long-haul routes. European Commission's Horizon 2020 program funded STRATOFly project aims at developing a hypersonic aircraft which cruises at Mach 8, carries 300 passengers at stratospheric altitudes as high as 35 km. The propulsion system is at the heart of such an ambitious flight mission as being the most critical sub-system. In order to make sure economically viability and reusability, the vehicle should be powered by air-breathing engines throughout the complete flight trajectory. This new aircraft concept, called STRATOFly MR3, will be propelled with a combined cycle power plant composed of six air-turbo rocket (ATR) and a dual-mode ramjet/scramjet (DMR) engines. The ATR engines are used to taxi, take-off and accelerate the aircraft to supersonic speeds from the runway. Then the DMR engine kicks in ramjet mode to provide extra thrust to contribute the acceleration of the vehicle further up to Mach 4 - 4.5. Subsequently, the ATR engines are shut down and DMR engine provides the required thrust in scramjet mode to achieve hypersonic speeds and power the aircraft at nominal cruise conditions. Hydrogen is used as the single fuel throughout the entire flight duration for both engines of STRATOFly MR3.

A comprehensive thermodynamic analysis and optimization of the engine components are required to ensure seamless operation of the propulsion system. There are strong interdependencies amongst various elements of the engine. Heat regeneration from the exhaust stream through fuel system is essential to drive the turbo components. Therefore, the optimization of the heat-exchangers located around the combustion chamber and the propulsive nozzle has been accomplished in conjunction with sizing of turbomachinery parts as well as throttling conditions of both engines throughout the complete ascend trajectory of the vehicle. Figure 1 depicts the complexity and the interactions among different engines and engines components on a simplified schematic of the combined cycle power plant of MR3. The current study aims at summarizing the efforts devoted to optimize the engine components and their working conditions for an extended flight trajectory from the take-off till hypersonic speeds.

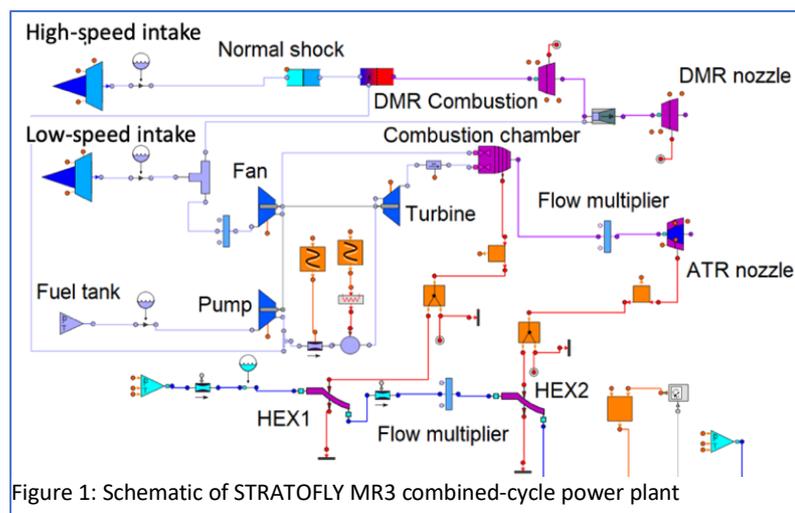


Figure 1: Schematic of STRATOFly MR3 combined-cycle power plant

## STS 16-6 The SABRE Hypersonic Test Bed (HTB) – A European Hypersonic Flight Research Vehicle

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### Abstract

**Keywords:** *Hypersonic Test Bed, Sabre, Intake, Bypass, Precooler*

Reaction Engines Ltd (REL) is currently developing the Synergetic Air-Breathing Rocket Engine (SABRE) to power future reusable launch vehicles. The SABRE airbreathing core and rocket engine are specifically designed to be ground testable to high TRL, since their performance is largely independent of altitude and flight Mach number. However, this is not the case for the nacelle sub-system comprising intake, precooler and bypass burner. Consequently, due to the Worldwide lack of hypersonic wind tunnels of adequate scale, Mach and enthalpy there is a requirement for a hypersonic test bed to develop these components as an integrated system in flight. The proposed test vehicle will be reusable with some degree of abort capability to permit an incremental flight test programme with multiple flights at low recurring cost. This will allow a classic test/fix development programme which would otherwise be prohibitively expensive if the nacelle was tested on a ballistic expendable rocket.

REL is currently studying three candidate architectures for this vehicle comprising a twin nacelle wing tip mounted version, a single dorsal mounted nacelle version, and finally a single dorsal mounted nacelle with rocket assist version. The pros/cons of these versions will be discussed and the rationale for the final selected architecture presented.

The engineering and design status of the Hypersonic Test Bed (HTB) will be described in some detail including trajectory modelling, layout, structural concept, mass breakdown, thermal protection system (TPS) concept, and outline cost estimates.

Finally, the opportunity for utilising the HTB as a general-purpose European hypersonic flight research vehicle will be explored. For example, the HTB could be utilised for flow physics research (boundary layer transition, base flowfield aerodynamics, etc.), propulsion system testing (scramjets, intakes, nozzles, etc.), airframe technology development (thermal management systems, structural concepts, cryogenic propellant systems, panel flutter), materials development (CMC's, TPS concepts), suborbital re-entry testing (high angle-of-attack (AOA) aerodynamics, thermal management of shock impingements, etc.), propellant management under near weightlessness conditions, and many others.

## **STS Discussion Session 4: Aeronautics – Wing Aerodynamics**

**Moderators: Jochen Wild, Marianna Braza**

### **Participating STS:**

#### **STS-07 Progress in Simulation and Validation of High-Lift System Aerodynamics**

*Chair: Jochen Wild*

#### **STS-17 Smart Morphing and Sensing for the Wings of the Future**

*Chair: Marianna Braza*

## **STS-07 Progress in Simulation and Validation of High-Lift System Aerodynamics**

**Chair: Jochen Wild\***

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### **Session Abstract**

**Keywords:** *High-lift aerodynamics, Flow separation control, High-lift system design*

The aerodynamics of high-lift systems on transport aircraft still poses high challenges on the capabilities of numerical simulations. While the demand on accurately predicting stall onset is still not achieved to a sophisticated level, new challenges arise with the progress on active flow control technologies and load control.

Previous issues of this STS have concentrated on progress in European projects performing and using high-level validation experiments for steady flows at stall onset. This issue of the STS is intended to provide insight into activities tackling the improvement of simulation capabilities for current challenges of high-lift system development, as there are:

- progress in high-lift system design for laminar wing technology;
- unsteady phenomena of high-lift system aerodynamics during high-lift system deployment;
- usage of high-lift systems for dynamic load control in low-speed flight regime;
- simulation of dynamic active flow control for stall performance improvements.

Contributions are expected from running international research projects governed by Horizon 2020 Research and Innovation Actions, contributions to Clean Sky 2, as well as other national and international cooperation activities.

**The following papers and speakers are foreseen:**

- **Design and Testing a Full Scale Laminar Wing Leading Edge High-Lift System**
  - Jochen Wild, DLR, Salvatore Palazzo, CIRA, Ionut Brinza, INCAS
- **Unsteady CFD Results for Deflecting High-Lift Systems**
  - Stefan Wallin, KTH Stockholm, Pierluigi Iannelli, CIRA, Ales Prachar, VZLU, Jorge Ponsin, INTA
- **A 2D Validation Experiment for Dynamic High-Lift System Aerodynamics**
  - Jochen Wild, DLR, Moritz Schmidt, Antoon Vervliet, ASCO, Geoffrey Tanguy, ONERA
- **Active Flow Separation Control on a Generic UHBR Engine High-Lift Configuration by Means of Suction and Oscillatory Blowing**
  - Junaid Ullah, Univ. Stuttgart, Shay Monat, Avraham Seifert, Tel Aviv Univ., Thorsten Lutz,
  - Ewald Krämer, Univ. Stuttgart

## STS 07-1 Design and Testing a Full Scale Laminar Wing Leading Edge High-Lift System

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### Abstract

**Keywords:** *Hybrid laminar flow control, High-lift system, Krueger flap, Wind tunnel test, Icing test*

The feasibility of laminar flow control technology for future wing is bound to the development of a leading edge high-lift system that complies with the requirements on smooth surfaces to enable maintaining the laminar boundary layer flow. Classical leading edge high-lift devices like slats are not suitable as they introduce disturbances in the very sensitive upper surface leading edge area.

Krueger flaps, which are deflected from the lower side of the wing, are a good alternative as they additionally offer the capability to shield the wing against contamination by insects, water or dirt. Already in 1985, Boeing proposed a concept of a vented Krueger forming a gap flow between main wing and Krueger flap together with a folding bull nose [1][2]. Although in principle the aerodynamic performance of a Krueger flap is less than for a slat, Rudolph [1] proposed to further develop this kind of Krueger device to provide aerodynamic characteristics comparable to a slat device. Within the EC project DeSiReH a vented foldable bull nose Krueger was designed that showed comparable high-lift aerodynamics [3].

Within the European AFLoNext project, a full scale HLFC leading edge demonstrator was designed and built that incorporated the vented foldable bull nose Krueger [4]. In summer 2018 this demonstrator was wind tunnel tested in the CIRA Icing Wind Tunnel facility. Within this test the aerodynamic design was verified. Additionally, it was tested whether the Krueger device would need a distinct de-icing system. The contribution summarizes the design of the Krueger device together with the findings from the full-scale wind tunnel test of the Krueger flap configuration.

### References:

- [1] P.K.C. Rudolph, High-Lift Systems on Commercial Subsonic Airliners, NASA-CR-474, 1996.
- [2] Boeing Commercial Aircraft Group, High Reynolds Number Hybrid Laminar Flow Control (HLFC) Flight Experiment; Part II. Aerodynamic Design, NASA-CR-209324, pp. 65-73, 1999.
- [3] H. Strüber, J. Wild, Aerodynamic Design of a High-Lift System Compatible with a Natural Laminar Flow Wing within the DeSiReH Project, 29th Congress of the International Council of the Aeronautical Sciences, ICAS 2014-0300, 2014.
- [4] D.M. Franke, J. Wild, Aerodynamic Design of a Folded Krueger Device for a HLFC Wing, in: New Results in Numerical and Experimental Fluid Mechanics X, Notes on Numerical Fluid Mechanics and Multidisciplinary Design vol. 132, Springer, pp. 17-27, 2016.

## STS-07-2 Unsteady CFD Results for Deflecting High-Lift Systems

Stefan Wallin<sup>1\*</sup>, Song Chen<sup>1</sup>, Francesco Capizzano<sup>2</sup>, Aleš Prachař<sup>3</sup> and Jorge Ponsin<sup>4</sup>

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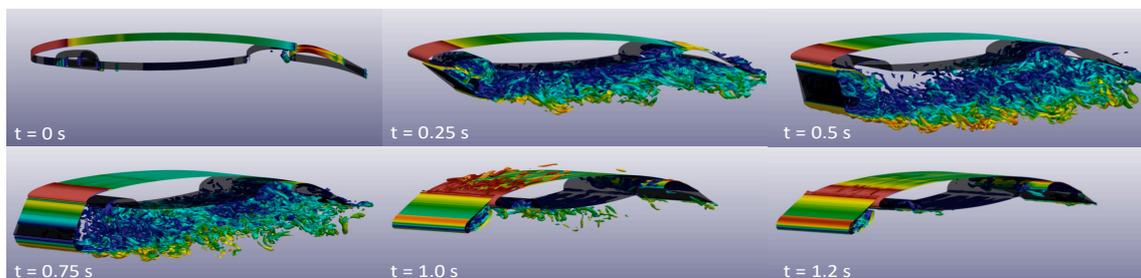
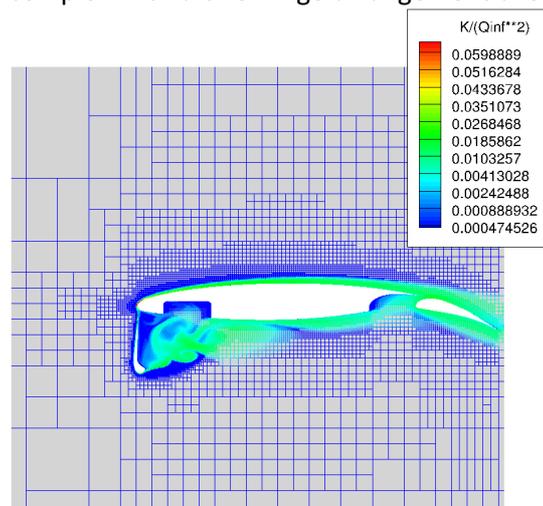
<sup>4</sup> Computational Aerodynamics Branch, INTA, Madrid, Spain, ponsin@inta.es, www.inta.es

### Abstract

**Keywords:** *High-lift aerodynamics, Krueger device, Unsteady CFD, Hybrid RANS LES, Lattice Boltzmann method, Immersed boundary method, Chimera grid technique.*

Laminar wing technology for reducing the fuel consumption and environmental impact requires new leading-edge high-lift devices. One solution is to introduce a Krüger device deployed from the lower wing surface leaving the upper surface undisturbed. During the deployment the aerodynamic performance becomes critical with large unsteady separation behind the device. The aerodynamics of high-lift systems on transport aircraft still poses high challenges on the capabilities of numerical simulations, and accurate prediction of the deployment of a Krüger device is yet beyond the state-of-art. In the H2020 project UHURA, CFD capabilities as well as validation experiments are addressed. In this paper we will present the achievements related to unsteady computations of the turbulent flow and aerodynamic performance during the unsteady deployment of such high-lift device.

The movement of the Krüger device is particularly complex with a two-hinge arrangement allowing the device to be folded in contracted position. Different strategies for capturing the movement are employed ranging from mesh deformation and remeshing (KTH, VZLU), immersed boundary (IB) methods (CIRA, right figure with U-RANS) as well as chimera grid techniques (VZLU). Moreover, different approaches for capturing the unsteady turbulent flow are adopted with unsteady RANS, hybrid RANS-LES (KTH, figure below with S-A DDES) and, as an alternative, a Lattice Boltzmann method employing wall-modelled LES (INTA). Focus has been on the development of accurate and efficient CFD methods with high fidelity, yet affordable for full-scale simulations of the complete deployment cycle. These will be presented in the final paper. Comparison and validation with high quality experimental data obtained within the UHURA project will come later.



## STS-07-3 A 2D Validation Experiment for Dynamic High-Lift System Aerodynamics

Jochen Wild<sup>1</sup>, Moritz Schmidt<sup>1</sup>, Antoon Vervliet<sup>2</sup>, Geoffrey Tanguy<sup>3</sup>

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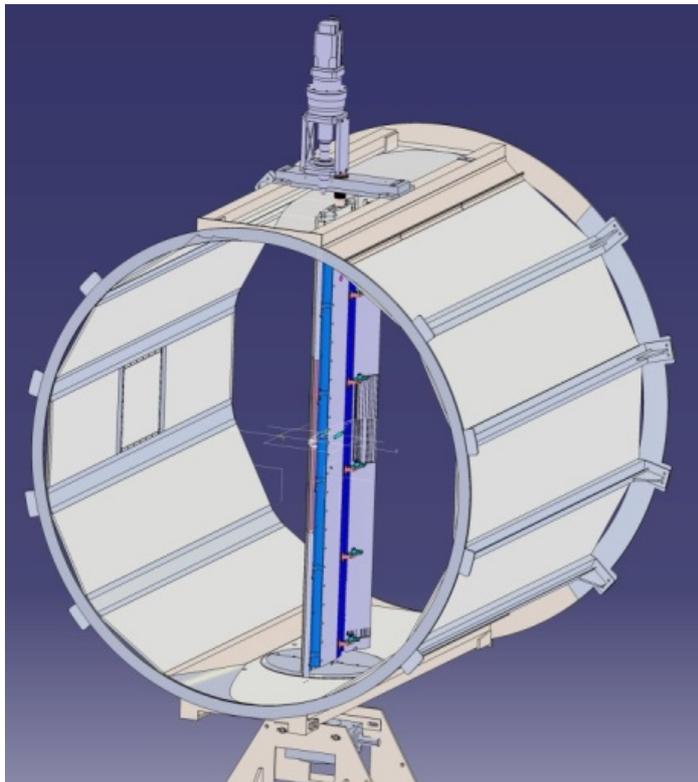
### Abstract

**Keywords:** *High-lift system, Krueger flap, Wind tunnel test, Unsteady aerodynamics.*

The feasibility of laminar flow control technology for future wing is bound to the development of a leading edge high-lift system that complies with the requirements on smooth surfaces to enable maintaining the laminar boundary layer flow, such as a Krueger flap [1]. Although in principle the aerodynamic performance of a Krueger flap is known, the unsteady behaviour of the flow during deployment and retraction is completely unknown. This is as even more important as during deployment the Krueger flap is exposed to highly unfavourable positions perpendicular to the flow. To mitigate the risk of unfavourable aircraft behaviour, it is therefore expected that a Krueger flap has to be deflected significantly fast and may trigger unsteady aerodynamic effects.

