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A Review of Industrial Aeroelasticity Practices at Dassault Aviation for Military Aircraft and Business Jets

Aircraft structure design is a complex industrial process that requires multidisciplinary analyzes and considerations in fields as diverse as aerodynamics, structure, materials and systems, as well as the right compromise between the constraints imposed by these different fields, in order to meet the overall performances required for aircraft.
In the field of business jets and military aircraft, given the research into ever more efficient aerodynamic formulas, the constant desire to design "as light as possible", and the increase in fuselage sizes, aircraft flexibility has increased considerably over the last few decades. This has required the consideration of increasingly complex aeroelastic coupling phenomena that are present in the flight envelope from the very first phases in aircraft development. The challenge goes far beyond the domain of aerostructural performance alone, since aeroelasticity can also have a significant impact on related domains, such as aircraft performances, handling qualities, or system design. It has merely reinforced the potentially major impacts of aeroelasticity on the risks, costs and deadlines for new aircraft programs: aeroelasticity is now seen as one of the main disciplines in design, and as one of the "critical" processes in the aircraft development logic.
This highly-challenging context has been the source of major and constant modifications in the field of aeroelasticity since the 1990s at Dassault Aviation. Today, this trend continues, and aeroelasticity will have to tackle a series of entirely new challenges and needs, and continue to reinvent itself at the same pace if it is to avoid hampering innovation and future technological breakthroughs.
In this perspective, this article gives an overview of the current best industrial practices in terms of aeroelasticity in the military aircraft and business jet domains at Dassault Aviation. The main aspects of this challenging and exciting field are covered: the numerical methods and tools, the experimental validation process, the aircraft program expectations and aspects relating to human organization. It discusses the principles and guidelines rather than details about the basic equations and methods. The last part presents the future industrial challenges in the field of aeroelasticity for Dassault Aviation.

Introduction

The design of aircraft structures is a complex industrial process that requires multi-disciplinary analyses and considerations in fields as diverse as aerodynamics, structure, materials or systems, as well as the need to find the right compromise between the constraints imposed by these different fields, in order to meet the overall performances required for aircraft.

In the field of business jets, given the research into ever more efficient aerodynamic formulas, the constant desire to design "as light as possible" and the increase in fuselage sizes, the flexibility of aircraft has grown considerably over the last few decades. This has required the consideration of increasingly complex aeroelastic coupling phenomena that are present in the aircraft flight envelope from the very first phases of development. The challenge goes far beyond the domain of aerostructural performance alone, since aeroelasticity can also have a significant impact on related domains, such as aircraft performances, handling qualities or system design.

In the military domain, the promotion of existing platforms in terms of the ability to carry multiple under-wing external store configurations, and the adaptation of these configurations to the needs and multi-role missions of customers, is also reflected by an increase in the aeroelastic phenomena present on the aircraft. The challenge is therefore to develop and certify new configurations by keeping major design modifications to a minimum (or, better yet, avoiding them), while preserving all of the performances of the existing aircraft. Aeroelasticity can motivate modifications to structures, upgrades to fly-by-wire (FBW) standards, or modifications to the architecture of aircraft systems.

Although in the early 1990s we may have thought that the domain of aeroelasticity for aircraft was one that we mastered well, and that really only required the tools and methods already envisaged in the 1960s to 1980s to be brought to maturity and industrialized in the future, the new challenges progressively imposed at Dassault Aviation at the end of the 2000s and at the start of the 21st century (design of the RAFALE air/ground standards, the FALCON 7X/8X/5X aircraft and the military nEUROn UAV) have placed aeroelasticity at the very heart of the aircraft design process, with major potential impact on the duration and costs of the various development phases and, more generally, the cost of the programs (and the associated risks). In preparing for the future, aeroelasticity has also become an indispensable factor for innovation.

This situation has been the source of major modifications to the field of aeroelasticity, in terms of the methods used, the calculation processes and the organization of human skills over the last 20 years, and, more specifically, over the last decade. Today, this trend continues, and aeroelasticity will have to tackle a series of entirely new challenges and needs, and continue to reinvent itself at the same pace, if it is to avoid hampering innovation and the setup of future technological breakthroughs.

In this context, this article gives a complete overview of the current best industrial practices in terms of aeroelasticity in the military aircraft and business jet domains at Dassault Aviation. The main aspects of this challenging and exciting field are covered: the numerical methods and tools, the experimental validation process, the program expectations and aspects relating to human organization. It discusses the principles and guidelines, rather than details about the basic equations and methods (more information about aeroelastic methods can be found in the list of references and extensive research literature). The final paragraph presents the future challenges in the field of aeroelasticity for Dassault Aviation.

The Growing Importance of Aeroelasticity Issues in Aircraft Projects

Since the end of the 1960s, aeroelasticity equations had already been well established, and the associated phenomena had already been experimentally studied in many publications. Due to a lack of computing power, engineers merely had to content themselves with simplified, and sometimes very conservative, methods to analyze this phenomenon.

Between the end of the 1960s (MIRAGE F1) and the end of the 1980s (FALCON 900, MIRAGE 2000, MIRAGE 4000 and the first RAFALE demonstrator; also CONCORDE at Sud-Aviation), the rapid growth of numerical aeroelasticity and the analysis of complex configurations, which had been difficult to obtain through analysis up until that point, were facilitated by a large number of projects at Dassault Aviation, the acquisition of the first scientific computers and, in parallel, the development of structural finite-element dynamic analyses [1]. Above all, the development of steady and unsteady linear aerodynamic numerical methods with interactions between lifting surfaces, such as the Doublet-Lattice Method (DLM) [2], [3], [4] contributed to this. A typical example is that of the delta/canard formula without stabilizer on the RAFALE.

Also over that same period, the development of in-flight instruments, telemetry and signal-processing techniques made it possible to observe and quantify the aeroelastic phenomena, and validate the associated models (or readjust them) using wind tunnel tests on flexible mock-ups or flight tests [5]. However, we should remember the accident that occurred on the first MIRAGE F1 prototype following horizontal stabilizer flutter at $M = 0.91$, at a low altitude. This accident occurred on May 16, 1967 during a training flight for a demonstration at the Paris Le Bourget airshow. It was a dark day in the history of Dassault Aviation, leaving René Bigand, the test pilot of the aircraft, no chance at all.

During this blossoming period for aeroelasticity, full of draft projects and tests on real structures (sometimes difficult), the growth and maturity of the various numerical and experimental techniques has been substantial at Dassault Aviation, and many of these techniques continue to be a point of reference, even to this day. This, to such an extent that we thought at the start of the 1990s that the field of aeroelasticity for aircraft was one that was mastered, and in the future would only require that the tools and methods already envisaged in the 1960s to 1980s reach maturity and be industrialized.

The experience of the following period between 1990 and 2020 (RAFALE, FALCON 2000/7X/8X/5X and nEUROn) and the conclusions that are drawn from it today show that, quite on the contrary, under the influence of the market and the competition, aeroelastic engineers continue to face constantly-evolving challenges today, due to the constant quest for innovative technological breakthroughs (unconventional architectures, complex configurations, introduction of composite materials, etc.), to increasingly efficient aerodynamic formulas, and to a constant desire to design "as light as possible" at reduced costs and with shorter deadlines, as well as to the increased flexibility of the aircraft and flight envelopes used and the increased importance of systems and their interaction with the aerostructure.

Aeroservoelasticity ("which adds servo in equal proportions to the other three fundamental disciplines in conventional aeroelasticity: elasticity, aerodynamics and dynamics" [82] is clearly a perfect illustration of these new challenges and of the way in which they have changed our way of looking at our practices in the field of aeroelasticity. This is a field that has been constantly evolving for more than 20 years and has witnessed exponential growth with the arrival of the first aircraft with fully digital Fly-By-Wire (FBW) controls: the RAFALE and the FALCON 7X. Today, this branch of aeroelasticity continues to develop at a fast pace, given the new system architectures and the increased power of the controllers, new sensor and actuator technologies and innovative control surface architectures. It is also based on the fact that the aircraft, its handling qualities and aerostructural performances, are increasingly dependent on these systems.

Initial work in the field of aeroservoelasticity mainly consisted in filtering, as much as possible, the aircraft's flexible mode shapes in flight, which are "seen" by the digital FBW sensors attached to the structure, in order to decouple the rigid aircraft displacements of these flexible mode shapes, thereby avoiding aeroservoelastic instability phenomena. We are now seeking to build upon this discipline to control "flexible" aircraft and improve the aircraft's aerostructural performances. In particular, we will look in more detail later on at the potential of active control technologies on loads and flutter using the digital FBW system, which are completely changing the way we look at the design process for modern business jets and military aircraft. Simply note at this stage, that the development of aeroservoelasticity as a new branch of aeroelasticity has been accompanied over the last 10 years by a lot of new work in the following areas:

- the production of "reduced" aeroelastic models suited to the design of control laws,
- the coupling of flight mechanics with structural dynamics,
- experimental techniques (wind-tunnel and in-flight tests) and the identification of systems and aeroelastic models using real test data,
- the active control of loads and flutter,
- the integration of the interaction between systems and aerostructures in certification procedures (nominal configurations and failure cases).

The example of aeroservoelasticity is just one example, amongst others, and clearly an important one, of the new challenges in modern aeroelasticity and the abundance of scientific and industrial research in this field. We could have also mentioned the evolution in steady and unsteady CFD (Computational Fluid Dynamics) codes to predict loads and flutter, non-linear aeroelasticity, aeroelastic optimization, aeroelasticity of highly-deformable structures, aerothermoelasticity, and so on. We will return to some of these new aeroelasticity branches later on to describe their scope of application at Dassault Aviation.

However, the wealth of the field of aeroelasticity cannot only be expressed from the point of view of the discipline; it must also be examined with respect to the development process of modern aircraft and the challenges associated with the aircraft project: the "program" challenges.

In the design process for modern aircraft, mastering aeroelasticity has now become a key point and a design driver. It concerns all stages of the aircraft development phases, from the design and definition phases (Phase "A", the "feasibility phase" to obtain the general configuration; Phase "B", the "preliminary design phase" to obtain the overall aircraft definition; through to Phase "C" for the detailed definition of parts), to the justification phases that are essentially centered on demonstrating the means of compliance in relation to the applicable regulations (Phases "D" and "E", including flight tests).

The experience of the most recent projects at Dassault Aviation (FALCON 7X/8X/5X, nEUROn) clearly shows that, by going as far back as possible in the development of risk reduction linked to aeroelastic requirements, this helps to avoid major (and costly!) redesigning in the more advanced phases of aircraft design that are required to ensure the project viability.

A significant limitation to this logic is, of course, the availability and stability of the "input" data available at time "t" in the project to perform the various aeroelastic loops: typically, the status of the overall definition of the external shapes (including control surfaces), the internal architecture of the structure (*i.e.*, "ribs and panels"), the structural and non-structural masses, the system definitions, etc. The more this data is variable and uncertain, the more aeroelastic loops there are that require a lot of interpretation and engineering judgment in order to roll them out and transpose them to the entire design space, which remains still very large. This is typically the case during the feasibility phases, in which several designs and trade-offs have been assessed and in which some definition data is not fully known, or is clearly variable. Therefore, the compromise that must be found in this case, relates to the speed of obtaining the aeroelastic analysis (and the robustness of the analysis) with respect to the importance of this analysis in relation to the design process and the risks incurred by the lack of knowledge about aeroelastic phenomena in this field.

