ACcTIOM
Advanced Pylon Noise Reduction Design and Characterization through flight worthy PIV

State of the art – Background

In the frame of increasingly stringent regulations governing the air transport sector, driven by environmental and economic concerns, efforts to reduce air traffic fuel consumption and to limit pollutant and noise emissions encourage both aircraft and powerplant manufacturers to develop innovative solutions for future aircrafts. In this context, Counter Rotating Open Rotor (CROR) propeller technologies are appearing as a promising alternative solution to Ultra High Bypass Ratio (UHBR) ducted engines, as it could cut fuel consumption and associated carbon dioxide emissions by 30 %. However, the promotion of this not yet fully mature technology, although it was initiated in the early 80's, raises numerous issues and imposes to address significant scientific and technological challenges.

Amongst these challenges, the interaction of the wake of the CROR engine pylon with the counter rotating blades, positioned downstream of the pylon (pusher configuration), promotes strong total pressure fluctuations on the powerplant structure. The latter are responsible for both airframe noise and vibrations that penalize aircraft certification. 'Erasing' the pylon wake such as to recover a strictly uniform flow upstream of the rotating blades would suppress this major source of airframe noise and vibrations. It therefore appears as a promising flow control strategy for the certification of future CROR propelled aircrafts.

Objectives

The ACcTIOM project is a collaborative research project launched in 2012 between ISAE, Airbus and Aéroconseil and funded by the European Commission through the Clean Sky SFWA (Smart Fixed Wing Aircraft) Demonstrator program. Its objectives are twofold. First it aims at designing, developing, manufacturing, implementing in the model of the CROR pylon and validating through exhaustive series of wind tunnel (WT) test experiments, an active flow control system dedicated to the reduction of noise emission through the pylon wake mitigation. Second, it aims at developing an advanced experimental methodology, based on vibration-controlled stereoscopic Particle Image Velocimetry (3C-PIV), able to be flight-operated and that will serve the validation of the above mentioned active flow control system when operated on the Flying Test Bench (FTB).

Description of work

The work led to meet the first major objective of the ACcTIOM project relates to the definition, development, conception and validation of the optimized CROR pylon and of its embedded active flow control system dedicated to the annihilation of the pylon wake. It is briefly described in items 1 to 5. 1/ On the basis of the providing by Airbus of the reference geometry of the CROR-propeller pylon (fig.1), an optimum design of the full scale aft part of the CROR engine pylon has first been defined (fig.2), *via* an optimization process based on Reynolds Averaged Navier Stokes (RANS) Computational Fluid Dynamics (CFD) simulations. Second, an innovative, full scale, active flow control system embedded in the pylon and able to erase the pylon wake, such as to comply with Airbus acoustic requirements, thanks to a coupled, boundary layer scooping and blowing strategy, has been developed *via* exhaustive high-fidelity RANS and Unsteady RANS CFD simulations. More than 600 2D computations and several 3D computations were achieved, covering a large range of parametric configurations -scooping and blowing mass flow rates, scooping/blowing slot positions, shapes, etc.-, for a total of more than 150.000 computing CPU hours. These tasks composed WP2. 2/ On the basis of WP2 specifications, a rigid WT model representative of the optimized CROR pylon shape and equipped with the full scale active flow control system designed in WP2 was developed and manufactured (fig.3 and fig.4). This WT model was operated in the ISAE-SUPAERO S4 WT. As such it took into account all the constraints of this WT (limited size and flow velocity, optical accesses for PIV measurements, scooping mass flow rate limitations). These tasks were part of WP3. 3/ An exhaustive series of WT tests were completed to validate *in situ* the flow control system-equipped CROR pylon WT model, on-board instrumentation, and data acquisition and control systems (fig.5). The WT tests were comprised of wall pressure coefficient taps, total pressure multi-probe (fig.6) and advanced stereoscopic Particle Image Velocimetry (3C-PIV) measurements (fig.7) in the wake of the CROR pylon. More than 150 active flow control configurations, where the scooping/blowing mass flow rate couples were varied, have been investigated for various configurations of the WT model (more or less turbulent boundary layer, partially obstructed blowing slots, various freestream flow velocities). They aimed at highlighting the efficiency and robustness of the developed embedded active flow control system in erasing the CROR pylon wake upstream of the actual location of the CROR blades (WP3), such as to comply with Airbus acoustic requirements. 4/ The exhaustive WT test databases were post processed and the physical analysis of the WT test results was fulfilled. 5/ The latter revealed the efficiency and the robustness of the embedded active flow control system in annihilating the CROR pylon wake before it interacts with the CROR blades (fig.8 to fig.10). They also provided guidelines for the transposition of the WT results to flight conditions. This closed WP3.

The work led to meet the second major objective of the ACcTIOM project is described in items 6 to 10. Figure 11 summarizes the main milestones. The corresponding tasks relate to the development of an advanced experimental methodology, based on vibration-controlled stereoscopic Particle Image Velocimetry (3C-PIV), able to be flight-operated inside the Flying Test Bench in order to validate the efficiency of the active flow control system. 6/ In the context of WP4, a Vibrating Environment Simulator (VES) was developed and validated. This VES is able to reproduce the vibration spectrum representative of vibration levels experienced in the implementation zone of the stereoscopic Particle Image Velocimetry (3C-PIV) system to be flight-operated in the cabin of the CROR powerplant equipped FTB (fig.12 and fig.13). 7/ The VES was then manufactured and series of tests were conducted. These tests were dedicated to the validation of the VES ability in imposing the above-mentioned vibration spectrum on the different PIV subsystems -cameras, laser sheet-, and in determining the envelop of acceptable *vs.* prohibitive misalignments of the PIV subsystems along each of the 6 misalignment axes (fig.14, fig.15). 8/ The influence of displacements and misalignments imposed by the vibratory environment in the FTB cabin, simulated via the VES, on 3C-PIV measurement errors, were quantified through the determination of the 6-axes envelop of acceptable *vs.* prohibitive misalignments. 9/ The definition and the conception of a vibration correction methodology (VCM), able to suppress the above-mentioned vibrations at the location of the PIV optical subsystems, were then completed (fig.16 to fig.20). The final goal is to achieve accurate and usable in-flight PIV measurements dedicated to the in-flight validation of the active flow control system developed in the context of WP2 and WP3. 10/ In the context of WP5, various strategies were finally proposed and detailed, relying on the VCM, that will permit to implement and operate 3C-PIV measurements in the FTB in a confident way.

