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WIND TUNNEL FLUTTER TESTS OF A U-TAIL CONFIGURATION

PART 1:

MODEL DESIGN AND TESTING

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Abstract: The aviation community is committed to reducing their environmental impact in light of increasing demand for extra passenger capacity. Explored through CleanSky research programme, innovative tail concepts have the potential for substantial reduction in fuel burn and noise reduction for the next generation of Business jets. In parallel to noise shielding performance evaluation, structural feasibility assessment of such concepts requires dedicated tests. Particularly, the flutter mechanism of intersecting surfaces, such as U-Tail configurations, in subsonic and transonic domains is investigated during Wind Tunnel Tests (WTT) to obtain a sufficient comprehension of the involved phenomena. This paper first presents the design stage of the model, highlighting the difficulties inherent to such geometrical configuration. Laboratory static tests results of unit components or sub-assemblies validating locally the structural behaviour are shown. Ground Vibration Tests (GVT) results obtained during qualification laboratory stage on the whole model, validating the global dynamic behaviour, are then exposed. Finally, WTT results, such as flutter domain and flutter curves, are presented. Additionally, a companion paper [1] focuses on the detailed experimental results obtained and their correlation with numerical results.

1 INTRODUCTION

Greening Air Transport is a global effort to which many aircraft manufacturers are deeply involved, and particularly collaboratively within the CleanSky European programme, guided by ACARE Vision 2020 objectives, i.e. gas emissions and noise reductions. Continuous assessments of environmental impacts of new technologies developed through this programme are performed, and especially within Smart Fixed Wing Aircraft Integrated Technology Demonstrator (SFWA ITD) activity, among these technologies, innovative empennage configurations are explored. Bringing such new concept from low to mid Technology Readiness Level (TRL) requires dedicated tests related to the aerodynamic, loads, noise and flutter characteristics in order to evaluate the noise shielding performance and the structural feasibility.

Specifically, the flutter mechanism of intersecting surfaces, such as U-Tail configurations, in subsonic and transonic domains is investigated during WTT to obtain a sufficient comprehension of the involved phenomena, consistent with the TRL required. Nonetheless, the path leading to WTT of such a model is not straightforward and is detailed hereafter.

ONERA has a valuable experience in transonic flutter tests, as illustrated in figure 1, mostly in the pressurised S2MA wind tunnel in Modane, France, with cable-mounted models such as AirbusA300B, Mirage F1, Mirage 2000, or with wall-mounted half model, dedicated to more specific studies such as non-linearities influence and flutter control. This experience starts from design and instrumentation of flutter model, up to data acquisition and processing, including essential safety systems.

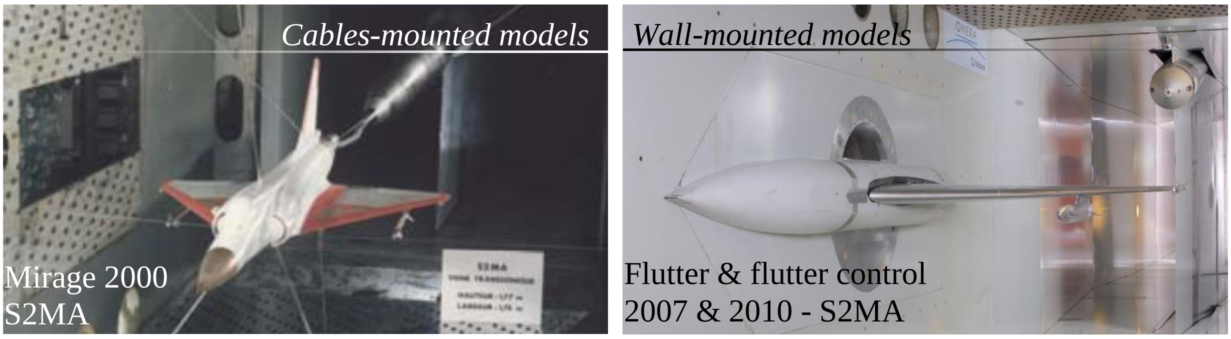


Figure 1: Example of flutter models (ONERA)

RUAG Aviation is a leading supplier, Maintenance Repair and Overhaul (MRO) and integrator of systems and components for civil and military aviation worldwide. The Department of Aerodynamics is a provider for aerodynamic related services including wind tunnel testing, design and manufacture of multi-component force balances as well as numerical flow calculations. With its Large Low-speed Wind Tunnel services in Emmen (LWTE), Switzerland, RUAG demonstrates over 70 years of experience including the design and instrumentation of highly complex wind tunnel models, as shown in figure 2 as example.

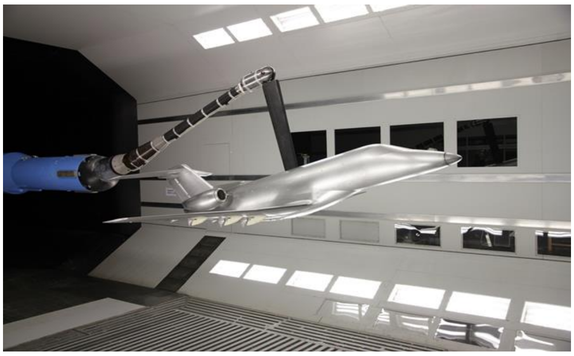


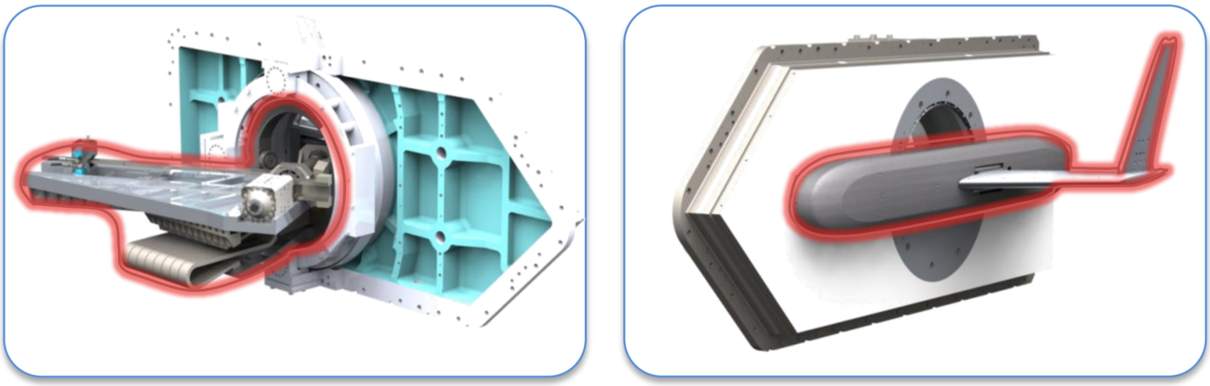
Figure 2: RUAG designed wind tunnel model of Pilatus PC-24 in the LWTE

2 DESIGN

Based on previous wall-mounted flutter model architecture, the design of this particular flutter model has been guided by respecting several key points relative to flutter behaviour and tunability, safety, and including all constraints on design and manufacturing of wind tunnel models imposed by ONERA Wind Tunnel Division, as well as constraints on instrumentation to observe adequately the expected phenomena.

2.1 Architecture and configurations overview

For the sake of clarity, let us first differentiate now the two main areas of the whole model, as shown in figure 3. The "test set-up" comprises all the parts outside the wind tunnel test section and determines the boundary conditions of the whole assembly, allowing modification of the flutter behaviour, and also allowing changing the mechanical configuration. The parts inside the test section are called in a shortened form the "model", and are directly submitted to the wind loading.



Parts outside the test section called the "test set-up"

Parts inside the test section called the "model"

Figure 3: The two main areas of the whole model

In "flutter" configuration, the boundary conditions target the flutter onset in a convenient zone of the wind tunnel test range of the S2MA transonic nozzle. Runs with continuously increasing stagnation pressure, to initially determine the critical pressure, or several stabilized runs stepping pressure, to plot the flutter curve, can be performed and acquired.

In "pressure" configuration, the kinematic and stiffness are modified so that flutter is not likely to occur as the specific boundary conditions shift the unstable domain far from the test points conditions. The purpose of this configuration is to acquire steady and unsteady aerodynamic data to supplement the global database for calibrating unsteady Computational Fluid Dynamics (CFD) tools. For this, the whole model, excluding the fuselage, can oscillate in pitch thanks to a hydraulic servo command, remotely controlled.

2.2 Overall process

The challenges of designing such a Wind Tunnel model require a large amount of specific works based on numerical simulations, which were distributed between the project partners, and consist of:

- obtaining an architecture leading to flutter for all configurations, with desired characteristics, and with structural constraints,
- making the aerodynamically cleanest and most modular design as possible,
- instrumenting the model accordingly to the expected phenomena.

As shown in figure 4, the design process starts with a feasibility study, to ensure an architecture leading to flutter can be found. Then, increasing the constraints on flutter behaviour, structural capacity and instrumentation, the detailed design leads to the final architecture. Designs of the model and the test set-up are performed in parallel. The general characteristics such as weight, inertial tensor and center of gravity location from the former are provided as complementary data for the latter.

