TEN YEARS OF AERO-SERVO-ELASTIC TESTS AT LARGE POLIMI'S WIND TUNNEL

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TWEET-IE / Twin Wind tunnels for Energy and the EnvironmenT - Innovations and Excellence

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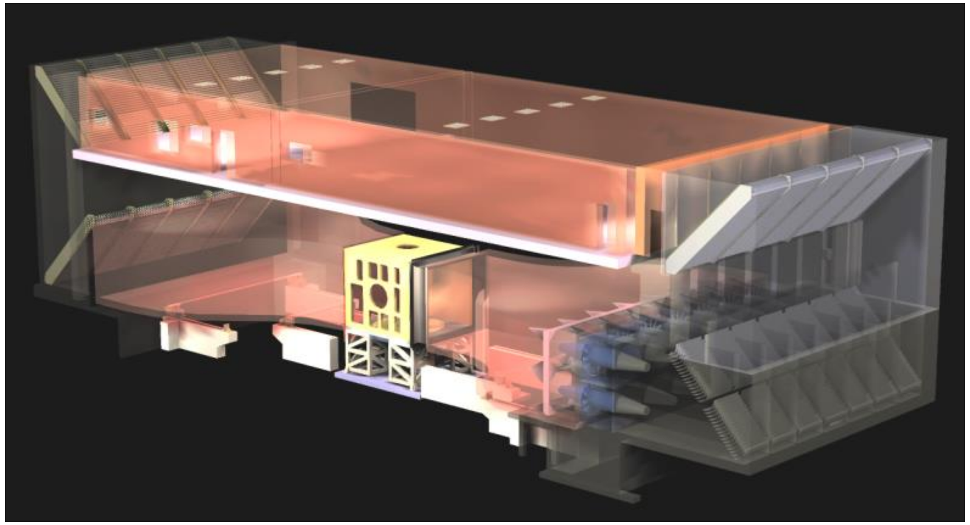
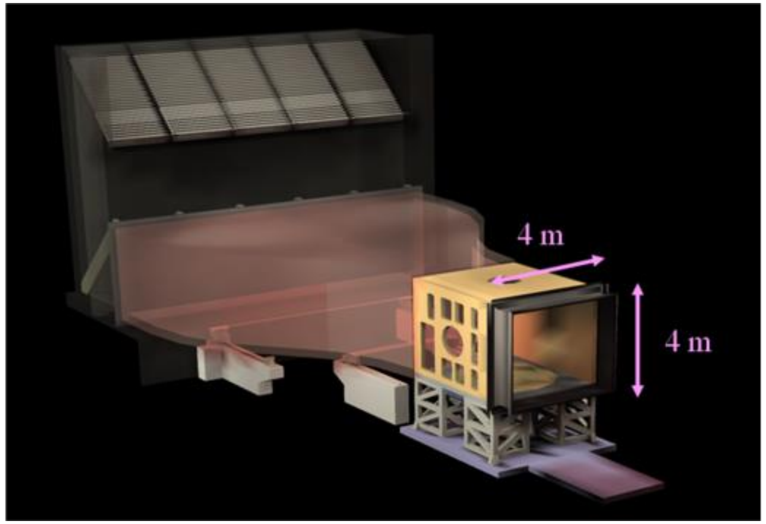
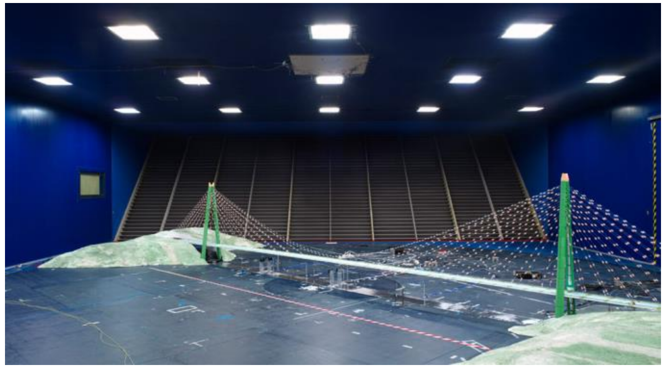
- Introduction
- Overview on aereoelastic wind tunnel validations
- Experiences on GLA technologies
- Experiences on AFS technologies
- Conclusions

POLIMI'S LARGE WIND TUNNEL







ASDL People (more than ones reported here…)

*A*ERO-*S*TRUCTURES *D*ESIGN *L*AB

Sergio Ricci
Head, Professor

Paolo Mantegazza
Professor, retired, but still
Aeroelastician Guru…

Luca Riccobene, PhD
Wind tunnel testing

Francesco Toffol, PhD
PostDoc, Aeroelastic aero-servo-elastic Optimization

Nicola Fonzi
PhD Candidate, Non-linear Aeroelasticity

Gian Luca Ghiringhelli
Affiliate, Professor

Giampiero Bindolino
Affiliate, Researcher
Aerodynamic and Aeroelasticity

Alessandro De Gaspari, PhD
Associate Professor, Morphing aircraft

Luca Marchetti
PhD Candidate Structural Design and Aeroelasticity

Vittorio Cavalieri
PhD Candidate, Morphing aircraft

This activity has been carried out under the umbrella of these EU projects:

CS1-GLAMOUR (NO. 620084):

GUST **L**OAD **A**LLEVIATION TECHNIQUES ASSESSMENT ON WIND T**U**NNEL **MO**DEL OF ADVANCED **R**EGIONAL AIRCRAFT

CS2-AIRGREEN2 (NO. 945548):

CS2-U-HARWARD (NO. 886552):

ULTRA **H**IGH **A**SPECT **R**ATIO **W**ING **A**DVANCED **R**ESEARCH AND **D**ESIGNS

AFS – DESIGN AND **V**ALIDATION **T**ECHNOLOGIES

DESIGN REQUIREMENTS & ADOPTED TECHNOLOGIES

GOALS

- Develop and Validate Load Alleviation techniques based on different control architectures
- Design and manufacturing of a wind tunnel models representing GRA aircraft
- Perform the wind tunnel test under **gust excitation** to validate all the control strategies and complete the final assessment

REQUIREMENTS

- Free plunge and pitch rigid body motion
- **Capability to measure 1*g* + gust loads**: the model must be trimmed for CL≠0