Results

During the first phase of the ACcTIOM project, the active flow control system, a combination of scooping/blowing strategies, was designed and optimised via a coupled approach combining exhaustive and high fidelity Computational Fluid Dynamics (Reynolds-averaged Navier-Stokes) simulations, test bench and comprehensive wind tunnel test experiments. These tests confirmed the strong efficiency of the developed embedded active flow control system in erasing the pylon wake, when operated in the region of optimal flow control parameters numerically and experimentally identified by the consortium scientists in charge of ACcTIOM. They have also highlighted the robustness of the flow control system in mitigating the wake of the pylon despite moderate variations of the flow conditions. This embedded active flow control system acts as an aerodynamic stealth system.

In the second phase of the ACcTIOM project, the consortium scientists have developed advanced optical methodologies, based on vibration-controlled 3C-PIV, able to be in-flight operated and dedicated to the validation of the efficiency of the above mentioned CROR pylon-embedded active flow control system in erasing the pylon wake on the CROR-propelled Flying Test Bench (FTB). To this avail they have first developed numerical models of the expected vibratory environment inside the cabin of the FTB. These models have permitted to design experimental test benches, hereafter denoted Vibrational Environment Simulator or VES, able to reproduce, in laboratory, the vibrational environment of the FTB and its influence on the optical misalignment of the different 3C-PIV subsystems and resulting 3C-PIV measurement issues. Further, the team has defined the hybrid, passive/active, vibration control strategy and required equipment for the design of a Vibration Correction Methodology (VCM) dedicated to the implementation and confident operation of in-flight 3C-PIV. The VCM will attenuate vibrations experienced by the 3C-PIV subsystems under VES influence during flight testing.

a) Timeline & main milestones

objective 1: erasing the CROR pylon wake

- 1st Feb. 2012: ACcTIOM starting date
- 24th Aug. 2012: the numerical design of the WT model of the CROR pylon and the definition of the

embedded active flow control system are achieved. **WP2 completed**.

- Feb. 2013: manufacturing and experimental validation of a first full scale active flow control module including the boundary layer scooping/blowing technology, constituting part of the final WT model.

- 26th Aug. 2013: the manufacturing of the full scale WT model of the CROR pylon, fully equipped with the active flow control system, whole set of dedicated sensors and data acquisition/control systems, is achieved.

- Dec. 2013 to Feb. 2014: four consecutive WT test campaigns are led in the ISAE S4 large subsonic wind tunnel.

- March to May 2014: post processing and physical analysis of the various experimental database acquired during the 4 WT test campaigns.

- Sept. 2014: the efficiency and robustness of the active flow control system, based on an original boundary layer scooping/blowing technology and invented in the context of the ACcTIOM project, is fully validated. The **active flow control system fully erases the CROR pylon wake** before it interacts with the CROR blades. It **allows to reach the acoustic requirements** imposed by Airbus. **WP3 completed**.

objective 2: vibration control for in-flight 3C-PIV

- Dec. 2012: **determination of the estimated Flying Test Bench vibration spectrum** expected to be experienced in the cabin of the CROR-equipped FTB aircraft. Global specification of the VES, consisting in 2 different test benches: **a static VES** for the characterization of the impact of vibration-induced misalignments of 3C-PIV subsystems on **3C-PIV measurement errors**, and a **dynamic VES** to reproduce the vibrational environment from in-flight to in-door.

- Feb. 2013: **definition of a hybrid control strategy for the VCM**. It will be based on a passive isolation platform coupled to an active, closed-loop, control system based on a hexapod technology.

- July 2014: manufacturing and validation of the dynamic VES.

- Oct. 2014: validation of the **passive isolation stage of the VCM** through various shaker test campaigns.

- Dec. 2014: receipt of the **active vibration control stage (hexapod)** of the VCM and characterization of its dynamics.

- Dec. 2015: manufacturing of the static VES.

- Feb. to May 2016: various test campaigns including both static and dynamic VES. **Quantification of vibration-induced 3C-PIV errrors**.

- June 2016: **validation of the Vibration Control Methodology** and **guidelines for the implementation and confident operation of a 3C-PIV system in the Flying Test Bench** for in-flight tests**. WP4 and WP5 completion.**

- 30th June 2016: ACcTIOM ending date

b) Environmental benefits

ACcTIOM technologies for active reduction of CROR engine noise associated with the innovative active flow control system embedded in the CROR engine pylon will speed up certification and commercialisation of more energy-efficient aircraft. In-flight use of advanced vibration-controlled 3C-PIV will enhance understanding of mechanisms in other airframe elements as well. The outcomes should significantly reduce the environmental impact of air travel.

c) Dissemination / exploitation of results

The whole set of deliverables (D2.1, D4.2, D4.3, D5.4) and complementary intermediate reports provided during periods 1, 2, 3 and 4, the numerous meetings organized during these periods and the four periodic reports provided to both Airbus and the JU have strongly participated to the dissemination activities. Moreover, several papers have been presented to international conferences and the submission of, at least, 2 articles to international peer-reviewed journals should be completed within the period Q1-Q2 2017. The latter are listed in the next section.

In terms of exploitation of results, the ACcTIOM project has provided:

1/ An **operable and highly efficient and robust active flow control system dedicated to the mitigation of the noise generated by CROR engines through CROR pylon wake alleviation**.

The optimized Counter Rotating Open Rotor (CROR) powerplant pylon and its associated innovative active flow control system developed in the context of the ACcTIOM project permit to fully erase the wake of the CROR powerplant pylon before it impacts the first blade stage of the CROR propeller. As such it alleviates the fluid-structure interaction-induced emission of noise of the future CROR-propelled aircraft. The prototype developed in the context of the ACcTIOM project directly serves the potential certification of this new generation of more energy-efficient aircraft, and consequently its commercialization. This concept has been patented by Airbus. The exhaustive description of the prototype has been transferred to Airbus. The technological adaptation from a wind tunnel operable prototype to an in-flight operable system is currently ongoing by Airbus. It should be exploited in the context of potential commercialization of the SFWA-based future aircraft.

2/ **knowledge advancement on wall jet/outer flow interaction and underlying physics**.

From a fundamental point of view, results obtained during the ACcTIOM project, WP2 and WP3, foster knowledge on the physical mechanisms driving the mixing of wall jets with outer flows. The latter are involved in several engineering applications, e.g. flow control for drag reduction of automotive or flying vehicles, fuel mixing, anti-icing systems, demisting/defrosting systems, etc. There is no direct exploitation of products expected here, but the enhancement of the physical understanding of underlying phenomena directly supports the definition of future innovative engineering systems dedicated to the aforementioned applications.

3/ A **vibration correction methodology and detailed implementation strategies to confidently implement and operate 3C-PIV measurements in the FTB for flight test measurements**.

The final goal is to achieve accurate and usable in-flight PIV measurements dedicated to the in-flight validation of the active flow control system developed in the context of WP2 and WP3.