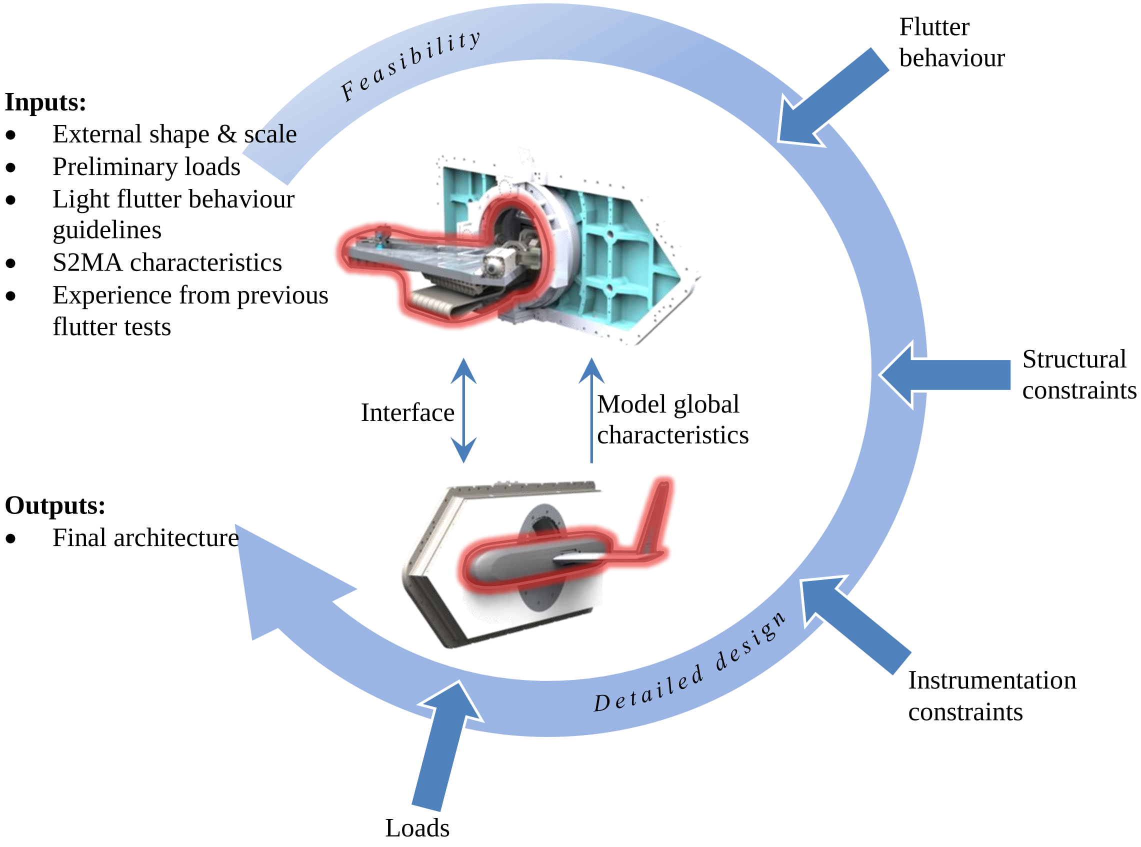


Figure 4: Design process

2.3 Guidelines

During the design phase, satisfying both flutter requirements and structural integrity constraints of the model is essential to converge to an acceptable architecture.

2.3.1 Flutter

The flutter behaviour must meet several requirements, listed here below and illustrated in figure 5:

- Flutter is a coupling between the first bending and torsion modes, with minimum interference from unwanted modes such as horizontal in-plane mode.
- The initial frequency gap (at Mach=0) of these two modes must be greater than 3 Hz.
- Flutter must ideally occur for stagnation pressure close to the atmospheric pressure for transonic flow.
- When flutter springs up, the coupling frequency must be lower than 20 Hz, and the sharpness of the phenomena must be greater than or equal to a predicted pressure variation of 0.3bar for 3% of additional structural damping.
- Flutter must exhibit sensitivity to stiffness and mass variations (tunability).

- Flutter must exhibit sensitivity to aerodynamic phenomena (variations of geometrical configuration).

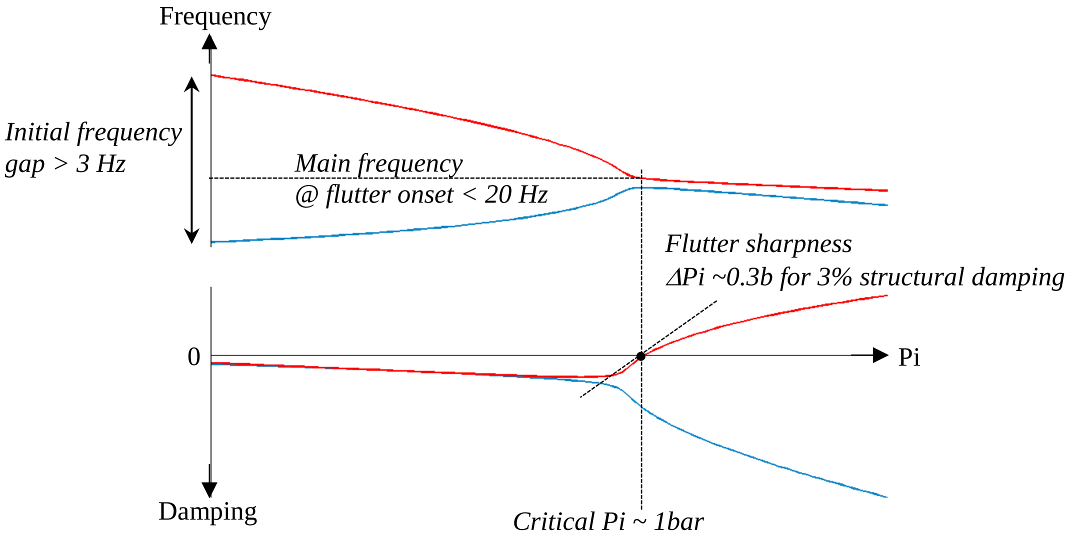


Figure 5: Flutter criteria

2.3.2 Structural integrity

The structural integrity of the whole model must be ensured by imposing the maximum stresses for all parts, following ONERA Wind Tunnel Division rules [2]. From this procedure, for all configurations and loadcases, let us call σ_{allow}, depending on the calculation made:

- the combined stress equal to min(¾ Fty, ½ Ftu),or
- the shear stress alone equal to ⅓ Fty,or
- the bearing stress equal to ⅔ Fbry,

where subscripts y, u, t and br respectively mean **y**ield, **u**ltimate, **t**ension and **b**ea**r**ing.

For such a model, the sizing strategy is closely linked to the safety system used. The safety of the model during the Wind Tunnel Tests is detailed in chapter 3. However, for the sake of clarity in this section, it is worth mentioning that the safety system is based on several sensors signals measurement. The parts on or in which the sensors are installed for monitoring are hereafter called the “monitored” parts. In agreement with ONERA/Wind Tunnel Division, the following rules have been established, for the critical configuration, i.e. flutter:

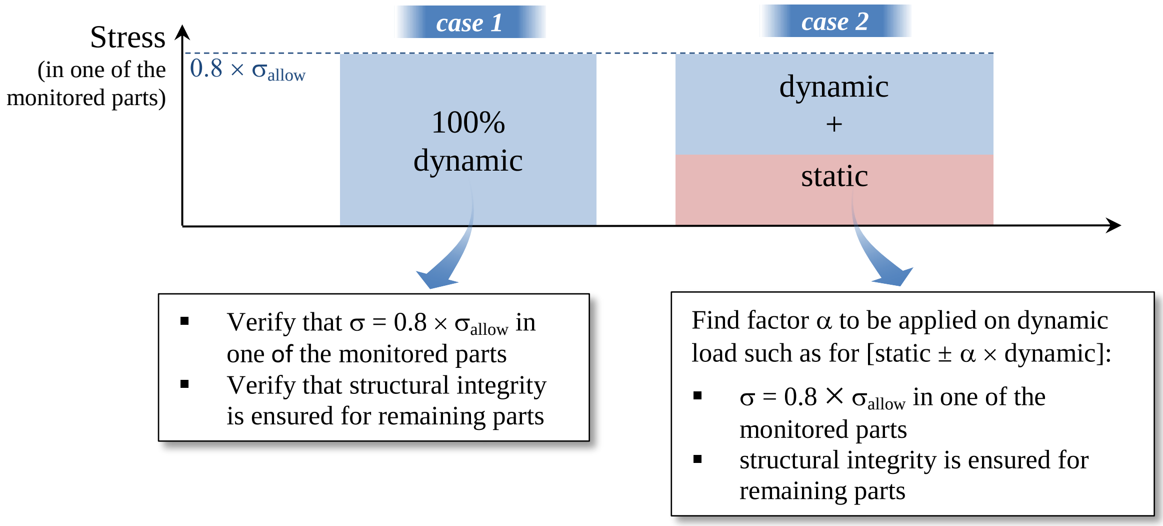
- Stresses in monitored test set-up parts must never exceed $\sigma_{allow} \times 0.8$, safety system settings adjusted consequently.
- Stresses in remaining parts must never exceed $\sigma_{allow} / 2$, safety system settings having been adjusted previously. This factor of 2 also leads to a more secure integrity of the model relatively to fatigue phenomenon during the whole test campaign, preventing the various flutter onsets from bringing too many cycles at too high amplitudes.
- Concerning static divergence, a safety factor of 3 is to be applied. However this particular model is designed such as flutter occurs first and at around atmospheric pressure, so much before static divergence.