Within the European H2020 project UHURA, currently a wind tunnel test is conducted incorporating the vented foldable bull nose Krueger [3]. A wind tunnel model based on the DLR-F15 airfoil has been designed and manufactured that features a part span and a full span Krueger device, which can be

actuated at high deflection rates up to 180°/s. First wind tunnel tests will be conducted at the ONERA L1 wind tunnel in Lille in May 2020. The tests include the measurements of internal forces, steady and unsteady pressures, as well as phase locked PIV to achieve high quality validation data for comparison with numerical methods.



**Figure 1:** DLR-F15-LLE wind tunnel model with Krueger flap installed in test section of the ONERA L1 wind tunnel – CAD of test setup

### References:

[1] P.K.C. Rudolph, High-Lift Systems on Commercial Subsonic Airliners, NASA-CR-474, 1996.

[2] H. Strüber, J. Wild, Aerodynamic Design of a High-Lift System Compatible with a Natural Laminar Flow Wing within the DeSiReH Project, 29<sup>th</sup> Congress of the International Council of the Aeronautical Sciences, ICAS 2014-0300, 2014.

## STS-07-4 Active Flow Separation Control on a Generic UHBR Engine High-Lift Configuration by Means of Suction and Oscillatory Blowing

Junaid Ullah<sup>1</sup>, Shay Monat<sup>2</sup>, Avraham Seifert<sup>2</sup>, Thorsten Lutz<sup>1</sup> and Ewald Krämer<sup>1</sup>

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<sup>2</sup> Tel Aviv University, Ramat Aviv, Israel, seifert@eng.tau.ac.il, www.eng.tau.ac.il

### Abstract

**Keywords:** *UHBR engine, Active flow control, Separation delay, Suction and oscillatory blowing*

Ultra-High Bypass Ratio (UHBR) engines represent one way to significantly reduce the thrust specific fuel consumption of large civil aircraft. However, under wing mounted UHBR engines require a close wing nacelle coupling due to ground clearance regulations and the large engine nacelle diameter. This necessitates a slat cutout to avoid collision between slat and nacelle during takeoff and landing. The unprotected wing section downstream of the engine is prone to flow separation which leads to premature initiation of stall. The physical closeness to the engine allows for extraction of highly pressurized bleed air. This paves the way for mass flow driven Active Flow Control (AFC) technology for recovery of the high-lift capabilities of an airliner. Experimental and numerical studies on a near full scale UHBR engine high-lift configuration at realistic inflow conditions were conducted within the European AFloNext project using pulsed blowing actuators [1]. They revealed that flow separation in the slat cutout region can be fully eliminated through pulsed blowing. The European CS2 INAFLOWT project aims at a reduction of mass flow requirements by employing the Suction and Oscillatory Blowing (SaOB) actuator [2] on the same configuration.

In this talk we will present validated CFD simulations of small-scale wind tunnel tests, see Fig. 1, which serve as preliminary step for the near full-scale tests. The actuator concepts steady suction and oscillatory blowing are evaluated in an individual and combined manner with the purpose to assess the additional benefit through upstream suction.

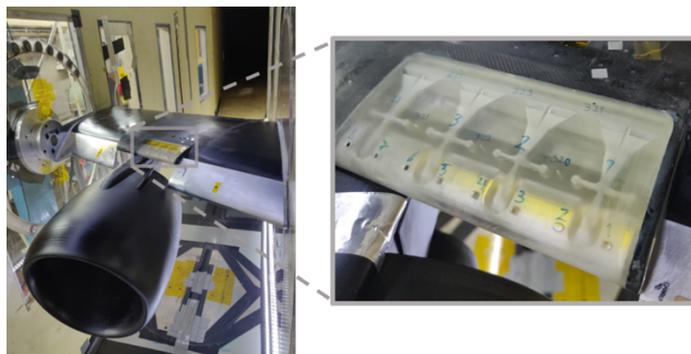


Figure 2: Wind tunnel model with AFC module inside the Knapp-Meadow wind tunnel at Tel-Aviv Univ.

### References:

- [1] P. Schlösser, V. Soudakov, M. Bauer and J. Wild, *Active Separation Control at the Pylon-Wing Junction of a Real-Scale Model*, AIAA Journal, Vol. 57(1) pp. 132-141, 2018
- [2] G. Arwatz, I. Fono and A. Seifert, *Suction and Oscillatory Blowing Actuator*, In: Morrison J.F., Birch D.M., Lavoie P. (Eds) IUTAM Symposium on Flow Control and MEMS. IUTAM Book series, vol 7. Springer, Dordrecht (2008)

## STS-17 Smart Morphing and Sensing for the Wings of the Future

Chair: Marianna Braza<sup>1</sup>

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### Session Abstract

**Keywords:** *Smart Morphing and Sensing, Wing design, High-fidelity numerical simulations, Aerodynamic performance*

This session aims at presenting main results from the European Research project N° 723402 “Smart Morphing and Sensing for Aeronautical Configurations” within Horizon 2020 [1] concerning the design disruptive wing configurations able to considerably increase the aerodynamic performances comparing conventional designs. This is achieved thanks to novel smart actuators electrically actuated and embedded under the “skin” of the lifting structure and new generation of sensors based on Bragg grating. Therefore, optimal deformations and vibrations are produced in multiple time and length scales, able to manipulate the surrounding turbulence structure in order to increase lift and simultaneously decrease drag and aerodynamic noise in all flight phases, take-off, landing and cruise. Results from High-Fidelity numerical simulations accompanied by experiments with the morphing wing configurations of A3xx type are discussed regarding the increase of the aerodynamic performances.

### References:

[1] [www.smartwing.org/SMS/EU](http://www.smartwing.org/SMS/EU)

The session will include six papers in the following topics:

- **Numerical Simulation of a Large-Scale High-Lift Morphing Wing of A320 Type, Based on Electro-Mechanical Actuators and Shape Memory Alloys**
  - Abderahmane Marouf, Alexandre Giraud, Bertrand Nogarede, Yannick Bmegaptche-Tekap, Mateus Carvalho, Dominique Harribey, Clément Nadal, Jean-François Rouchon, Marianna Braza, abderahmane.marouf@imft.fr, alexandre.giraud@novatem-sas.com
- **Numerical Simulation of the Aerodynamic Performance of an A320 Type Morphing Wing in the Transonic Regime**
  - Jean-Baptiste Tô, Pawel Flaszynski, Richard Szwaba, Piotr Doerffer, Nikolaos Simiriotis, Abderahmane Marouf, Yannick Hoarau, Jean-François Rouchon, Marianna Braza, jean-baptiste.to@imft.fr, pawel.flaszynski@imp.gda.pl
- **Electroactive Morphing Effects in the Aerodynamic Performance of a Cambered A320 Wing by Means of Numerical Simulation, TRPIV and Controller Design**
  - Mateus Carvalho, Cédric Raibaud, Carsten Döll, Philippe Mouyon, Clément Nadal, Dominique Harribey, Jean-François Rouchon, Marianna Braza, mateus.carvalho@imft.fr, Cedric.Raibaud@onera.fr
- **Numerical Simulation of a Morphing A320 Wing in Subsonic Speeds and Sensitivity Evaluation**
  - Nikolaos Simiriotis, Abderahmane Marouf, Konstantinos Diakakis, George Tzabiras, Felix Kramer, Frank Thiele, Yannick Hoarau, Marianna Braza, nikolaos.simiriotis@imft.fr
- **Aerodynamic Performance Increase of a Morphing A320 Wing with High-Lift Flap by Means of Hi-Fi CFD Approaches**
  - Abderahmane Marouf, Nikolaos Simiriotis, Jean-Baptiste Tô, Dominique Charbonnier, Jan Vos, Yannick Hoarau, Marianna Braza, abderahmane.marouf@imft.fr
- **Numerical Simulation of Multi-Point Sensing Compared with Dynamic Pressure Measurements through Bragg Grating**
  - Amaury Kitouni, Jean-Baptiste Paris, Vincent Lamour, Abderahmane Marouf, Nikolaos Simiriotis, Yannick Bmegaptche, Marianna Braza, amaurykitouni@cementys.com

## STS-17-1 Numerical Simulation of a Large-Scale High-Lift Morphing Wing of A320 Type, Based on Electro-Mechanical actuators and Shape Memory Alloys

**Abderahmane Marouf<sup>1,2</sup>, Alexandre Giraud<sup>3</sup>, Bertrand Nogarede<sup>3</sup>, Yannick Bmegaptche-Tekap<sup>1</sup>, Mateus Carvalho<sup>1,4</sup>, Dominique Harribey<sup>4</sup>, Clement Nadal<sup>4</sup>, Jean-François Rouchon<sup>4</sup>, Marianna Braza<sup>1</sup>**

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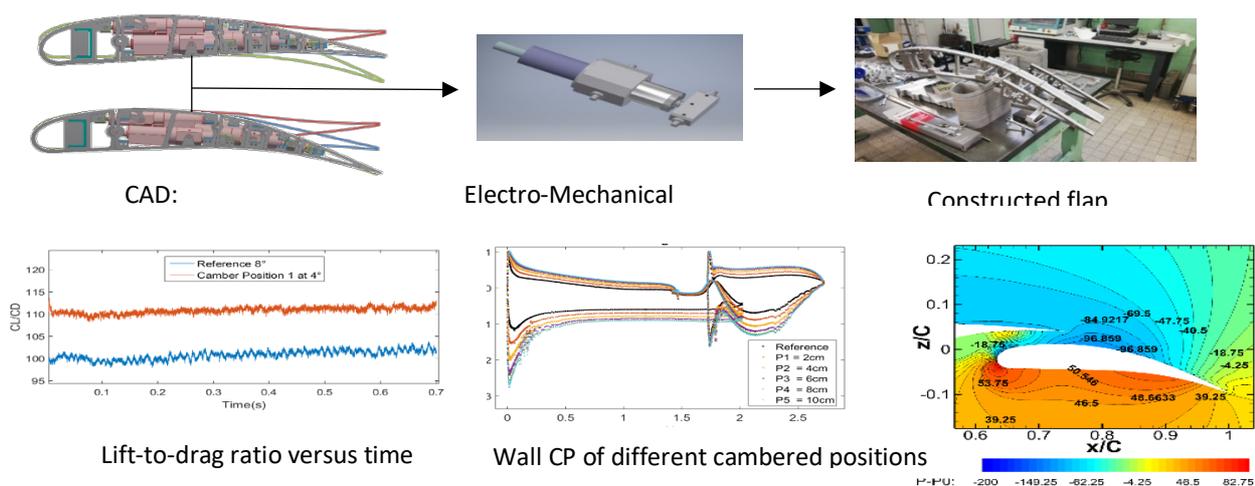
### Abstract

**Keywords:** *Morphing, Wing, High-lift configuration, Turbulence modelling, Aerodynamic performance*

The aim of this study is to investigate the numerical effects of a deformable flap by means of a quasi-static and dynamic cambering. A new designed concept of an Airbus A320 high-lift system is proposed. A flap prototype of chord 1 m at a real scale has been studied in the context of the European project Smart Morphing and Sensing (SMS) [1]. This prototype able to camber by means of the Electro-Mechanical Actuators (EMA) to achieve high amplitude deformation up to 10 cm. This mechanism allows to improve the aerodynamic performances of high-lift systems during the take-off flight stage. This work proposes a synergy between numerical and experimental results and reveals the effects of cambering over the pressure field around the flap in different suggested positions. A considerable increase of the static pressure in the pressure side of the flap and a high low-pressure in its suction side are illustrated in Figure 1 for the cambered flap compared to the baseline case. This leads to improve the lift-to-drag ratio. At a certain achieved camber position coupled with an angle of attack of 4° reveals better CL/CD than a baseline at higher angle of 8°. The application of the cambering will help avoiding stall angles, increase the aerodynamic performances and reduce fuel consumption.

**Figure 1:** Numerical simulations used for the design of the Large-Scale prototype for the high-lift configuration in the SMS European project

**References** [1] [www.smartwing.org/SMS/EU](http://www.smartwing.org/SMS/EU)



## STS-17-2 Numerical Simulation of the Aerodynamic Performance of an A320 Type Morphing Wing in the Transonic Regime

**Jean-Baptiste Tô<sup>1</sup>, Pawel Flaszynski<sup>2</sup>, Richard Szwaba<sup>2</sup>, Michal Piotrowicz<sup>2</sup>, Piotr Doerffer<sup>2</sup>, Nikolaos Simiriotis<sup>1</sup>, Abderahmane Marouf<sup>1,3</sup>, Yannick Hoarau<sup>3</sup>, Jean-François Rouchon<sup>4</sup>, Marianna Braza<sup>1</sup>**

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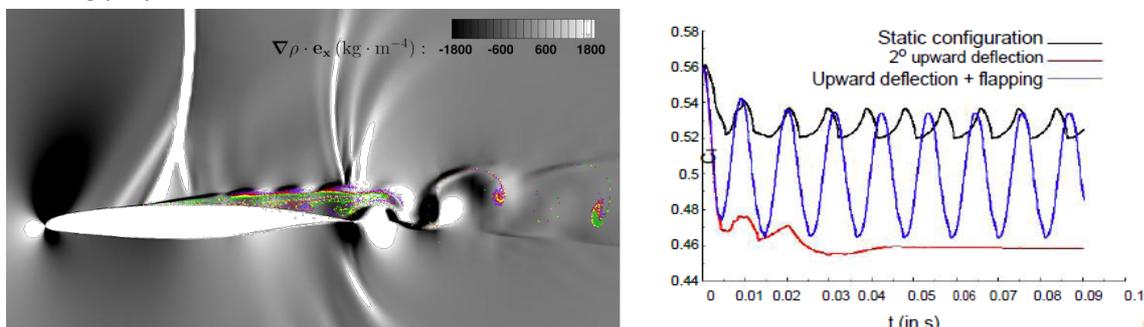
<sup>3</sup> ICUBE, Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie, Université de Strasbourg, France, hoarau@unistra.fr

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### Abstract

**Keywords:** *Morphing wing, Transonic regime, Drag reduction, Lift increase*

By actuating the rear part of a wing at amplitudes and frequencies pertaining to optimal ranges, Jodin et al. (2017) have shown experimentally that lift can be increased and drag decreased when combining high frequency and low amplitude vibrations with low frequency and high amplitude camber of the trailing edge. This draws inspiration from papers by Hunt et al. (2008), Hunt et al. (1999) or Szubert et al. (2015) which highlight a shear sheltering phenomenon due to the injection of vorticity in shear layers. The resultant eddy-blocking effect can be used to constrict the turbulent wake and as a consequence, diminish shape drag and increase aerodynamic efficiency. The same phenomenon can be applied in the case of a transonic flow regime to help broaden flight envelope during cruise. Another consequence of this shear layer manipulation is the dampening of transonic buffet, an unsteady coordinated motion of the shock and the boundary layer that results from intense Shock-Wave/Boundary-Layer Interactions (SWBLI). 2D computations have first been carried out to determine the effects of a vibrating trailing edge on the manipulation of turbulence aft a supercritical Airbus A320 airfoil of chord  $c = 0.15$  m at a Reynolds number of  $2.93 \cdot 10^6$ , Mach number  $Ma = 0.78$  and angle of incidence  $= 1.8^\circ$ . This has been done by testing several actuation frequencies ranging from 70 Hz to 2000 Hz and multiple deformation amplitudes using an Arbitrary Lagrangian-Eulerian method (ALE) to deform the whole computational domain. While low frequency vibrations lock the buffet frequency  $f_B$  to the actuation frequency fact due to  $f_B$  being of the same order of magnitude as fact, higher frequencies (fact  $> 500$  Hz) indicate that buffet can be suppressed altogether. Deflecting the trailing edge upwards also achieves buffet annihilation (see Figure 1) and decreases the amount of drag on the wing on average, while also increasing mean lift to drag ratio by up to 20% compared to the non-actuated «static» case. In this study, 3D computations are also carried out to analyse the effects of morphing on the onset of buffet and SWBLI manipulation. This analysis will serve to complement experiments done in Gdansk Academy, Poland, as part of the Smart Morphing and Sensing project (2017).