4/ **knowledge advancement on advanced optical methodology for the comprehensive characterization of fluid flows and their interaction with structures and systems**.

Results of the ACcTIOM project, WP4 and WP5, are directly transposable to the application of in-flight, or more generally on-board, stereoscopic Particle Image Velocimetry (3C-PIV). There is no direct exploitation of products expected here, but an immediate impact on R&D activities involving the experimental characterization of airflows (or more globally fluid flows) past systems, through wind tunnel or on-board, potentially in-flight, test campaigns.

d) Communication

A poster has been presented at the French identification working group (Groupe de Travail en Identification) which depends on the Modelisation, Analysis and Control of dynamic Systems research group (GDR MACS).

2 papers have been presented at the 50th 3AF International Conference on Applied Aerodynamics, held in Toulouse the 30th, 31st of March and 1st of April 2015.

1 article has been published in the Proceedings of the European Control Conference, held on July 16th 2015 in Linz, Austria.

2 papers have been presented at the Aviation 2016 Conference of the American Institute of Aeronautics and Astronautics on June 13th-17th 2016 in Washington, United States of America.

1 paper has been presented at the Applied Aerodynamics Conference of the Royal Aeronautical Society on July 19-21 2016, in Bristol, UK.

1 paper has been presented at the Greener Aviation of 3AF on October 11th-13th 2016 in Brussels, Belgium.

List of communications

- **Bury, Yannick and Bordron, Alban and Belloc, Hervé and Prat, Damien**. *Development of an Innovative Active Flow Control System for CROR Powerplant Noise Reduction through Pylon Wake Mitigation*. In 50th 3AF International Conference on Applied Aerodynamics, 29-30 March – 01 April **2015**, Toulouse - France.
- **Gourdain, Nicolas and Bury, Yannick and Dupont, Louis and Bodart, Julien**. *Large Eddy Simulation of a flow control device for noise reduction due to a CROR/pylon interaction*. In 50th 3AF International Conference on Applied Aerodynamics, 29-30 March – 01 April **2015**, Toulouse - France.
- **Vayssettes, Jérémy and Mercère, Guillaume and Bury, Yannick and Budinger, Valérie**. *Structured model identification algorithm based on constrained optimisation*. In Proceedings of the European Control Conference, Linz, Austria, **2015**.
- **Budinger, Valérie and Bury, Yannick and Michon, Guilhem and Napias, Gaël**. *In-flight PIV for CROR flight-test demonstration*. In AIAA Aviation 2016, AIAA Aviation and Aeronautics Forum and Exposition, 13-17 June **2016**, Washington DC, USA.
- **Bury, Yannick and Bordron, Alban and Belloc, Hervé and Prat, Damien**. *CROR-powerplant pylon wake mitigation for noise reduction through innovative blowing/suction-based active flow control system*. In AIAA Aviation 2016, AIAA Aviation and Aeronautics Forum and Exposition, 13-17 June **2016**, Washington DC, USA.
- **Gourdain, Nicolas and Bury, Yannick and Bodart, Julien**. *Large-Eddy Simulation and analysis of the controlled turbulent wake generated by a thick profile*. In 2016 Applied Aerodynamic Conference of the Royal Aeronautical Society, 19-21 July **2016**, Bristol, UK.
- **Napias, Gaël and Bury, Yannick and Budinger, Valérie**. *In-flight PIV for CROR flight-test demonstration*. In Greener Aviation 2016, 3AF Conference, 11-13 October **2016**, Bruxelles, Belgium.

Planned – peer reviewed international journals

1 article related to WP2-3 results, describing the active flow control system and demonstrating its efficiency in erasing the CROR pylon wake, will be submitted at the AIAA Journal within the period Q1-Q2 2017.

1 article related to WP4-5 results, describing the Synthetic Flow Device and its application to the PIV measurement error envelope approach, will be submitted at the Experiments in Fluids Journal within the period Q1-Q2 2017.

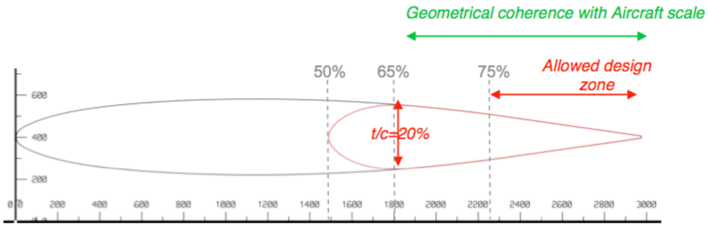

Figure 1. Airbus concept-based, full-scale pylon reference geometry (black) and baseline geometry of the WT model (red).

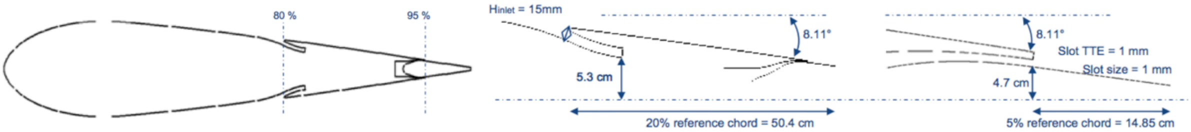

Figure 2. Aft part of the optimized WT geometry and indicative location of the scooping/blowing slots.

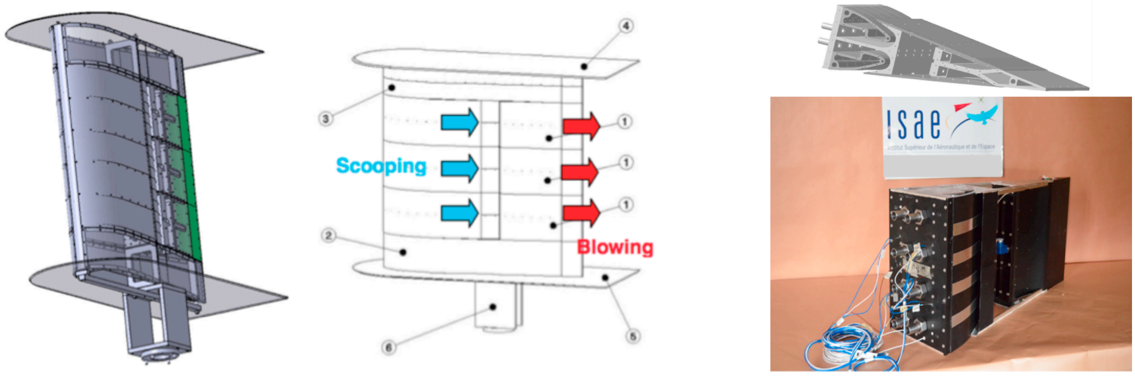

Figure 3. (left) Schematic of the WT model. (1): active modules, (2) and (3): passive end-modules, (4) and (5): tip-wall sets, (6): mechanical interface for the fixing of the WT model in the WT test section. (right) 3D view and picture of one of the modules constituting the active flow control system