2.4 Loads

Preliminary loadcases are supplied at the beginning of the design phase by Dassault-Aviation to rough out the design. Navier-Stokes calculations provide the stationary loads, whereas dynamic loads cannot be computed at this stage and are coarsely estimated based on previous flutter experiments.

Once guidelines of the structural integrity defined and the design iterations at an advanced stage, load envelopes for structural substantiation of parts are generated more precisely for each mechanical configuration among all aerodynamic conditions. Static loads are due to the aerodynamic pressure distribution on the model resulting from wind loading, and dynamic loads consist of aerodynamic loads on the model, computed by Doublet Lattice Method (DLM), and inertial loads on the test set-up. It is worth mentioning that the highest loads, and thus the highest stress levels in parts, are reached when flutter onset is stopped by the safety system and consequently are directly linked to the parameters of the latter.

Model structural substantiation is fully based on the generated loads, in the most conservative way. Loads used for the test set-up structural substantiation are however adapted subtly to avoid reaching unacceptable stress levels, as shown in figure 6. Whatever the combination of static and dynamic loads, the safety system parameters will be adjusted progressively during the WTT campaign to guarantee that the highest stress in monitored parts never exceeds $0.8 \times \sigma_{allow}$.



- Verify that $\sigma = 0.8 \times \sigma_{allow}$ in one of the monitored parts
- Verify that structural integrity is ensured for remaining parts

Find factor α to be applied on dynamic load such as for [static $\pm \alpha \times$ dynamic]:

- $\sigma = 0.8 \times \sigma_{allow}$ in one of the monitored parts
- structural integrity is ensured for remaining parts

Figure 6: Adapted methodology for test set-up parts structural substantiation

2.5 Test set-up design

Past flutter wind tunnel tests performed in ONERA concerned classically wings, or sometimes fins, but never U-Tails. As new problem may require new solution, the very first step during the design phase is to verify that it is still possible to get flutter conditions compatible with S2MA test domain. Once this step validated, a detailed design can be initiated.

2.5.1 Feasibility

To find an acceptable architecture respecting lightened constraints on flutter behaviour, a MATLAB optimisation process is developed, using a limited set of variables such as dimensions of key parts, location of horizontal plane interface. For each iteration during this process, a Finite Element Model using 1D and 2D elements is generated in NASTRAN format with the updated optimization variables, then a modal solution is run, and finally a flutter calculation using Doublet Lattice Method is launched. Due to the type of FEM generated, it is obviously not possible to add stress constraints at this stage.

Architecture of previous flutter models consisted in a horizontal plane mounted at the end of a shaft, rotating thanks to a pair of bearings. Flutter conditions were adjusted by changing the working length of a straight beam. Based on this configuration, no acceptable solution is obtained. Either the solution is unrealistic, i.e. that cannot be manufactured, and/or the flutter conditions are not reachable within the S2MA test domain.

It is consequently decided to improve the previous initial architecture by enhancing the kinematic and adding more flexibility, as shown in figure 7. The table on which the previous architecture was installed has now the ability to roll thanks to a new pair of bearings, and is hold by S-shape springs, called S-beams. Therefore, the flutter behaviour is now mainly determined by two stiffnesses, one from the straight beam, and the other from the S-beams. Based on this new configuration, solutions fulfilling the requirements are obtained, allowing going to the next step: the detailed design.

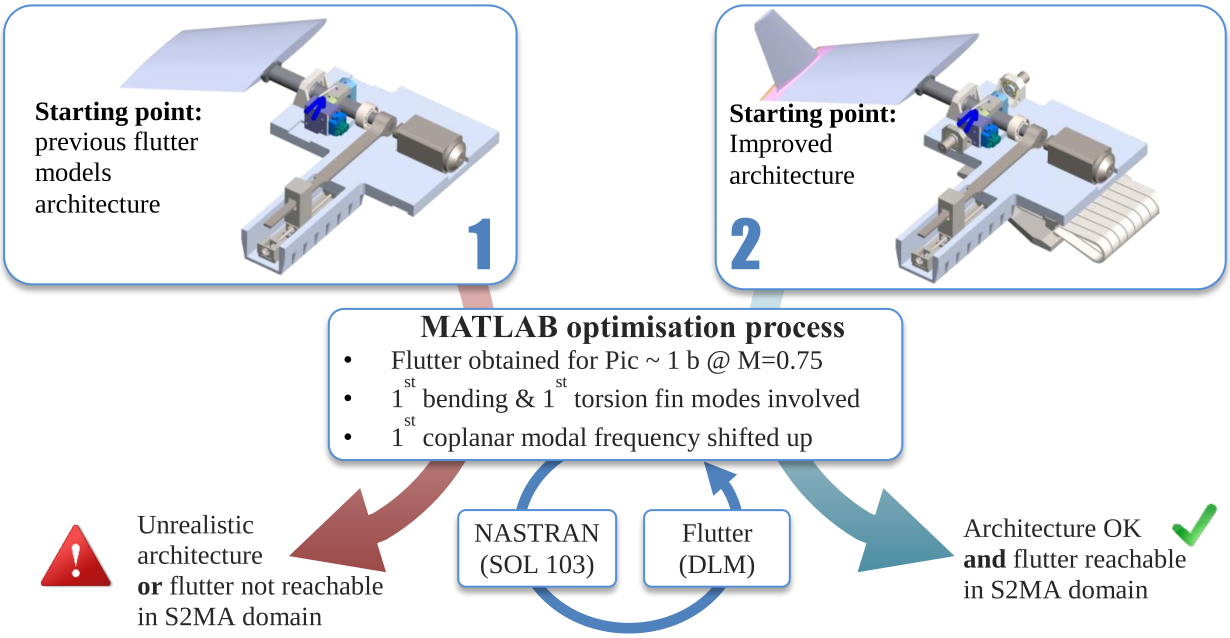


Figure 7: Feasibility iterative process

2.5.2 Detailed design

Transition from preliminary to final design is not straightforward, as many key parts must be included, constrained by Wind Tunnel (WT) wall integration, mounting and dismounting, operator accessibility, electrical wiring, hydraulic tubing, and very little room for integration in some areas. Changing the mechanical configuration during the WTT must be as little time-consuming as possible, which must be considered as well. Figure 8 shows the key parts of the test set-up, essential for safety, excitation, WTT efficiency, and flutter behaviour adjustability. As the probability that the real critical pressure for such a complex model noticeably differs from the predicted one is not negligible, it is necessary to implement the ability to modify some characteristics of the test set-up. At first, several beams are designed to adjust the test set-up dynamic behaviour and thus to obtain flutter onsets in the WT domain. Moreover, a movable clamping system is installed and acts on the straight beam, allowing changing its working length remotely to avoid time-consuming and unproductive stops of the WT.