At this point in the paper, we are looking at one of the major future challenges with respect to the construction of the aircraft project: that of adapting the aeroelasticity tools and practices at the rate and short duration of the multidisciplinary design loops in the feasibility phases. Several studies are currently in progress in this field at Dassault Aviation (projects "OSANGE", "OSAVP", etc. See [6]). The challenge that clearly emerges is that of adapting the "traditional" aeroelasticity tools and practices (*i.e.*, those that were calibrated to provide the precise quantitative data needed for the safety of the flight envelope opening and to draw up certification and substantiation documents) to the logic of the feasibility phase, in which we want to prioritize the speed of analysis, and the "agility" of the tools and practices to rapidly issue qualitative derivatives and trends in "order of magnitude".

Figure 1, simplified for the sake of comprehension, summarizes all of the main aeroelastic analyses performed in the various development phases of any new civilian or military aircraft at Dassault Aviation.

The expected outcomes of the main aeroelastic loops are thus summarized as follows:

- **In Phase A – "Feasibility phase"**, as soon as an initial external shape of the aircraft and an internal structural architecture are set ("ribs and panels"):
  - Calculation of the flexible aircraft aerodynamic center and the deformed shape of the wings at different flight points during fast-cruise or long-range flight ➔ this can have a direct impact on the longitudinal position of the wings, and the jig shape of the wings.
  - Calculation of the global flexible coefficients of the aircraft and its control surfaces (aerodistortion and effectiveness) ➔ this enables the construction of the first reference aerodynamic databases (longitudinally and laterally) and an initial assessment of the aircraft handling qualities ➔ it can have a direct

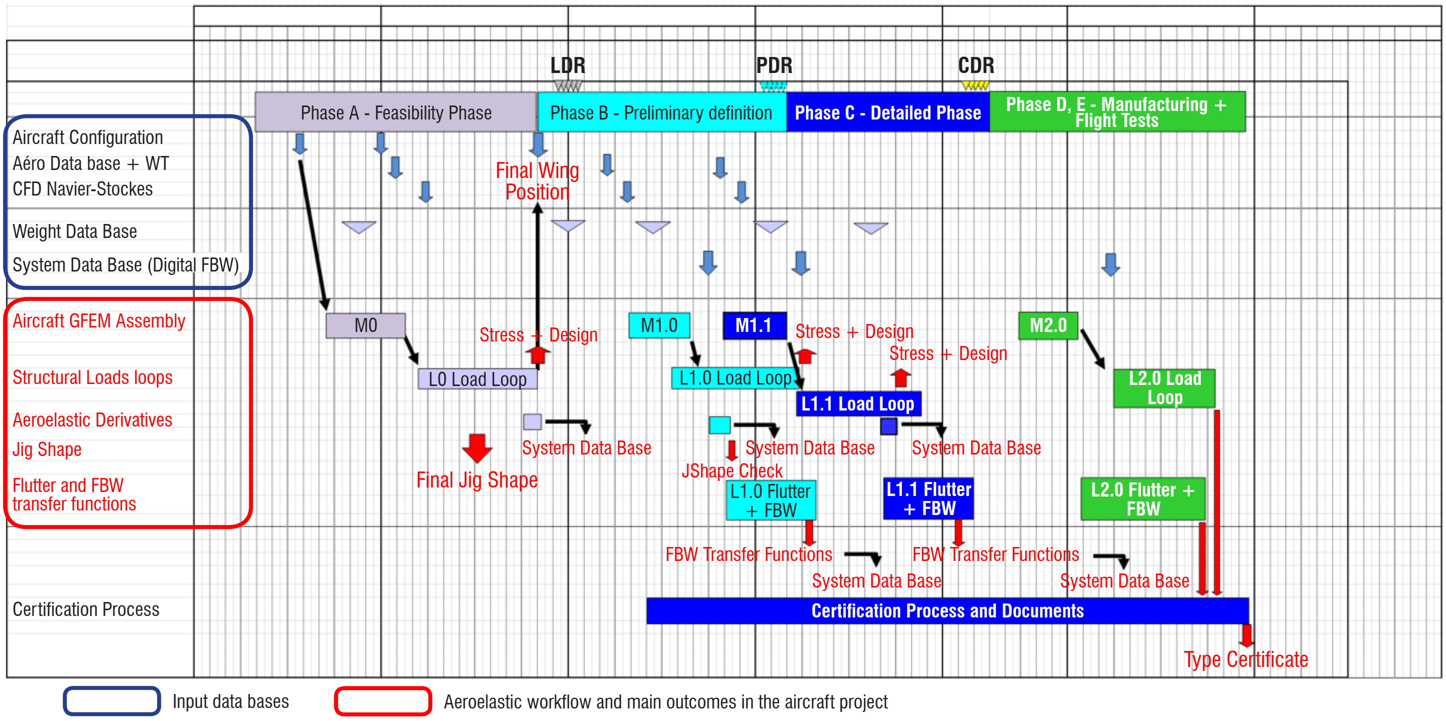


Figure 1 – Typical overall development logic for a new aircraft and the related aeroelastic analyses

impact on any redefinition of the external shapes of the aircraft (wing surface, vertical and horizontal stabilizer) and a direct impact on the surfaces or architecture of the control surfaces.

- Calculation of the loop "L0" pre-design loads ➔ this contributes to an initial assessment of the structural mass of the aircraft in the feasibility phase, after the wing, vertical and horizontal stabilizer panels have been sized at these loads. These loads will also be used at the very start of Phase "B", as initial preliminary loads in the structural design.

- **In Phase B – "Preliminary design phase":**
  - Calculation of the "L1.0" structural design loads. These loads are used to provide an initial consolidated estimate of the sizing of all of the primary structural parts (*i.e.*, panels, stiffeners, spars, frames, etc.).
  - Calculation of the flutter speeds. This estimate is done using the structure sampled in the previous step. It is used to define the delta mass to be added to the L1.0 load sized structure to meet the aeroelastic stability objectives.
  - Calculation of the flexible response of the aircraft excited by control surface deflection at the digital FBW sensors ➔ this is used to define the best position for the digital FBW sensors in the aircraft: as near as possible to the vibration modal nodes likely to be excited by the control surfaces.
  - Final assessment of the position of the flexible aerodynamic center and the overall flexible coefficients of the aircraft and its control surfaces ➔ at this stage in the project, since the overall architecture is frozen, this data will be used to draw up the aerodynamic databases and the aircraft handling qualities, but can no longer result in architectural modifications (with no major impact on the costs and deadlines of the overall aircraft project)

- **In Phase C – "Detailed definition phase"** (aim of the end of Phase C = freezing of the definition of all structural parts in the aircraft and delivery of this definition to manufacturing for industrialization):
  - Calculation of the final "L1.1" structural design loads. These loads enable a final convergence of the sizing of all of the parts in the primary structure.
  - Verification of the flutter speeds.
  - Calculation of the flexible response of the aircraft excited by control surface deflections by the digital FBW sensors ➔ this is used to define the notch-filters that will be programmed in the digital FBW controls loops.

- **In Phases D and E – "Aircraft manufacturing, flight tests and certification phase":**
  - Calculation of the "L2.0" certification loads. These loads are the loads retained for structural strength certification. They are validated on the basis of flight tests performed on the first production aircraft specifically instrumented for the purposes of this validation.
  - Flutter and vibration synthesis. This synthesis is based on both the theoretical flutter predictions and the ground and flight vibration tests performed on the first production aircraft specifically instrumented for the purposes of certification.

All of these analyses in the perspective of the program organization call for the following comments:

- Even though flutter stability is of the utmost importance in aircraft design and certification, it is the analysis of the aerostructural loads that will be used as a baseline to size the structure. We will then try to minimize the additional structural mass to be added to this baseline, in order to satisfy the flutter requirements (given that these additions in mass for flutter are typically likely to increase the aircraft loads due to the stiffness increment that they induce through lower aeroelasticity or the dynamic effects that they can have on gust or ground loads).

The load calculation process is, therefore, certainly one of the most challenging processes in the development of an aircraft and, as such, is the attention focus of all programs.

- Each of the loads and flutter loops significantly contribute to the program expected outcomes. Indeed, these loops, which can represent several months of analysis, are needed to provide the loads that will enable the sizing of each structural part. They are, therefore, on the critical path of the program schedule for the design, manufacturing and certification of the structure. An incorrect estimate of the loads can have serious consequences on the drawing of the parts, and can result in considerable additional delays and costs. Even though load verification steps are possible during development, the ultimate load check through flight testing of the overall structure takes place at a very late stage in the program, and can be a source of major re-design risks. Therefore, one can easily see the crucial importance of predictive calculation methods for aeroelastic loads, which:
  - increase the accuracy of the assessment of structural sizing loads, directly related to the design mass,
  - are progressively enriched with partial tests during the program (wind-tunnel tests, systems tests, partial-stiffness tests, etc.) to minimize the risk of having to rework these loads at a very late stage in aircraft development.

- In the past, structural design methods were deemed conservative. Nowadays, the many improvements made to structural predictive tools, such as the finite-element method, and the improvements in drawing up structural strength criteria, have helped to reduce the margins that were traditionally adopted in design practices. Inaccuracies in the load calculation process are, therefore, more difficult to compensate for by the structural margin policy, whereas the constant innovation in the aerodynamic shapes of "modern" aircraft (for improved performance) has increased these sources of inaccuracies.

- Each of the loads and flutter loops previously mentioned are performed in conjunction with the other aircraft design disciplines, which in turn interact with the aeroelasticity and load results: typically, the drawing and the layout of the structure, the structural sizing, the aerodynamic databases and handling qualities, and the digital FBW system. These loops are therefore embedded in a more overall multidisciplinary/multi-trade process, which is complex to plan for, both from a human resources point of view, as well as from that of the calculations and associated tests. This entire process is one of the "critical" processes in aircraft design. It is a core part of the aircraft manufacturer's know-how.

The Industrial Numerical Approach to Aeroelasticity

General Principles

The development of aeroelasticity tools and methods at Dassault Aviation has been done in successive stages. It is materialized in the form of the *ELFINI*© proprietary platform developed for aircraft design needs ([7], [8], and [9]), which combines the main aerostructural analysis branches around a core of finite-elements solvers (see Figure 2 hereafter):

- calculations of static linear and non-linear stresses,
- thermomechanics,
- calculation and management of design loads (ground and flight),
- calculation of vibration modes,
- static and dynamic aeroelasticity,
- calculation of transitory dynamic and forced responses.