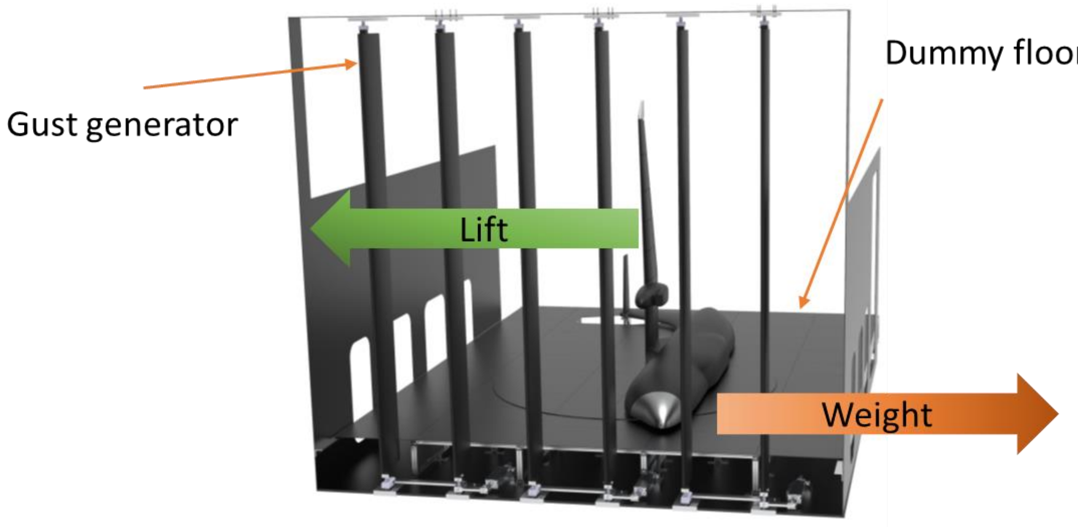
→ Design of a special device called **Weight Augmentation System** (WAS)

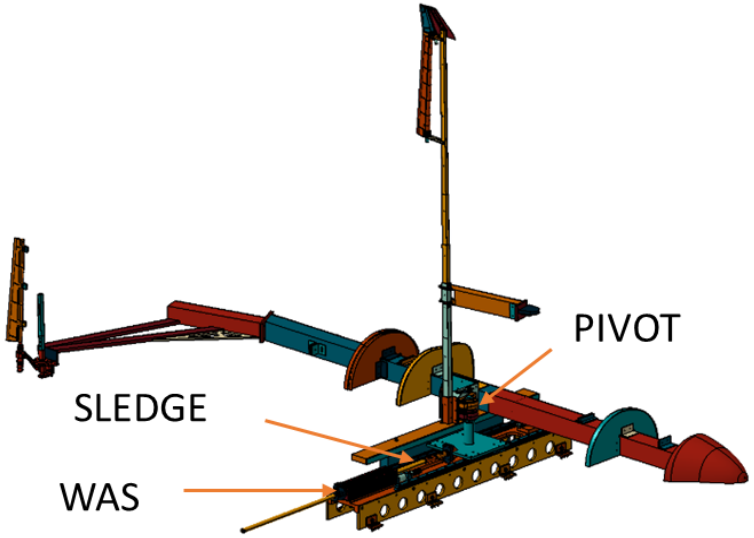
TECHNOLOGIES

- Model Scaling
- Fast model design and manufacturing by combining traditional composited and 3D printing
- Onboard computing system
- In house development and implementation of advanced control systems

WT TESTING REQUIREMENTS AND CHALLENGING

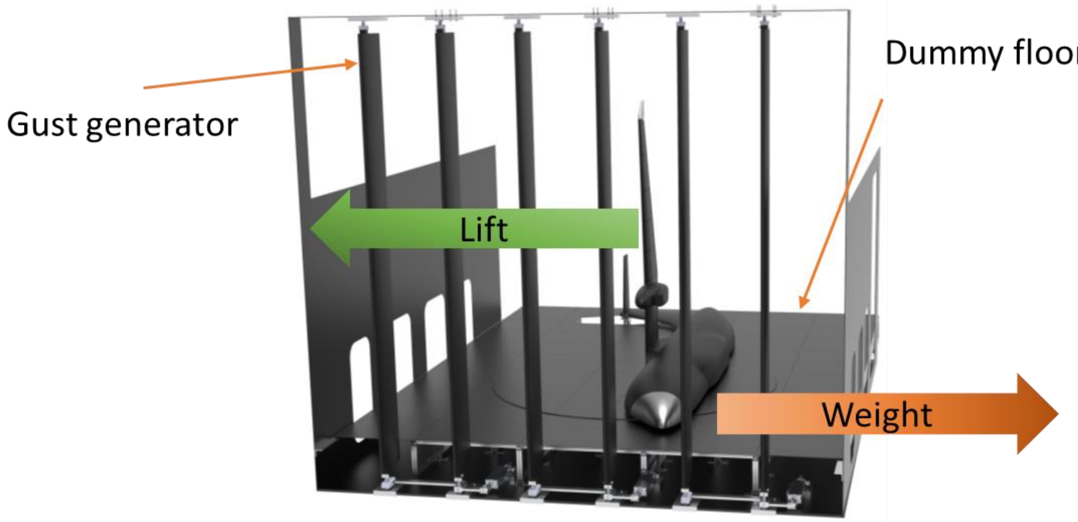
- Representative, producing results scalable to full scale
- Need to reproduce the rigid body motion
- Aeroelastic scaling
- Friction in case of half model
- Performances of electric drivers (max torque, max bandwidth, possible freeplay)
- Two control logics: displacement and force control