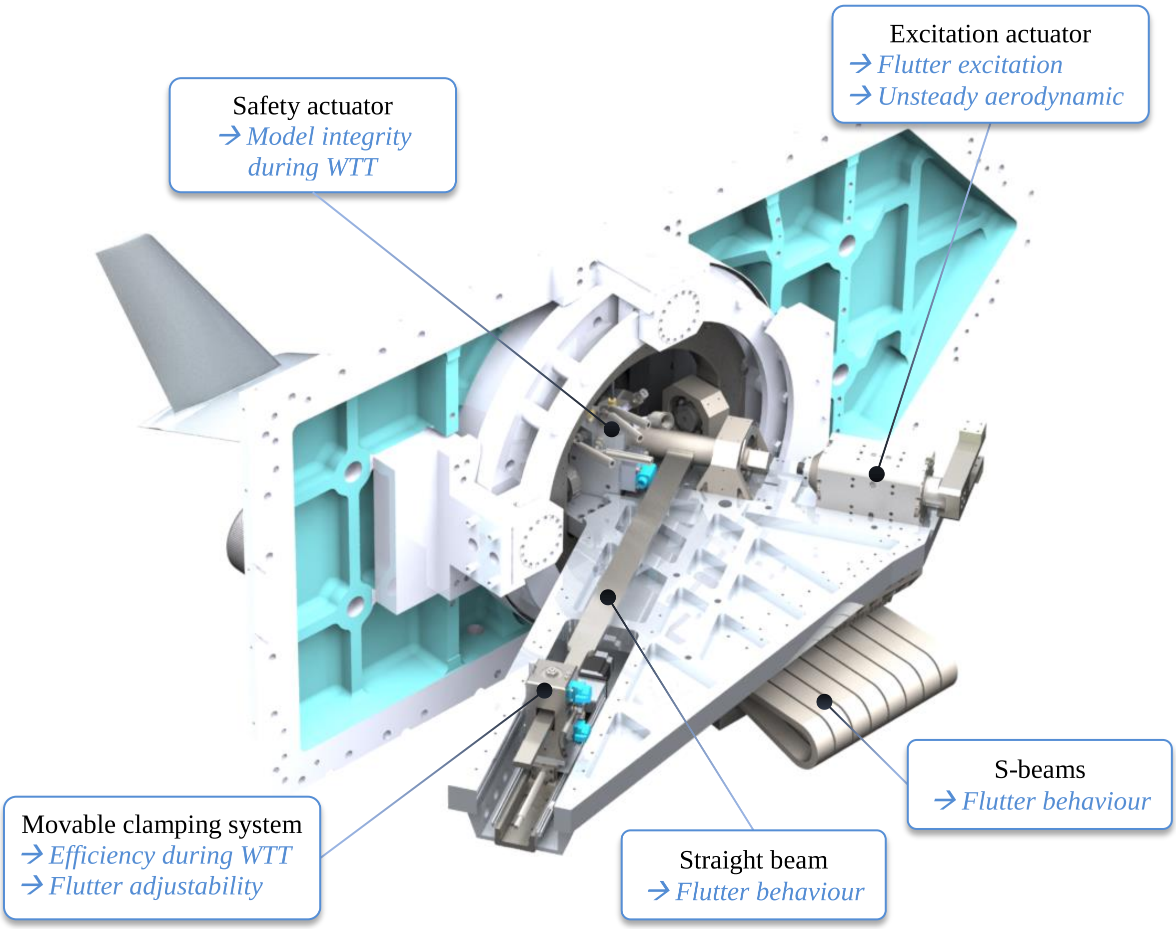


Figure 8: Test set-up detailed design

At this stage, sizing and structural substantiation of parts require to accurately calculate the stress level in critical areas, and if necessary modify the design of some parts. For this purpose, a Finite Element Model (FEM) is built in NASTRAN format, using mostly second order tetrahedral elements, as represented in figure 9. The parts inside the test section are replaced by a 0D element with appropriate mass and inertia tensor, at the end of the shaft. Similarly, the excitation and safety actuators are replaced by 0D elements with appropriate mass and offset information. This FEM comprises 1.1M+ nodes and 1.6M+ elements, and calculation time is approximately half an hour for a complete static analysis and one hour for modal analysis up to 10 modes, using an 8-cores & 50 Gb RAM dedicated computer. Although flutter calculations are performed once for validation as illustrated in figure 10, using modal results, this FEM is obviously not suitable for parametric studies for which many calculations are required. Consequently, a lighter FEM is specifically developed for a better representation of the dynamic behaviour [1].

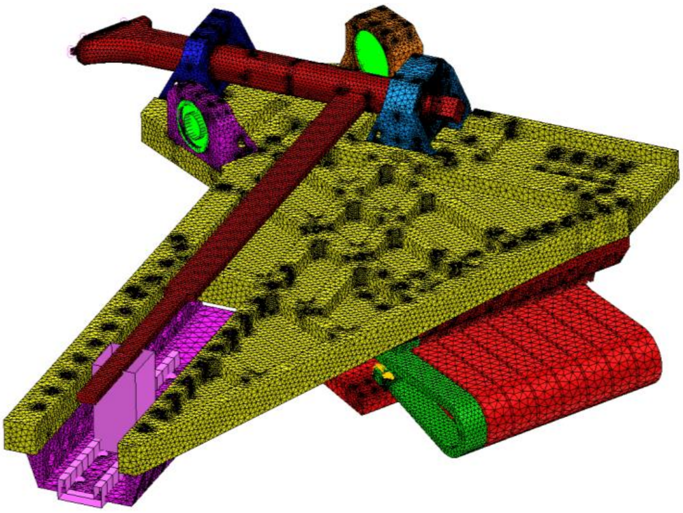


Figure 9: Test set-up 3D FEM used for structural substantiation

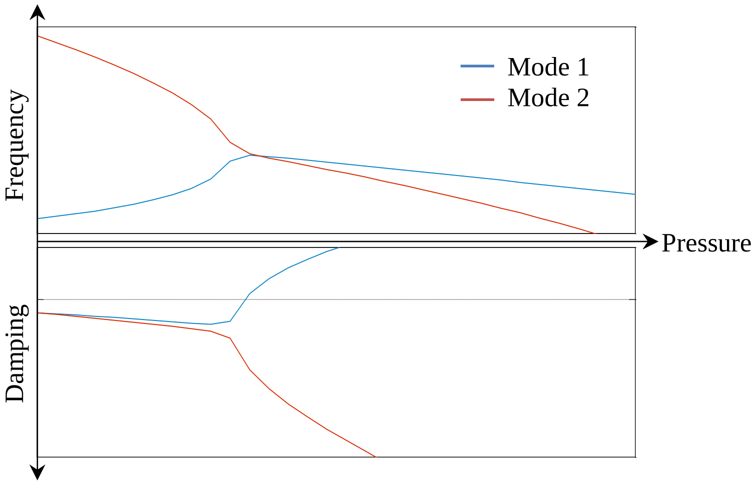


Figure 10: Detailed design, nominal U-tail configuration – Flutter prediction at Mach=0.75

Assembling all the parts of the test set-up requires more than 150 fasteners that must withstand the highest loads, even in failsafe conditions. Unscrewing due to vibrations must also be avoided by an adequate sizing and/or threadlocker. Regular inspections are planned for most of them.

For the most loaded junctions, specific bolts group calculation is made to verify that the maximum stress level in the fasteners and parts locally remains acceptable, and no separation of the assembled parts occurs, for every loadcase and every condition (nominal and failsafe). The complete methodology, with formulas, to finally calculate the stress level in the fasteners and in the parts is described in [4]. Several iterations are sometimes necessary to determine acceptable conditions of installation. The lubrication condition may be changed to reduce the torsion stress in the fasteners, for a given preloading force. Greasing the junction lowers the friction coefficient, typically down to 0.1 and consequently, the preloading torque becomes reduced. Recommendations of VDI 2230 [5] are followed to calculate the stiffness of the assembled parts, for which also the loading introduction factor is determined regarding theirs geometric characteristics. Knowing the maximum tension external force on the most loaded fastener, the minimum preloading force is calculated to ensure no separation of parts. Based on force / moment relation, given the fastener size and greasing condition, the preloading force is converted to a preloading torque. Finally the induced stress level in the most loaded fastener is calculated and must conform to ONERA Wind Tunnel Division rules [2].

2.6 Model design

The objective of the project is to get a deeper knowledge of flutter for intersected surfaces, with various geometrical configurations. This means that the model must be designed to allow variation of geometry, and must be adequately instrumented to observe the aerodynamic phenomena.

The horizontal part has a 0.46m span and the vertical part has a 0.5m height. Considered independently, these parts can be considered as relatively small to withstands the highest loads and be equipped with numerous sensors, which represent a significant challenge.

2.6.1 Modularity

Changing the geometrical configuration during the WTT must be as time inexpensive as possible, structurally safe and keeping the cleanest external shape from an aerodynamic point of view. Another major consideration is to get a minimum of parts to be manufactured. As all these constraints may lead to opposite design trends, a compromise is found, as exposed in figure 11. The adaptor and the adaptor cover are the key parts for modularity: one part must be designed and manufactured per geometrical configuration. Sensors wires are routed through these parts, so to avoid damaging the instrumentation, a great care must be taken during a configuration change.

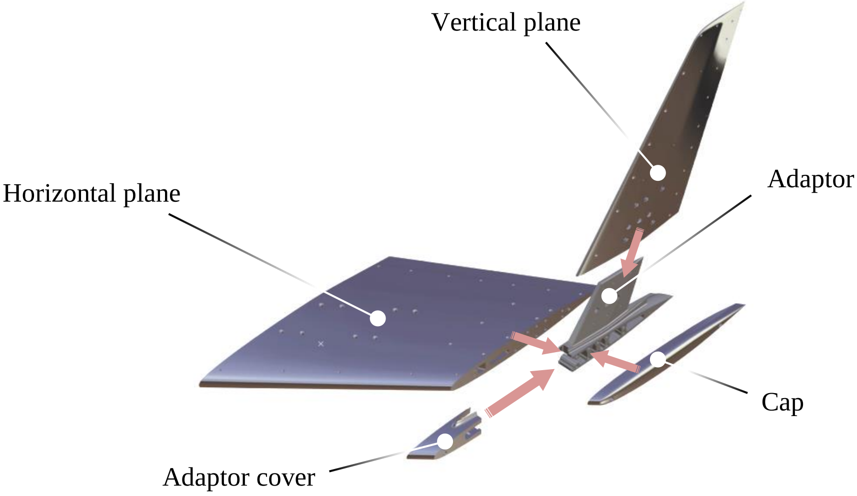
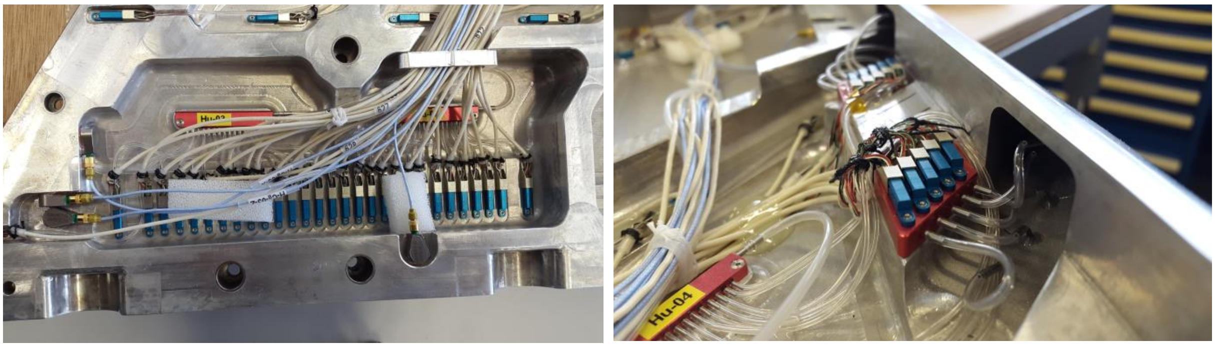