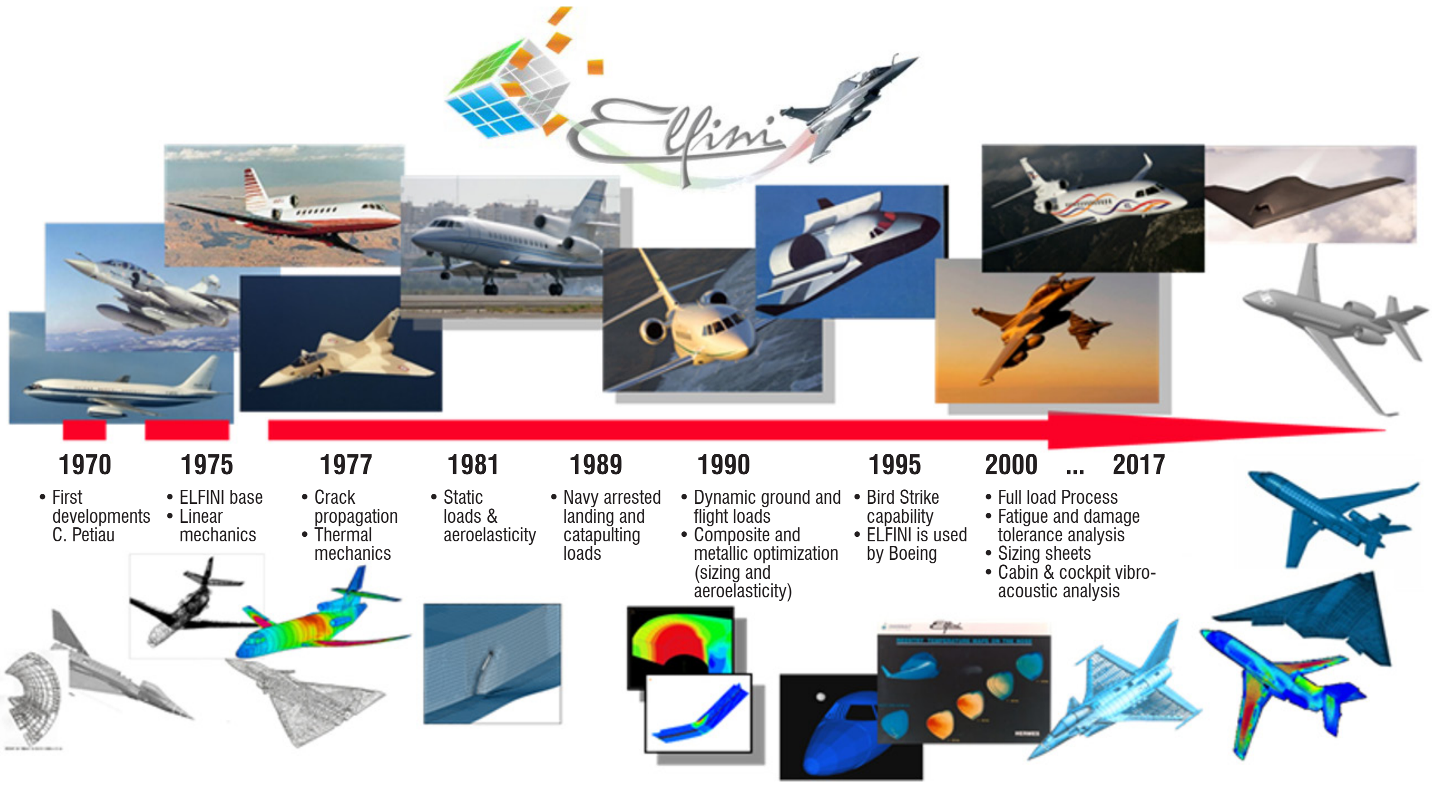


Figure 2 – *ELFINI*©: over 45 years of experience in aircraft structure design

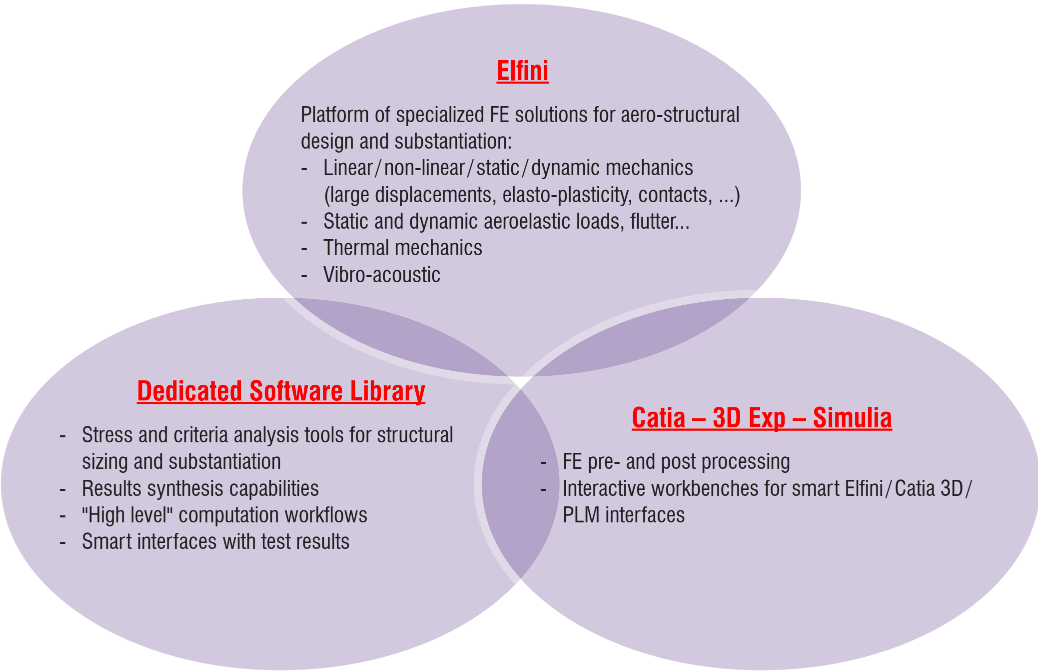


Figure 3 – *CATIA*© / *ELFINI*© cooperative platforms

As is often the case in the aeronautical industry, the main evolutions in the field of numerical aeroelasticity, and more generally in the field of structural calculations, have been mainly brought about by new aircraft programs. By imposing new challenges in terms of new technologies, the scope of use of the aircraft, industrial cooperation strategies, the organization of human and IT (Information Technologies) resources, and so on, these new programs have been formidable drivers that have quite literally propelled the advances in methods and IT architectures (see Figure 2).

A key point and an undeniable strength for all Dassault Aviation aeroelastic tools are the close links between the *ELFINI*© platform with the geometric modeler *CATIA*©, its finite-element pre/post-processor and its PLM (see Figure 3). We will see, in particular, how the parameterization of the aircraft geometry and its "inheritance" in the *ELFINI*© "computation workflow" have helped to revolutionize the practices of aeroelastic engineers in terms of calculation management, as well as in the field of aerostructural optimization.

Similarly, the traceability of models, input conditions and calculation results that are essential to the certification process, but no less vital in the design stages of the aircraft development cycle, has been greatly strengthened and made much easier in terms of its management thanks to the integration in the *CATIA*© PLM of the structural finite element, aerodynamic and aeroelastic models as well as the aircraft geometric definition models.

Over the years, the desire to mostly keep linear solvers was one of the main priorities that drove the development of tools and methods in the field of aeroelasticity at Dassault Aviation. When aeroelastic phenomena of a non-linear nature (with the non-linearity being either of aerodynamical or mechanical origin) needed to be modelled, piecewise-linear methods were preferred. This "linear" culture for aeroelastic analysis (almost a philosophy at Dassault Aviation) has indeed proved its effectiveness in the industrial domain, both in design and in certification, in terms of:

- the management of calculations and the effectiveness of the numerical processes,
- the architecture of tools and their coding,
- the understanding of calculation results, their validation by engineering judgment and their interpretation with respect to the phenomena encountered on the aircraft,
- the validation of models and their readjustment through experience,
- the communication and discussions with other aircraft design disciplines (aerodynamics, handling qualities, etc.), in which the "condensing" of the aeroelasticity field in the form of linear operators proved highly effective and industrially relevant.

Figure 4 below gives the general aeroelastic analysis process (and the associated mathematical models), as used these days by Dassault Aviation aeroelastic engineers in the *ELFINI*© environment.

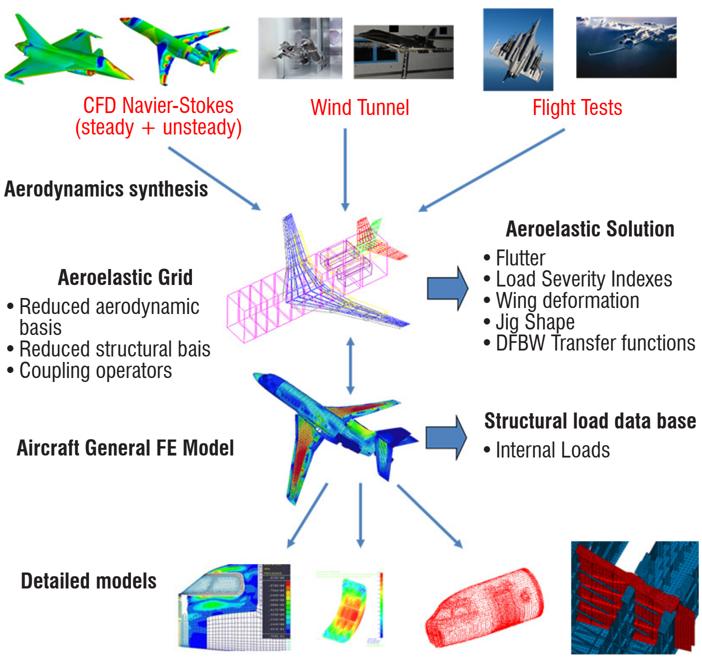


Figure 4 – Loads and aeroelasticity numerical process

The main characteristics of this process are detailed in the following chapters. However, at this stage, we can highlight the specific features that constitute its originality and its effectiveness from an industrial point of view:

- **The use of a single aerodynamic database, supported by the *ELFINI* © "aeroelastic grid" entity**, which synthetizes all of the aerodynamic information that will contribute to the aerostructural load calculations for the aircraft in flight. This information is available in the form of pressure fields on 2D grids (lifting surfaces typically) or in the form of aerodynamic field tensors "by zone" (called "boxes" in ELFINI© terminology: fuselage, high-lift devices, winglets, excrescences, etc.). At the start of the project, the aerodynamic database is mostly composed of theoretical information from the CFD calculations, readjusted by wind-tunnel tests. At the end of the project, these fields are enriched with flight-test results. It should be noted that the aerodynamic database contains both the quasi-steady part and the unsteady part of the aerodynamic field (recorded separately), which facilitates the adjustment of these two quantities independently from one another. The density of the 2D grid elements and the "boxes" is determined independently from the CFD mesh density. It is by physical consideration adjusted to enable sufficient discretization of the loads with respect to the structural sizing goal. This has the advantage of not being linked to the numerical mesh density convergence criteria of the CFD solvers, and thus of reducing the CPU calculations and processing, done within the aerodynamic database for the load calculation.

- **The use of a single structural load database, formalized by the aircraft's Global Finite-Element Model (GFEM).** The GFEM is the database of all cases of loads that the aircraft structure is subjected to. It is this same model that is also used by stress engineers to extract the internal flows inside the aircraft, which correspond to the various load cases that will be used to size the structural parts. The use of a single model shared by stress engineers and aeroelastic engineers has made it possible to eliminate redundant models, significantly reduce calculation cycles and avoid the time spent (and the resulting errors) transferring information between structural models and aeroelastic models.