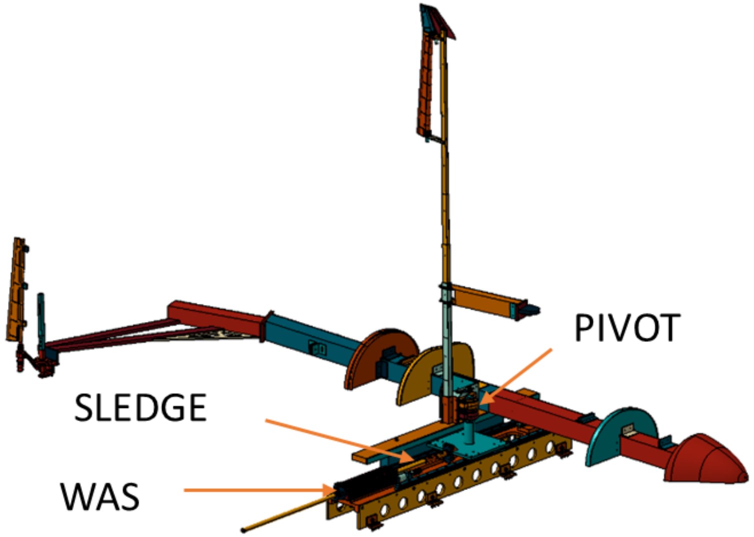




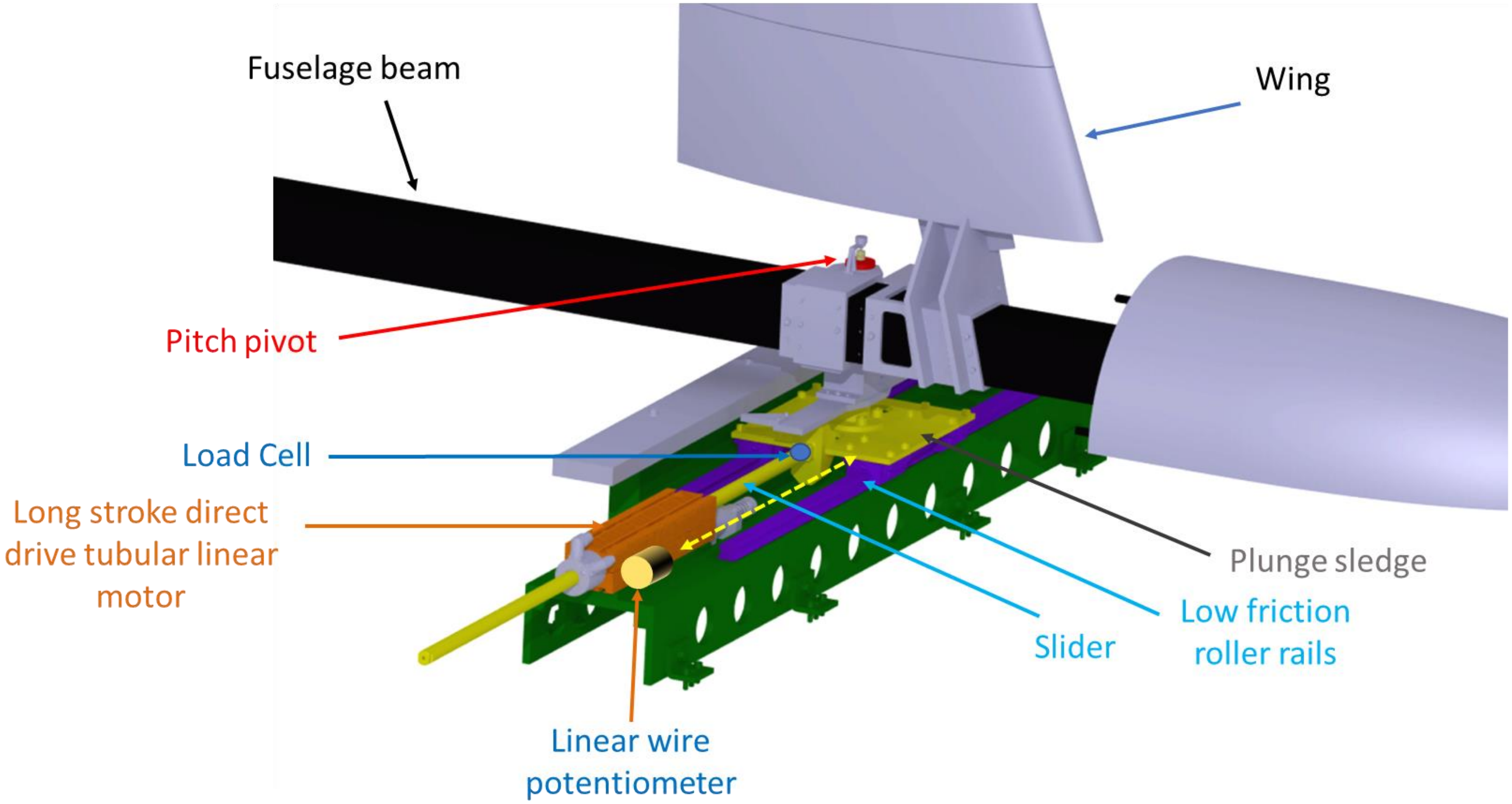
Clean Sky 2
JOINT UNDERTAKING

- Iso-frequency scaling to apply directly the controller develop for full A/C. Only control input magnitude is scaled. Mass and stiffness from the Stick Model.
- 1:12 scale to fit Polimi WT (4x4x5m), model to small and velocity to low.
- 1:6 half WT model vertically mounted
- Pitch and plunge free body motion
- Weight Augmentation System to reproduce the weight force and trim the A/C