**Figure 1:** *Illustration (left) of the shock boundary-layer and vortex interaction in respect of the shear-layer and von Karman vortices by means of the OES - Organised Eddy Simulation approach. Suppression of buffet thanks to morphing (right).*

## STS 17-3 Electroactive Morphing Effects in the Aerodynamic Performance of a Cambered A320 Wing by Means of Numerical Simulation, TR-PIV and Controller Design

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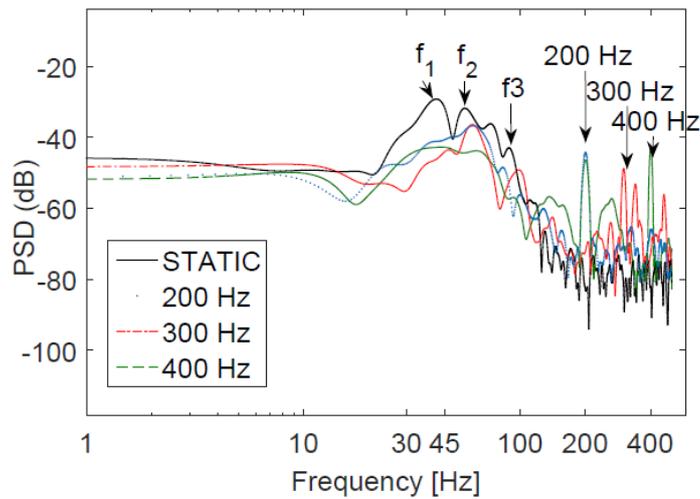
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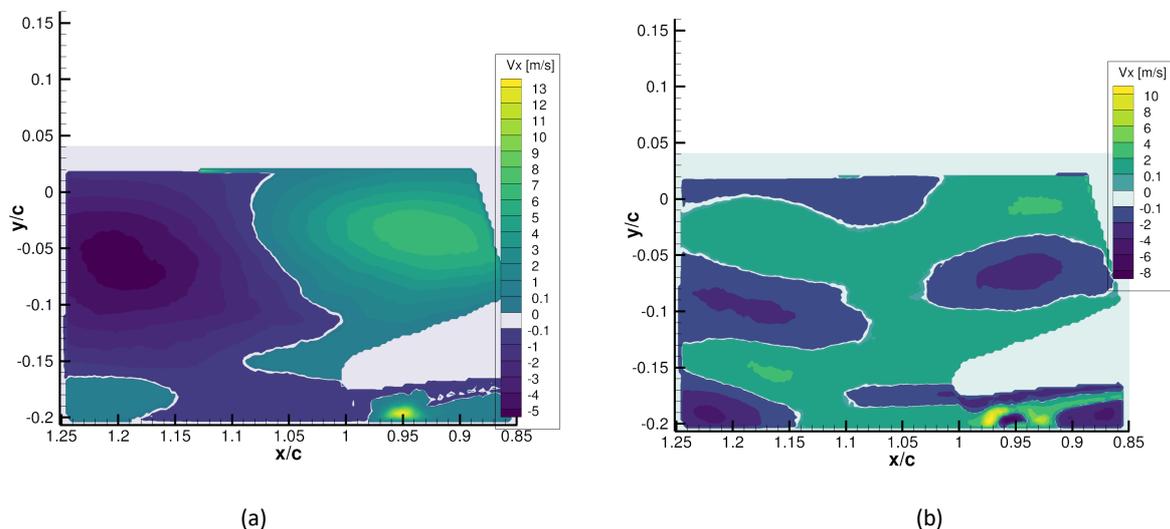
### Abstract

**Keywords:** *Aviation, Aerodynamics, Turbulence, Morphing, Actuators, PIV, Feedback control, CFD*

For the next 20 years, the quantity of air travellers in the world is expected to rise to almost the double of the current number. This growth is followed by the eminent increase of greenhouse gas emissions linked to climate change. Another obvious consequence is the higher operation cost for airline companies. These factors explain the need for better efficiency for modern aircrafts. Among these studies, there is the Smart Morphing and Sensing European Project ([www.smartwing.org/SMS/EU](http://www.smartwing.org/SMS/EU)). The goal of the project is to design a system of electroactive actuators for two different time scales. Shape Memory Alloys (SMA) are used for low-frequency camber control of an A320 wing prototype at reduced scale, developed by LAPLACE, while piezoelectric based actuators are responsible for high frequency vibration of its trailing-edge. The experiments have been carried out in the S4 subsonic wind tunnel at the IMFT facilities in Toulouse. TR-PIV results were acquired at Reynolds Number of 1 million. In addition, lift and unsteady pressure measurements were obtained at different upstream velocities. PSD analysis of crossflow velocity by means of numerical simulations show good match with the experimental results both for reduced [1] and large [2] scales for take-off configuration. SMA and piezoelectric actuation allow us to obtain better drag-lift ratios by acting at the same time on coherent structures such as the von Kármán instabilities and on the shear layer. Performances are increased using feedback control approaches [3]. Instantaneous pressure signals are acquired in real-time to update the actuators control signal. Using a cost function  $J$  based on the pressure fluctuation, experimental adaptive control is performed to optimize the control law parameters by minimizing the cost function.



**Figure 1:** Power spectral density of the crossflow velocity for different high frequency actuation cases [3]



**Figure 2:** PIV results: snapshots of reconstructed velocity field from reduced number of POD modes. (a) Modes 4 and 5; (b) from mode 10 to 30.

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## STS-17-4 Numerical Simulation of a Morphing A320 Wing in Subsonic Speeds and Sensitivity Evaluation

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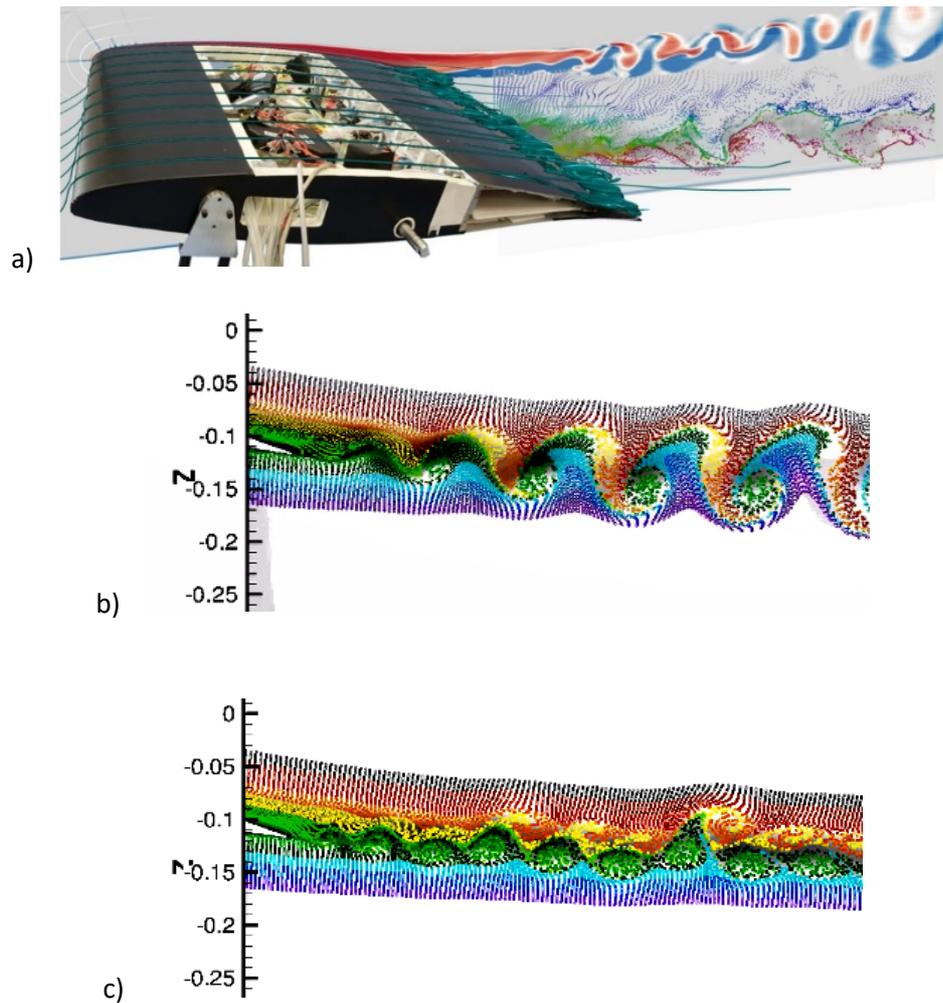
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### Abstract

**Keywords:** *Morphing wing, Reduced-Scale prototype, Aerodynamic performance, Subsonic regime*

This contribution examines the effect of trailing-edge region deformation and vibration on the turbulent structures developing around and in the wake of a supercritical wing of A320 type in the low subsonic regimes corresponding to take-off and landing. The work presented has been carried out numerically and is accompanied by experimental results from tests carried out in the S4 wind tunnel of IMFT by means of TRPIV (Time-Resolved PIV - sampling rate around 10 KHz for the velocity fields). The Reynolds number is 1 Million. The present study focuses on the investigation of a case where no morphing is applied, in order to distinguish all the characteristic features present in the flow followed by morphing cases in order to identify optimal vibration frequency and amplitude ranges of the near trailing-edge region. The alternating vortex shedding is established. This "von Karman" shedding takes place over a range of frequencies leading to a bump (instead of clear and sharp peaks) when studying the spectral information of the flow. This evident non-linearity in the flow is justified by the elevated Reynolds number. The range of the bump has been correctly captured by means of numerical simulation, when comparing with the respective experimental results. For high-frequency changes of the shape, a very sensitive region on the lower airfoil very close to the trailing edge could be identified. The addition of small amplitude vibrations in the trailing edge region was implemented using the Arbitrary Lagrangian-Eulerian (ALE) methodology. Following the experiments, the morphing effects were evaluated with numerical tests that were carried out on different frequency/amplitudes sets. The resulting phenomena were evaluated on the effects evident on the aerodynamic coefficients (average and rms values) and on the interactions that they prompt in the wake region. The effect on the average flow quantities and the development of the wake were also investigated. By means of Proper Orthogonal Decomposition (POD), the near wake structure is analyzed in respect of the morphing effects for frequencies outside the natural shedding frequency range. For the lower the wake region. For the frequency of 300 Hz, the respective mode takes the place of the natural shedding frequencies.



**Figure 1:** The Reduced-Scale morphing wing (a) of the SMS project (chord 70cm) with embedded Shape Memory Alloys ensuring high deformations of order 15% of the chord in low frequency (order 1Hz) and piezo actuators in the trailing-edge region ensuring higher-frequency vibrations (order of 500 Hz) in low deformations (order of 1-4 mm). Numerical simulations with the OES turbulence modelling approach showing the wake's vortex breakdown (c), suppression of the von Karman eddies and reduction of the wake's width thanks to the morphing, comparing with the non-morphing case (b)

## STS-17-5 Aerodynamic Performance Increase of a Morphing A320 Wing with High-Lift Flap by Means of Hi-Fi CFD Approaches

**Abderahmane Marouf<sup>1,2</sup>, Nikolaos Simiriotis<sup>2</sup>, Jean-Baptiste Tô<sup>2</sup>, Dominique Charbonnier<sup>3</sup>, Jan Vos<sup>3</sup>, Yannick Hoarau<sup>2</sup>, Marianna Braza<sup>1</sup>**

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### Abstract

**Keywords:** *Morphing, Wing, High-lift configuration, Turbulence modelling, Aerodynamic performance*

This study illustrates the morphing effects around a large-scale high-lift configuration of the Airbus A320 with two element airfoil-flap in take-off configuration, in the context of the Smart Morphing and Sensing European project ([www.smartwing.org/SMS/EU](http://www.smartwing.org/SMS/EU)). The flow around the wing and its near wake is analysed in respect of slight deformation and vibration of the near trailing-edge region of the high-lift flap, known as morphing through novel piezo-actuators in our studies in the context of the present European project. Experimental results obtained in the subsonic wind tunnel of IMFT are discussed in association with High-Fidelity numerical simulation results obtained by using the NSMB (Navier Stokes Multi-Block) code with advanced turbulent modelling approaches. These are able to correctly capture the predominant instabilities and coherent structure dynamics. The results show a considerable increase of the lift-to-drag ratio comparing to the static (no-morphing) case. A detailed spectral analysis and streaklines visualization are performed to reveal the modification due to the morphing (Figure 1), yielding to a reduction of the wake's width and beneficial feedback effects in respect of lift increase, drag and noise sources reduction. The optimal frequency ranges of the vibrations and of the deformation amplitudes are investigated. Optimal morphing has proven able to attenuate the predominant natural shear-layer frequency and to create beneficial vortex breakdowns of the coherent vortices, thus producing simultaneously lift increase and drag reduction.

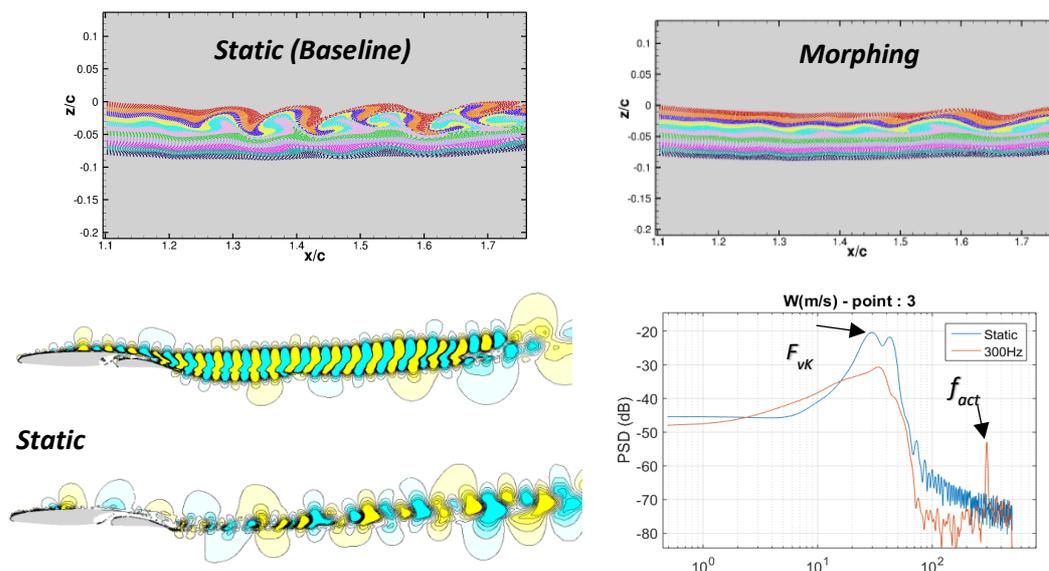


Figure 1.: Comparison of numerical results of the static and the morphing cases in the SMS European project

## **STS Discussion Session 5: Aeronautics – Fluid Dynamics and Aero-acoustics**

**Moderators: Piotr Doerffer, Tatiana Kozubskaya, Leonidas Siozos-Rousoulis**

### **Participating STS:**

#### **STS-02 EU-Funded Research on Advanced Computational Methods for Fluid Dynamics and Aero-Acoustics**

*Chair: Leonidas Siozos-Rousoulis*

#### **STS-20 Flow Separation Induced by Strong Interactions**

*Chairs: Piotr Doerffer, Pawel Flaszynski*

#### **STS-22 EU-China Aeronautics Research Cooperation – Drag Reduction in Turbulent Boundary Layer via Flow Control**

*Chairs: Eusebio Valero, Yao Zheng, Gabriel Buggeda*

#### **STS-26 Computational Experiment in Aeroacoustics and Associated Aerodynamics for Aerospace Industries**

*Chair: Tatiana Kozubskaya*

## STS-02 EU-Funded Research on Advanced Computational Methods for Fluid Dynamics and Aero-Acoustics

**Leonidas Siozos-Rousoulis**

European Commission – INEA, 1049 Brussels, Belgium  
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### Session Abstract

**Keywords:** *Computational fluid dynamics, Multidisciplinary optimisation, High-fidelity numerical methods, Aircraft flight physics*

Europe's Vision for Aviation 'Flightpath 2020' sets ambitious goals for the aviation sector. Reducing environmental impact, as well as maintaining and extending industrial leadership will continue to be key drivers for aviation. To this end, streamlined design and manufacturing processes are required, in order to achieve reduced aircraft design costs and time.

Fast and accurate modelling of flight physics can significantly contribute to reducing the aircraft design-cycle, obviating the need for costly prototyping and testing during development stages. More importantly, advanced computational methods are key enablers for the development and design of future disruptive configurations.

In the high-level international setting of the WCCM-ECCOMAS Virtual Congress 2021, the European Commission and its Innovation and Networks Executive Agency (INEA) are organising a dedicated session on advanced numerical methods for flight-physics modelling.