Figure 11: U-Tail modularity

The horizontal and vertical planes, and the cap are permanent for the whole test campaign. To guarantee a correct installation whatever the configuration chosen, and as parts are manufactured individually, manufacturing tolerances are very tight. A maximum misalignment of 0.05mm is required between all surfaces and the airfoil tolerance must remain within 0.1mm.

2.6.2 Instrumentation

The model poses several challenges for instrumentation. In general, there is hardly enough space for the large amount of sensors that have to be packed inside the model. The sensors consist of strain gauges, unsteady pressure sensors and accelerometers. Only small cavities are available for the instrumentation due to stiffness and stress requirements from the structural design side. This creates difficulties regarding placement of sensors and the electrical and pneumatic harness, as presented in figure 12, especially in interface locations like the adaptor.



Details of vertical plane root instrumentation *Details of horizontal plane leading edge instrumentation*

Figure 12: Dense instrumentation areas

Another challenge is the requirement of reusability of the expensive unsteady pressure sensors after the test. The standard procedure of gluing the sensors directly into the model would make it difficult to remove them later without damage. Therefore the concept of the L-adaptor is developed, as illustrated in figure 13. The sensor is glued into the adaptor which is fixed to the model by M1 countersunk screws. Special care is taken in the design of the adaptor because this type of sensor is sensitive to mechanical stress transmitted through the mounting. To prevent leakage a miniature O-ring seal is installed. The adaptor can be easily removed without the risk of breaking it and reused in another model.

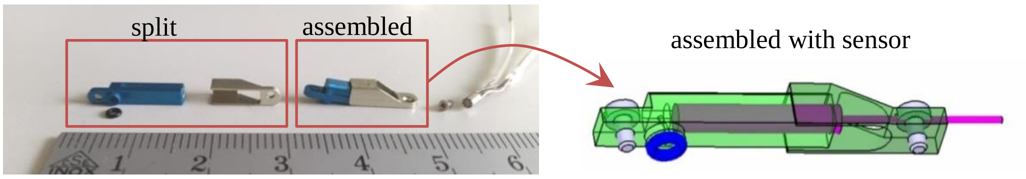


Figure 13: L-adaptor concept

The drawback of the L-adaptor is that in front of the sensor is a cavity which is connected by a bore to the surface of the model. This could cause distortion in amplitude and phase. Standard procedure calls for checking the sensors after installation with a pistonphone. But they normally offer only fixed frequency. Using a loudspeaker would not provide enough pressure variation. Instead, an electrodynamic shaker normally connected to a piston is used to generate the pressure signal. With the help of this "pistonphone" a directly mounted sensor and one in an L-adaptor are excited at the same time, enabling to measure a Frequency Response Function (FRF). No relevant distortions are found in the frequency range of interest, as presented in figure 14.

In several locations it is not possible to mount the pressure sensors directly using the L-adaptor due to space restrictions. Tubes have to be used to get from the pressure tap to the sensor. The effect of those tubes with regard to damping/amplification and phase shift is also checked with the setup above. Based on the results, restrictions are introduced regarding the maximum tube length.

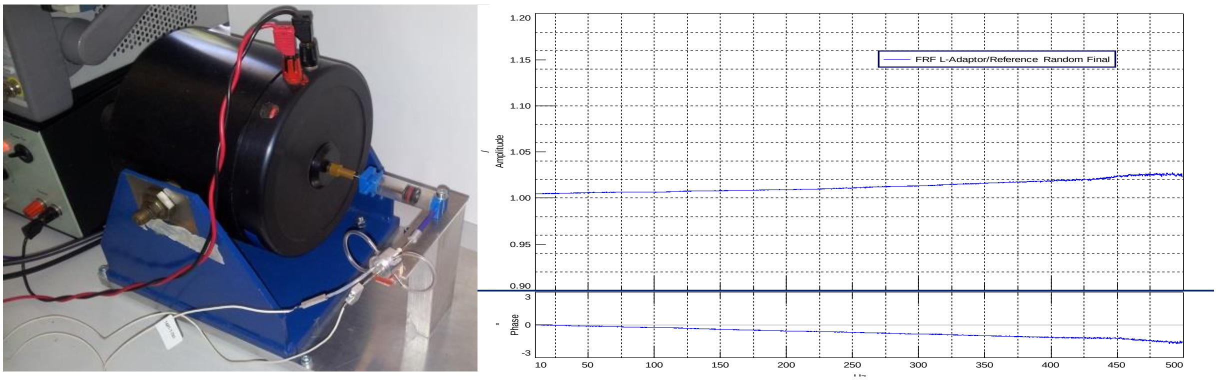


Figure 14: L-adaptor FRF

The use of differential sensors creates challenges as well due to the necessary pneumatic harness. While absolute pressure sensors of this type are also available, the differential ones offer better resolution but need tubing for the reference pressure. With more than 250 sensors it is not possible to route a reference tube to each single sensor from the outside. Reference tubes are connected to dedicated “manifolders” inside the model which are then connected via larger "main tubes" the outside of the model. This reduces the space required for the pneumatic harness considerably, but increases the risk of leakage. If one of the “main tubes” would leak, all sensors connected to its “manifolder” would be unusable.

Both, the L-adaptors and the “manifolders” are designed and manufactured by RUAG.

3 SAFETY

Safety of the model is ensured by several systems:

- a complex and real-time adjustable electro-hydraulic system,
- mechanical stops to limit the amplitude of movement at defined points of the table,
- a large hydraulic accumulator in case of Wind Tunnel global power outage, allowing to keep enough pressure in the hydraulic circuit as well as a minimal flow to trigger the safety if necessary,
- associated to the previous point, all devices related to safety will be plugged into an uninterrupted power supply, such as triggering can be done quickly after power outage onset.

Mechanically, the safety is based on a hydraulic actuator that adds, when triggered, pitch stiffness to the model by blocking the shaft rotation on which the U-Tail is mounted. Consequently, the frequency gap of the two modes involved into flutter increases suddenly, cancelling the flutter onset.

Besides this, two electronic devices are used with partial redundancy to determine the triggering action depending on several sensors in the model and the test set-up. The first device, an ONERA made analog/digital hardware, can only receive signals from two accelerometers with adjustable parameters (threshold and number of overpasses) and one TTL signal. The second device is a real-time dSPACE platform, which duplicates the functioning of the first device, but with enhanced possibilities such as adding more sensors as inputs and more complex safety laws, and real-time visualisation. Parameters of both devices can be real-time changed.

Figure 15 describes the general principle of the electro-hydraulic safety system used during the WTT. Nonetheless, different mechanical configurations (‘flutter’ and ‘pressure’) are set during the WTT and safety must be slightly adapted from one configuration to another.

In ‘flutter’ configuration, the excitation hydraulic actuator is not connected to the shaft. Thus, any triggering signal must activate the safety hydraulic actuator as fast as possible.

Although the ‘pressure’ configuration is flutter free, the safety remains active, in case of unexpected event or unstable phenomenon. In this configuration, the excitation actuator is directly connected to the shaft, so great care must be taken to avoid damage or failure of the parts (actuator rotor end, shaft end, connection parts) that could occur if excitation is still active while safety actuator is triggered. Considering this, a triggering box has been designed by ONERA to slightly delay the safety TTL command, for the “pressure” configuration only (oppositely to the “flutter” conf. for which no delay is applied).