RIGID BODY MOTION



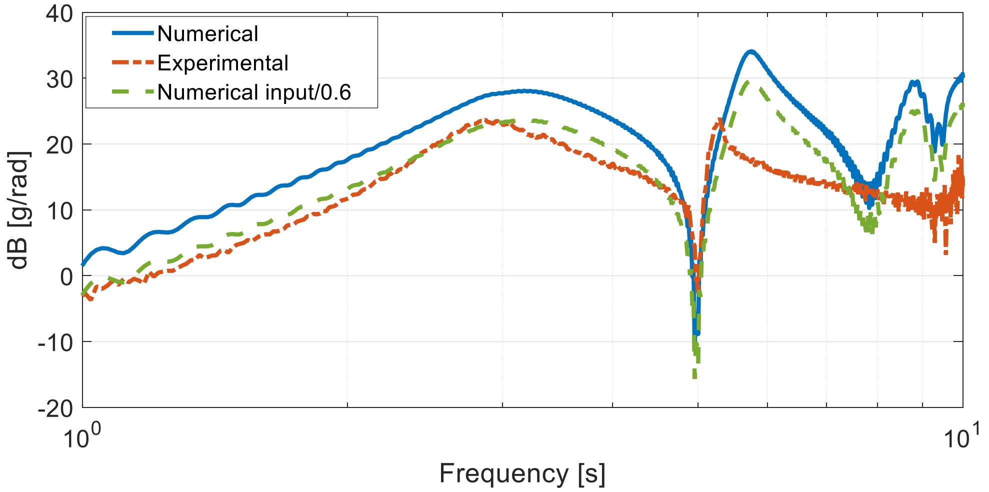
WIND TUNNEL MODEL(S) TECHNOLOGY

YouTube

DRY TEST FOR MODEL AND SYSTEMS VERIFICATION

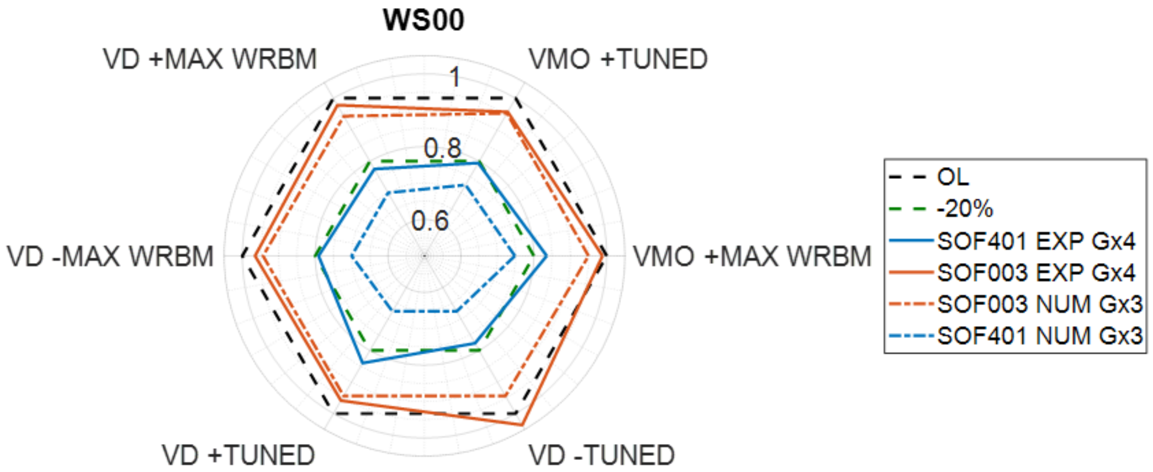
MODEL CORRELATION & HF RESULTS

- Problem with the free body motion, it influences the control input!
- Control surfaces are less effective



A multiplication factor of 0.6 should be used to recover the actual effectiveness of control surfaces in wind tunnel.

The HF controllers allow to increase the gains of SOF controllers until the stability limits



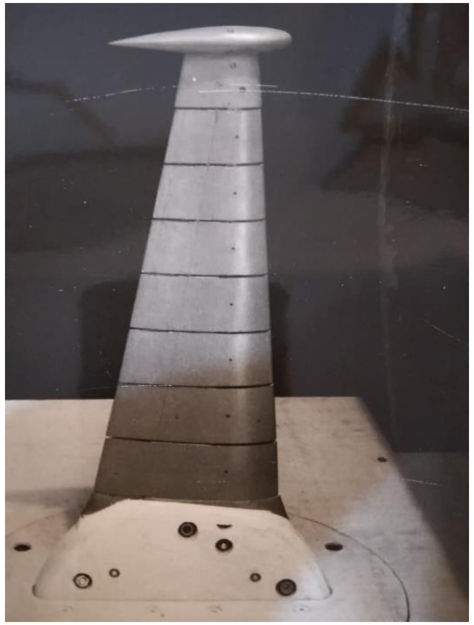
Improved correlation, still missing the rigid body part that is an open issue

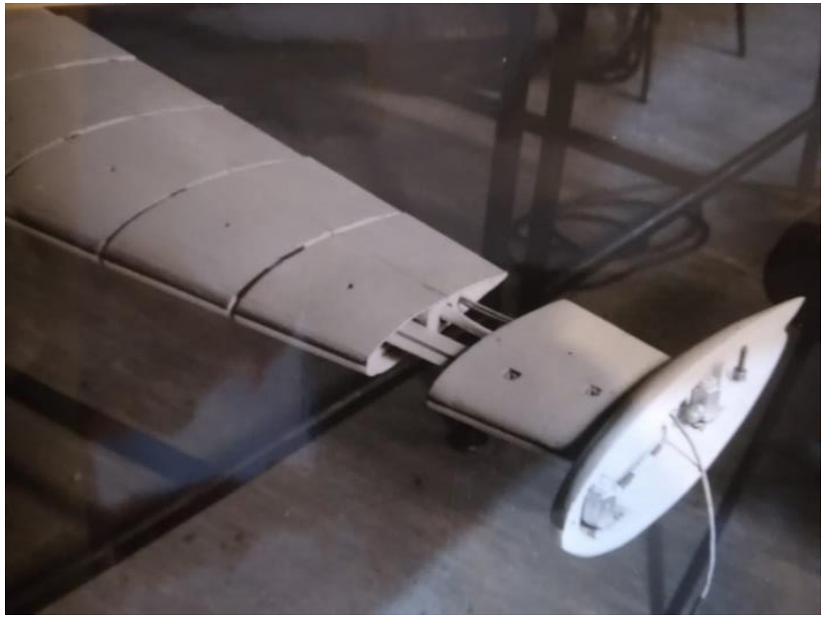
RESULTS OF FOLDING WING TIP CONCEPT

YouTube

U-HARWARD

OUR HERITAGE ON FLUTTER CONTROL





1980

Calculation of Eigenvalue and Eigenvector Derivatives for Algebraic Flutter and Divergence Eigenproblems, C. Cardani and P. Mantegazza, AIAA Journal, Volume 17, Issue 4, Apr 1979, https://doi.org/10.2514/3.61140

Active flutter suppression for a wing model, G. L. Ghiringhelli, M. Lanz and P. Mantegazza, Journal of Aircraft, Volume 27, Issue 4, Jul 1990, https://doi.org/10.2514/3.25277

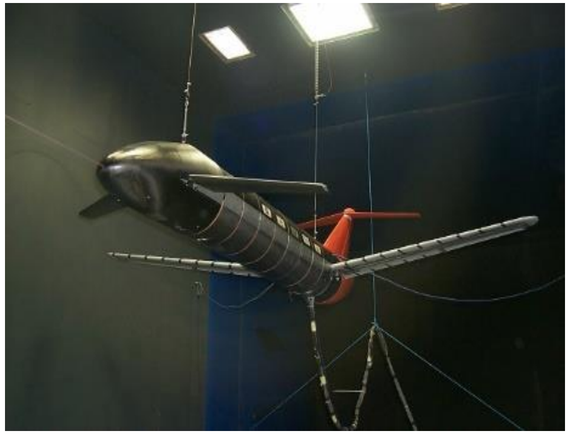
Multi-Input/Multi-Output Adaptive Active Flutter Suppression for a Wing Model, M. Andrighettoni and P. Mantegazza, Journal of Aircraft, Volume 35, Issue 3, May 1998, https://doi.org/10.2514/2.2319