- **Effective model-reduction techniques:**
  - For the structural part [10]: the finite-element displacements are reduced to a "generic" load basis, which consists of a few hundred displacements statically solved on the complete aircraft GFEM (> 100000 dof) by the loads obtained from: pressure cases projected from the "aeroelastic grid" individual pressure elements, cases of inertia loads and cases of some chosen individual interface loads (typically at the landing gear fasteners and engine or external store interfaces).
  - For the aerodynamic part [10]: the available aerodynamic quantities (pressure coefficient fields or aerodynamic load tensors per area) are linearly condensed in the form of operators that give the linearized variation of those aerodynamic quantities for unitary analytical displacements of the "monomial polynomial" type, in which the normal displacement $N(M)$ of a point $M(X,Y,Z)$ from a given lifting surface is defined in the analytical form: $N(M)=X^{\alpha}Y^{\beta}Z^{\gamma}$ (where α, β, γ are the degrees of the exponents of the "monomial" considered). This monomial base of displacements is used to represent global rigid displacements of the aircraft (plunge, pitch, roll, etc.) or partial rigid deflection of the control surfaces using 0 or 1-degree monomials, as well as analytical flexible displacements of the structure using monomials with degrees greater than 1. Note that, when drawing up the aerodynamic database and "reducing" it to the monomial basis, the definition of monomial is completely separated from the flexible displacements of the complete aircraft GFEM. Several hundred monomials are typically used for a complete aircraft, distributed in a typical manner over the aircraft wings, fuselage and stabilizers.

- **An effective organization of the coupling between the structural domain and the aerodynamic domain,** in which the aim is to perform "complex" and "heavy" calculation operations on the aircraft GFEM and in the aerodynamic database, independently from one another (these operations can be done in parallel by two different teams) and, above all, independently from all of the flight configurations and mass distributions to be considered. Only after a reduction in the structural and aerodynamic databases of only a few hundred degrees of freedom each (see previous point), can the aeroelastic coupling be solved and analyzed.

Box 1 below illustrates the main key equations, general principles and organization of the aeroelastic analyses, as performed at Dassault Aviation with the *ELFINI* © platform. The technical details of the equations and associated numerical approaches, in particular the projection operators for the pressure fields from the aerodynamic database to the aircraft GFEM, or the projection of the structural displacements from the aircraft GFEM onto the aerodynamic CFD meshes, which are today problems that have been fully mastered, can be found in References [7], [10] and [11].

Multiplicity of the Aeroelastic Calculation Conditions

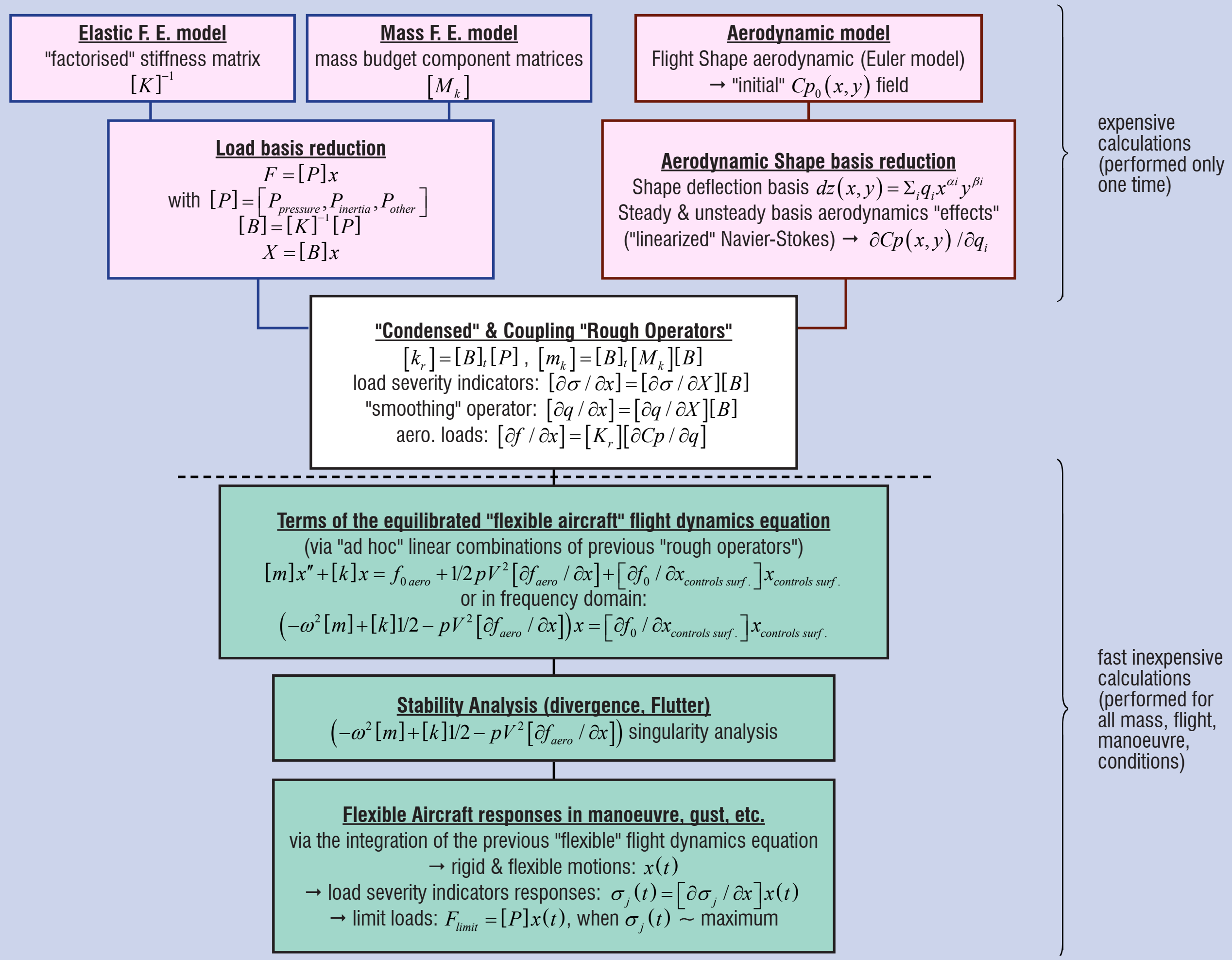
One characteristic of aeroelastic analyses in the context of aircraft design and certification is the multiplicity of configurations and calculation conditions to be taken into account. It needs to cover:

- all aircraft configurations (wings in clean configuration or with high-lift devices or landing gear extended, for example),
- the entire Mach and altitude flight envelope,
- all of the internal mass distributions possible (payload configurations, tank filling, etc.),
- all external store configurations or sub-configurations for military aircraft,
- all of the maneuvers possible and external solicitations (discrete gust, continuous turbulence, etc.),
- all of the possible cases of system failures (including failures in the digital FBW control system, anti-icing system, pressure system, etc.).

In all, several hundreds of thousands of aeroelastic calculation conditions (nearly a million!) are needed to cover the design and justification of a civilian aircraft of the type FALCON 8X or 5X.

The trend over the last few years continues to be an increase in the number of cases to be considered, given the (fully understandable) desire to not overlook a critical condition, and to avoid late redesigns, as well as to reduce margins as much as possible, so that unnecessary structural mass is not allocated.

Box 1 - Organization of aeroelastic analyses with "Load" and "Aerodynamic shape" basis reductions



One element that also contributes to this trend towards ever more calculation conditions is the effectiveness of the analysis process itself. It gives the aeroelastic engineer the impression that having a lot of calculation cases does not significantly affect the analysis process as a whole. When this drift stems from this impression, it absolutely needs to be tackled because it tends to completely hinder the aeroelasticity engineer's intuition. Since they are fully occupied with managing the pre- and post-processing stages of the analysis results and the sheer amount of data, aeroelasticity engineers can no longer intuitively discern the most critical calculation conditions (since they forget to use their physical intuition, for example), nor are they able to focus all of their attention on these conditions, which are nonetheless of the utmost importance for the structural design and mass.

Model Organization and Implementation

As already discussed, all of the architecture in the aeroelastic analysis process at Dassault Aviation has been built and arranged in such a way as to reduce analysis cycles as much as possible, on the critical path of structural design (and therefore of the manufacture of the first series-production aircraft). With this aim, the definition of structural, aerodynamic and aeroelastic models is essential to enable each domain to be expressed with known quantities that are necessary and sufficient, as well as to avoid model redundancy and reduce information transfers from one field to another.

The fineness and density of these models to the "just enough" amount are also important issues. Especially so when there is a very large amount of calculation cases to be considered for the aeroelasticity analysis.

Another basic principle was also to build a calculation process that is similar throughout the aircraft design and certification cycle, and to apply the changes in definition, throughout the aircraft development, to just the models and not the calculation process itself. The aim of this is to minimize calculation workflows and tool variants and, consequently, the risk of handling errors and construction errors in these workflows.

To tackle the large volume of aeroelastic analyses and calculations, we have in the past opted for simplicity, by using a finite-element "stick model" (also called "beam models") to represent elasticity and the distribution of aircraft masses, and to project the aeroelasticity equations. The elastic part of this model thus resulted from the beam theory. In this case, configuration scanning was inexpensive, and the analysis of results and empirical corrections was simple. For a long time, these advantages have concealed the weaknesses in terms of the quality of the stick model representativeness: we tried to compensate for this shortcoming through stick-model calibrations on test results, or on more sophisticated calculation results.

The "topological" inability to represent the delta wings of military aircraft using stick models have led to the direct use of the GFEM for the complete aircraft and to link it directly to the aerodynamic models available via what is called the "aeroelastic grid" in the *ELFINI*© organization (see the illustration in Figure 5). The challenge was, therefore, to find an organization to solve aeroelasticity that was almost as flexible as the one using stick models.

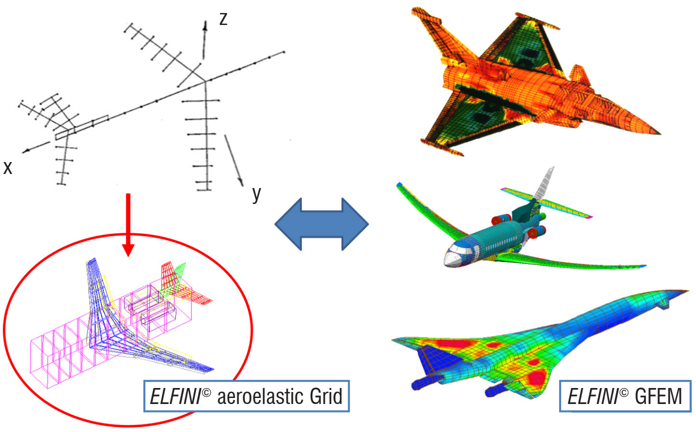


Figure 5 – From stick model to the use of an aeroelastic grid in the *ELFINI*© load and aeroelastic process

This organization is now based on 3 types of model:

- **The structural GFEM and the aerodynamic CFD model for the aircraft**, which are complex in nature and for which the definition could evolve in stages, according to the project definition status (see Figure 6 below).