The objectives of the STS are:

1. To present an overview of current EU-funded research on computational methods for flight-physics modelling and a snapshot of progress at European and international levels;
2. To identify gaps between needs and the current state of the art, and gather recommendations on specific topics, which should be addressed in the short, medium, and long term, including aspects such as:
  - Progress on research topics considered in the ACARE Strategic Research & Innovation Agenda (e.g., Challenges 1, 2, and 3);
  - high-fidelity computational fluid dynamics (CFD) capable of modelling turbulent and transitional flows, and the role of artificial intelligence and high-performance computing;
  - multi-disciplinary optimisation (MDO) methodologies, which can be integrated into the aircraft design-cycle to drastically reduce design cost and time;
3. To bring together relevant EU and international aviation research and innovation stakeholders.

The following presentations will be given:

- **Aerodynamic Performance Increase for a High-lift Two-element Configuration of a morphing A3xx Wing by Means of Numerical Simulation (*EU-Project SMS*)**
  - Abderahmane Marouf, Nikolaos Simiriotis, Yannick Bmegaptche-Tekap, IMFT, Toulouse, France, Yannick Hoarau, Univ. of Strasbourg, France, Jean-François Rouchon, LAPLACE, Toulouse, France, G. Harran, Marianna Braza, IMFT, Toulouse, France, marianna.braza@imft.fr
- **Direct Comparison of Radial Basis Functions and Artificial Neural Networks for the Dynamic Metamodelling in Multidisciplinary Optimization Frameworks**
  - Francesco Centracchio, Monica Rossetti and Umberto Iemma, Universita Roma Tre, Rome, Italy, umberto.iemma@uniroma3.it

## STS-02-5 Direct Comparison of Radial Basis Functions and Artificial Neural Networks for the Dynamic Metamodelling in Multidisciplinary Optimization Frameworks

Francesco Centracchio<sup>1</sup>, Monica Rossetti<sup>2</sup> and Umberto Iemma<sup>3</sup>

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### Abstract

**Keywords:** *Dynamic metamodelling, Radial basis functions, Artificial neural networks*

The present work deals with metamodelling techniques aimed at reproducing the dynamics of linear and nonlinear systems. The research is focused on the comparison of dynamic metamodels based on Radial Basis Functions (RBF) and Artificial Neural Networks (ANN). The relevant framework is the robust and reliable optimal design of complex systems, with emphasis on unconventional aeronautical configurations. This class of applications is typically constrained by the computational burden required by high-fidelity solvers, needed to guarantee accurate solutions, and the high number of function evaluations required by the optimization to converge. As a consequence, the identification of efficient modelling techniques represents a key challenge for the designers.

The use of suitable metamodels, i.e. surrogate models, has been demonstrated to significantly reduce the number of high-fidelity evaluations, thus substantially alleviating the overall computing costs. For this reason, the engineering community is gradually switching from the design approach based only on direct simulations to a massive use of metamodeling techniques. Recently, function-adaptive approaches, also referred to as dynamic metamodels, have been developed in order to make even more efficient the metamodelling process. The dynamic approach takes advantage of information retrieved during the analysis process itself, considerably improving the fitting capability. Dynamic properties of a metamodel can be related to both the domain adaptive sampling and the auto-tuning. In this work, RBF- and ANN-based surrogate models are formalised and applied to engineering problems of aeronautical interest, with particular attention to aero-acoustic problems. The used algorithms have demonstrated to be accurate and efficient, and the observed performance discloses the possibility to implement numerical strategies for the reliable and robust optimal design.

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## STS-02-6 Aerodynamic Performance Increase for a High-lift Two-element Configuration of a Morphing A3xx Wing by Means of Numerical Simulation

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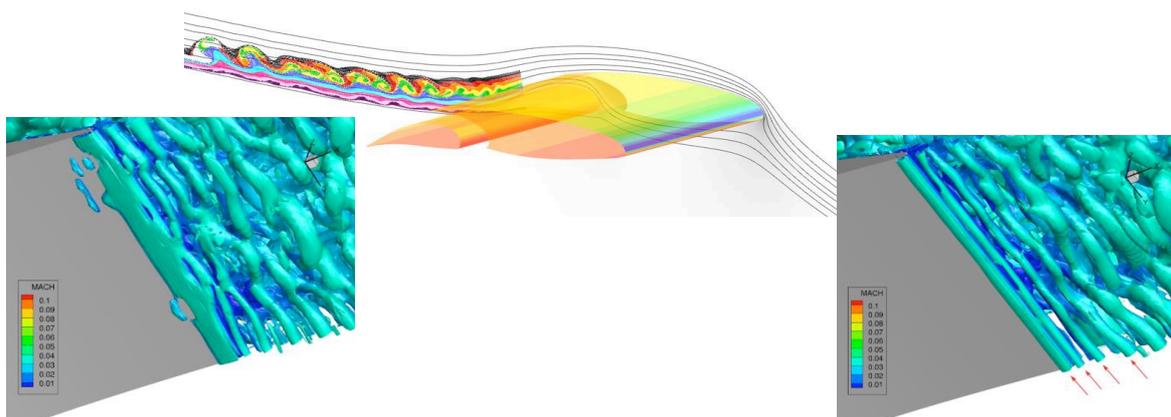
<sup>3</sup> LAPLACE Laboratoire Plasma et Conversion d'Énergie CNRS-INPT-UT3, Toulouse

### Abstract

**Keywords:** *Morphing wing-flap, Navier Stokes Multi Block, Drag reduction, Lift increase*

This study analyses by means of High-Fidelity numerical simulation the increase of aerodynamic performances of a morphing wing-flap configuration of an A3xx type in take-off conditions. The electroactive morphing has been realized by novel actuators embedded under the “skin” of the lifting structure and are able to optimally deform and vibrate the rear part of the wing in multiple time and length scales. In this way, through manipulation of the different classes of turbulent vortices breakdown of harmful coherent vortices is obtained and simultaneously, enhancement of beneficial ones, yielding optimal pressure distribution on the overall structure. These studies have been carried out by means of High-Fidelity numerical simulations by using the NSMB – Navier Stokes Multi Block code with advanced turbulence modelling closures, as well as by refined physical experiments of the morphing wing prototypes built in the Horizon 2020 N° 723402 European research project SMS: Smart Morphing and Sensing for aeronautical configurations ([www.smartwing.org/SMS/EU](http://www.smartwing.org/SMS/EU)). It has been shown that the electroactive morphing concepts are able to provide significant improvements of the aerodynamic performances: an order of 7% of lift increase, of 5% drag reduction and a decrease of the amplitude of the predominant frequency modes associated to noise sources produced by the trailing edge vortices, by an order of 8%. The fundamental mechanisms leading to these improvements are analysed in detail by means of the numerical simulations.

**Figure 1:** Suppression of the three-dimensionality and of the vortex dislocations past the two-element wing configuration. Left: static, right: morphing by means of slight deformation and 300 Hz vibration of the near trailing edge region at Reynolds number 2,2 Million, by means of hybrid Delayed Detached



Eddy Simulation - Organised Eddy Simulation - OES turbulence modelling (Shinde, Hoarau, Braza et al, J. Fluids & Structures 2014)

## STS-20 Flow Separation Induced by Strong Interactions

Chairs: Piotr Doerffer<sup>1</sup>, Pawel Flaszynski<sup>2</sup>

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### Session Abstract

**Keywords:** *Separation, Strong disturbances, Shock wave, Compression, Boundary layer, Shockwave-boundary layer interaction*

Flow separation depreciates flow quality and increases drag and losses. Strong interactions may be induced by flow itself, as shock waves or rapid compressions. But such interactions may be also induced by bounding walls shape as upstream or downstream facing steps, sharp corners and leading or trailing edges.

Proposed here topic includes flow control methods aimed at separation reduction or its elimination. Flow control methods and their physical mechanisms are important topics of the STS session. Physical modelling of the flow control methods are important to simplify their inclusion in CFD approach to separated flow analysis.

This STS “Flow Separation Induced by Strong Interactions” will include five papers, addressing different aspects of the theme.

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**Foreseen paper titles and speakers:**

- **Transition Location Effect on Shock Wave Boundary Layer Interaction – Lessons Learnt from the EU Project TFAST**
  - Piotr Doerffer, Institute of Fluid Flow Machinery, IMP PAN, Gdańsk, Poland
- **High-resolution Unsteady Simulations of Transitional Shock Wave / Boundary Layer Interactions**
  - Lionel Larchevêque, Aix Marseille Univ., CNRS, IUSTI, Marseille, France  
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- **Numerical Simulation of a 3-D Transonic Regime around a Supercritical Wing Involving Strong Separation**
  - N. Simiriotis (1), Damian Szubert (1, 2), I. Asproulias (1), J.B. Tô (1), Y. Hoarau (3), Marianna Braza (1)
  - Institut de Mécanique des Fluides de Toulouse, UMR CNRS 5502,  
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  - ICUBE, Univ. Strasbourg, UMR CNRS 7357, hoarau@unistra.fr
- **Parametric Study of Multiple Shock Wave/Turbulent Boundary Layer Interactions with a Reynolds Stress Model**
  - K. Boychev, G.N. Barakos, R. Steijl, CFD Laboratory, School of Engineering, University of Glasgow, UK
  - Kiril.Boychev@glasgow.ac.uk
- **Numerical Simulation for Shock Wave Induced Separation on Gas Turbine Profile with Film Cooling**
  - Pawel Flaszynski, M. Piotrowicz, Inst. of Fluid Flow Machinery, IMP PAN, Gdańsk, Poland pflaszyn@imp.gda.pl

## STS 20-2 High-Resolution Unsteady Simulations of Transitional Shock Wave / Boundary Layer Interactions

Lionel Larchevêque<sup>1</sup>

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### Abstract

**Keywords:** *Flight Tests, A320 Vertical Tail Plane, Drag Reduction, Hybrid Laminar Flow Control, Boundary Layer Suction.*

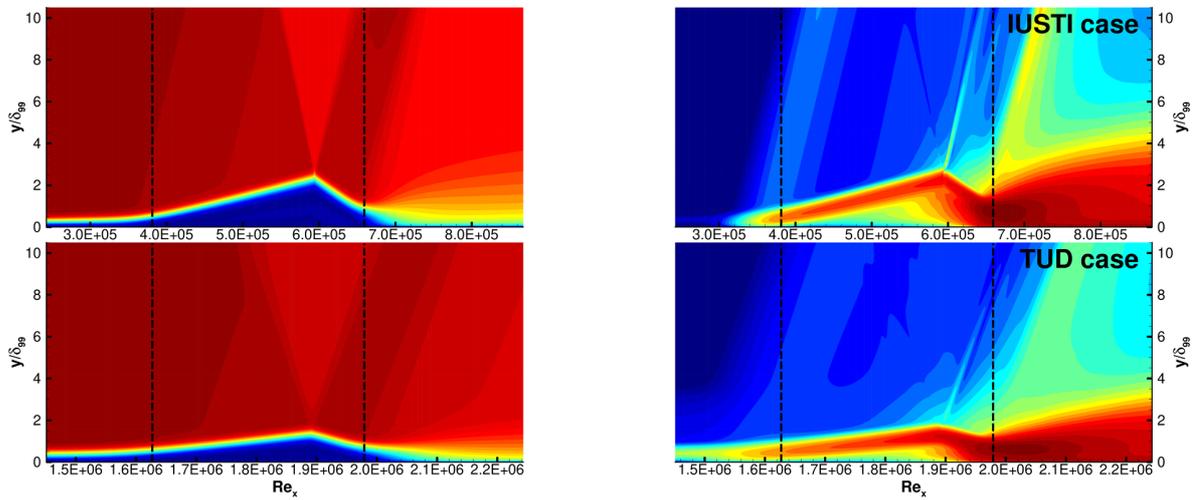
The intended talk will describe numerical simulations of several shock wave / boundary layer interactions for which the incoming boundary layer is laminar and undergoes transition due to a shock impingement. The retained flow parameters correspond to configurations, for which experimental measurement have been made available recently by the EU-funded TFAST project.

Two  $M=1.7$  shock mixing layer will also be analysed and differences in their space and frequency distributions with respect to experiments and simulations from the TFAST project will be discussed.

Maps of the Mach number (left) and of the logarithm of the streamwise velocity fluctuation (right) for the  $Re_x=6 \cdot 10^5$  (top) and  $Re_x=1.9 \cdot 10^6$  (bottom) cases. Vertical dashed lines denote locations of the separation and reattachment points.

reflections impingement Reynolds numbers of  $6 \cdot 10^5$  and  $1.9 \cdot 10^6$  are studied numerically by means of Large-Eddy Simulations. Such a modelling allows the simulation of flows transitioning to turbulence while being computationally tractable enough to make feasible long-time computations addressing the low-frequency unsteadiness encountered in separated flows. The drawback of this strategy is that the turbulence modelling can alter the receptivity process and the amplification of the instability modes of the laminar boundary layer, resulting in mis-prediction of the separation length for a given level of external flow perturbation. Moreover, quantitative information on external perturbations (nature, amplitude, length-scale) are difficult to extract from experimental measurements. The present work get around these difficulties by directly injecting velocity fluctuations in the incoming boundary layer through a synthetic eddy method, with amplitudes adjusted so as to result in separation lengths equal to the ones observed experimentally.

Results from the grid convergence study as well as comparison with the velocity measurements will be presented, focusing on the separation-induced transition. Flow unsteadiness, ranging from the breathing of the separated region to the development of the mixing layer will also be analysed and differences in their space and frequency distributions with respect to experiments and simulations from the TFAST project will be discussed.



Maps of the Mach number (left) and of the logarithm of the streamwise velocity fluctuation (right) for the  $Re_x=6 \cdot 10^5$  (top) and  $Re_x=1.9 \cdot 10^6$  (bottom) cases. Vertical dashed lines denote locations of the separation and reattachment points.

## STS 20-3 Numerical Simulation of a 3-D Transonic Regime around a Supercritical Wing Involving Strong Separation

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### Abstract

**Keywords:** *Hybrid turbulence modelling, Buffet phenomenon, Organised Eddy Simulation (OES)*

The present paper details the simulations carried out for the 3D-V2C wing configuration designed by Dassault Aviation in the context of the European programme TFAST - Transition location effect on shock boundary layer interaction. The results concern the constant section wing and the swept one. In the second case, the transition location is imposed by numerical tripping of the eddy-viscosity in order to examine the impact of its location on the buffet's onset. The computations have been carried out by using URANS, OES and hybrid approaches. The results analyse transonic buffet dynamics by means of spectral and proper orthogonal decomposition (POD) analysis in case of the constant section wing. They also examine onset of unsteadiness at 5° and 7° of incidence for the swept wing. Due to the chord's length variation, there are sections, where the local Reynolds number is subcritical or supercritical regarding the buffet instability.

A numerical study by means of statistical and hybrid turbulence modelling involving stochastic forcing has been carried out to analyse the buffet phenomenon around a transonic wing of constant section and a swept wing at high Reynolds number. The predictions, obtained by using the NSMB - Navier Stokes Multi Block code (Vos et al. (1998), Hoarau) have shown the ability of all the methods in capturing the buffet's frequency bump, but at different spectral amplitudes and width of the bump. The DDES-SST simulations indicated a too strong suction effect and enhancement of the separation and of the shock's amplitude. The OES - Organised Eddy Simulation (Braza et al 2006, Bourguet et al (2008), Szubert et al, 2015) simulations provided a moderate shock amplitude and a good comparison of the mean forces coefficients with experiments carried out in the context of the TFAST project coordinated by IMP-PAN. A detailed POD study shows the role of the most energetic modes in respect of the buffet spatial oscillation amplitude as well as the impact of higher-order modes in the shear layer dynamics and in the stochastic forcing.