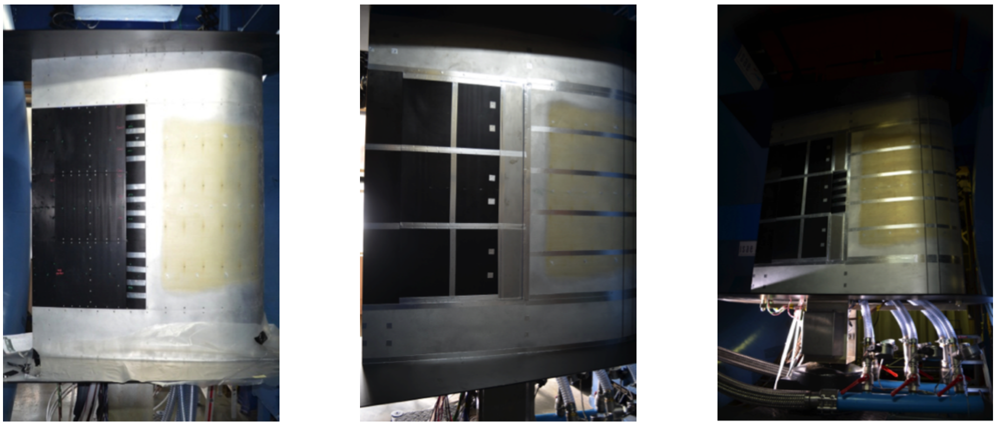
(a) *(b)* *(c)*

Figure 4. view of the three different tested configurations of the WT model. (a) *conf0*: scooping slots opened, with or without turbulent triggering strips (no strips on this picture), control off. (b) *conf1*: scooping slots closed, with or without turbulent triggering strips (strips present on this picture), control off. (c) *conf2*: central module scooping slots opened, upper and lower module scooping slots closed, with turbulent triggering strips, control on/off.

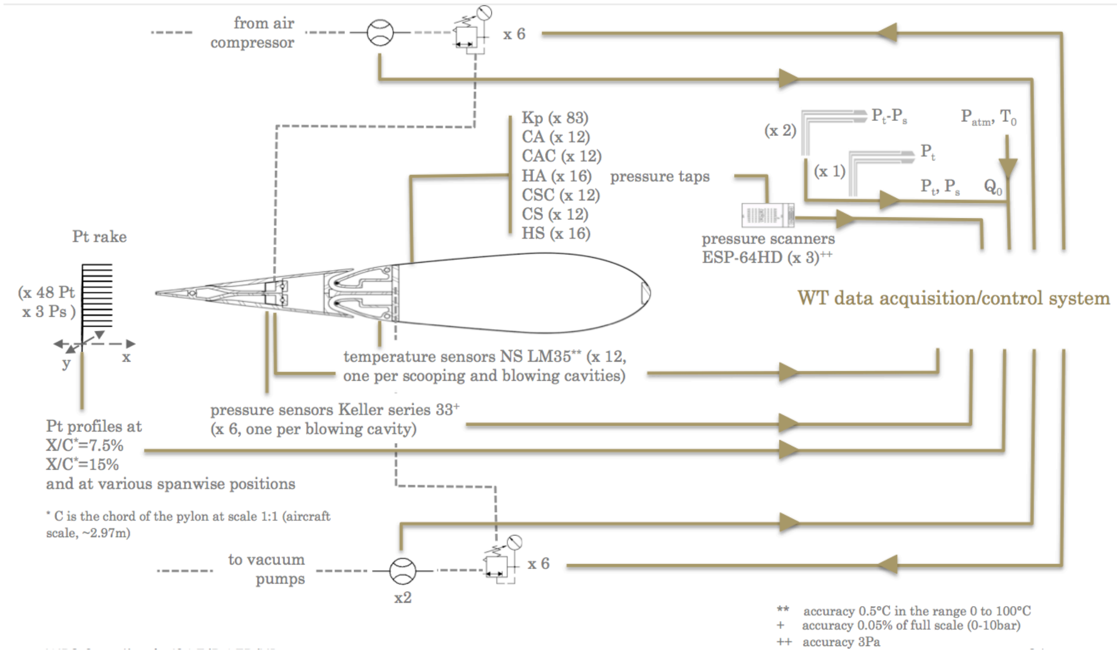

Figure 5. block diagram of the measure/control instrumentation and data acquisition systems.

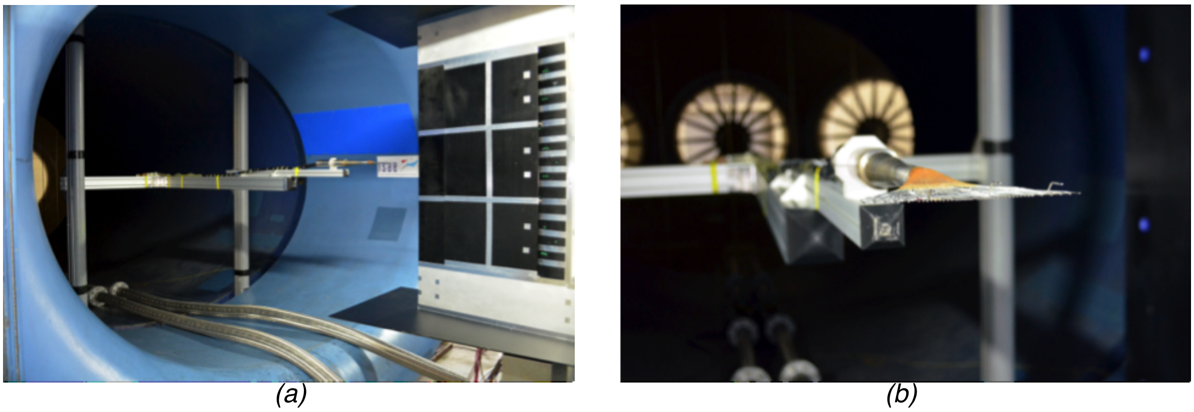

Figure 6. (a) view of the aft part of the pylon, composed of the 3 active flow control modules (in black), of the P_t rake (here positioned at *X/C* = 7.5% downstream of the pylon trailing edge), and of the 2 vacuum lines connected to the 2 scooping devices of the central module (one per WT model side) respectively, (b) detailed view of the P_t rake, composed of 48 total pressure probes and 3 static pressure probes (Airbus Filton property).