Active Flutter Suppression for a Three-Surface Transport Aircraft by Recurrent Neural Networks, Mattia Mattaboni, Giuseppe Quaranta and Paolo Mantegazza Journal of Guidance, Control, and Dynamics, Volume 32, Issue 4, Jul/Aug 2009, https://doi.org/10.2514/1.40774

Phase I: AFS Design and Validation Technologies

MOTIVATIONS, MODELS DESIGN AND MANUFACTURING

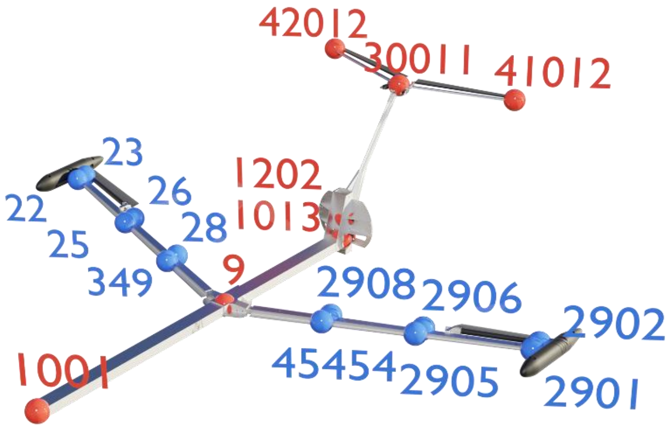
- Advanced control systems, growing flexibility, potential weight reduction by means of optimized composite frames seem to have made the adoption of Active Flutter Suppression (AFS) technology closer than ever before.
- Need for a deep experimental activity especially from the perspectives of uncertainty, reliability, and the safety of flight vehicles in which this technology is adopted
- Need for aeroservoelastic wind tunnel models, easy to build, easily configurable, not so expensive, but very reliable, to be able to test the robustness of AFS systems in presence of parameters variability



1995-2005 | 2005-2012 | 2018-2022

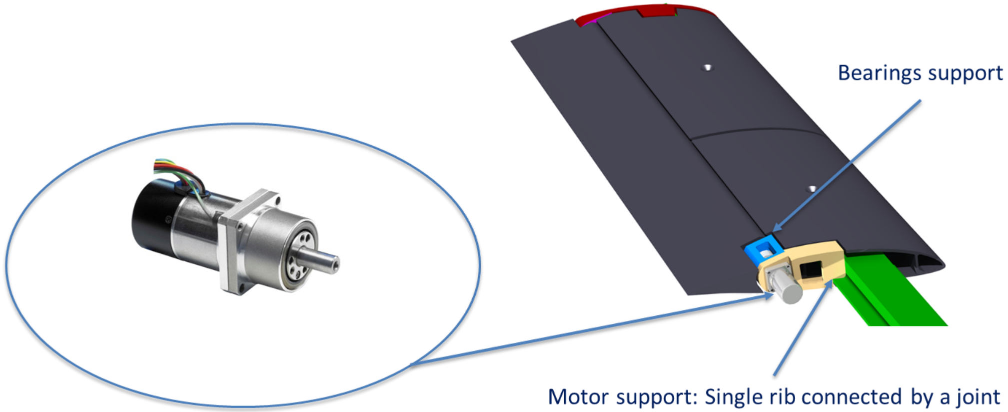
DATA ACQUISITION AND CONTROL SYSTEMS

- A small embedded computer installed on-board to manage both data acquisition and active control duties, equipped with the in house Real Time operating system based on Linux and based on PC-104 form factor cards.
- 20 MEMS PCB accelerometers
- Ailerons and rudder control system based on RSF-5B and RSF-9B Harmonic Drive electric motors, respectively.



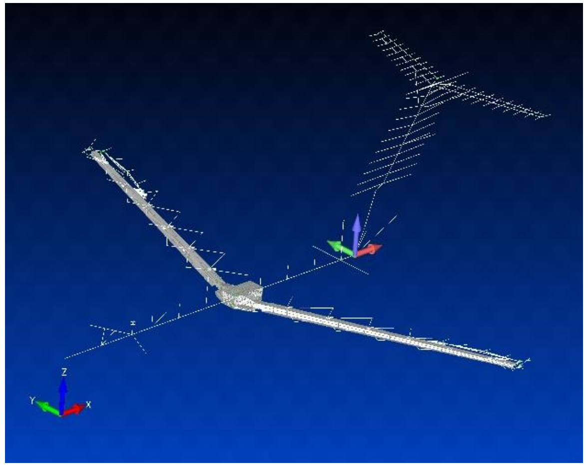
The installed accelerometers

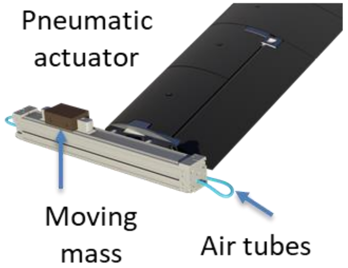
Onboard embedder computers and the PCM MEMS accelerometers



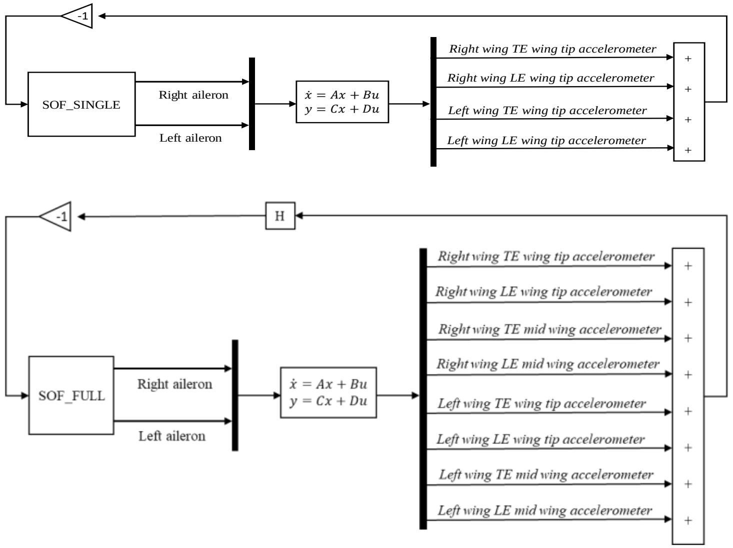
THE MATH MODEL

- **Goals**: to replicate the complete process typical of full scale aircraft
- Dynamic model correlated and updated (**two steps**) on the basis of GVT results
- Aero-servo-elastic **state-space** model
- A dedicated **low level PID** controller to drive the ailerons (*15Hz* bandwidth)
- **Four** high level controllers for AFS purpose (optimized for one velocity, no gains scheduling)
  - **Static Output Feedback** (SOF), in 2 configurations, SINGLE and FULL (POLIMI)
  - **ILAF** and **LQG** Controllers (UWA)