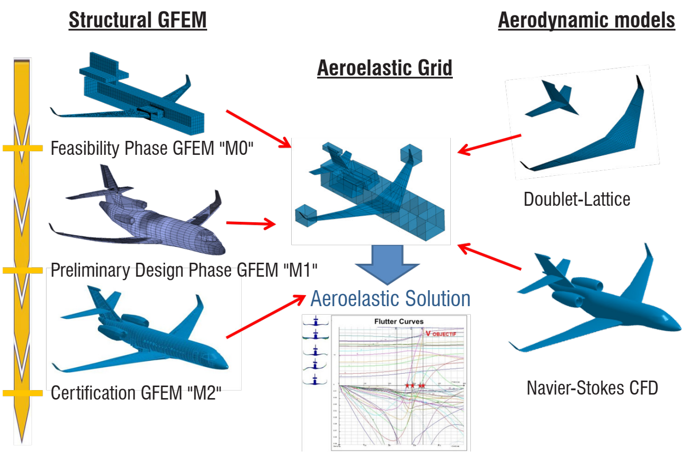


Figure 6 – The aeroelastic grid as the backbone of the ELFINI© aeroelastic analysis process

- **The "aeroelastic grid"**, which, in the spirit of the stick model, will be at the heart of aeroelastic solving. The "aeroelastic grid" is a conceptual entity used to:
  - manage the fineness of the reduced load database and the reduced monomial displacement base for aerodynamic calculations,
  - include all condensed and reduced operators, containing the only data involved in aeroelastic coupling. These operators are calculated using the aerodynamic CFD model and the aircraft GFEM:
    - reduced stiffness and mass matrices in the load basis,
    - smoothing operators of the finite-element displacements by the monomial analytic displacements,
    - reduced structural monitored quantities in the load basis: reactions to interfaces, general loads, flows and local stresses, etc. These monitored quantities will make it possible to determine the severity of loads on the structure sizing (see the notion of Load Severity Indexes detailed hereafter in this paper),
    - aerodynamic projection operators: used to either go from pressure field coefficients on CFD meshes to "peak" pressure fields centered on each node of the "aeroelastic grid" or "box" resultants; or go from pressure fields on the "aeroelastic grid" to finite-element node loads of the aircraft GFEM.

In this organization, the "aeroelastic grid" is the sole recipient for all of the aeroelastic solutions produced: the analysis of dynamic and static loads, flutter, aeroservoelasticity, control surface effectiveness and global flexible coefficients.

A very important aspect, in terms of the previously-described challenges, is that the definition of the "aeroelastic grid" (density, pressure zones, "boxes") will only change very little (or better yet, not at all, which is the aim) throughout the aircraft project. This will enable highly-similar aeroelasticity solutions, with the same granularity regardless of the mesh density and the level of precision of the aircraft GFEM or the CFD model.

Another important aspect is that the "aeroelastic grid" density is determined by "physical" representativeness criteria for structural loads from a structural sizing point of view. These criteria are completely independent from the criteria that govern the aircraft GFEM mesh density, or those of the aerodynamic CFD mesh cells, which are, in essence, dictated by numerical convergence criteria. When uncorrelated from all "numeric" density criteria, "aeroelastic grid" handling becomes much easier and uses far less CPU resources than the aircraft GFEM does, or than that of the aerodynamic CFD model.

Once the design loads have been calculated in the reduced load basis, they can be restored to the aircraft GFEM for analysis by the stress engineers who are designing the structure and who share the same finite-element model for the aircraft as the aeroelastic engineers. The "model cascade" technique (see Figures 4 and 7), which is now "a classic", is used to go from the representation of internal load flows in the aircraft to local stresses located at critical points in the structure panels (hole edges, assemblies, stiffener stops, etc.) or to the buckling stability analysis of critical aircraft structural elements

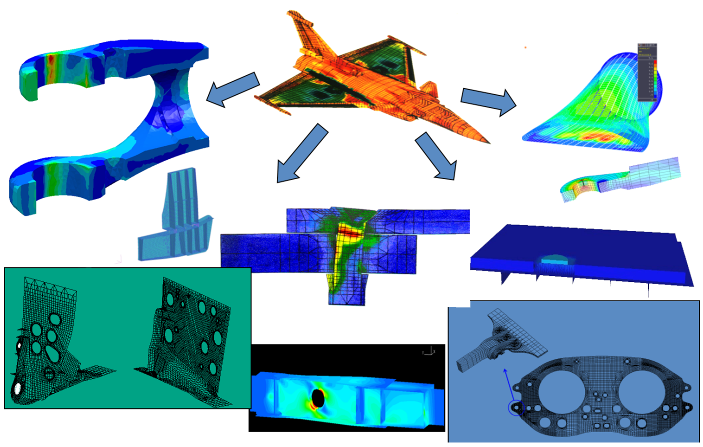


Figure 7 – Model cascade: from global internal loads to local critical stress analysis

(panels, stiffeners, etc.). To do so, the aircraft GFEM is used to define balanced load conditions on "isolated" refined finite-element models of structural parts or sections of the aircraft, which, given their mesh densities, are used to precisely discretize the geometry and any structural damage (see the damage tolerance analysis).

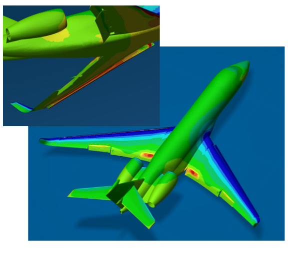
The Great Potential of CFD Aerodynamic Modelling

One of the greatest advances over the last 20 years at Dassault Aviation in the field of aeroelasticity was the progressive replacement of Doublet-Lattice linear aerodynamic modelling with steady and unsteady aerodynamic CFD codes.

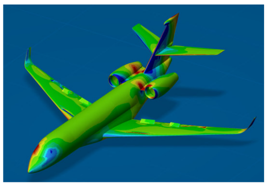
These "high-fidelity" codes have the crucial advantage of capturing viscous phenomena and the effects of compressibility, whether steady or unsteady, even for highly-complex configurations, such as heavily armed military aircraft or FALCON high-lift configurations (see Figure 8 hereafter), without losing precision in the subsonic or supersonic regimes with respect to the Doublet-Lattice method.

At Dassault Aviation, the introduction and use of CFD for aeroelastic analysis has been done in stages: firstly, by the introduction of the Full Potential method, the Euler method and finally the Navier-Stokes method ([13] to [21]). The change involved first using the CFD codes to calculate rigid effects, while keeping the Doublet-Lattice modelling for flexible aeroelastic effects. Then CFD progressively took hold to model aeroelasticity as well.

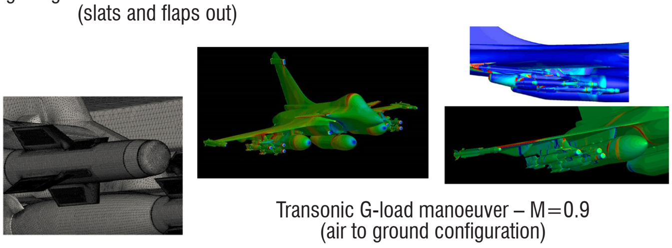
Nowadays, the standard reference CFD for aeroelasticity, used as part of the development and certification of the latest aircraft produced by Dassault Aviation (FALCON 7X/8X/5X and the most recent RAFALE standards), is the Navier-Stokes CFD AETHER code, for steady and unsteady computations [21]. This code was developed internally at Dassault Aviation by the Aerodynamics department. The Doublet-Lattice method does, however, continue to be used as a backup for CFD, given its extensive use in the aeroelastic design practices for the previous aircraft method and the experience accumulated in flight tests. All of this makes it a reference method at Dassault Aviation, which we would not wish to abandon completely.



High angle of attack manoeuver – M=0.3
(slats and flaps out)



Sideslip effect – M=0.85
(airbrakes out)



Transonic G-load manoeuver – M=0.9
(air to ground configuration)

Figure 8 – Example of typical CFD Navier-Stokes analyses for structural load predictions in complex configurations

The introduction of a Navier-Stokes CFD code in the aeroelastic analysis process has raised a range of difficulties in practice:

- From the point of view of numerical techniques, the use of this code within the framework of aeroelastic analysis poses new problems with respect to the CFD calculations done "classically" for aircraft performance studies (drag, max Cz, buffeting, etc.):
  - the aeroelastic deformations of the aircraft structure can lead to aerodynamic mesh deformations with unacceptable element volumes or topological distortions in aerodynamic mesh elements,
  - the modelling of turbulence in the steady and unsteady regimes (Spalart-Allmaras, K-ε, K-ω, K-ℓ, K-KL, etc.) can have a considerable impact on the results of the aeroelastic behavior calculations for the aircraft, particularly in the case of strong aerodynamic interactions or separations.

- The preparation time for CFD models and the associated resolution times can be highly prohibitive with respect to the Doublet-Lattice method.

- The Navier-Stokes equations are non-linear in nature. It is not naturally easy to solve and process these equations within the efficient linear aeroelasticity organization designed and implemented for decades at Dassault Aviation in the *ELFINI*© platform.

- Even though this code has been relatively well validated in the steady regime in the past, based on the many wind-tunnel tests on pseudo-rigid mock-ups (for aspects related to drag predictions in particular), it lacks experimental validations in the unsteady domain.

It was quickly decided that the top priority should be to solve the 3rd point detailed above and to adapt the use of CFD to aeroelasticity in an organization that is just as flexible and effective as the one that we have with traditional linear methods. To do so, the method adopted for aeroelasticity was to solve the steady and unsteady Navier-Stokes linearized equations for small structural displacements.

Many publications describe in detail this work, which has resulted in the production of a linearized Navier-Stokes CFD code for aeroelasticity applications at Dassault Aviation (with [18], [19], [21] as typical references). These developments have been achieved thanks to support from the DGA and DGAC ([22], [23], and [24]). They would not have been completed so efficiently without the close cooperation between Dassault Aviation and ONERA. ONERA has played a crucial role in R&D, and in the numerical and experimental validation of these new approaches. This theoretical work has also helped to solve the numerical difficulties linked to the first point in the previous list.

It is also noted that one of the major benefits of the exact linearization of Navier-Stokes equations lies in the fact that complex aerodynamic calculations can be performed only once, at the start of the project, on the basis of monomial analytical displacement shapes, regardless of the knowledge of aircraft structural modes and displacement cases under load conditions. The aerodynamic fields resulting from any structural mode shape or from any displacement case under load conditions can then be obtained, for a marginal additional cost, by combining these "basic" pressure fields via the smoothing operator for a structural flexible displacement in the monomial basis. This property distinguishes the "exact" linearization method of the Navier-Stokes equations adopted by Dassault Aviation from the time-domain harmonic balanced linearization methods that can be found in some publications ([25], [26]): in the case of time domain harmonic balanced methods, the derivatives for the aerodynamic quantities are numerically obtained with an accuracy linked to the numerical residual. When these residuals are recombined through the monomial displacement smoothing operator, they may completely ruin the precision of the recombined aerodynamic field, rendering it very inaccurate.

In parallel to these developments, substantial investments have been made at Dassault Aviation to experimentally validate these methods, again thanks to the support from the DGA and DGAC and in active collaboration with ONERA (including the use of the ONERA Modane wind-tunnel facilities). These validation campaigns were performed using flexible mock-ups, designed, manufactured, instrumented and implemented in wind tunnels by ONERA. The details of these validation campaigns are given in "Experimental validations and model-calibration methods".