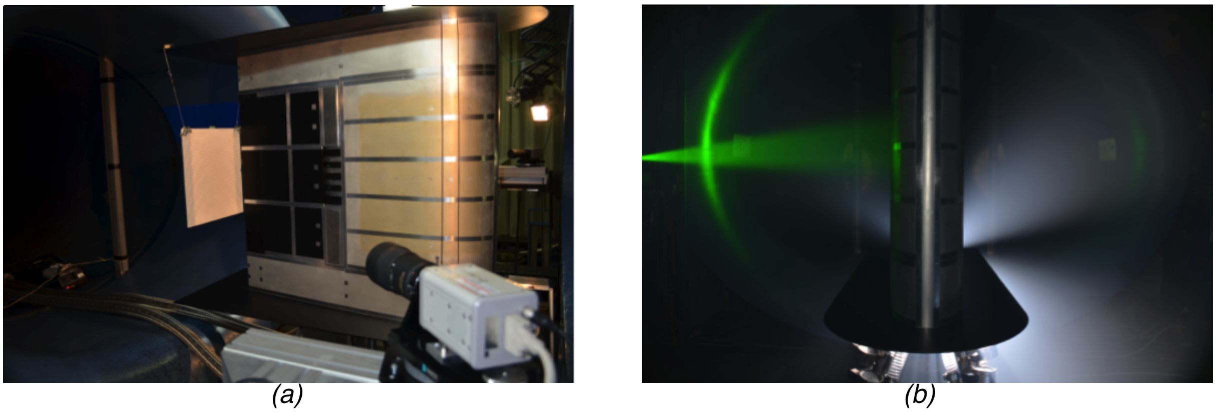

Figure 7. (a) view of the pylon, the two PIV cameras positioned on both sides of the WT test section, the remote-controlled displacement tables, and the 3D target, positioned for 3D calibration (here at *X/C* = 7.5%), (b) view of the laser sheet at *X/C* = 7.5% (ambient lighting turned on for sake of clarity).

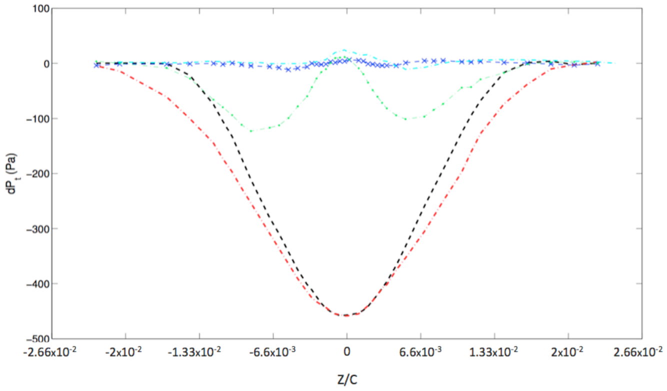

Figure 8. Normalized total pressure profiles in the close wake of the pylon trailing edge. ($Pt - Pt^{out-wake}$) profiles at station ($X/C = 7.5\%$, $Y/C = 0$) for conf1 (−−), conf2-{control-off} (−·), conf2-{control-on} with $[Q_{scoop}, Q_{blow}] = [0/m, 0.011/m]$ (−•−), $[0.026/m, 0.01/m]$ (−·) (conf2/4) and $[0.058/m, 0.008/m]$ (−×−) (conf2/6) respectively. Conf2/4 and Conf2/6 are optimum flow control configurations.

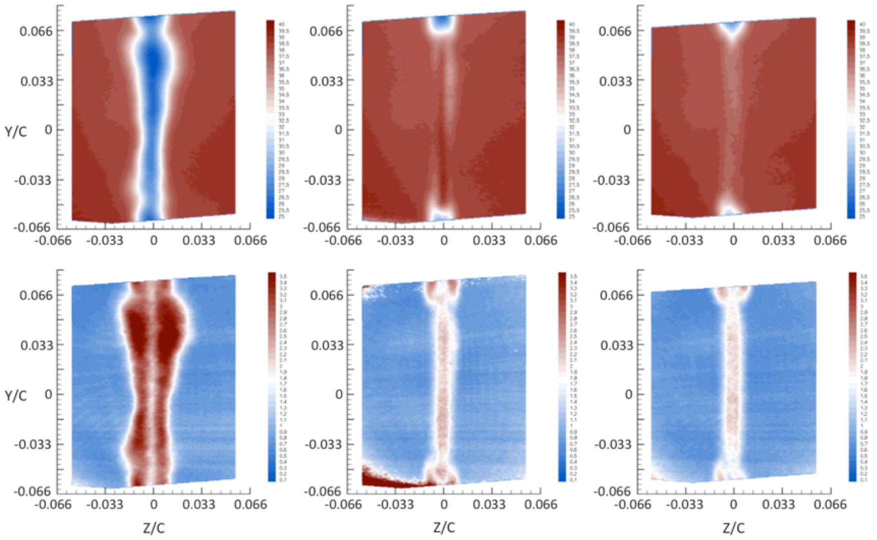

Figure 9. 3C-PIV velocity field in the close wake of the pylon trailing edge. (upper line) U_X mean velocity and (lower line) u'_X r.m.s. fluctuating velocity cross-planes at $X/C = 7.5\%$ for (left) conf2/off, (center) conf2/4 and (right) conf2/6.

(Upper line: Red is the freestream velocity, blue corresponds to velocity deficit in the wake of the pylon. Lower line: red corresponds to larger velocity fluctuations in the wake, blue to lower fluctuations)

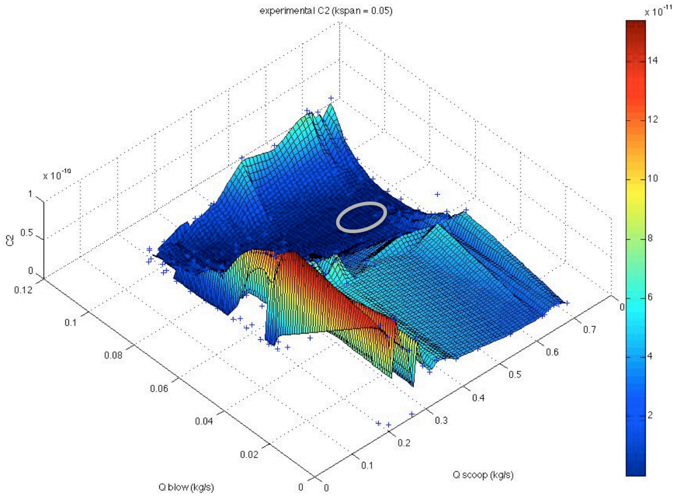

Figure 10. Response surface of the acoustic criterion to the scooping and blowing mass flow rate active flow control parameters (experimental results based on the total pressure probe measurement WT campaign). Grey circle depicts the optimum zone where the acoustic criterion is satisfied (Conf2/4 and Conf2/6 lie in this circle).