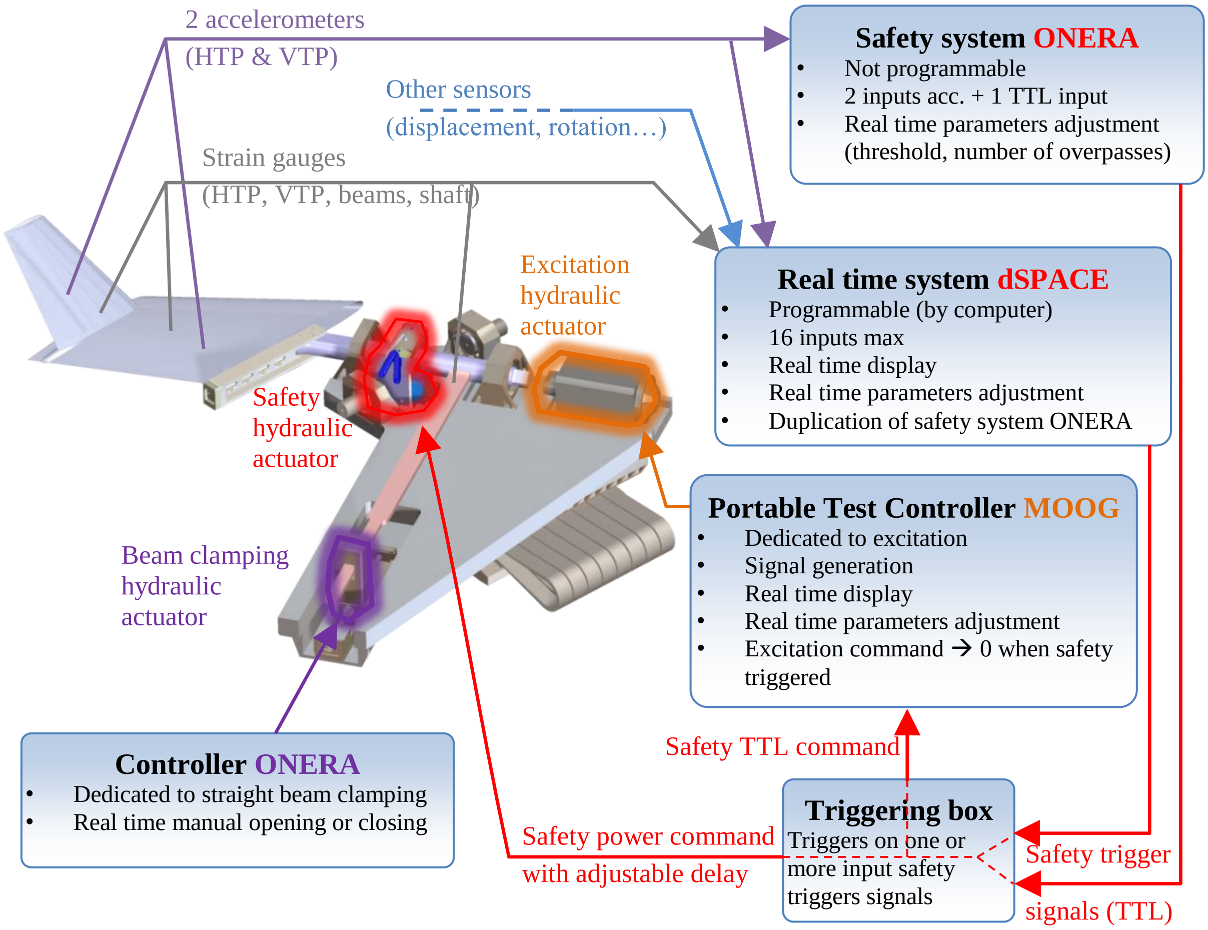


Figure 15: Electro-hydraulic real-time system

4 LABORATORY TESTS

Laboratory tests are a necessary phase before the WTT to check the structural static and/or dynamic behaviour of all parts, from single components to the final assembly, during static and dynamic tests, and the operational capability of all systems.

Several static tests are performed in ONERA Châtillon laboratory for various purposes:

- to check the structural linear behaviour of single components, as well as the low variability of the results among identical parts, such as the S-beams, illustrated in figure 16 for example,
- to check the structural linear behaviour of sub-assemblies, such as the support for S-beams and the stiffeners / interface ring junction, and full assembly (the complete model),
- to correlate the experimental results to the numerical results from FEA based on the FEM used for the structural substantiation, again depicted in figure 16.

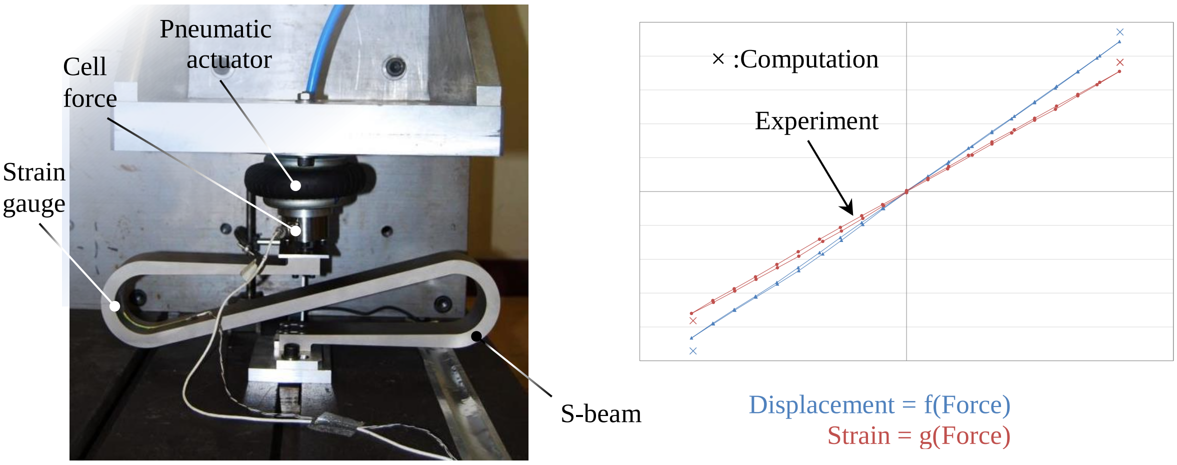


Figure 16: Laboratory static test of one S-beam (compression on left picture)

Ground Vibrations Tests (GVT) aim at getting modal bases of the model in various mechanical and geometrical configurations, for various variations of parameters such as straight beam length, additional masses, safety triggering, and hydraulic pressure default. Combinations of some parameters variations are also evaluated. From time-signals measurement, FRF are calculated with cell-force signal as reference, using H_1 estimator. Then modal identification generate the modal bases, focusing especially on local synthesis to get correct modal masses, and are used for knowledge of the structural evolution relatively to the variations mentioned above and flutter prediction. GVT are performed in ONERA Châtillon laboratory and in S2MA preparation hall, the whole model being installed on the test section movable wall.

Some results for the nominal U-Tail configuration, with 0° dihedral angle, are exposed here below. As illustrated in figure 17, the model is excited by an electrodynamic shaker, suspended in ONERA Châtillon laboratory and fixed to a lift table in S2MA preparation hall, close to the horizontal plane leading edge, with frequency sweep sinusoidal signal. For each tested geometrical configuration, variations of modal frequencies are first evaluated from very low excitation level up to the highest reachable level. The impedance curves presented hereafter show very low non-linearity of the two first modes relatively to the excitation level.