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## STS 20-4 Parametric Study of Multiple Shock Wave/Turbulent Boundary Layer Interactions with a Reynolds Stress Model

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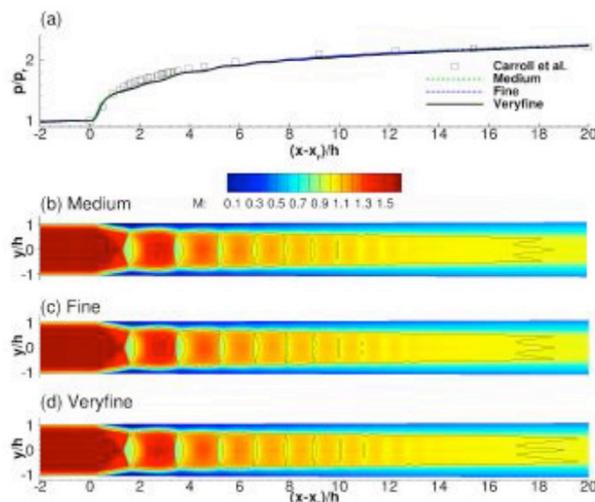
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### Abstract

**Keywords:** *Pseudo shock, Shock train, Multiple shock wave boundary layer interaction, MSWBLLI, Parametric study, Corner flows, EARSM*

A parametric study of Multiple Shock Wave Boundary Layer Interactions is presented in this paper. All results were obtained using the in-house Computational Fluid Dynamics solver of Glasgow University. Such interactions often occur in high-speed intakes which have recently seen a renewed interest. Simulations of a multiple shock wave boundary layer interaction in a rectangular duct were first performed and the results were compared to the experiments. Using the same numerical setup a parametric study investigating the effect of Mach number, Reynolds number and confinement on the baseline solution was then performed. Efficiency metrics were also defined to quantify the interactions. The results show that Reynolds-stress based turbulence models are better suited than linear models. The corner separations affect the separation at the centre of the domain which in turn alters the structure of the initial shock and the subsequent interaction. Reduced flow confinement is found to be beneficial for higher pressure recovery. Indicative results from this study are shown in Figure 1 where the three levels of mesh refinement are compared with the text data of Carroll et al. (B. Carroll et al., 1993, Journal of Propulsion and Power, Issue, Vol. 9, pp. 405–411). The employed explicit algebraic stress model predicted the correct size of corner flow, and gave fair results for the extent of flow separation and length of shock train.



**Figure 1:** *Wall pressure and mid-plane Mach number contours for three levels of refinement of the employed CFD mesh. All computations employed an explicit algebraic Reynolds stress model.*

## STS 20-5 Numerical Simulation for Shock Wave Induced Separation on Gas Turbine Profile with Film Cooling

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### Abstract

**Keywords:** *High pressure turbine stages, Shock wave boundary layer interaction, Transition location, Numerical simulation, Shock induced separation*

Modern High Pressure (HP) turbine stages consist of highly loaded aerofoils, including transonic and even supersonic flow regions. In the case of the stators a normal shock wave in the passage throat chokes the flow, stabilizing the flow conditions at the operating point. In addition to these flow phenomena, the strong acceleration along the early suction side leads to a re-laminarisation of the flow, which in turn has a strong impact on the size of the shock induced separation bubble. The injection of film coolant via rows of cooling holes influences the boundary layer state. As heat transfer and film cooling effectiveness are of crucial importance in high pressure turbines, an in-depth understanding of transition mechanisms is needed for a competitive design.

The effect of transition location on the shock wave boundary layer interaction was the main objective of the EU project TFAST (Transition Location Effect on Shock Wave Boundary Layer Interaction). Such interaction on the suction side of the gas turbine profile and the investigation of the film cooling effect and the possibility of the jet vortex generators application upstream of the shock wave was the objective of the work package focused on the turbine configuration.

Numerical simulations are presented and compared with experimental data. Numerical simulations have been carried out by means of Fine/Turbo Numeca code for three cases:

- reference without film cooling and jet vortex generators (JVG),
- with cooling and without jet vortex generators,
- with cooling and with jet vortex generators.

The investigation of the film cooling and jet vortex generators effect on the shock wave boundary layer interaction on the suction side of turbine profile has been carried out in the IMP PAN transonic wind tunnel configuration. For this purpose, a single passage test was designed according to data for turbine cascade delivered by Rolls-Royce Deutschland (TFAST Partner).

## STS-22 EU-China Aeronautics Research Cooperation – Drag Reduction in Turbulent Boundary Layer via Flow Control

Chairs: Eusebio Valero<sup>1</sup>, Yao Zheng<sup>2</sup>, Gabriel Bugeda<sup>3</sup>

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### Session Abstract

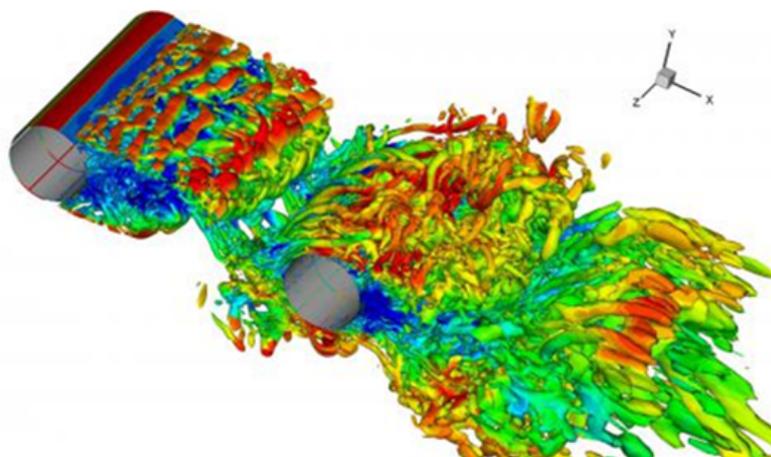
**Keywords:** *Aircraft drag reduction, Turbulent boundary layer control, Flow-control technique*

Within the EU-China research cooperation in aeronautics, the joint EU-China project DRAGY addressed the problem of drag reduction of aircraft through the investigation of flow-control techniques. Almost 50% of total drag is related to the friction drag of the aircraft caused by the interaction of the airflow with the aircraft surface. Studies on the aircraft and flow interactions, together with developments of advanced flow-control technologies, can effectively reduce about 15% of the total drag, which has, therefore, major implications on fuel consumption.

In addition, by using new algorithms and exploiting efficiently large computing facilities, the project is improving the understanding of the underlying physics behind the control techniques and their interaction with the airflow near the aircraft surface (i.e. the boundary layer) to maximize their efficiency.

Turbulent Boundary Layer Control for skin-friction drag reduction is a relatively new technology made possible through the advances in computational-simulation capabilities, which have improved our understanding of the flow structures of turbulence. Advances in micro-electronic technology have enabled the fabrication of actuation systems capable of manipulating these structures. The combination of simulation, understanding and micro-actuation technologies offer new opportunities to significantly decrease drag, and by doing so, increase fuel efficiency of future aircraft.

Almost 50% of total drag is due to the viscous drag, which is directly related to the friction drag of the aircraft caused by the interaction of the turbulent boundary layer flow with the aircraft surface. Studies showed, that turbulent boundary layer interactions, together with developments of advanced flow-control technologies, can effectively reduce more than 40% of the viscous drag (if the actuation power is ignored), which is equivalent to about 15% of the total aircraft drag. Therefore, it has major implications to fuel consumption of commercial aircraft, already if a small proportion of this reduction level is realised.



**Paper titles and speakers of STS 22:**

- **Drag Reduction Control in Turbulent Channel with Spanwise Traveling Wave of Blowing and Suction**
  - Song Fu, fs-dem@mail.tsinghua.edu.cn
  - Yi Huang
  - School of Aerospace Engineering, Tsinghua University, Beijing, China

## STS-22-4 Drag Reduction Control in Turbulent Channel with Spanwise Traveling Wave of Blowing and Suction

Yi Huang<sup>1</sup>, Song Fu<sup>1</sup>

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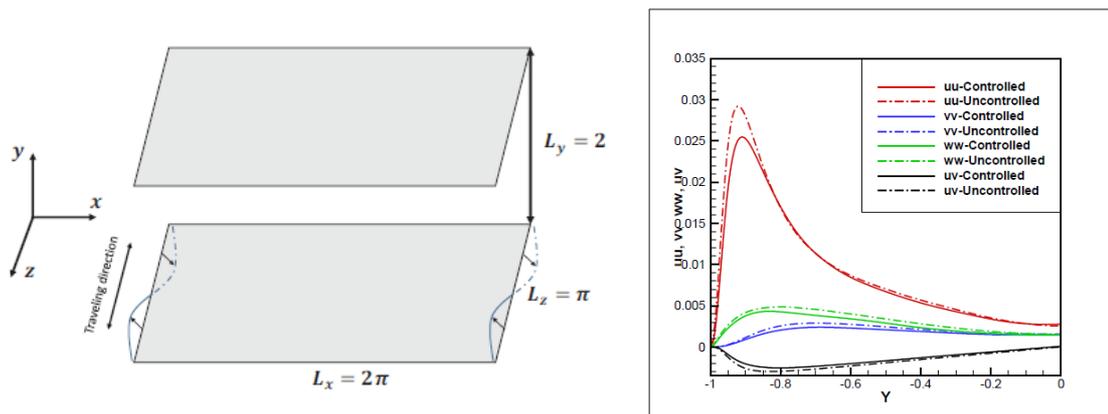
fs-dem@mail.tsinghua.edu.cn

### Abstract

**Keywords:** Drag reduction, Flow control, blowing and suction control, Turbulent channel, High accuracy flux reconstruction method, Direct numerical simulation

Drag reduction control is an important part in flow control field since there are about 50% of the total drag is the viscous drag for a Boeing aircraft. As for the energy consumption, 1% drag reduction in viscous drag will lead to 0.75% reduction in fuel consumption with an estimation. For the energy input aspect, the control strategies can be separated into two categories, passive control and active control. For passive control, riblets have been proved to be an effective way, which give about 8% drag reduction by limiting the transverse motion in the near wall region [1]. For active control, spanwise wall oscillation can achieve about 40% drag reduction [2]. The periodic wall motion weakens the streaks and constraints the autonomous cycle of the near wall turbulence.

Min et al. [3] proposed streamwise traveling wave of blowing and suction in turbulent channel, and he found the drag can be reduced even beyond the corresponding laminar level when the wave is propagating oppositely to streamwise direction. Fukagata *et al.* [4] studied the flow induced by the traveling of blowing and suction, and they thought the actuation will induce a total flux opposite to the wave propagation direction, which will decrease the pressure drop in Min's experiments thus reducing the drag. The channel flow is conducted with constant flow rate (CFR) concept. The numerical methods used here are based on the high accuracy flux reconstruction method (FR) or the correction procedure via reconstruction (CPR) [5]. All simulation is conducted with direct numerical simulation. Different from Min's work, our control strategy is a spanwise traveling wave, and to mimic the effect of wall oscillation, which has a relatively larger drag reduction, our actuation is periodically varying.



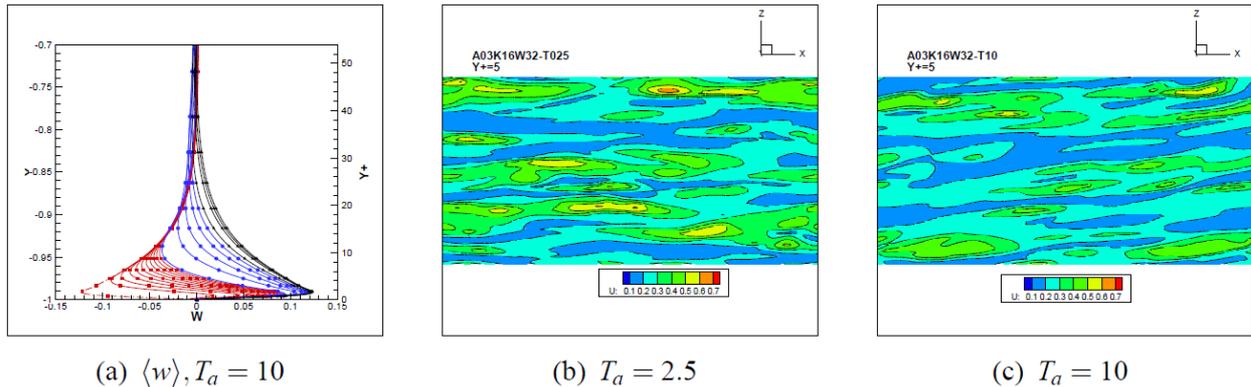
(a) Control sketch

(b) Reynolds stress

**Figure 1:** Reynolds stress of controlled case compared with uncontrolled case

The spanwise average velocity distribution at different time phase is showed in Fig. 2(a). The induced spanwise average and its gradient makes the streaks inline to spanwise direction periodically similar to the phenomena in wall oscillation.

This effect weakens and forbids the re-establish of the streamwise streaks. Among the different  $T\alpha = 2.5, 5, 7.5, 10, 12.5$ ,  $T\alpha = 5, T+a = 115$  gives the largest drag reduction, which is very close to the optimal periods  $T+ = 125$  in wall oscillation control. Blesbois et al. used generalized optimal perturbation (GOP) methods to predict the streak formation in turbulent channel with wall oscillation control. They thought the period of the streak formation is about  $T+ = 80$  in turbulent channel, and, if the oscillation period is larger than it, the streaks will re-establish and the drag recover. In our case, it is showed in Fig. 2, and when  $T\alpha = 2.5$ , the streaks are always aligned in streamwise direction, while in  $T\alpha = 10$ , the streaks are inclined. It shows that the smaller  $T\alpha$  with more rapidly varying spanwise velocity and shear strain forbidden the streaks establish in inclined direction.



**Figure 2:** Streak in controlled channel flow at  $y+ = 5$

We tried spanwise traveling wave of blowing and suction control in turbulent channel flow. The effect of the actuation is close to that of wall oscillation control. The actuation weakens the autonomous cycle of the near wall turbulence by constraining the formation for the streamwise streaks. This leads to smaller turbulent shear stress  $u''v''$  compared to uncontrolled case. In addition, the streaks are inclined in  $+z$  and  $-z$  direction periodically, which means the streaks forms in the inlined direction. With larger period  $T\alpha$ , there is enough time for streaks re-establish and drag recovers. The optimal period in our case and of our tests is  $T\alpha = 5$ , which gives a drag reduction rate is 14%.

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## STS-26 Computational Experiment in Aeroacoustics and Associated Aerodynamics for Aerospace Industries

*Chair: Tatiana Kozubskaya*<sup>1</sup>

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### Session Abstract

**Keywords:** *Turbulent flow, Scale-resolving simulation, Unsteady loads, Far-field acoustics, Airframe noise, Aircrafts, Helicopter, Aviation engines, Space vehicles*

The goal of this STS is to assess the state-of-the-art of computational experiment in aeroacoustics and associated aerodynamics as a research tool used in engineering design of modern aircrafts including airframes, helicopters, space vehicles and aviation engines. We focus on reducing the noise generated by aircrafts since nowadays it is a mandatory requirement, to protect the environment. We treat the associated aerodynamics as dynamics of unsteady turbulent flows over airframes since it underlies the formation of distributed acoustic sources.

At the STS, we discuss several CFD/CAA predictions oriented towards different aerospace industries. The simulations of relevant turbulent flows using the advanced RANS-LES scale-resolving methods are of particular interest. Among the issues under consideration, there are unsteady flow characteristics, aerodynamic and acoustic loads, near-field and far-field acoustics.

We pay a special attention to the validation of the developed numerical algorithms and the CFD/CAA codes providing computational experiments. The set-ups of experimental cases and validation results are also within the scope.

The STS follows the ideas of regular international workshops “Computational Experiment in Aeroacoustics and associated Aerodynamics” <http://ceaa-w.imamod.ru/> and, in particular, the Sixth forum taking place in September 2020.



**Figure 1:** Instantaneous flow fields: dual-stream jet (left), acoustic radiation by 30P30N HLD configuration (middle), vortical flow generated by helicopter rotor at hover mode (right).

**List of paper titles and authors:**

- **Simulation of Helmholtz Resonator Using Immersed Boundary Method**
  - Xin Zhang, aexzhang@ust.hk, and Siyang Zhong, Hong Kong University of Science and Technology – HKUST, Hong Kong
  
- **Adaptive Metamodelling Techniques for Acoustics and Aerodynamics**
  - Umberto Iemma, u.iemma@uniroma3.it, Lorenzo Burghignoli, Francesco Centracchio, Giorgio Palma, and Monica Rossetti, Roma Tre University, Rome, Italy
  
- **Two Validation Cases for Essentially Unsteady Turbulent Flows**
  - Alexey Duben and Tatiana Kozubskaya, tatiana.kozubskaya@gmail.com, Keldysh Institute of Applied Mathematics, Moscow, Russia
  
- **Analysis and Modelling of the Flow and Far-Field Noise of a Turbulent Subsonic Jet from Experimental and Numerical Data**
  - Maxime Huet, maxime.huet@onera.fr, DAAA, ONERA, Université Paris Saclay, Châtillon, France,
  - Georgy A. Faranosov, Oleg P. Bychkov, Central Aerohydrodynamic Institute (TsAGI), Moscow, Russia,
  - and François Vuillot, DMPE, ONERA, Université Paris Saclay, Palaiseau, France
  
- **Numerical Simulation of Ducted Fan Aerodynamics and Aeroacoustics**
  - Tao Zhang and George N. Barakos, George.Barakos@glasgow.ac.uk, CFD Laboratory, School of Engineering, University of Glasgow, Scotland, UK

## STS-26-2    **Simulation of Helmholtz Resonator Using Immersed Boundary Method**

**Maxime Huet<sup>1</sup>, Wei Ying<sup>1</sup>, Ryu Fattah<sup>1</sup>, Siyang Zhong<sup>1</sup>, Sinfiorano Cantos<sup>1</sup>, Xin Zhang<sup>1</sup>**

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### **Abstract**

**Keywords:**    *Liner, Resonator, Computational aeroacoustics*

Acoustic liners are typically installed in aircraft engines for noise reduction. Traditional liners have simple designs tuned to a specific frequency. The noise attenuation mechanisms by complex honeycomb structures can be challenging to model numerically. Using an immersed boundary model, the properties of uniquely shaped acoustic resonators, such as extended-neck Helmholtz resonators, can be evaluated efficiently.