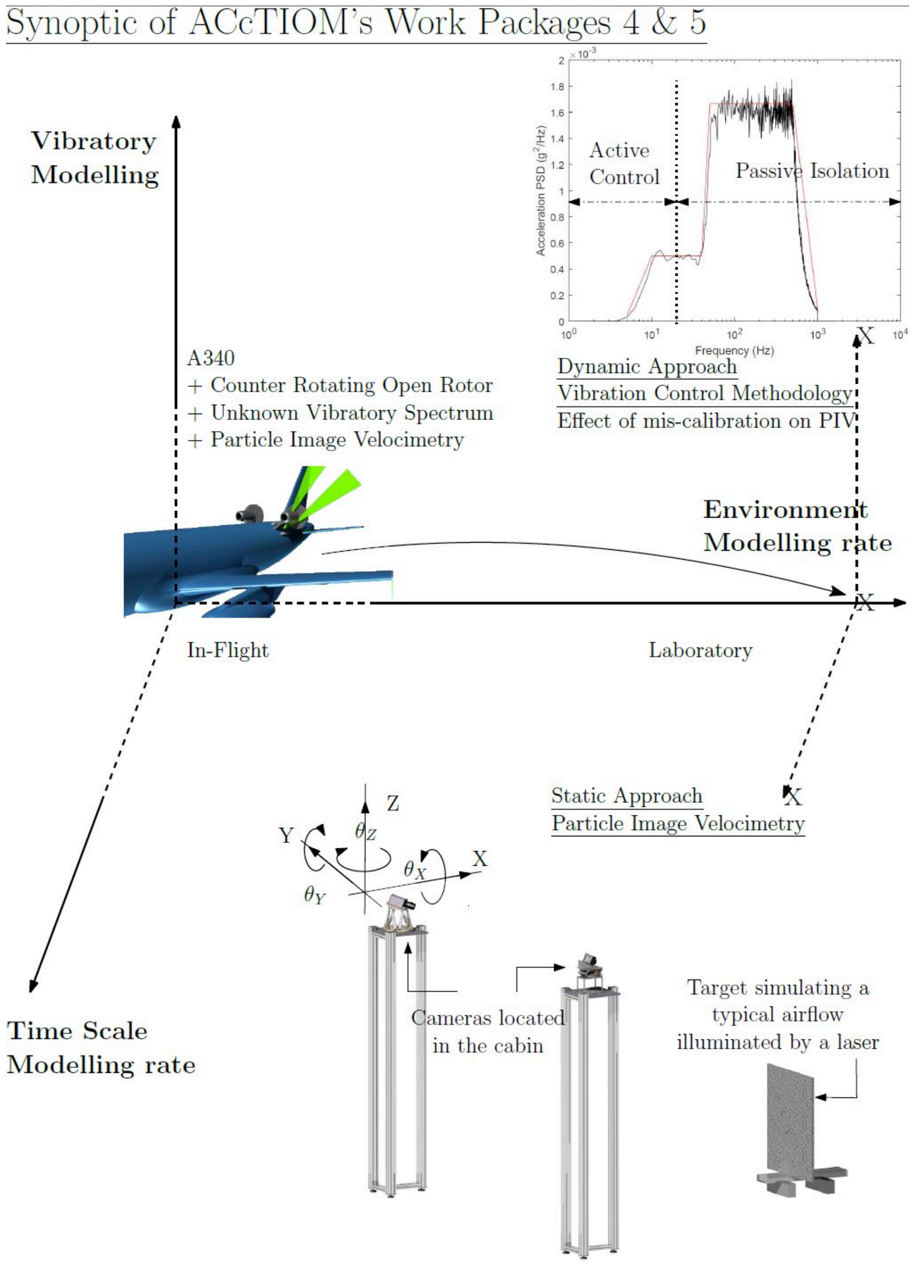

Figure 11. Synoptic of WP4 and WP5.

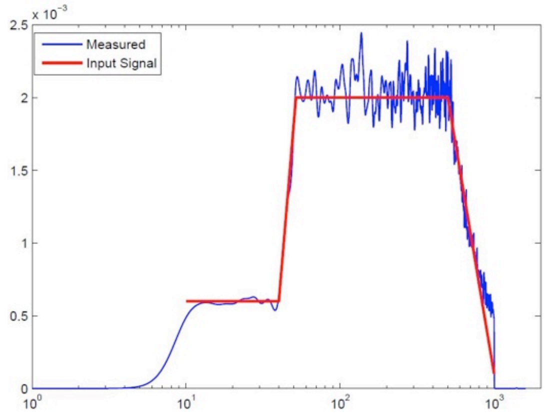

Figure12. Reshaped vertical acceleration PSD of the vibrations assumed to be experienced in the cabin of the CROR engine-equipped FTB.

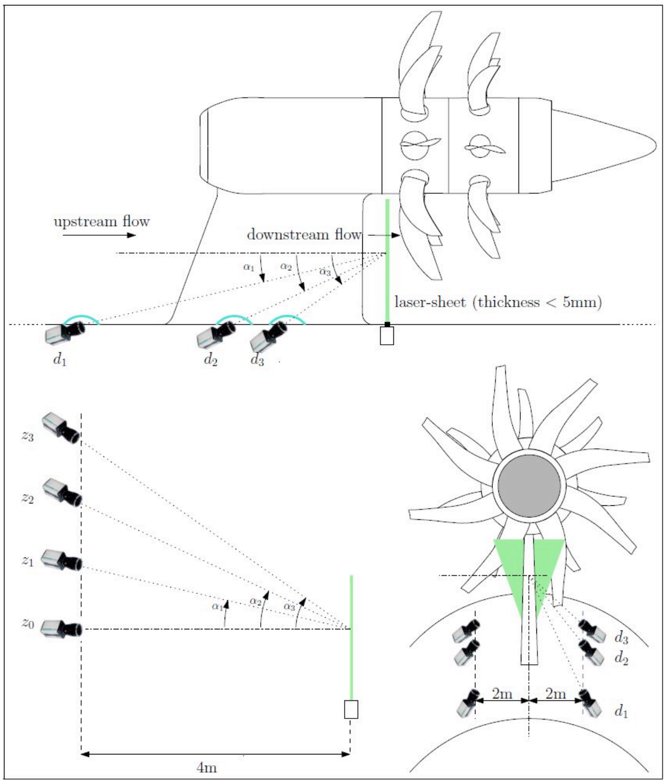

Figure 13. ISAE proposal for the position of the 3C-PIV cameras and laser sheet for in-flight measurements on the FTB equipped with a CROR propeller.