Finally, we note that specific "direct coupling" tools in the time domain for structural and aerodynamic steady and unsteady equations have also been developed (full CFD-CSM codes coupled in the time domain, *i.e.*, "big game"). These tools, which are "beyond" the normal industrial process itself, given their prohibitively high costs and the fact that highly-specialized skills are required to handle them, are reserved for cases of extremely non-linear and highly-complex coupling between the structure and the aerodynamics, like those of the B-1 bomber [27] or of the F16 in heavy under-wing external store configuration [28]. If these cases are encountered during the development of an aircraft, the policy adopted by Dassault Aviation (where possible) is to deal with the aerodynamic design of the aircraft as a priority and to regularize the phenomena first, in order to avoid ever having to use such a tool for the aeroelastic analysis. It could, therefore, be thought that the simple analysis of the aerodynamic field (*i.e.*, position of separations, position of any shock waves, etc.) for imposed structural mode shapes would suffice to make designers think carefully about modifications in the aerodynamic design, without needing to model the complexity of coupling between the structure and the aerodynamics. Past experience has shown that the aerodynamic design criteria taken from the military domain (subsonic and supersonic) for designing the external aerodynamic shapes of Dassault Aviation aircraft have made it possible to prevent this type of phenomenon from occurring. This is true even in the business-jet domain, which was able to benefit from these aerodynamic design rules derived from the know-how in the military domain.

The "Global" Approach for Selecting Critical Load Cases

Given the millions of load cases that must be considered to size and certify the structure (see §"Multiplicity of aeroelastic calculation conditions"), it is inconceivable that they will all lead to detailed stress analyses. Otherwise, the analysis capabilities would be saturated, designers would be unable to focus their attention on the most critical cases, and the costs for the project and the lead times for each aeroelastic analysis "loop" would increase excessively.

The approach adopted at Dassault Aviation consists in using the notion of Load Severity Indexes (LSI) along the resolution of aeroelasticity and for load calculations. This is only possible because the aircraft GFEM is unique and shared by the aeroelastic and stress engineers who are sizing the structure.

LSI are defined as a set of finite-element operators (called "gages" or "monitored quantities" in *ELFINI*© jargon) that apply to the aircraft GFEM displacements, and are used to produce quantities ("indexes") that will monitor the rupture modes for a complete section or part of the aircraft structure. The LSI will, therefore, be used to check the severity of a load case by applying this operator to the solved displacement case for this load case on the aircraft GFEM, and by comparing the value obtained with respect to a limit value in relation to the structural strength of the section considered.

Note that this approach is a "global" one and not a "local" one:

- The LSI are properly defined on the aircraft GFEM (shared by the stress engineers and aeroelastic engineers), and not in a detailed finite-element model of a structural section. This will enable their reduction in the reduced-load basis used to solve aeroelasticity (see the equations in Box 1).

- The LSI are not intended to give an indication that is directly comparable to a strength allowable locally (therefore, it alone cannot judge the structural strength with respect to a load case); it is intended to give a global evaluation of the severity of a load case with respect to another one over an entire structural area/section of the aircraft.

Figure 9 illustrates the example of a typical set of LSI used to ascertain the severity of FALCON load cases on the various structural sections: wing, fuselage sections, horizontal and vertical stabilizer. On a FALCON wing, which is close to a beam behavior, the LSIs typically used are general loads over approximately twenty pre-defined cuts.

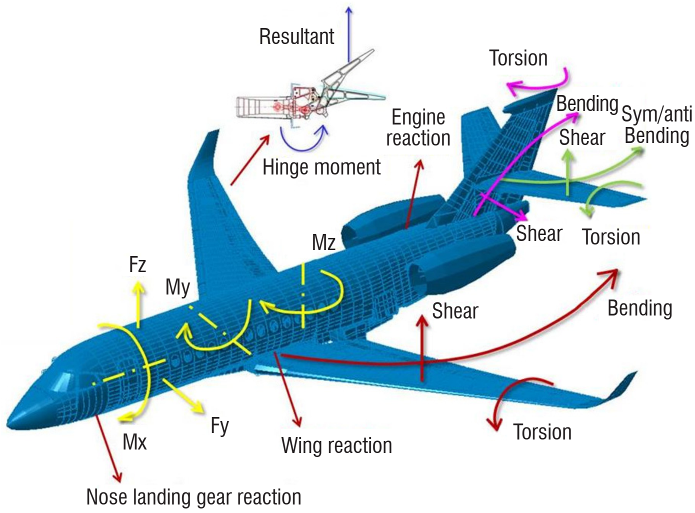


Figure 9 – Typical Load Severity Indexes (LSI) on a generic Falcon

Once all of the LSI have been reduced in the reduced load basis used to solve the aeroelasticity (see Box 1 above), it is calculated very quickly and can be done for all of the multiple calculation conditions to be considered in the aircraft load analysis. The analysis of the LSI values thus obtained is used to select the most critical load cases for each aircraft section. We typically go from a million load cases calculated for the load analysis to a few dozen critical-load cases. These are the critical cases known as "envelope-load cases" (or "sizing-load cases"), which are returned to the aircraft GFEM and are subject to a precise structural strength analysis by the stress engineers. Figure 10 given below illustrates the few typical "envelope-load cases" that are well-known to size the wing of a generic FALCON.

For digital FBW aircraft (FALCON 7X/8X/5X, nEUROn and RAFALE), the LSI approach is also used to adjust the flight-control system gains and demonstrate that, regardless of the flight conditions, the FBW system keeps the aircraft within its structural design domain (*i.e.*, "carefree handling" philosophy). For this, the aeroelastic model is introduced into the simulation models used to design the FBW system. The LSI thus enable the "FBW system engineers" to check the effect of the FBW system gains on the structural loads induced by the pilot and the internal control loops of the system itself.

During the first part of the development phase of a new aircraft, this method has the advantage of being able to reach compromises between the aircraft performance delivered by the digital FBW system and the level of the design loads (therefore, the structural mass needed to size the aircraft) in a simple and optimal manner. In the more advanced project phases, this helps to ensure that every time a new digital FBW standard is set (and some can occur at a very late stage in the project), the aircraft design loads are not affected.

To be correctly implemented, note that this approach calls for a high degree of consistency between the aircraft's aerodynamic flexible global coefficients used to compute the structural loads and those used in flight mechanics to determine the digital FBW control laws.

Linear Flutter

The preferred method to solve linear flutter at Dassault Aviation is the P-K method modified by J. P. Brevan in the 1970s and incorporated since then in *ELFINI*©. Its essence relies on the matched-point algorithm ([7], [29]).

Since its initial development up to the current day, flutter solution has not changed very much in terms of its theoretical principles. The main changes concern:

- **The introduction of digital FBW laws in formulating the flutter** eigenvalue problem to be solved; the implementation of the P-K method, meanwhile, remains identical. Two variants are possible [30]:
  - either the impedance of the digital FBW system is formulated in the frequency domain, and introduced into the flutter solution in a similar fashion to that of the general aerodynamic force matrix; therefore, we only monitor the evolution of the elastic poles coupled with aerodynamics, according to the flight point,
  - or we have a formulation of the digital FBW system laws in a state-space form (state-space model), and the flutter equation is "increased", alongside the general structural elastic degrees, to introduce the additional degrees of freedom coming from the internal digital FBW system variables. This variant is useful to be able to monitor the change in the digital FBW system poles coupled with aerodynamics according to the flight point, in the same manner as elastic poles. However, as the size of the aeroservoelastic system to be solved increases with respect to the first variant, the flutter resolution times using the P-K method are longer.

- **The use of a representation of the generalized aerodynamic forces in a state-space form.** To achieve this, the general aerodynamic forces are rationalized in the Laplace domain, using the Roger method [31] or the Karpel method [32]. The Karpel method is used, with a lesser degree of precision, to conduct a minimum-state method in terms of internal degrees of freedom. Once this operation is performed, the flutter equation can be formulated under a "state-space" form, with the degrees of

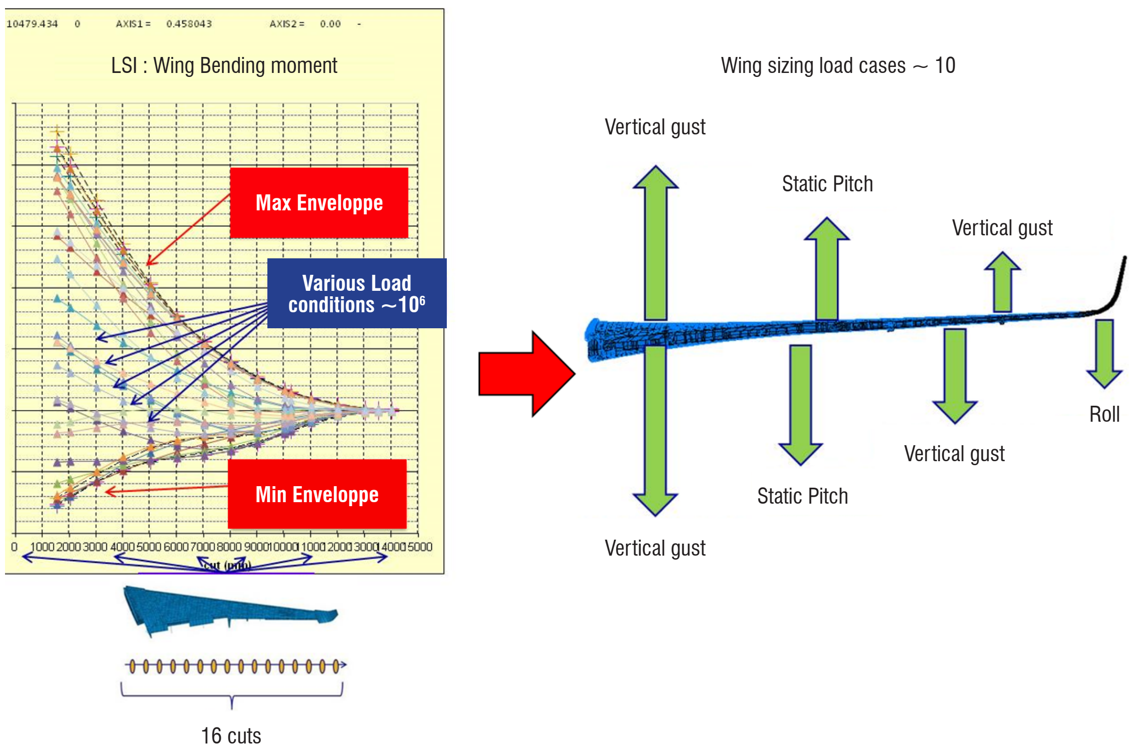


Figure 10 – Typical application of LSI for the selection of the wing envelope (sizing) load cases on a generic FALCON

freedom still being the concatenation of elastic degrees and "aerodynamic" degrees coming from the aerodynamic rationalization. The eigenvalue problem can then be resolved by classical methods like the QR algorithm, using the Hessenberg matrix form [33]. The advantage of this representation for the generalized aerodynamic forces is that:

- The specific flutter value equation can be solved by a "direct" non-iterative method, unlike the P-K method, making it possible to avoid some of the convergence issues arising from the P-K method if the modal density for the structure is high.
- It "naturally" enables the introduction of the digital FBW system in the same ways as in the 2nd variant of the previous point. The flutter equation solution therefore enables the monitoring of elastic, aerodynamic and digital FBW system poles in the flight envelope.