GVT session inside the WT chamber, the final hybrid FEM model, and the anti-flutter safety device

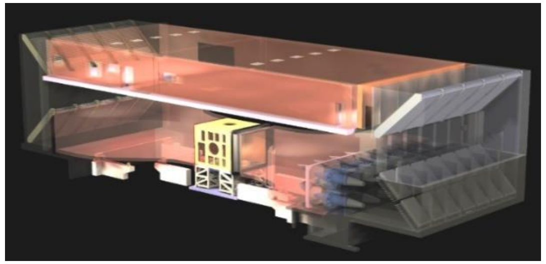


SOF-SINGLE and SOF–FULL controllers

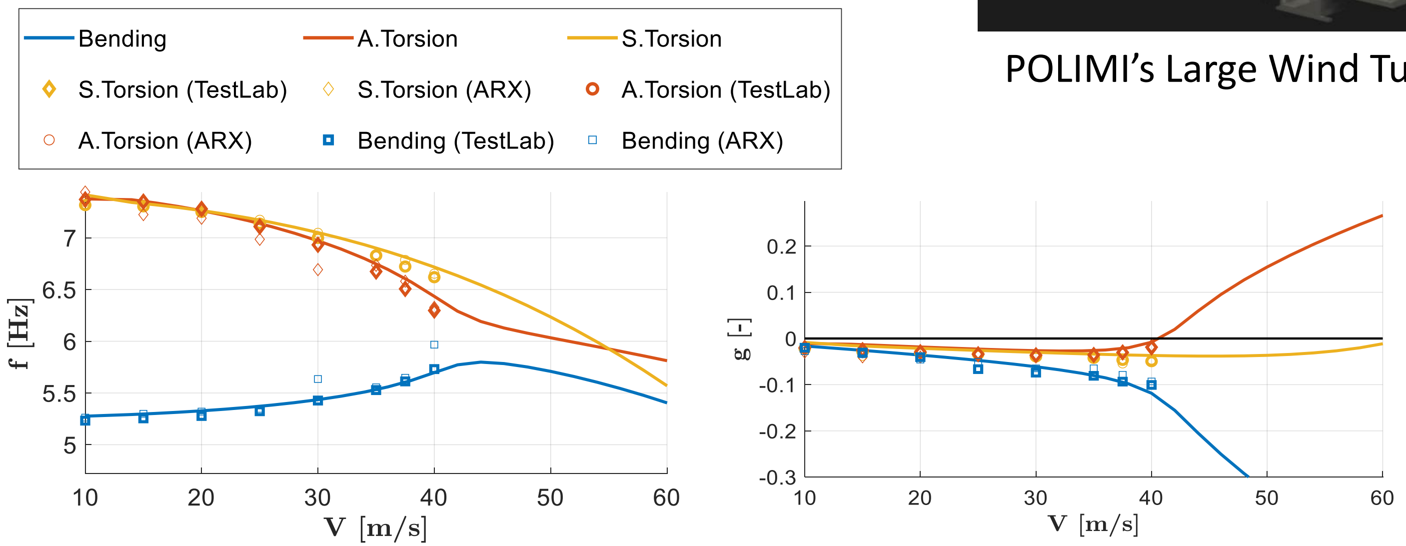
THE FINAL WIND TUNNEL TEST CAMPAIGN

- **Goals**: Flutter Identification, AFS technologies validation, Robustness check
- More than **100 runs** in 6 days of testing
- More than **18 flutter conditions** reached
- **No model damages** encountered
- Flutter speed extended **up to 50 m/s**

AIM	INPUT	CONTROLLER	VELOCITY [m/s]
AFS	WN	SOF-SINGLE	From 40, to **47** step 0.5
AFS	WN	SOF-FULL	From 40 to 50 step 2
AFS	WN	ILAF	Da 40 a **43.5** step 0.5
AFS	WN	LQG40	40, 41.5, 42, **43**
AFS	WN	LQG45	40, 41.5, 42, 43, 44, **44.5**
AFS	Pulse	LQG45	41.5, 42.5, 43.5, 44, 44.5, **45**