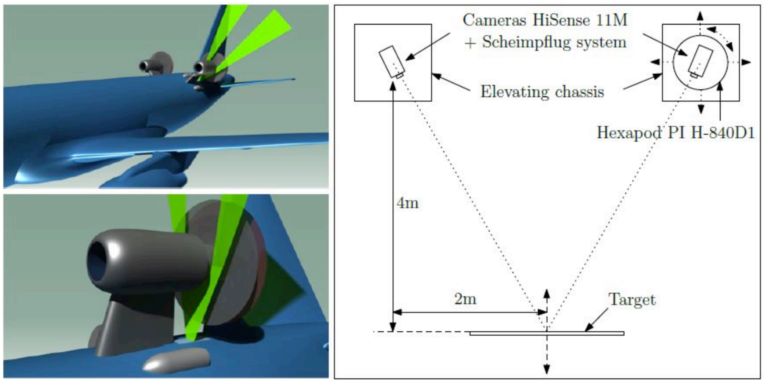

Figure 14. In-Flight ISAE proposal (left) to Indoor (right) 3C-PIV Measurements.

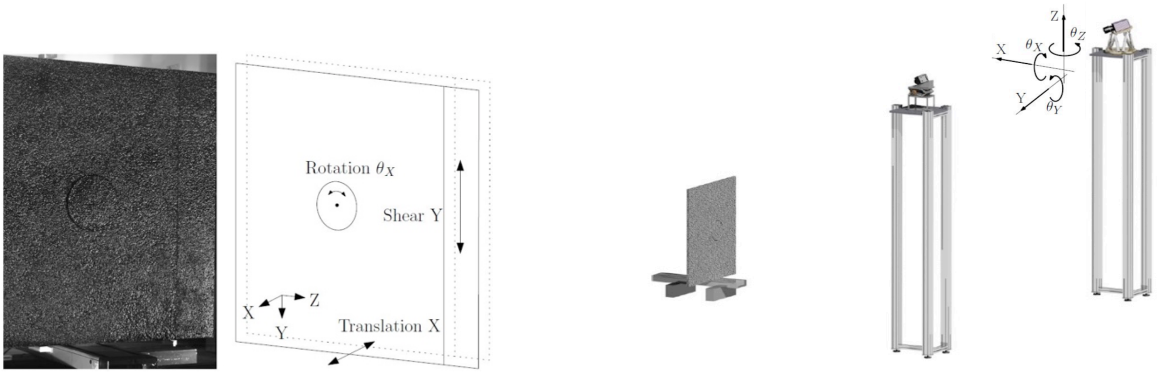

Figure 15. Indoor 3C-PIV measurements: static VES test bench.

(left) Synthetic Flow Device (SFD) with the coating used to simulate particle images and drawing defining moving parts of the SFD to mimic a pseudo-velocity field. (right) static VES in configuration "z = 2500 mm" – FTB Cabin situation, illustrating the possible displacements of the PIV camera to mimic the vibrational environment of the FTB.

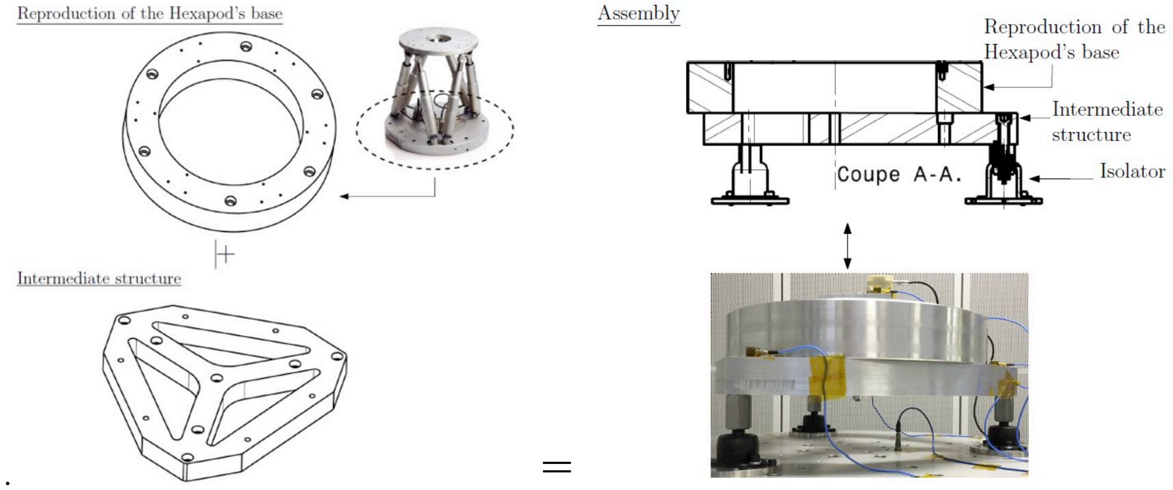

Figure 16. Passive platform of the VCM.
(Top left) Base of the hexapod, (Bottom left) Structure between passive isolators and the hexapod, (Right) Assembly of intermediate structure, hexapod's base and isolators (side view)