In this work, the Brinkman-based Volume Penalisation Method will be employed, together with high order numerical schemes. The paper will outline the numerical methods, results from canonical validation cases typically applied in computational aeroacoustics, and finally report on the numerical simulations of acoustic resonators.

## STS-26-3 Adaptive Metamodelling Techniques for Acoustics and Aerodynamics

Lorenzo Burghignoli<sup>1</sup>, Francesco Centracchio<sup>2</sup>, Giorgio Palma<sup>3</sup>, Monica Rossetti<sup>4</sup>  
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### Abstract

**Keywords:** *Adaptive metamodelling, Acoustics, Aerodynamics*

The present work outlines an investigation on the use of adaptive metamodels based on Radial Basis Functions (RBF) applied to aerodynamic and acoustic problems. The relevance of the topic lies on the massive use of metamodelling techniques within the design optimisation process of disruptive aircraft layouts. Indeed, the air traffic growth, consequently the hard environmental constraints imposed by regulations, will make a technological breakthrough an imperative need within few years. As consequence, the engineering community is paying particular attention to the development of innovative techniques for the design of unconventional configurations. For this class of applications the designer cannot successfully rely on historical data or low-fidelity models, and the expensive direct simulations remain the only valuable design strategy. In this regard, it can be demonstrated that the use of surrogate models, i.e. metamodels, significantly reduces the computing costs, especially in view of a robust approach to the optimised design. In order to further improve the efficiency of metamodel-based techniques, dynamic approaches based on auto-tuning methods and adaptive sampling procedures have been recently developed. The application presented here pertains the exploiting of dynamic RBF-based metamodels applied to aerodynamic and acoustic problems of aeronautical interest. The analysis of the metamodel performances and its convergence properties shows how the choice of the RBF kernel function plays a key role, strongly depending on the specific physical problem.

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## STS-26-4 Two Validation Cases for Essentially Unsteady High-Speed Turbulent Flows

**Alexey P. Duben<sup>1</sup>, Tatiana K. Kozubskaya<sup>1</sup> and Sergey Bosnyakov<sup>2</sup>**

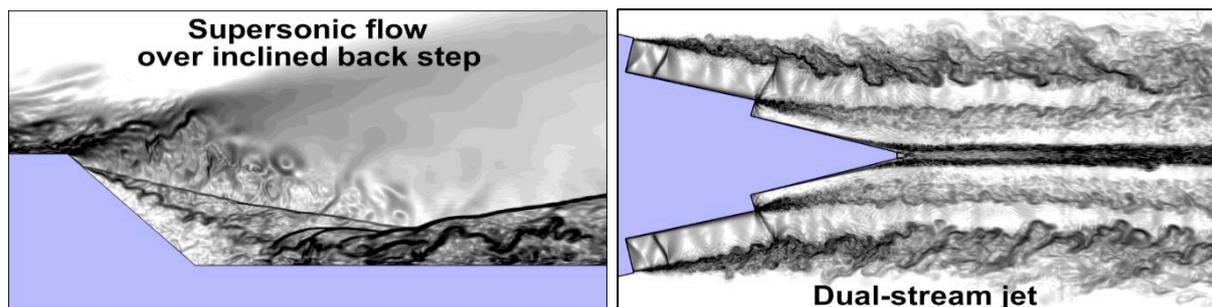
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### Abstract

**Keywords:** *Turbulent flow, Supersonic flow, Scale-resolving simulation, Inclined backward-facing step, Dual-stream jet*

In many industrially relevant cases, the RANS-based approaches to model turbulent flows cannot provide the proper data both on unsteady loads and far-field acoustics. However, this data is of crucial importance when finding the optimal shape of the vehicle and developing the low-noise aircrafts. Such information can be derived from using the scale-resolving methods and the hybrid RANS-LES models, in particular. In the talk, we consider two validation cases for high-speed turbulent flows where unsteady motions of vortical structures strongly affect the flow field and must be predicted rather accurately. The first case is the supersonic flow at  $M=3$  and  $Re_h=3.2 \times 10^7$  over the  $45^\circ$ -inclined backward facing step [1]. The second one is the axisymmetric high-Reynolds dual-stream jet: slightly underexpanded at the bypass duct and subsonic at the main duct [2]. The both physical experiments are performed by ITAM SB RAS, Novosibirsk, Russia.



To simulate the cases, we exploit the DES-family methods implemented using the EBR-WENO scheme [3] for unstructured meshes. The numerical results are discussed.

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## STS-26-5 Analysis and Modelling of the Flow and Far-Field Noise of a Turbulent Subsonic Jet from Experimental and Numerical Data

Maxime Huet<sup>1</sup>, Georgy A. Faranosov<sup>2</sup>, Oleg P. Bychkov<sup>2</sup> and Francois Vuillot<sup>3</sup>

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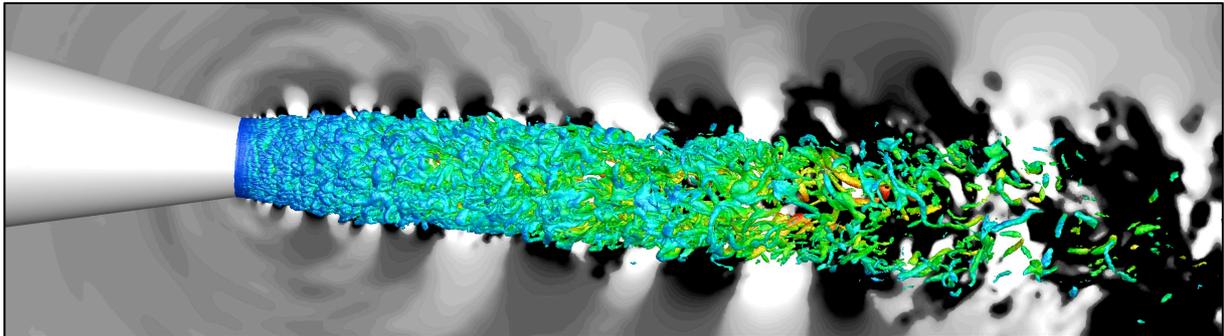
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### Abstract

**Keywords:** *Jet noise, Turbulent flow, Aeroacoustics, Large-Eddy Simulation, Experiment*

The noise generated by a single stream jet with a diameter-based Reynolds number  $Re_D = 550\,000$  and Mach number  $M_j = 0.55$  is investigated numerically using Large-Eddy Simulation. Particular attention is focused on the resolution of the nozzle boundary layer, which plays a crucial role in flow development and noise radiation. The boundary layer is expected to be turbulent according to the Reynolds number and turbulence is seeded numerically through a geometrical tripping on the nozzle wall. The simulation is assessed through a detailed comparison with measurements and reproduces quite correctly the experimental jet. In particular, turbulence is fully developed in the jet plume and simulated pressure near-field spectra and far-field modal decomposition collapse with the experiments. A slight overestimation of the simulated turbulence is noticed but limits to an overprediction below 2 dB for the far-field noise.



The final objective of the study is to develop more precise semi-empirical models, especially for installation noise prediction. To this end, additional investigations will be detailed during the presentation. Of particular interest are:

- (i) jet axis velocity (wavepackets identification),
- (ii) near-field pressure (azimuthal content, phase velocities, POD modes characteristics) and
- (iii) far pressure field (azimuthal content, correlation properties).

### References:

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## STS-26-6 Numerical Simulation of Ducted Fan Aerodynamics and Aeroacoustics

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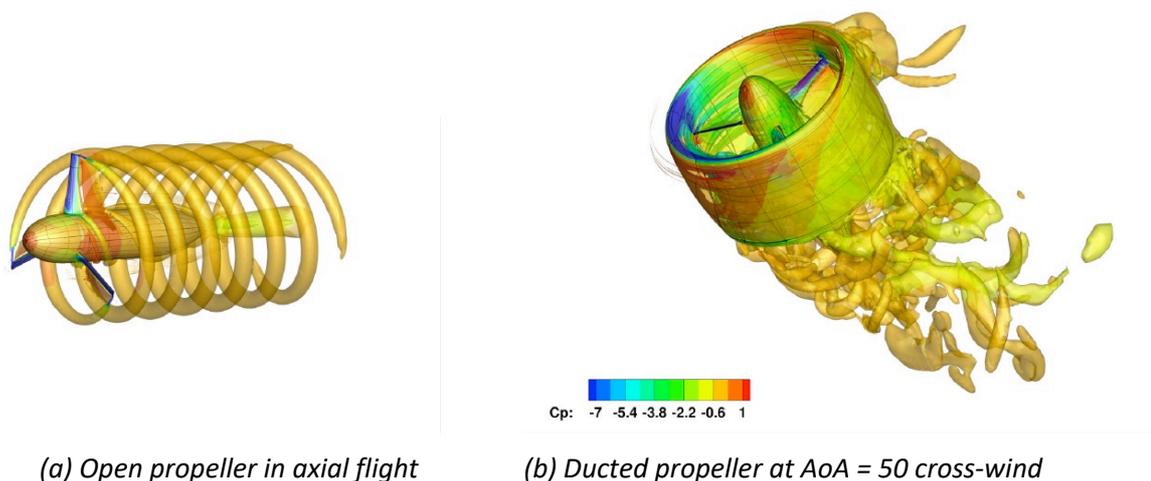
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### Abstract

**Keywords:** *Ducted fan, High-fidelity computational fluid dynamics, Computational aeroacoustics*

The ducted fan is a propeller enclosed by an annular duct. In hover, or at low advance ratios, the duct induces higher or lower mass and momentum flow rates through the propeller disk, depending on the specific duct shape, thereby increasing or decreasing the total propulsor thrust. Apart from the thrust augmentation, noise reduction is also expected due to the duct shielding. The presence of the duct significantly changes the acoustic patterns of a rotating propeller. Stronger radiation directivity and noise reduction are the two major features, comparing to open propellers. Considering the complex flow features imposed by the duct/propeller interaction, modern CFD and CAA methods are especially suitable for the investigation of ducted fan acoustics. Nevertheless, very few studies exist on the topic using high-fidelity flow simulations. In the present work, high-fidelity CFD simulations on ducted fans are performed using the HMB3 solver (M. Biava et al. AIAA Journal, 2015, Vol 54, 2, pp.735-749).

Good agreement with test data by Grunwald et al. (K. Grunwald et al., 1962, NASA TN D-995) are noted. Comparisons are also made against the un-ducted propeller, and the superior performance of the ducted propeller is confirmed. As shown in Figure 1, flow-fields of the ducted and un-ducted propellers at different angles of attack are resolved in detail. The pressure fields are then extracted and the farfield acoustic are calculated using the Ffowcs-Williams & Hawkings (FWH) acoustic analogy. Detailed analysis of the ducted fan aerodynamics and acoustics is presented in the full paper.



**Figure 1:** Iso-surfaces of non-dimensional Q criterion for the open and ducted propellers, colored with pressure coefficients.

## **STS Discussion Session 6: Aeronautics – Structures, Design and Optimisation Methods**

**Moderators: Christophe Hermans, Jacques Periaux, Carlo Poloni, Dietrich Knoerzer**

### **Participating STS:**

#### **STS-01 Advances in Materials, Structures and Manufacturing for Aeronautics Applications**

*Chair: Dietrich Knoerzer*

#### **STS-11 Integration and Use of Material and Process Modelling for Decision Making**

*Chairs: Carlo Poloni, Carlos Kavka, Alesandro Segatto, Borek Patzak, Salim Belouettar*

#### **STS-13 Integration Challenges of New Disruptive and Innovative Aircraft Design Solutions: A Multi-fidelity Paradigm for Computationally Efficient Prediction of Complex Physics**

*Chairs: Christophe Hermans and Pierre Bescond*

#### **STS-18 Advanced Optimisation Methods and Tools Tackling the Climate Change – Applications to the Design of Innovative Aircraft & Aero-engine Architectures**

*Chairs: Jacques Periaux and Michael Kyriakopoulos*

## STS-01      **Advances in Materials, Structures and Manufacturing for Aeronautics Applications**

**Chair: Dietrich Knoerzer**

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### **Session Abstract**

**Keywords:**      *Lightweight materials, Composite structures, Multifunctional materials and structures for weight saving, Reduced manufacturing cost*

According to the Strategic Research and Innovation Agenda of the Advisory Council for Aviation Research & Innovation in Europe (ACARE), new technologies, materials, manufacturing processes and system concepts are vital for the European aviation sector.

Environmental protection is, and will continue to be, a key driver for aviation. The environmental goals in Flightpath 2050 recognise the need for aviation to accelerate its effort nuisance and air quality for the benefit of all citizens and to allow sustainable traffic growth.

For future airliners, the airframes, including cabin interiors, must contribute benefit from increased innovation in lightweight materials, including composites. Their use will require new approaches to design and manufacturing, with multifunctional materials and structures for weight-saving, reduced manufacturing cost and increased production rate. Design for end-to-end performance improvement must be achieved with multidisciplinary approaches such as multi-criteria optimisation and digital model-based engineering.

In this session, experimental and numerical technologies and new research of advanced materials, structures and related manufacturing processes for applications in aerospace will be presented.

Amongst others, a numerical simulation methodology of Additive Manufacturing process for open lattice cellular materials will be presented. Investigations of new composite structures on their mechanical and dynamic behaviour will be addressed.

**The following papers will be presented:**

- **Numerical Modelling and Mechanical Behaviour of Cellular Materials Produced by Additive Manufacturing Process**
  - George Lampeas, Harry Psihoyos and Spiros Pantelakis, Univ. of Patras, Greece
- **Active Vibration Control of Lattice Core-Sandwich Structures Using Macro-Fiber Composite Actuators**
  - Narasimha Rao Mekala and Kai-Uwe Schröder, RWTH Aachen University, Germany
- **Numerical Analysis of a Mechanical De-Icing Process by Low Frequency Oscillation of a CFRP layer**
  - Felix Grubert, Miguel Nuño Spiewak and Kai-Uwe Schröder, RWTH Aachen Univ., Germany
- **The implementation of a Novel Holistic Index for the Optimization of the Automated Fiber Placement Process with Regard to Quality, Life Cycle Costs and Environmental Performance**
  - Christos Katsiropoulos and Spiros Pantelakis, Univ. of Patras, Greece

## STS-01-1 Numerical Modelling and Mechanical Behaviour of Cellular Materials Produced by Additive Manufacturing Process

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### Abstract

**Keywords:** *Additive Manufacturing, Numerical simulation, Selective Laser Melting*

In the present paper a numerical simulation methodology of Additive Manufacturing (AM) process for open lattice cellular materials is presented, followed by derivation of cellular material mechanical behaviour. The simulations aim to derive the relations between the manufacturing process parameters and the produced material behaviour.

To this purpose, the Selective Laser Melting AM manufacturing process is initially thermo-mechanically simulated. The heat transfer occurring by all three mechanisms i.e. conduction, convection and radiation is simulated using the developed finite element model. Heat is provided to the part by the laser beam and then is transferred to the part volume via conduction through the solid and the powder material. Heat is lost from the system by means of convection and radiation of the free surfaces. The numerical simulation is used to predict the final geometry of the open-lattice material system, the temperature history and the residual stress/ distortions as function of AM process parameters applied. Provided that the simulation of AM manufacturing process of open-lattice cellular structures is computationally very demanding, it has been currently limited at the macro scale and considered a single unit-cell. The results of the developed finite element AM simulation models are successfully compared to experimental results validating the AM simulation methodology.

Consequently, the Selective Laser Melting process simulation output serve as input to detailed numerical mechanical models, which have been developed in order to predict the cellular core failure under different loading modes. The methodology is demonstrated in the cases metallic and plastic open-lattice Body-Centred-Cubic (BCC) cellular cores. The numerical predictions are validated by cellular material compression experimental tests.