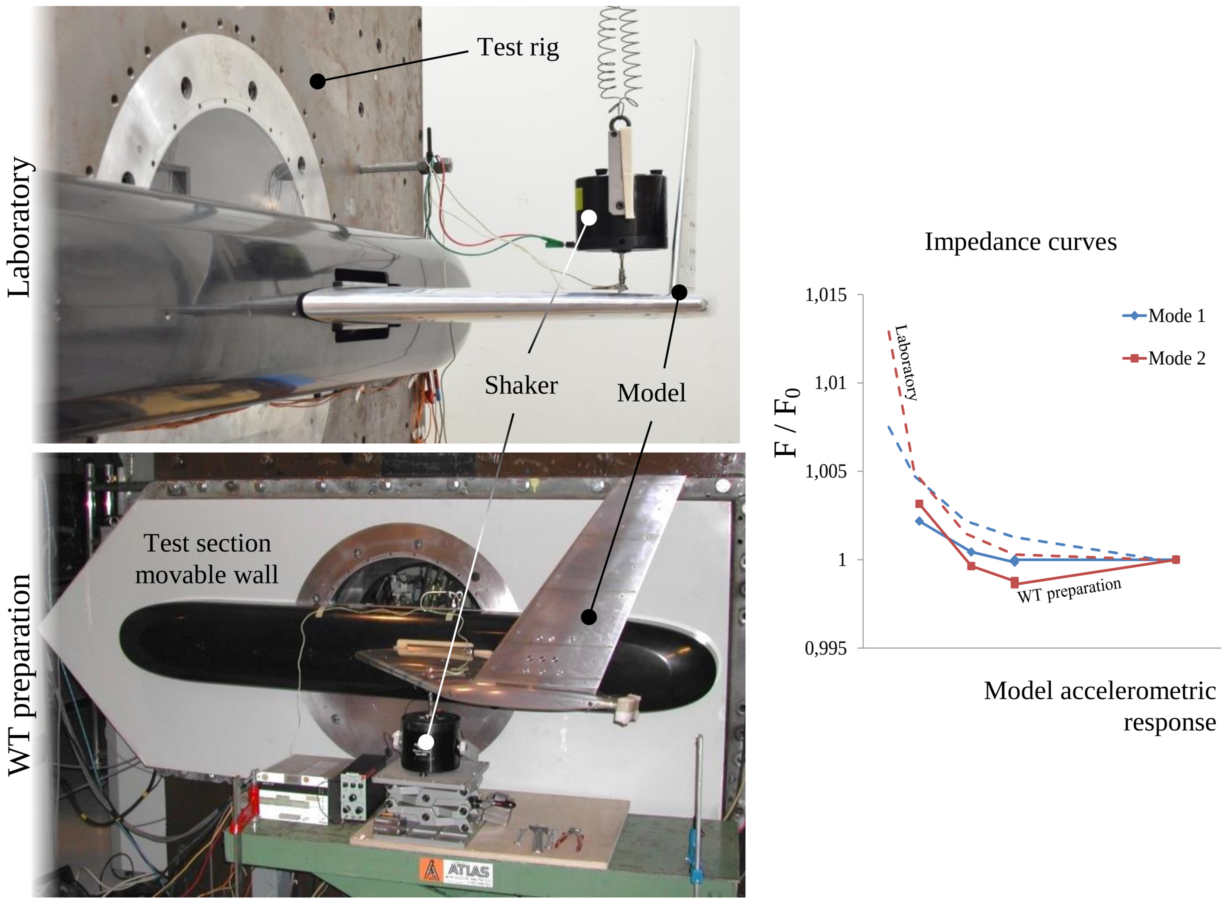


Figure 17: GVT of U-Tail, 0° dihedral – Test description and impedance curves

Parameters variations are then performed, and for each of them, flutter calculations using DLM are executed based on the experimental modal bases. As an example, the critical pressure evolution relatively to straight beam length is depicted in figure 18, for both test locations. This clearly highlights the influence of boundary conditions on modal parameters and predicted flutter critical pressure, and demonstrates the need to always perform GVT in conditions as close as possible to those found in WT test section. It can also be noticed that the predicted aeroelastic coupling is not straightforward, relatively to parameter variations, such as straight beam length for example.

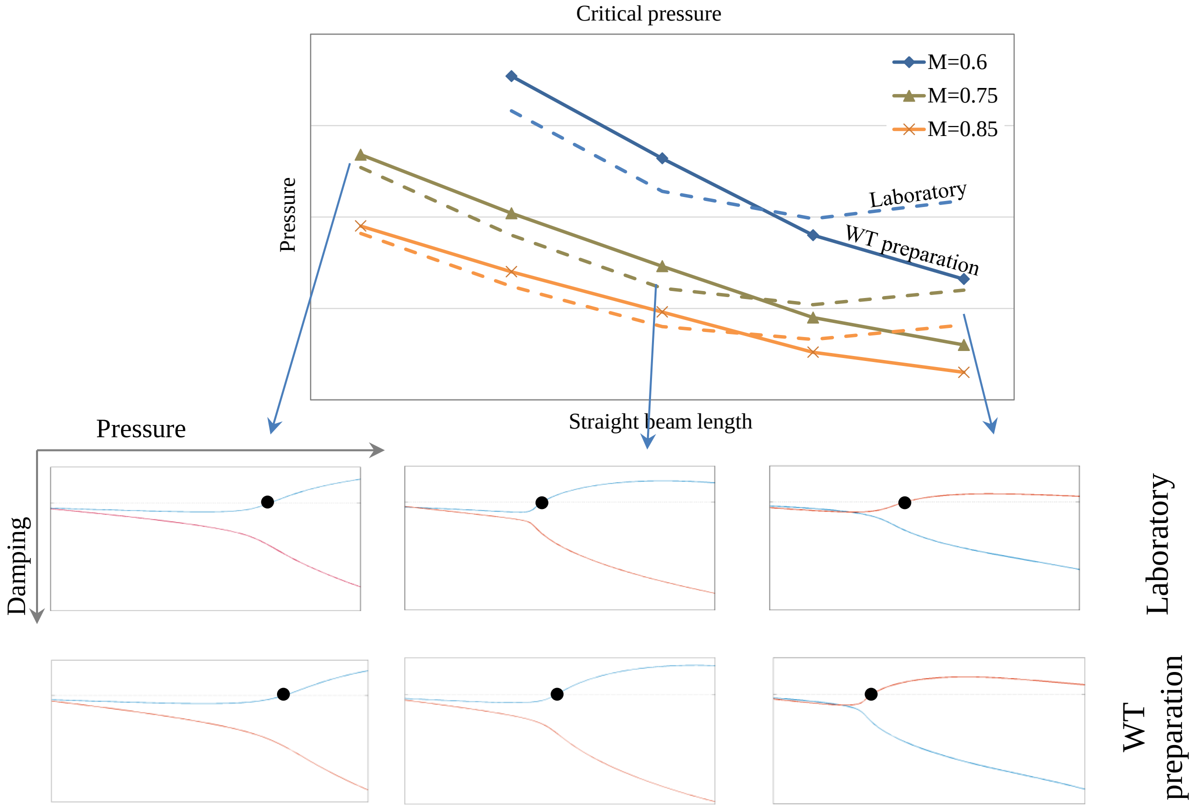


Figure 18: GVT of U-Tail, 0° dihedral – Influence of straight beam length on predicted critical pressure and damping evolution

5 WIND TUNNEL TESTS

The model finally installed in the test section of ONERA S2MA pressurised wind tunnel is shown in figure 19, in the nominal geometrical configuration, i.e. with 0° dihedral angle.

Figure 19: U-Tail flutter model in ONERA S2MA

Up to 354 channels are recorded simultaneously, in the most instrumented configuration. Specific software are developed in WPF / VB.net / Python to manage the measurements database, to synchronize the acquisitions of the two measurement systems used, one dedicated to unsteady and the other to slow sampling steady acquisitions, to export the raw data in a usable format and finally process these data in order to deliver in a slightly delayed time all timedata in a corrected and readable format to the partners, as well as preliminary results, such as pressure distributions (images and text files), spectra…

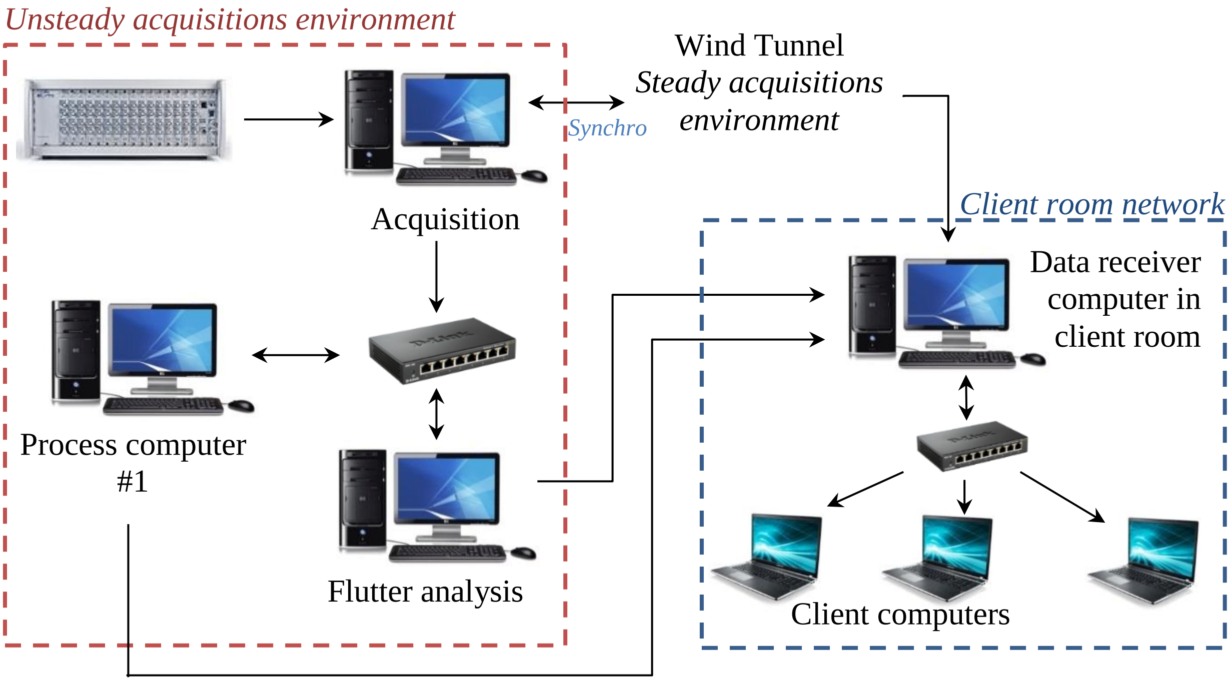


Figure 20 - Networking

The flutter configuration aims at getting the flutter onsets critical pressure, and at recording test points to build the flutter curves.