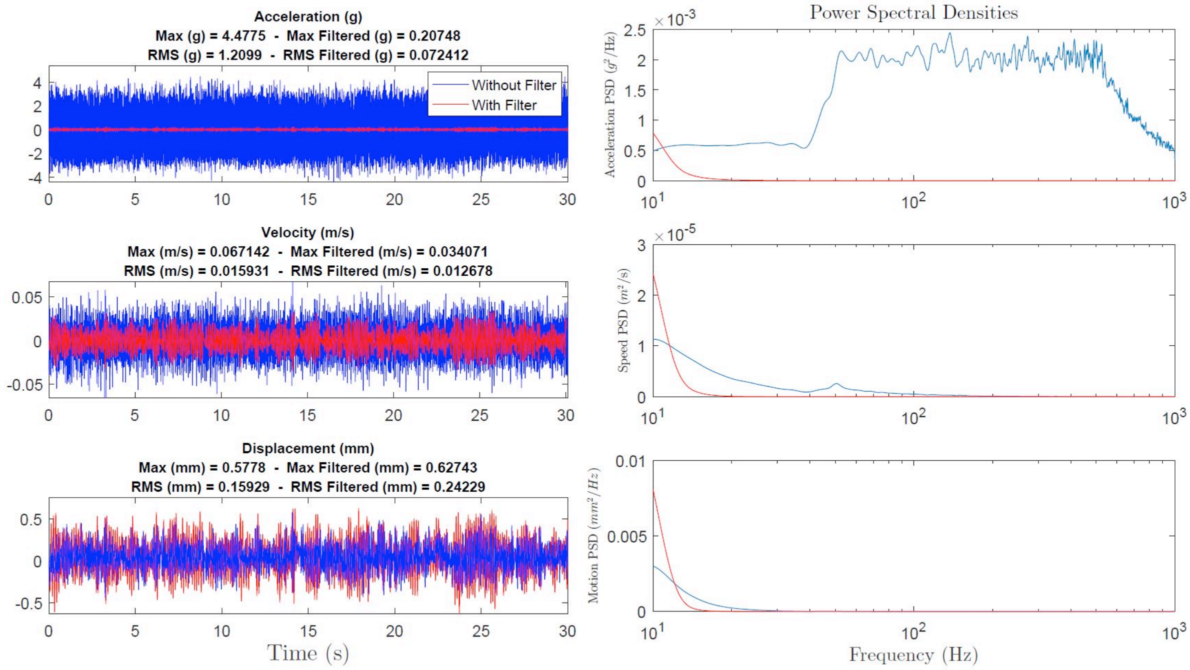

Figure 17. Simulink Model – Time responses and PSD accelerations for a z-direction excitation with passive platform (Paulstradyn-7) for the input spectrum [10Hz - 1000Hz].

Angular velocity	≥ 35 °/s
Rotation angle	≥ 0.5 °
Velocity	≥ 25 mm/s
Displacements	≥ 1 mm
Frequency bandwidth	0 to 15 Hz min.

Figure 18. Dynamic specifications required for the active control stage (hexapod) of the VCM.

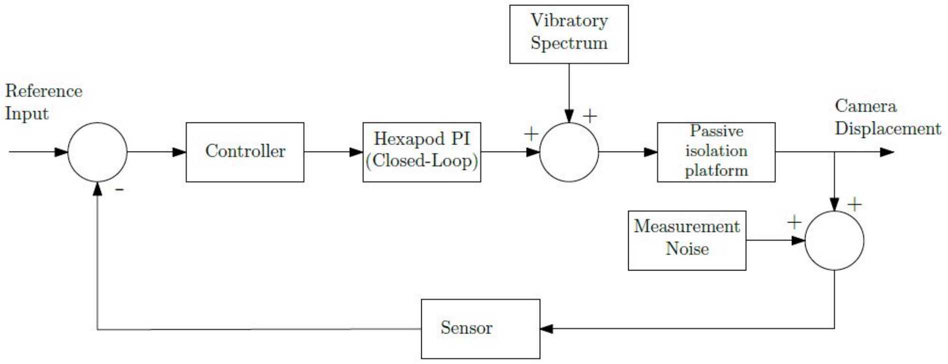

Figure 19. Active stage of the VCM.
Scheme of the hybrid solution in closed loop

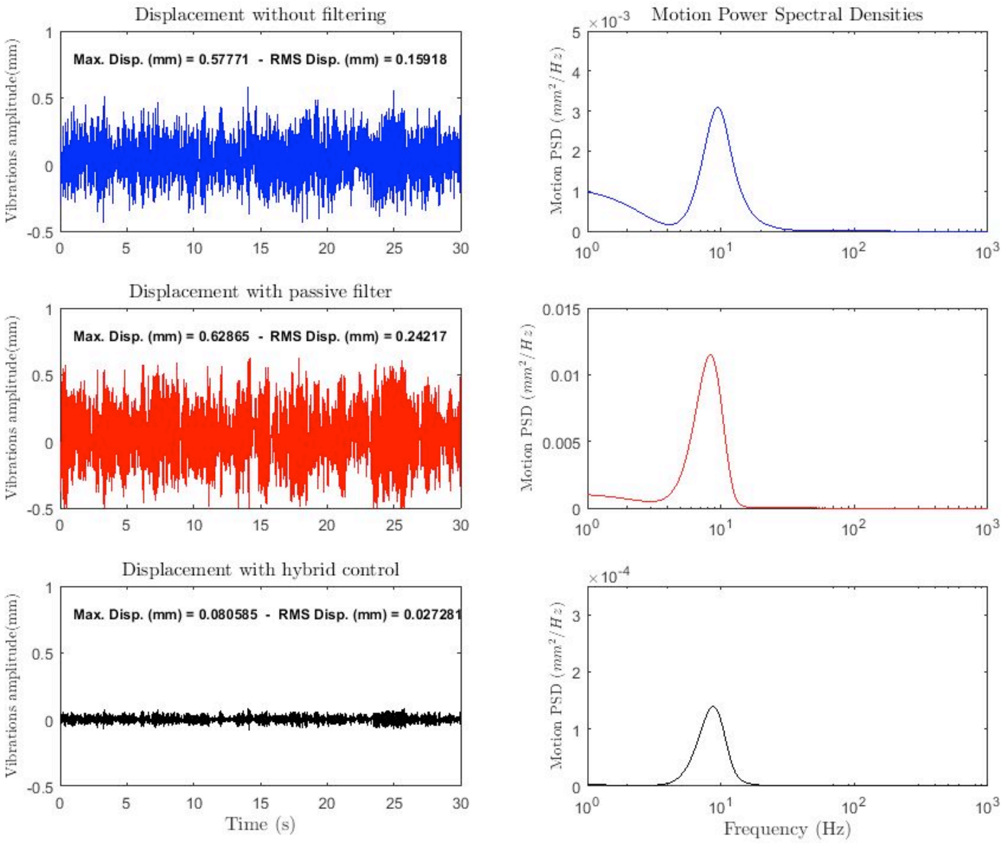

Figure 20. Simulink Model of the VCM in operation when submitted to the active VES.
Vibration amplitudes as a function of time and amplitude spectrum - (top) without any isolation vibration system, (middle) with passive filter, (bottom) with passive dampers and hexapod (hybrid)

Project Summary

Acronym:	ACcTIOM
Name of proposal:	Advanced Pylon Noise Reduction Design and Characterization through flight worthy PIV
Involved ITD	Smart Fixed Wing Aircraft ITD
Grant Agreement:	298187
Instrument:	Clean Sky
Total Cost:	570,160.00 €
Clean Sky contribution:	390,860.00 €
Call:	SP1-JTI-CS-2011-02
Starting date:	01/02/2012
Ending date:	30/06/2016
Duration:	53 months
Coordinator contact details:	Dr Yannick BURY (ISAE - Supaéro) yannick.bury@isae.fr
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Participating members	ISAE - Supaéro AKKA Technologies Aéroconseil Airbus Operation S.A.S.