The application of the proposed approach contributes to the first-time right process parameters selection, which enable the production of cores with pre-defined properties. The developed methodology is extendable in two directions, i.e. locally in the micro-scale, such that the processed material porosity is predicted, as well as in full part geometry, such that residual stress and distortion results are more realistically calculated.

## STS-01-2     **Active Vibration Control of Lattice Core Sandwich Structures Using Macro-Fiber Composite Actuators**

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### **Abstract**

**Keywords:**     *Active vibration control, Numerical simulation, Lattice core sandwich structures*

Sandwich structures possess a high bending stiffness compared to monolithic structures with a similar weight. This makes them very suitable for lightweight applications where high stiffness to weight ratios are needed. The process of lightweight design often results in thin-walled structures. Thin-walled structures are more prone to vibrations and damping of vibrations under various loads are very important. One of the approaches to damp the vibrations of the structures is using active control systems.

In this paper, active vibration control of lattice core-sandwich structures using macro-fiber composite (MFC) actuators is presented. Layer-wise modelling of lattice core-sandwich structures is considered in the present paper by evaluating the equivalent material properties using multi-scale modelling of pyramidal truss cores. A geometrically nonlinear shell finite element model is developed for MFC bonded structures. To model electro-mechanical coupling in MFC actuators, more accurately, nonlinear dependence of electro-mechanical coupling coefficients with respect to applied electric fields are considered.

With the developed numerical model, various examples of lattice-core sandwich structures with a different number of unit cells under both static and dynamic loads are simulated numerically. The mechanical behaviour of MFC bonded lattice core-sandwich structures is studied under both mechanical and applied electric loads. The influence on the mechanical behaviour of lattice core-sandwich structures by varying parameters like the number of unit cells and lattice core dimensions are studied by performing the numerical simulations with developed numerical models. Furthermore, active vibration control of sandwich structures with MFC actuators is performed to suppress the vibrations. To understand vibration behaviour, frequency response analysis performed for the pyramidal lattice core structures with various parameters of truss cores and later active vibration control for these structures also studied in the present paper.

## STS-01-3 Numerical Analysis of a Mechanical De-Icing Process by Low Frequency Oscillation of a CFRP Layer

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### Abstract

**Keywords:** *General aviation, Ice, Mechanical de-icing, Oscillation*

De-icing of general aviation aircraft is usually realized by chemical or thermal processes. This leads to an increase in fuel consumption or usage of electrical energy. Mechanical de-icing could be a way to significantly reduce this consumption. In mechanical de-icing, a surface is deformed so that the required failure mechanisms are induced in the ice, causing it to detach.

In this paper, the release behaviour of ice on a CFRP layer is investigated. The CFRP layer consists of two plies, each 0.3 mm thick. A numerical calculation is performed to determine the natural frequency and the required amplitudes of the vibration. In addition, the relationship between the various failure mechanisms of ice and the ice layer thickness, as well as the control values are determined. Furthermore, tests are performed to validate these control values. For this purpose, the surface of a CFRP layer is iced with water in a climate chamber at -10°C. An electrodynamic vibration exciter is connected to the CFRP and generates the required displacements at desired frequencies to observe the release of the ice.

## STS-01-4 The Implementation of a Novel Holistic Index for the Optimization of the Automated Fiber Placement Process with regard to Quality, Life Cycle Costs and Environmental Performance

Christos V. Katsiropoulos<sup>1</sup> and Spiros G. Pantelakis<sup>2</sup>

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### Abstract

**Keywords:** *Process optimization, Holistic index, Automated fiber placement, Thermoplastics, Quality, Cost, Environmental footprint*

The mainstream composite material type for aeronautical applications is carbon fiber reinforced epoxies. However, issues associated with their long curing cycles which lead to low production rates, the growing environmental concerns associated with their end-of-life treatment as well as the adoption of stricter environmental policies have turned the attention of the aeronautical industry to thermoplastic composites as a promising alternative solution [e.g. 1].

Thermoplastic composites exhibit superior impact and chemical resistance, unlimited self-life as well as the ability of assembling sub-structures by welding and recyclability [e.g. 2]. On the downside the higher processing temperatures and pressures needed for processing these materials, leading to increased energy consumption and cost, are key barriers for their wide range use for the construction of primary structures by the aeronautical industry [e.g. 3]. Additionally, the deterioration of the mechanical properties of the materials during the recycling process due to the difficulties in the incorporation of the recycled fiber systems into the matrices [1] poses a burden for further exploiting their recyclability. Regardless whether dealing with thermosets or thermoplastics, cost and environmental footprint for producing an aircraft component are nowadays of critical concern, in addition to the non-negotiable demand for reduced weight by satisfactory quality.

In general, the assessment of cost and environmental footprint for producing an aircraft component is nowadays a common practice. In this context Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) models are used individually prior manufacturing as tools either for the selection of the most suitable process among a number of candidates or for the process optimization if the manufacturing technique is already predefined [e.g. 6]. In addition, meeting the quality of the component, in terms of predefined quality features like eg. critical mechanical properties etc., is a non-negotiable demand. In parallel, efforts have been undertaken in optimizing structural components with regard to their quality and cost by considering quality and cost as interdependent functions of the manufacturing process parameters [e.g. 5].

Yet, in most cases a quality increase is associated to an increase of cost and in several cases also to an increase of the environmental footprint and vice versa. Therefore, quality of the component as well as the overall environmental footprint and cost of the product including component manufacturing process and End-of-Life-Cycle need to be considered already at the component design phase as component optimization interdependent objective functions. However, despite the mentioned efforts, tools and concepts allowing for a holistic and interdependent optimization of a product with regard to quality, cost and environmental impact still need to be developed.

In the present work, a novel holistic component and process optimization index is introduced. The Index is aimed to provide a decision support tool for the optimization of aircraft composite components and manufacturing processes as well as for the selection of the appropriate manufacturing technique of a component when various techniques are considered as manufacturing

options. The criteria involved in the index are quality, cost and environmental footprint functions which are considered to be interdependent. In the present concept quality is quantified through measurable technological features which are required for the component under consideration. Cost has been estimated by implementing the Activity Based Concept (ABC) using an in house developed tool. Environmental footprint is assessed by exploiting the ReCiPe method using the 'open LCA' software. The weight factor of each of the above criteria in the Index is calculated by using the Multi Criteria Decision (MCD) method Analytic Hierarchy Process (AHP). The Index developed has been applied to support the selection of the appropriate production technique for a typical aeronautical composite part. The alternative manufacturing options considered have been the Automated Fiber Placement (AFP) as well as the classical Autoclave manufacturing technique. By considering quality as the prevailing factor for meeting a decision the index confirms the advantage of the Autoclave process. Yet, by considering the environmental footprint and/or cost to be of equal or higher significance to quality, the implementation of the index demonstrates the clear advantage of AFP process.

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## STS-11 Integration and Use of Material and Process Modelling for Decision Making

**Chairs:** Carlo Poloni<sup>1</sup>, Carlos Kavka<sup>1</sup>, Alesandro Segatto<sup>1</sup>, Borek Patzak<sup>2</sup>, Salim Belouettar<sup>3</sup>

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### Session Abstract

**Keywords:** *Computational materials and structure design, Business process modelling and design, Decision support system, Interoperability, Model selection, Material and process selection, Data and metadata*

Decision making process is a knowledge and data intensive process, with modelling, data and knowledge playing a significant role in speeding up and effecting decisions. As the pace of digital transformation, industries need to use more than ever modelling and simulation for decision-making. In this context, capturing, managing, and reusing of decision related knowledge such as company business processes, alternatives, parameters, constraints, goals, dependencies, and the design process in the design of complex material and manufacturing systems is an effective way for providing effective decision support.

This STS aims to provide a forum for presenting and discussing recent advances and challenges related to the integration of material and process modelling in decision-making. This includes:

Modelling and Simulation frameworks for decision making supporting interoperability for modelling linked and coupled physical phenomena, which will make the integration of different types models and the development of workflows much faster and less error prone.

Interoperability and Metadata, data structures, schemas and associated metadata to guarantee interoperability among different materials modelling components as well as to support knowledge management across materials modelling data and business data, or LCE models.

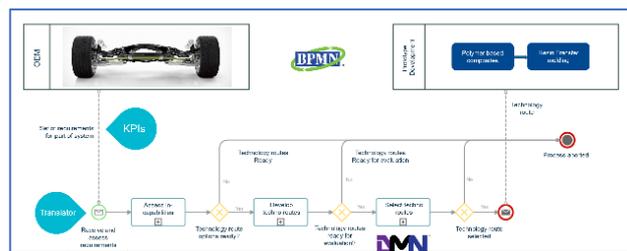
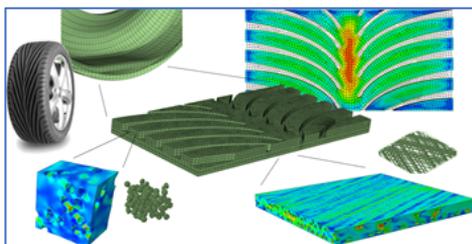
Model selection and model adaptivity for decision-making.

Integration of materials models with structured and unstructured data for decision-making and techniques for efficient exploration of multi-level design spaces.

Multidisciplinary design optimization, considering different approaches and methodologies that account for performance while combining tools to estimate the profitability of designed products.

Business Decision Workflows and Business Requirements using the Business Process Models and standards therefore providing the missing link between business processes and materials science/engineering workflows. This includes the creation of use-case scenarios and analysis and development of algorithms to enable KPIs-based business decisions.

The session will host industrial application from the Horizon 2020 project COMPOSELECTOR in the transport industry (automotive and aerospace), where complex composite materials need to be considered for performance, availability and lifecycle.



**The following papers will be presented in this STS 11:**

- **COMPOSELECTOR: A Material Modelling and Data-Driven Empowered Business Decision Support System (DSS)**
  - Salim Belouettar, Luxembourg Inst. of S&T, Carlos Kavka, Alessandro Segato, ESTECO SpA, Trieste, Hein Koelman, Koelman Consulting
- **MuPIF: Open Distributed Simulation Platform**
  - Bořek Patzák, Vít Šmilauer, Martin Horák, Stanislav Šulc, Edita Dvořáková, CVUT, Prague, Czech Republic
- **A Business Decision Support System Supporting Early Stage Composites Part Design**
  - Hein Koelman, Koelman Consulting, Tom A.M. Verbrugge, DOW Belgium, Dario Campagna, Carlos Kavka, Alessandro Segato, ESTECO SpA, Trieste, Italy, Salim Belouettar, Luxembourg Inst. of S&T
- **A Standard Approach for Decision Making in Materials and Process Selection**
  - Carlos Kavka, Alessandro Segatto, Dario Campagna, Mattia Milleri, Alan Del Piccolo, ESTECO, Trieste, Italy, Astrid Soumoy, Polytechnique de Montréal
- **System Models Simulation Process Management and Collaborative Multidisciplinary Optimization**
  - Carlo Poloni, ESTECO SpA and Univ. of Trieste, Trieste, Italy

## STS-11-1 COMPOSELECTOR: A Material Modelling and Data-Driven Empowered Business Decision Support System (DSS)

Salim Belouettar<sup>1</sup>, Carlos Kavka<sup>2</sup>, Alessandro Segato<sup>2</sup>, Hein Koelman<sup>3</sup>

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### Abstract

**Keywords:** *Decision making, Modelling and simulation, Data, Business decision, Multi-criteria optimization, Model selection, Key performance indicators, Business decision support system*

A decision-making process for product development involves making a choice among a number of scenarios taking into account a number of Key performance indicators and attributes or the improvement of an alternative through modification by making a trade-off among multiple design objectives.

Intelligent well-informed decisions have to be made in a timely manner by industry on the choice of materials and processing needed for enhancing existing products and creating novel market differentiating products. The combination of materials and business modelling to explore what technical solutions are economically viable is not yet exploited to the extent it could. The paper proposes to demonstrate how integrated material and business process offers modelling supports early design decision making in product development. The developed DSS integrates materials and process modelling outcomes (source information) into state-of-the-art business decision support systems to make more knowledgeable decisions based not only on existing legacy data, but also on new data generated by state-of-the-art modelling and simulation workflows. This new paradigm of DSS for material and process selection and design is finding application in material systems of ever-increasing complexity such as polymer composite materials. The developed technology helps implementing alternative strategies with user in the loop to the current material selection, building upon a multi-actor framework to cover the entire value-chain, and eventually bring to implementing a roadmap to improve composite material selection & design.

**Acknowledgement:** The project leading to this presentation has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 721105.

## STS-11-2 MuPIF: Open Distributed Simulation Platform

**Bořek Patzák, Vít Šmilauer, Martin Horák, Stanislav Šulc, Edita Dvořáková<sup>1</sup>**

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### Abstract

**Keywords:** *Simulation platform, Distributed computing, Object-oriented design, Decision making, Modelling and simulation, Interoperability.*

A reliable multiscale and multi-physics modelling requires including all relevant physical phenomena along the process chain and across multiple scales. The complexity of problems requires combination of knowledge from different fields. This, among others, brings in the changeless for software engineering. There is a strong need for integration platforms, which enable interoperable integration of existing simulations tools and databases into a complex simulation workflow, providing capability to exchange information and efficiently use available computing resources. Traditional approaches have been based on syntactic interoperability, based on specific communication protocols and conversion tools. The more attractive are approaches based on semantic interoperability, where data are exchanged together with their meaning, which allows for automated machine interpretation, translation, and verification.

The presented contribution introduces multi-physics integration platform MuPIF ([www.mupif.org](http://www.mupif.org)). MuPIF is a distributed, object-oriented framework written in Python. The top-level abstract classes are introduced for models (simulation tools) and generic data types. They define standardized interfaces allowing to manipulate and steer derived classes (representing individual models and specific data components) using the same generic interface. One of the key features of the MuPIF platform is the definition of abstract interfaces for models as well as for high level data types (spatial fields, microstructures or properties, for example). This allows to achieve true plug and play architecture. As the same concept is applied for high level data, the platform natively supports different data formats, storage schemes and even data repositories.

MuPIF is natively supporting distributed workflows, where individual simulations and data can be executed/stored on remote computers, taking advantage of secure communication, public/private key authentication and resource allocation. The distributed capabilities can be exploited in many ways, allowing to utilize HPC resources, or offering individual remote applications as a service. Recent applications proved MuPIF capabilities in design and optimization of complex composite materials and components in frame of COMPOSELECTOR project.

### Acknowledgement:

The project leading to this presentation has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the grant agreement No 721105.

## STS-11-3 A Business Decision Support System Supporting Early Stage Composites Part Design

Hein Koelman<sup>1</sup>, Tom A.M. Verbrugge<sup>2</sup>, Dario Campagna<sup>3</sup>, Carlos Kavka<sup>3</sup>, Alessandro Segato<sup>3</sup>, Salim Belouettar<sup>4</sup>

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### Abstract

**Keywords:** *Decision making, Modelling and simulation, Data, Business decision, Multi-criteria optimization, Model selection, Cost modelling, Key performance indicators, Business decision support system, Composites*

In the concept design stage for composites parts, there can be an overwhelming amount of options available to the development team in terms of materials, material design, processing/ manufacturing and part design. In order to decide on any of the combinations of options to pursue, a business decision system (BDSS) supporting this decision process is key in order to select and evaluate options and obtaining an overall assessment of the design in the concept stage. The key performance indicators (KPI's) for a composite part can be a combination of technical, financial and environmental indicators, each requiring data from different actors within an organization, and are tracked in a dashboard throughout the part development.

Within the COMPOSELECTOR platform the business decision process for the composite part is structured and defined, using the industry standard BPMN. This business decision layer links to databases and simulation and modelling applications, which are activated to generate data needed for the evaluation of the KPI's and which will populate the dashboard. The development and use of the business layer will be showcased for a composite part design which has technical KPI's requiring simulations to be run, as well as financial KPI's like part costs which are obtained through running cost modelling apps. The business decision support system and its business decision layer can be structured and run to reflect the existing decision process with all its actors within an organization or across the value chain.

**Acknowledgement:** The project leading to this presentation has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 721105.

## STS-11-4 A Standard Approach for Decision Making in Materials and Process Selection

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### Abstract

**Keywords:** *Decision making, Modelling and simulation, Data, Multi-criteria optimization, Business decision, Model selection, Key performance indicators, Business decision support system.*

The selection and design of composite materials and its associated manufacturing process require a comprehensive material modelling physical and engineering simulation and optimization framework, with models that describe the behaviour and relationships of the materials at different physical scales. However, the availability of a framework like this is not enough to support effective decision making. In fact, a modern decision-making process must consider not only models, but also an understanding of risks, costs and business opportunities, or even more elaborated aspects like societal requirements for health and sustainability. Business and modelling cannot work on isolation, the complexity and the interdisciplinary of the decision-making processes require a fully integrated framework consisting of materials models coupled to process models workflows, associated solvers, post-processors together with business models.