Figure 21 illustrates the former point, the critical pressure being dependent on several parameters such as the Mach number, the straight beam length, and the dihedral angle. Moreover, the flutter onset repeatability is exposed by adding a scatter plot, and differs over all parameters variations. The straight beam length is adjusted, depending on the explored Mach number range, in order to get flutters onset at a reasonable wind tunnel stagnation pressure. Practically, during the WTT, the flutter onsets are reached by increasing the wind tunnel stagnation pressure while keeping the Mach number constant.

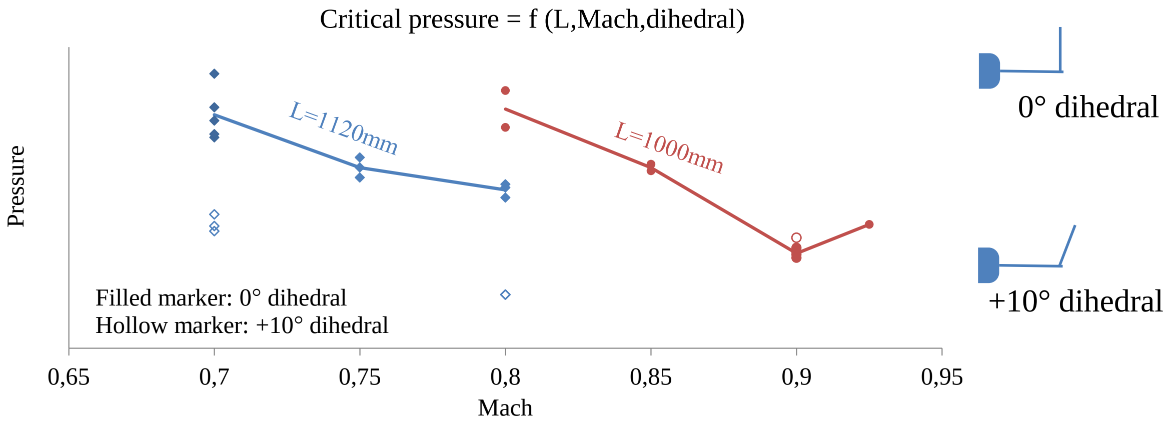


Figure 21: Critical pressure function of various parameters

To build the flutter curves, an analysis is performed at each pressure stabilized point and consists mainly, and similarly to the laboratory tests, in calculating the FRF of accelerometric responses relatively to the excitation actuator rotary variable differential transformer (RVDT) signal, identifying finally the modal parameters using LMS Polymax [3]. In this configuration, the excitation is generated by an inertial system, based on a hydraulic actuator and an off-balanced arm, as shown in figure 22. An example of experimental flutter curve is given in figure 23, for a Mach number of 0.8 and a straight beam length of 1000mm, and shows the first mode undamping.

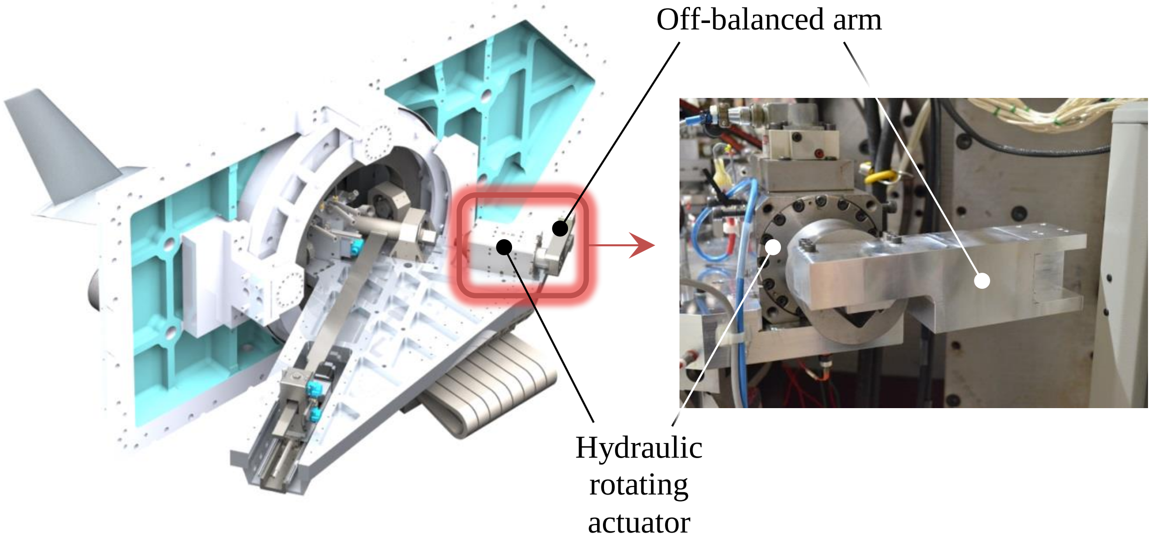


Figure 22: Flutter configuration – Excitation system

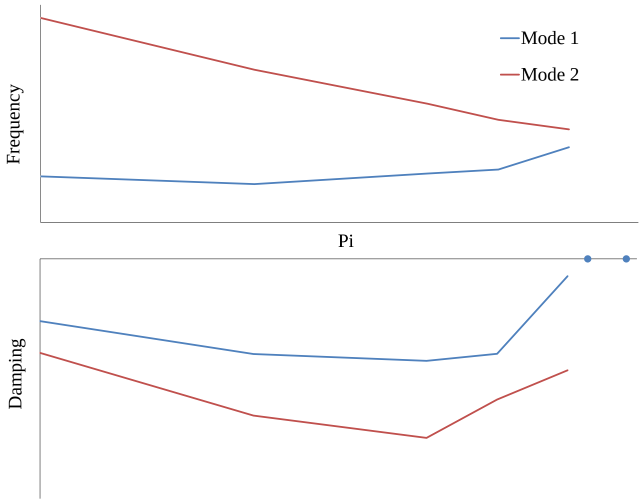


Figure 23: Experimental flutter curve @M=0.8, L=1000mm

More than eighty flutter onsets are safely observed during the whole campaign, thanks to the safety system described previously. Moreover, the safety thresholds set lead to reach a maximum strain of approximately 800 µε (⇔ 157 MPa) in the straight beam at all flutter onsets, as plotted in figure 24, which represents approximately 30% of the maximum allowable threshold (2667 µε ⇔ 524MPa), this beam being made of 17-4PH H900 high strength steel. Consequently, safety is ensured with comfortable margins. From fatigue point of view, considering conservatively and roughly 10s of critical cycling per flutter onset (average on the whole campaign), with a stress ratio equal to -1 corresponding to a purely alternate cycling, more than 12000 cycles are observed. From MIL-HDBK-5J material data [6], experimental fatigue results on this steel indicate that crack initiation may start at approximately 160 Ksi (⇔ ~1103 MPa) for 20000 cycles, which is much higher than the maximum stress observed in the straight beam. The model and the test set-up can consequently withstand many more flutter onsets, in case of future WTT.

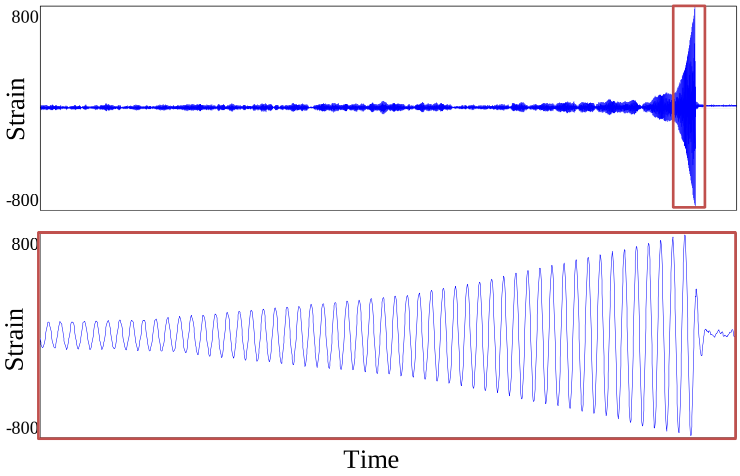


Figure 24: Example of flutter onset observed by the full bridge strain gauges installed on the straight beam

6 CONCLUSION

The design and testing of a U-Tail model is achieved successfully, thanks to a close cooperation between RUAG, Dassault-Aviation and ONERA.

A new architecture of the test set-up is found, associated with a U-Tail model, allowing flutter onsets to be observed in the S2MA wind tunnel domain for all parameters variations, such as Mach number, geometrical configuration, and thanks to a dynamic behaviour tuning system which remains essential for flutter tests in transonic regime where prediction uncertainties are still significant.

No damage is noticed on any part of the model and the test set-up, which demonstrates the efficiency and the adequate settings of the safety system, as well as an associated relevant design. All parts can be re-used for eventual new WTT campaign.

Moreover, more than 700 test points are recorded by the unsteady acquisition system during the whole campaign, with geometrical and mechanical variations, generating an important and rich database for further detailed data analysis of aeroelastic phenomena relative to innovative aft body configurations, and useful for calibration of aeroelastic numerical tools.

7 ACKNOWLEDGMENTS

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