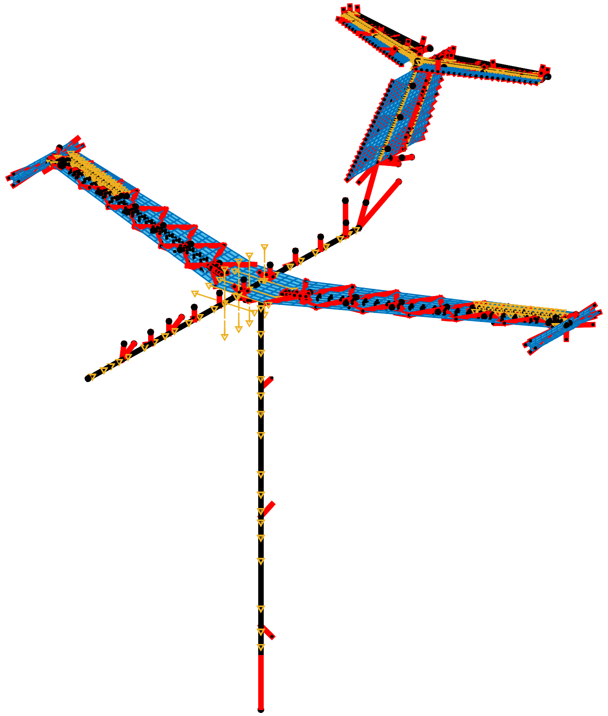


POLIMI's Large Wind Tunnel

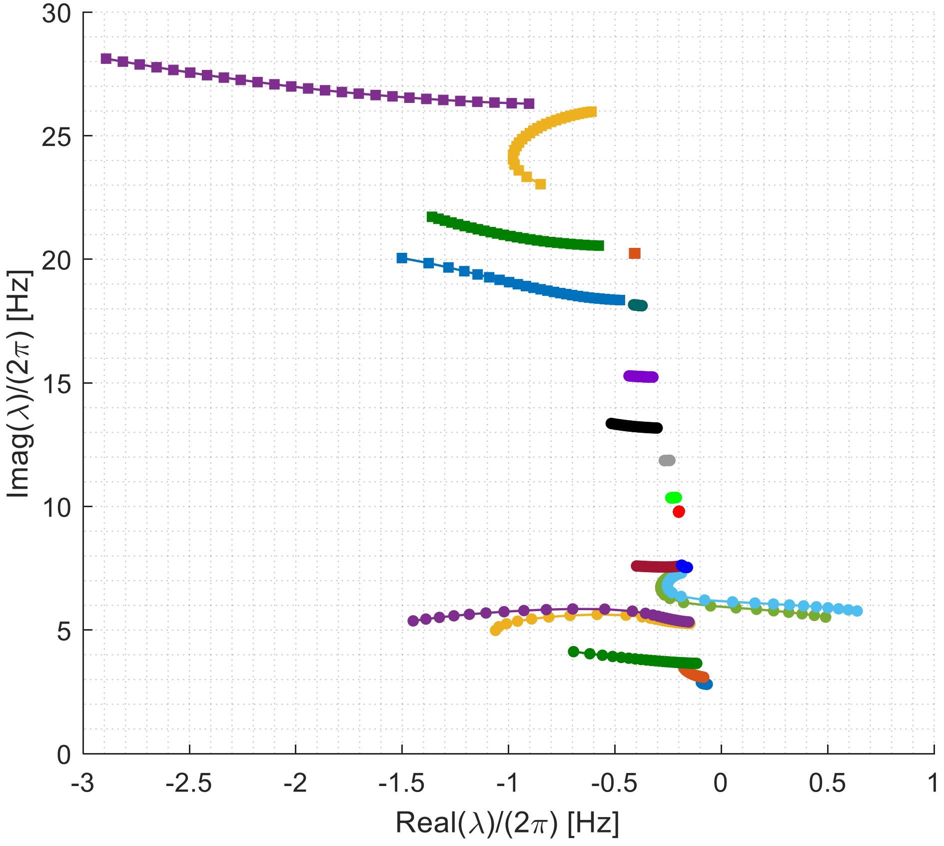


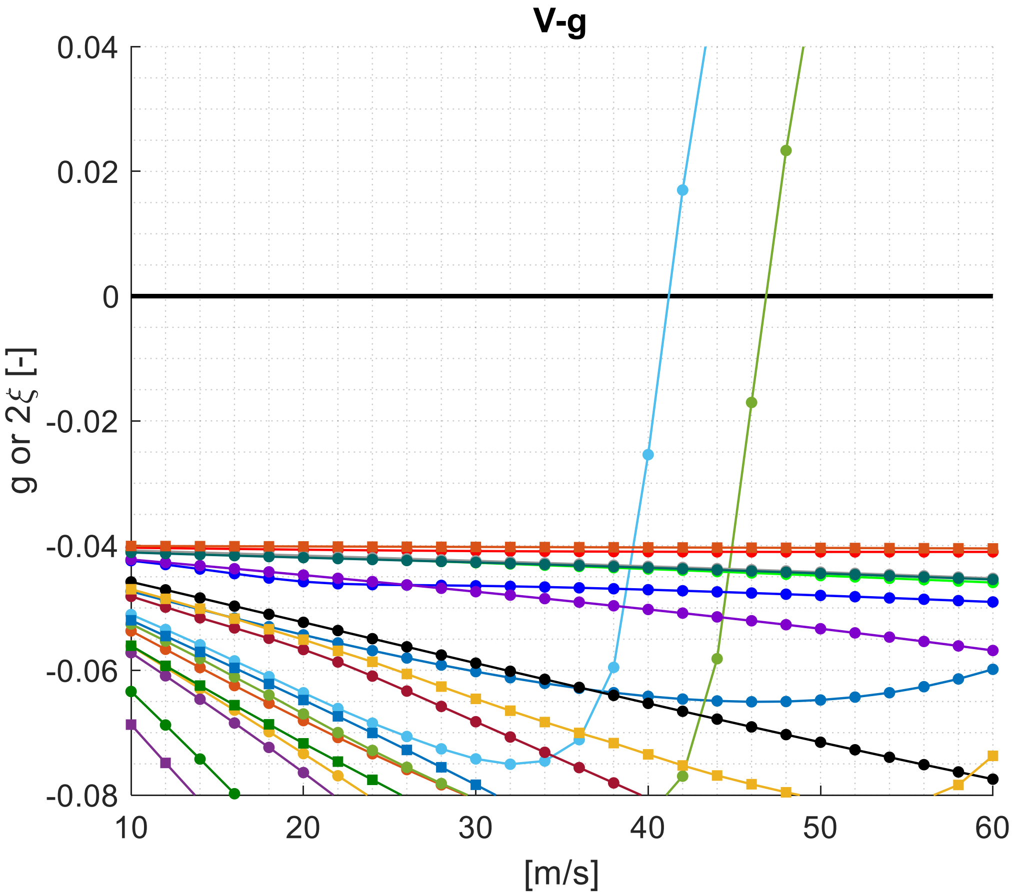
Numerical vs. experimental *Vg* plot correlation