The partners of the COMPOSELECTOR European Project works collectively on the definition and implementation of a business decision support system, intended to provide the missing link between business processes and materials science/engineering workflow, providing decision makers with actionable choices that are results of multidisciplinary design optimization over all stages of product development, taking uncertainties, risks and opportunities into account. One of the crucial distinctive aspect of the approach is the integration of material modelling, business tools and databases by using BPMN, the well-defined and widely-used ISO standard notation for business process, and DMN, the standard notation for decision making strategies. The use of standards is a key factor that contributes to the removal of technical barriers for platform users, reducing development time, cost and risks, increasing productivity and efficiency, facilitating the exchange of information between technical and non-technical personnel.

The business decision support system implementation is based on state-of-the-art web technologies, providing a fresh, modern and user-friendly look, in order to enable users to deal with business processes and business data, complemented with historical information on previous executions and decisions. Developers can define business processes graphically by using a web-based online environment. A mobile application has also been defined to contribute to the democratization of the use of simulation, optimization and decision techniques even to non-expert users. Many use-case scenarios to enable business decisions based on key performance indicators have already been implemented.

### Acknowledgement:

The project leading to this presentation has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the grant agreement No 721105.

## STS-11-5 System Models Simulation Process Management and Collaborative Multidisciplinary Optimization

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### Abstract

**Keywords:** *Decision making, Modelling and simulation, Data, Multi-criteria optimization, Business decision, Model selection, Key performance indicators, Business decision support system*

Design optimization is a key activity to improve product performance in the design of modern manufacturing products, in order to reduce costs and time to market. Design optimization makes extensive use of virtual prototype simulations in the automatic search of the design space. Nowadays, engineering products draw together many components assembled in subsystems and systems. Each component is described by different physics, and the performance assessment covers the whole range of engineering analysis - e.g. mechanical, structural, thermal, electromagnetic, etc.-, requiring multiple simulation processes.

Many groups are involved in providing these different components and the simulation of physics dimensions are carried out by each single player counting on disparate levels of expertise and computing resources while exploration algorithms orchestrate the selection and execution of design alternatives.

This paper shows how VOLTA framework collaborative and distributed execution framework is used to compose multiple simulation processes at component level to generate system models managing the complexity of running multidisciplinary design projects. Driving process, component and subsystem knowledge with system models, VOLTA allows a larger inference space for design, the ability to continually connect at the system level, and a basis for knowledge capture.

In this paper a real test case performed on the design and optimization of wind turbine is presented. The design workflow is managed by different engineering experts through a collaborative framework.

## STS-13      **Integration challenges of new disruptive and innovative aircraft design solutions: A multi-fidelity paradigm for computationally efficient prediction of complex physics**

**Chairs: Christophe Hermans<sup>1</sup> and Pierre Bescond<sup>2</sup>**

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### **Session Abstract**

**Keywords:**      *Distributed propulsion, Boundary layer ingestion, Flow laminarity, Morphing concepts, Load alleviation, Active flow control*

Commercial air traffic has shown a continuous growth ever since, despite major conflicts with global impact and volatility of oil prices. The amount of travel by air is forecasted to double by 2030 with more than six billion passengers. This shows that significant efforts are required to cope with challenges like airport congestion and capacity limitations, climate change and community noise. The next generation aircraft has to be much more environmentally friendly, burn less fuel with fewer emissions, and will be less noisy. To achieve a step change, new technologies like distributed propulsion, boundary layer ingestion, flow laminarity, morphing concepts and load alleviation through active flow control have to be considered. They all bring not only new aircraft integration challenges, but also pose major challenges to predictive capabilities.

Existing methods for aeronautical engineering analysis used for conceptual design optimization are biased towards conventional 'wing-tube' aircraft configurations. The subject STS aims at presenting the integration of new capabilities into Multi-Disciplinary Optimization (MDO) frameworks with treatment of aerodynamic, structural and acoustics analysis methods, uncertainty analysis and multi-fidelity approaches. The STS will deal with development of design frameworks providing flexibility to accommodate insertion of high-fidelity knowledge of physics (dealing with new disruptive and innovative aircraft design solutions) without jeopardizing the efficiency of the numerical processes.

#### **Paper titles and speakers:**

- **Disciplinary Implications of a System Architecting Approach to Collaborative Aircraft Design**
  - Jan-Niclas Walther, Pier D. Ciampa, Björn Nagel, DLR - German Aerospace Center, Hamburg, Germany, Jan-Niclas.Walther@dlr.de
- **An Overview of ONERA Research at Aircraft Level towards Greener Aviation**
  - Peter Schmollgruber, ONERA, Peter.Schmollgruber@onera.fr, Eric Coustols, ONERA, Toulouse, France, Eric.Coustols@onera.fr
- **Multidisciplinary Modelling, Analysis and Optimisation for Aircraft and System Level Design and Validation**
  - Johan Kos, Jos Vankan, NLR - Royal Netherlands Aerospace Center, Amsterdam, The Netherlands, jos.vankan@nlr.nl
- **Automated Approach for Aerodynamic Design**
  - Jesus Matesanz Garcia, Cranfield University, Cranfield, United Kingdom, Jesus.Matesanz-Garcia@cranfield.ac.uk

## STS-13-1      **Disciplinary Implications of a System Architecting Approach to Collaborative Aircraft Design**

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### **Abstract**

**Keywords:**      *Unconventional configurations, Virtual aircraft, Preliminary aircraft design, CPACS (Common Parametric Aircraft Configuration Schema)*

In the face of growing public awareness of environmental issues such as climate change, the pressure to provide efficient and ecological new air transport solutions is higher than ever on the aviation community. To this aim, unconventional configurations, which are radically different from the established tube-and-wing architecture, may hold a lot of potential. However, aerospace OEMs today usually shy away from such configurations due to the significantly increased uncertainty and entrepreneurial risk connected to such drastic design changes.

In order to reduce the risk and increase knowledge about a new configuration, the application of physics-based analyses on a virtual aircraft can add significant value, when applied in the early stages of the design process by bringing new technologies to higher technology readiness levels (TRLs) quickly. Due to the highly multidisciplinary nature of the aircraft design task, the success of this approach largely depends not only on the well-organized handling of the available product data at any point in the design process but also the smart sequencing of the disciplinary contributions based on their mutual dependencies.

A methodology for an integrated and collaborative approach to preliminary aircraft design will be presented. It applies several well established components, such as CPACS (Common Parametric Aircraft Configuration Schema) as a central product data schema and RCE (Remote Component Environment), which enables an automated collaborative approach to aircraft design, and combines them with methods from system architecting and model-based system engineering. Furthermore, the requirements for a disciplinary tool to contribute to an integrated multidisciplinary design process are highlighted.

## STS-13-2    **An Overview of ONERA Research at Aircraft Level towards Greener Aviation**

**Peter Schmollgruber<sup>1</sup>, Eric Coustols<sup>2</sup>**

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### **Abstract**

**Keywords:**    *Aerodynamics, Propulsive systems, New configurations*

Considering the urgent societal need to reduce the environmental impact of aviation, new technologies that will decrease aircraft energy consumption must be investigated. Among these technologies, some will improve aerodynamics while others will reduce aircraft weight. In some cases, new propulsive systems with important potential benefits in energy saving are also considered. Last, some studies are carried out in order to assess assets and drawbacks of new configurations that may in addition feature specific technologies. The ONERA presentation will give an overview of recent works carried both by the disciplinary experts and overall aircraft design team about these different options.

## STS-13-3    **Multidisciplinary Modelling, Analysis and Optimisation for Aircraft and System Level Design and Validation**

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### **Abstract**

**Keywords:**    *Emission reduction, Unconventional propulsion, Multidisciplinary modelling, Multidisciplinary design optimization (MDO), Validation*

Against the background of the big environmental and societal challenges as formulated for example in Flightpath 2050, current developments in aircraft design are aiming at further emission reduction through integrated, unconventional propulsion, systems and airframe innovations. This requires the further integration of methods for multidisciplinary modelling, analysis and optimisation for aircraft design, but also for propulsion and system level designs. Moreover, experimental validation of the methods and physical testing of critical unconventional propulsion and system designs are prerequisites for industrially relevant development processes. This paper will present key aspects of computationally efficient MDO frameworks and of multidisciplinary design and validation of propulsion systems.

## STS-18      **Advanced Optimisation Methods and Tools Tackling the Climate Change— Applications to the Design of Innovative Aircraft & Aero-engine Architectures**

**Chairs: Jacques Periaux<sup>1</sup> and Michael Kyriakopoulos<sup>2</sup>**

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### **Session Abstract**

**Keywords:**      *Low-carbon fuel propulsion, Emission reduction, Optimization methods, Novel aircraft architecture, Evolutionary algorithms*

As mentioned in the editorial of a recent Clean Sky document ‘Skyline’, Europe has on its shoulders the urgency of addressing climate change. In that respect, universities, research organizations and industry will continue their effort in Horizon Europe to work on a new Clean Aviation programme.

For achieving the ambitious goals for aircraft emission reductions, novel aircraft architectures using low-carbon fuel need to reduce drag, emissions and also noise to counter the environmental impacts of aviation. Optimised solutions for novel approaches have to be developed.

In this challenging and ambitious context, this STS will propose advanced numerical methods and tools with their associated software for optimising greener aircraft and aero-engine design using hybridized adjunct methods, evolutionary algorithms and games strategies, developed by research institutions and installed in the industrial design environment.

To support the increasing global demand for air travel and achieve significant CO<sup>2</sup>, NO<sub>x</sub> and Noise emission reductions, the aviation industry has more intensively to develop environmentally friendly technologies and their implementation in the novel aircraft generations.

Contributors of this STS will address new concepts and methods for design optimization and for reducing significantly emissions aiming for a decreasing aviation impact on the environment.

### **The following papers will be presented in this STS:**

- **Optimization of a Turbine Inlet Guide Vane by Gradient-based and Metamodel-assisted Methods**
  - Mohamed H. Aissa, Roberto Maffulli, Lasse Mueller and Tom Verstraete, VKI, Brussels, Belgium
- **Non-cooperative Game Hybridization of a Memetic Optimization Approach**
  - Jordi Pons-Prats, Martí Coma, Gabriel Bugada, CIMNE/ UPC, Barcelona, Spain
- **Gust Load Alleviation by Circulation Control for Future Greener Aircraft**
  - Ning Qin, Univ. of Sheffield, Sheffield, UK

## STS-18-1 Optimization of a Turbine Inlet Guide Vane by Gradient-based and Metamodel-assisted Methods

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### Abstract

**Keywords:** *Automated optimization methods, Metamodel-assisted method, Multipoint aerodynamic optimization*

Modern aircraft have a reduced CO<sub>2</sub> emission and fuel consumption compared to airplanes of the last century with a threefold decrease of aircraft energy usage per Available Seat Kilometer (ASK) from the fifties to the end of the twentieth century. This is the result of a continuous optimization process of the whole aircraft but it is worth to note that a large portion of the reduction in the specific fuel consumption is due to advances in gas turbines and propulsion in general enabled mainly by the improvements in the design process.

Design processes nowadays rely more and more on automated optimization methods to shorten the development cycle and reach higher performances. Within those optimization methods, gradient-free ones converge slower but rather to a global optimum, while gradient-based methods converge faster to a local optimum. Quite recently gradient-free methods have been assisted by metamodels to improve their convergence and gradient-based methods are making use of adjoints to speed up the gradient evaluation.

In this work, we compare an adjoint-assisted gradient-based and a metamodel-assisted gradient-free method with respect to convergence, local/global optima and especially the computational time. On a constrained multipoint aerodynamic optimization of a turbine inlet vane, gradient-based and gradient-free methods reached 22% and 24%, respectively, of total pressure loss reduction. The metamodel-assisted method reached a 2% higher objective value at double the cost of flow evaluations, an additional cost related mainly to the evaluation of an initial database.

## STS-18-2    **Non-cooperative Game Hybridization of a Memetic Optimization Approach**

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### **Abstract**

**Keywords:**    *Hybrid optimization, Memetic Algorithms, Multi-population hybridization, Genetic Algorithms*

Hybrid optimization algorithms are gaining attention due to the combination of the capabilities which lead to a better result. The most common way of hybridization is to combine one method providing large search capabilities, with one method that provides fine tuning; what is called the coupling between exploration and exploitation. This approach is well exploited in the Memetic Algorithms (MAs) which initiate the procedure with a global search optimizer, like evolutionary techniques, to refine the solution (even intermediate solutions) with local search techniques, like gradient-based methods. Multi-population hybridization is largely used in operational research, defining two populations of the same characteristics one of them used for exploration and the second one used for exploitation. This approach can be considered as a second strategy to hybridise, since it fits nicely with the characteristics and procedures of Genetic Algorithms (GAs).

The paper presents the research on multi-population hybridisation using multiple optimization algorithms. Each population will use a different optimization algorithm and after each iteration, the information is shared among populations to enrich the genetic information following game procedures. Two main combination have been tested, the first one is using two population-based algorithms, while the second one is using a population-based and a gradient-based method. How to setup the game, synchronising the two populations and sharing information, is the key for achieving a good performance of the hybridisation. Mathematical benchmarks are used to test the methods and compare the results. A final assessment of the methodology is presented as a first step towards the application of the proposed method to real-life engineering problems.

As a first approach to the methodology, the present communication will provide conclusions and the description of the further steps proposed by the authors.

## STS-18-4 Gust Load Alleviation by Circulation Control for Future Greener Aircraft

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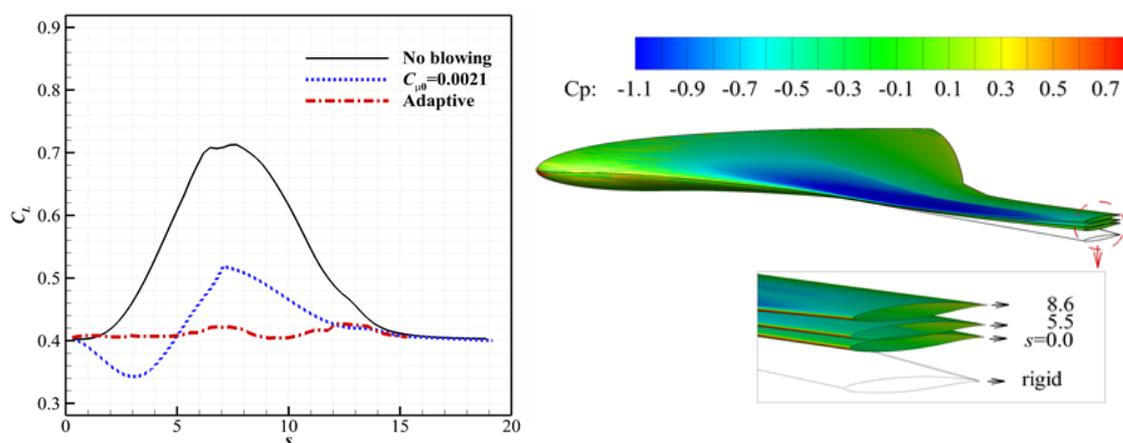
### Abstract

**Keywords:** *Load control, Blended wing body, Circulation control, Gust alleviation*

Gust encounter is a crucial factor in aircraft structural design, often dictating the structural load and weight. Effective control and alleviation of wing load due to gust encounter can lead to significant reduction of wing structural weight. This can in turn provide an alternative way to reduce aircraft drag and therefore emission for future greener aviation.

In this presentation, we show an investigation on the effectiveness and feasibility of a fluidic actuator for load control and gust load alleviation at subsonic and transonic flow conditions. Specifically, we explored numerically the capability of circulation control (CC) by blowing tangentially through the trailing-edge Coanda surfaces. We will show some detailed analysis of load control mechanisms and effectiveness under constant and dynamic blowing, momentum coefficients. For future greener air transport, we investigated the implementation of circulation control for load control on a blended-wing-body (BWB) configuration. We will show that gust load can be effectively alleviated with reference to the gust conditions defined by the certification specifications of large commercial aircraft covered by the European Union Aviation Safety Agency CS-25. The results from the case studies demonstrate that CC has the capability for load control and gust load alleviation for both subsonic and transonic incoming flows conditions. Due to the fast-frequency response characteristics, the method is capable for adaptive gust load controls. This research provides further insights into the feasibility of gust load attenuation by means of circulation control. This can potentially contribute to the design of future more efficient transport aircraft for significant reduction of aircraft drag and emission.

**Figure 1:** Alleviation of Gust Load on a Blended Wind Body Aircraft at Transonic Speed



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