The progress made over the last 10 years in linear flutter analysis at Dassault Aviation has mainly been in the development of dedicated post-processing tools, which will help the aeroelastic engineers to have a better "physical" understanding of the flutter mechanisms for which the numerical solution remains highly mathematical in nature (*i.e.*, solution of an eigenvalue equation):

- calculation of the complex mode shapes at the flutter points (see Video 1 of a typical flutter displacement mechanism computed on the RAFALE in air-to-ground configuration, far away from the flight-domain envelope),
- calculation of the energy exchanges between the modes involved in the flutter mechanisms,
- automatic reduction and simplification (on energy principles) of the flutter mechanism to the main contributing modes (with variable energy threshold criteria used to refine this reduction to a greater or lesser extent),
- calculation of the power flows at the flutter points used to discern the dissipating lifting surfaces from the lifting surfaces contributing to the instability mechanisms (see Figure 11) [20],
- automatic plotting of the response surfaces of the instability speeds according to multiple structural parameters (rigidity and mass of the structural parts involved in the flutter mechanism modes), aerodynamic parameters (for example: pressure coefficients due to wing tip/winglet interactions or wing tip/missile interactions), external shapes (winglet sweepback or dihedral,) or "system" parameters (control surface servo-actuator stiffness, typically).

These flutter post-processing tools have proven to be essential in many design situations to better understand the flutter instability

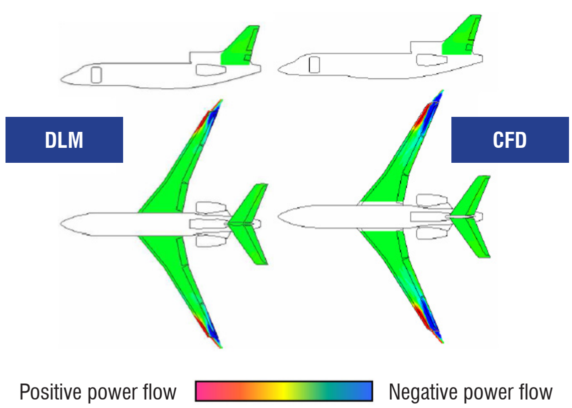


Figure 11 – Aerodynamic power flow on a flutter point of a generic FALCON

mechanisms, physically-speaking, particularly in the case of FALCON business jets, or in the case of heavily-armed configurations for military aircraft, given the major complexity of the flutter mechanisms encountered (resulting from the increased flexibility of the structures, the high modal density, and the potential coupling between the various lifting surfaces). These tools have provided a greater understanding, which has successfully guided the designers in the various modifications possible to the structural design, where the experience of a designer alone, without an effective analysis tool, may not have sufficed and could have led to excess mass over an area certainly far larger than necessary, and the risk that flutter stability objectives would not be met.

Aeroservoelasticity

On both military and civilian aircraft, the introduction of digital FBW controls (RAFALE, nEUROn, FALCON 7X/8X/5X) and their major interaction with handling qualities and aircraft performances, have reinforced the need to also analyze possible couplings between the domains of digital FBW control and aeroelasticity.

One of the reasons for this is that, when designing FBW control laws, "system" engineers consider the aircraft to be a "quasi-rigid" aircraft. However, the increased flexibility of structures (FALCON 7X vs. FALCON 900 or RAFALE vs. MIRAGE 2000), and the heavily loaded configurations with multiple external stores in the case of military aircraft, such as the RAFALE, mean that the structural modes have frequencies that are getting closer and closer to the frequencies of flight mechanics "modes" (angle of attack oscillation, Dutch roll, etc.). The current strategy used at Dassault Aviation, therefore consists in filtering the flexibility information measured by the digital FBW sensors attached to the structure, using notch-filters, before determining the control surface order via the digital FBW system, on the basis of this information.

In the 1980s to 1990s, the design of the notch-filters was mostly based on the ground and flight measurements of the flexible transfer functions between the FBW sensors and control surface excitation. This was done using pole extraction and identification techniques on those tests. There were many drawbacks to this strategy:

- Very "heavy" ground and flight test campaigns that comprised many flight points and multiple configurations.

- The risk of having to rework notch-filters at a very late stage in the aircraft development, at the time of the first ground or flight tests. This could have significant consequences if these filter modifications, given the dephasing that they could induce at low frequencies, were to be the source of delays in the digital FBW control loops, and these delays themselves could be the cause of deteriorated handling qualities of the aircraft.

- In the case of military aircraft, there was the risk of building flight-test programs that would be unable to measure the "worst" configurations with respect to the flexible transfer functions at the FBW sensors, given the large amount of configurations and sub-configurations to be considered (multiple external stores and fuel consumption in internal or external fuel tanks, etc.).

Over the last 15 years, the major challenge presented by aeroservoelasticity at Dassault Aviation was therefore to rely more and

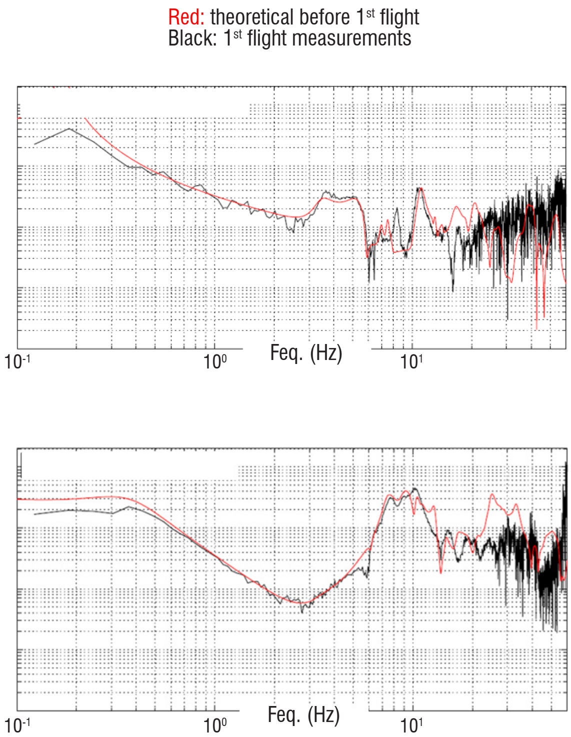


Figure 12 – Comparison of theoretically predicted and measured (very first flight) digital FBW transfer functions on F7X

more on dynamic aeroelastic predictions and to introduce it in the notch-filter design cycle as early as possible in the aircraft development, to reduce the disadvantages listed above. The efforts made in modelling and the associated investments (drafting of "specific" modelling rules and practices based on prior experience, introduction of linear Navier-Stokes CFD models in the aeroelastic tools, re-calibration tools on the basis of partial or complete ground and flight tests, specific pre- and post-processing tools, etc.) have been enormous given the stakes, but also due to the fact that the modelling of aeroelastic flexible transfer functions at digital FBW sensors needs to be much more precise for the purposes of aeroservoelasticity (and the design of notch-filters) than in the case of other dynamic aeroelastic analyses.

As an illustration, Figure 12 gives the precision of the predictions for some of the digital FBW sensor transfer functions obtained by the aeroelastic model before the first flight of the FALCON 7X and the comparison with the very first results obtained subsequently during the first flights of this aircraft.

On the RAFALE, this strategy of using the aeroelastic model for aeroservoelasticity was also successfully applied in the development and certification of the "F2" air-to-ground standard [83]. Particularly to:

- Calculate several tens of thousands of external store configurations and sub-configurations for this standard and to only keep a few dozen of the most critical configurations with respect to the aeroservoelastic stability of the aircraft.

- Only rework the preceding standard "F1" (preceding the "F2" standard) notch-filters on the longitudinal or lateral axes and frequency domains to just the right amount with respect to the information given by the theoretical aeroelastic model, in order to minimize the impact on the aircraft handling qualities.

- Build flight test programs limited solely to the configurations (and sub-configurations) identified as being the most critical by aeroelastic calculations, with respect to the aeroservoelastic stability (see first point above).

Figure 13 gives an illustration of some of these calculations in the case of two asymmetric air-to-ground configurations of the RAFALE, including a comparison with flight-test measurements.

Figure 14 shows how the introduction of CFD with respect to the Doublet-Lattice method has contributed to the assessment of an aeroservoelastic transfer function.

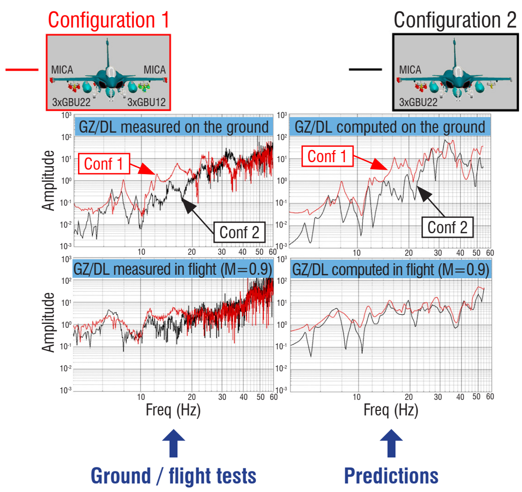


Figure 13 – Comparison of predicted and measured digital FBW transfer functions "Gz/sym elevons" on two asymmetrical air-to-ground configurations of the RAFALE

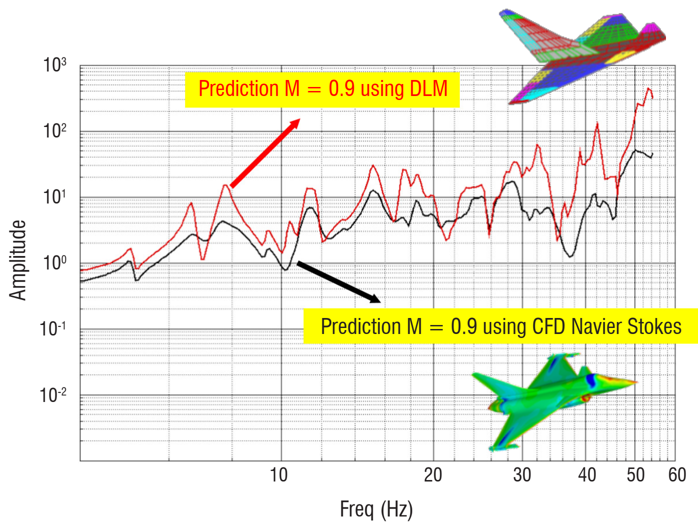
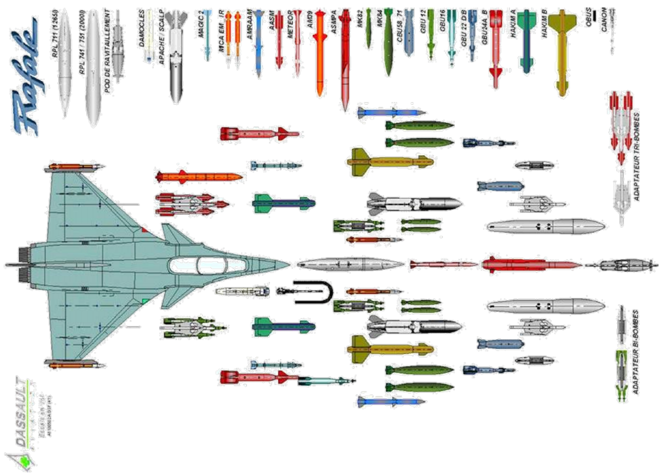


Figure 14 – Comparison of predicted digital FBW transfer functions "Gz/sym elevons" computed with Doublet-Lattice Method and CFD Navier-Stokes for configuration 1 of Figure 13

Figure 15 gives an estimate of the number of flights "saved" by using the aeroelastic model for aeroservoelasticity studies with respect to the initial estimate made by applying the conventional strategy of producing and validating notch-filters through ground and flight test campaigns [83].