AFS TEST ON XDIA MODEL ON THE PYLON



THE TWO FLUTTERS PROBLEM





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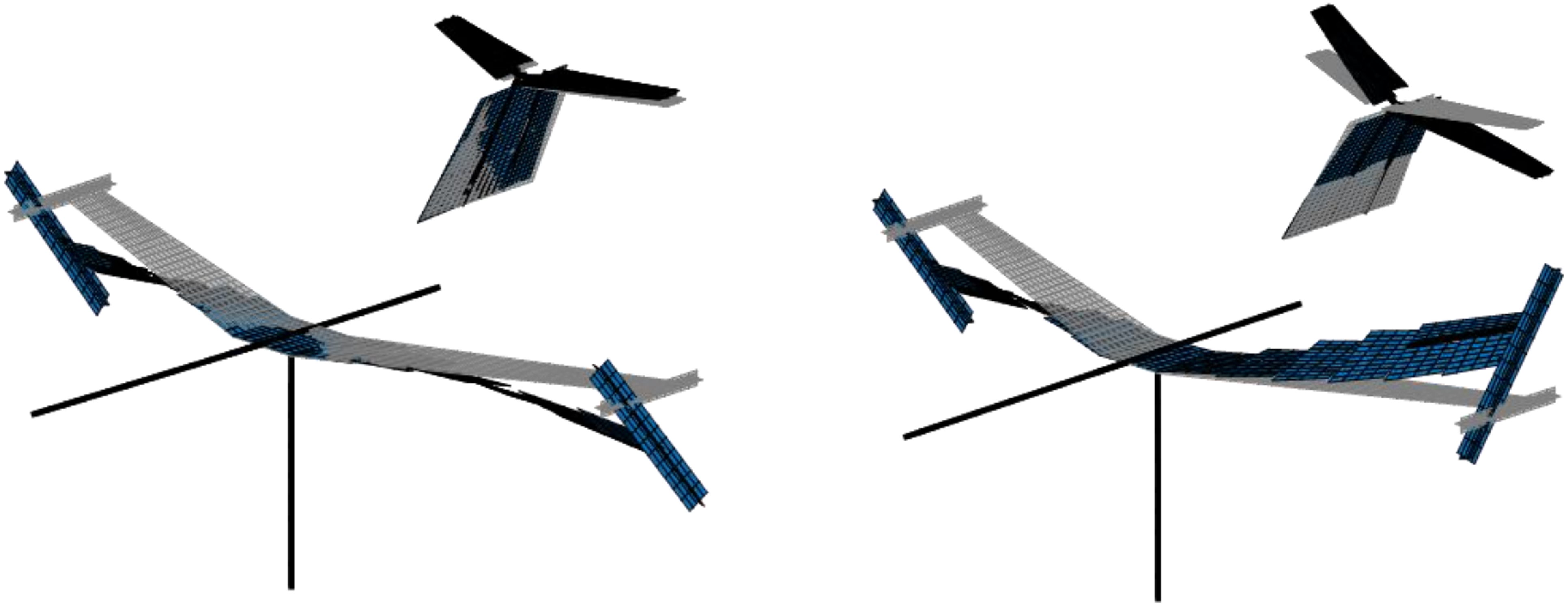
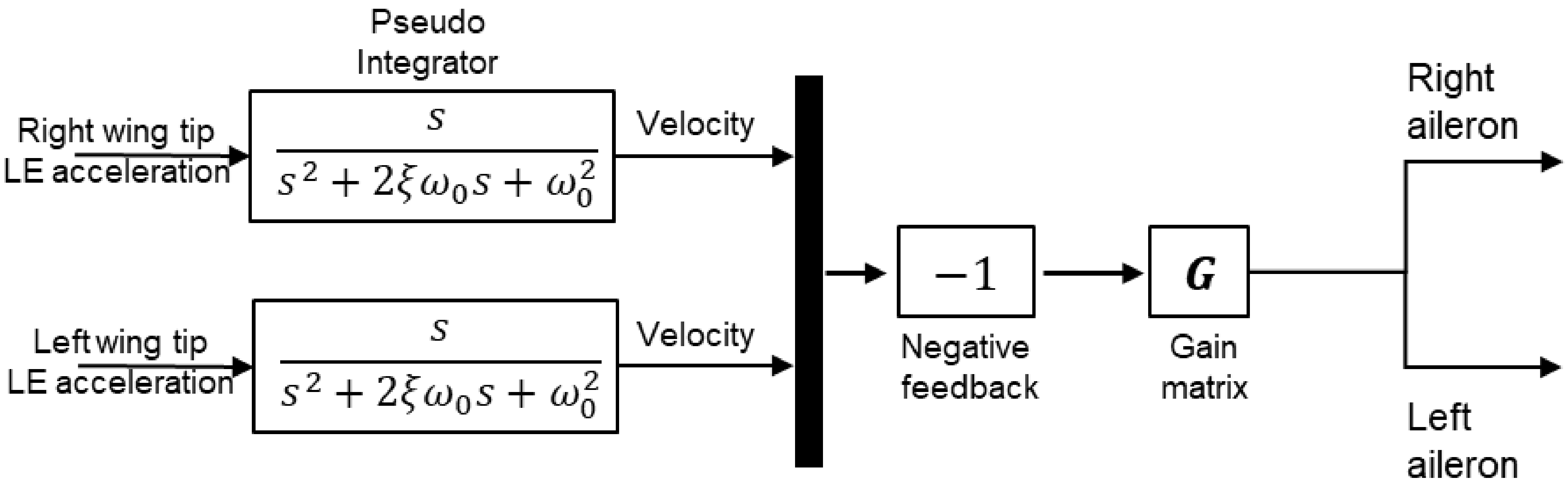


Symmetric torsion-bending (left) and anti-symmetric torsion-bending (right) flutter mechanisms.



Block diagram of the closed loop flutter controller (Static Output Feedback)

SYMMETRIC FLUTTER, OPEN LOOP

YouTube

ANTY SYMMETRIC FLUTTER OPEN & SYMMETRIC CLOSED LOOP

CONCLUSIONS

- I'm sure I've already used up all the time available…
- We've done a huge work, we've had a lot of problems, but we've learned much more than expected… and finally we had a lot of fun!

Acknowledgement

The large set of aeroelastic activities in the framework of different international projects has been possible thanks to the passion, dedication, and competence of many colleagues and students at different level involved. I would like to thank first Prof. Paolo Mantegazza that about 35 years ago founded the aeroelasticity branch at DAER-POLIMI. Then, the contribution of L. Riccobene, A. De Gaspari, F. Fonte, F. Toffol, L. Marchetti, N. Fonzi, V. Cavalieri and G. Bindolino is kindly acknowledged.

The financial support received by EU for project CS1-GLAMOUR (no. 620084), CS2-AIRGREEN2 (no. 945548) and CS2-U-HARWARD (no. 886552) is kindly acknowledged.

- I'm sure I’ve already used up all the time available…
- We've done a huge work, we've had a lot of problems, but we've learned much more than expected…

Thanks for your attention!

Any question?

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