As we can see in Figure 15 hereafter, the gain is over 150 flights, representing several months of flight-test activities. These savings alone justify the investments made to develop, debug and validate the computing aeroservoelastic approaches implemented, which also include the additional tests that were needed to recalibrate and gain confidence in the aeroelastic models.



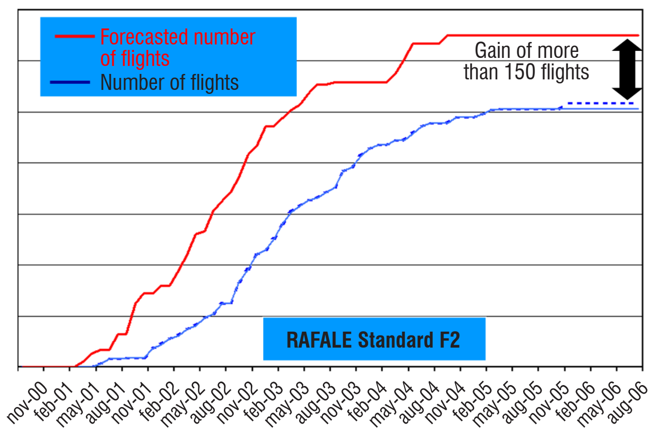


Figure 15 – RAFALE F2 "air-to-ground" standard: gain in number of flights obtained by using the aeroelastic prediction tool for aero-servo-elastic stability clearance

Non-Linear Aeroelasticity and Limit Cycle Oscillations (LCO)

The sources of aeroelastic non-linearity mostly encountered on military aircraft and business jets are either of an aerodynamic nature:

- transonic regime,
- static and dynamic load non-linearities due to large angles of attack or sideslip angles of the aircraft, or due to large control surface deflections,
- unattached flows,
- stalling,
- turbulent-laminar flow transition,
- etc.,

or of a mechanical nature:

- contact non-linearities linked to the clearance possibilities included in a "dormant" secondary fail-safe load path, or due to the effects of wear or failure cases in the systems that "release" mechanical clearances (typical case of the start of a fire, which, due to increased temperature, causes the destruction of flexible elastomer suspensions at the engine mounts),
- non-linearities in the behavior of systems: hydraulic servoactuator non-linearities on the control surfaces; etc.,
- geometric non-linearities, such as local membrane effects that can have an impact on the dynamic properties,
- etc.

In the presence of an aeroelastic instability, non-linear behavior can lead to an asymptomatic limitation of the instability in the form of Limit Cycle Oscillations (LCO). This limitation can be due to either a non-linear variation in the aeroelastic stiffness, which, by modifying the frequency or aeroelastic mode shapes, periodically "destroys" the instability mechanism (typical case of mechanical contact non-linearities), or a dissipation phenomenon caused by the non-linear behavior of the aeroelastic system (typical case of a "fluid damper" type non-linearity), or to a non-linear effect which reduces the aerodynamic work in the flexible-mode shapes when the amplitude of the modal displacement increases (typical case of aerodynamic-based non-linearities). Even though an LCO phenomenon is less of a cause for concern than aeroelastic instability like flutter, it is to be studied in detail and to be precluded, if possible, since it can be a source of premature wear and fatigue in structures, and can result in serious human factors among pilots, such as discomfort, or an inability to read the instruments or maneuver the aircraft controls properly.

As regards non-linearities of an aerodynamic nature, the current practice at Dassault Aviation is to perform an aeroelastic analysis that is "linearized by parts", based on the linearized Navier-Stokes CFD calculations, and enriched with wind-tunnel measurements and flight tests (when this information is available). Whether in the military domain, and more specifically the certification of configurations laden with multiple underwing stores, or in the business jet domain, there are no cases that we know of today in which this kind of "linear by parts" approach would not be able to explain the nature of a non-linear aerodynamic phenomenon encountered and, possibly, the flight domain areas in which this non-linearity would degenerate either into instability or into LCO.

In some typical cases where the LCO is linked to an aerodynamic work limitation with increased structural displacement amplitude, the linearized Navier-Stokes approach could be no longer sufficient to provide the amplitude of the LCO. Time domain harmonic balanced approaches [36], [37] may therefore be used. Those tools are specific tools beyond the normal industrial process itself, either for structural sizing or certification purposes, and would require highly specialized skills. Again, the preferred strategy at Dassault Aviation would be to use, instead, the linearized Navier-Stokes CFD tools to only predict the LCO areas in the flight domain (without seeking a precise prediction of the LCO amplitude), to "physically" understand the mechanism of this LCO and to guide the design to "push" those LCO areas "outside" the aircraft required flight domain. The literature is rich with examples where this strategy has been successfully applied in the aeroelastic domain for various industrial applications [68], [69].

Some other cases of LCO, the origin of which seems to be a strong non-linear aerodynamic behavior in the presence of a strong aero-structural coupling, are discussed in detail in publications ([27] for example), and are known for only being able to be analyzed by highly advanced coupling of CSM (Computational Structural Mechanics) and CFD tools in the time domain (*i.e.*, "big game"). Even though this type of tool is available at Dassault Aviation, they are still in the prototype phase, and it is hard to make use of them in an industrial process and achieve certifiable approaches. The analysis of these cases gives us reason to think that, when this type of tool needs to be used, the design is not very robust and the associated non-linear aeroelastic phenomena are highly uncertain, with a lot of variability from one aircraft to another in the same series. In such a case, we recommend focusing on the aerodynamic design of the aircraft as a priority to regulate the underlying non-linear aerodynamic phenomenon and avoid implementing this type of analysis.

As regards mechanical non-linearities, there are two processes that are essentially equivalent in terms of results which are commonly used at Dassault Aviation according to the type of non-linearity (with a preference for the first):

- **First harmonic linearization of the mechanical non-linear behavior for a varying number of structural displacement amplitudes** and the calculations in the frequency domain with these linearized characteristics of flutter curves by the standard PK- method (see §"Linear flutter"). This approach is mostly used if the mechanical non-linearities only concern a few localized degrees of freedom or limited aircraft areas, which are the majority of cases encountered on military and business jet aircraft (localized free-play or servoactuator non-linearities, typically). The linearization amplitude for which the flutter curve is stable in behavior, unlike the lesser amplitudes that resulted in instabilities, corresponds to the amplitude of possible LCO. In the case of geometric non-linearities, first harmonic linearization can be replaced with an exact calculation of the tangential stiffness matrix of the structure (typical output of a non-linear module such as that of *ELFINI*©). The entire aeroelastic computation workflow (reduced load basis, vibration modes and flutter curves) is, in this case, performed using this tangential stiffness.

- **Direct time integration of the non-linear aeroelastic dynamic equilibrium equation of the structure.** Working in the time domain is problematic in terms of formulating unsteady aerodynamic forces in this domain (unsteady aerodynamic calculations are performed 'natively' in the frequency domain by the linearized Navier-Stokes CFD method). The general aerodynamic forces are therefore rationalized in the form of state-space models in the Laplace domain using the Roger method [31] or the Karpel method [32]. The Karpel method is used, with a lesser degree of precision, to conduct a minimum-state method in terms of internal degrees of freedom. Once the generalized aerodynamic forces have been formulated in a state-space model, the linear degrees of the aeroelastic system can be condensed without difficulty at the boundaries of the non-linear degrees of the structure, in the form of "super aeroelastic elements". This allows the non-linear equilibrium of the structure to be resolved in the time domain for the non-linear degrees of the structure only, which are often limited. Classical time-stepping approaches can be used, such as the Houbolt, Newmark or Runge Kutta methods [38].

[39], [40] give details of the method and equations that are implemented as part of the time integration method for an aeroelastic system, including mechanical non-linearities. These references also present the cases for industrial application of this method, in aeroelastic prediction of LCO on a FALCON aircraft, as illustrated in Figure 16.

[34], [35] detail the method and results obtained during the aeroelastic stability analysis of thermal protection tiles in the HERMES project, for which non-linearity is related to "structural membrane" behavior.

[41] shows the equivalence of the two previously explained methods (frequency resolution after first harmonic linearization of the non-linearity, and "direct" full non-linear time resolution) within the framework of the aeroelastic behavior study on a generic FALCON, for which the rudder is coupled to a hydraulic servoactuator equipped with a passive non-linear anti-flutter system. Figure 17 offers an illustration of those results.

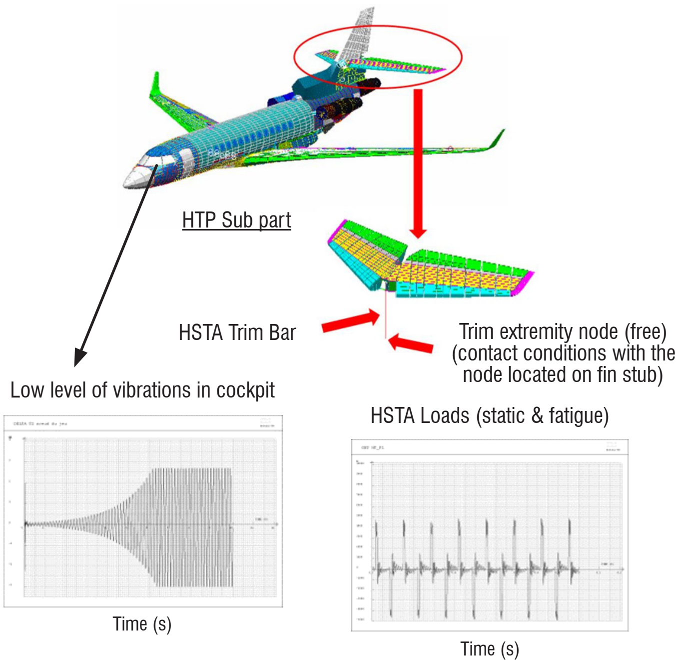


Figure 16 – LCOs prediction in the case of a Horizontal Stabilizer Trim Actuator (HSTA) in fail-safe condition (presence of free-plays) – direct time non-linear integration (from [39]).

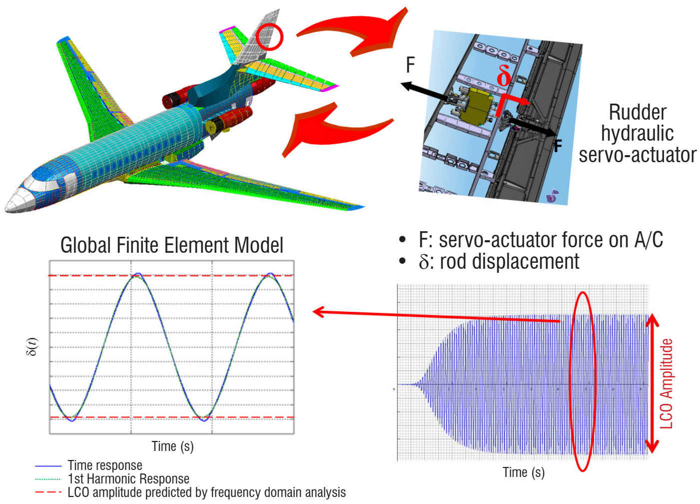


Figure 17 – Comparison of direct full non-linear time resolution and 1st harmonic linearization methods for the prediction of the LCOs of a rudder under an anti-flutter condition (from [41]).

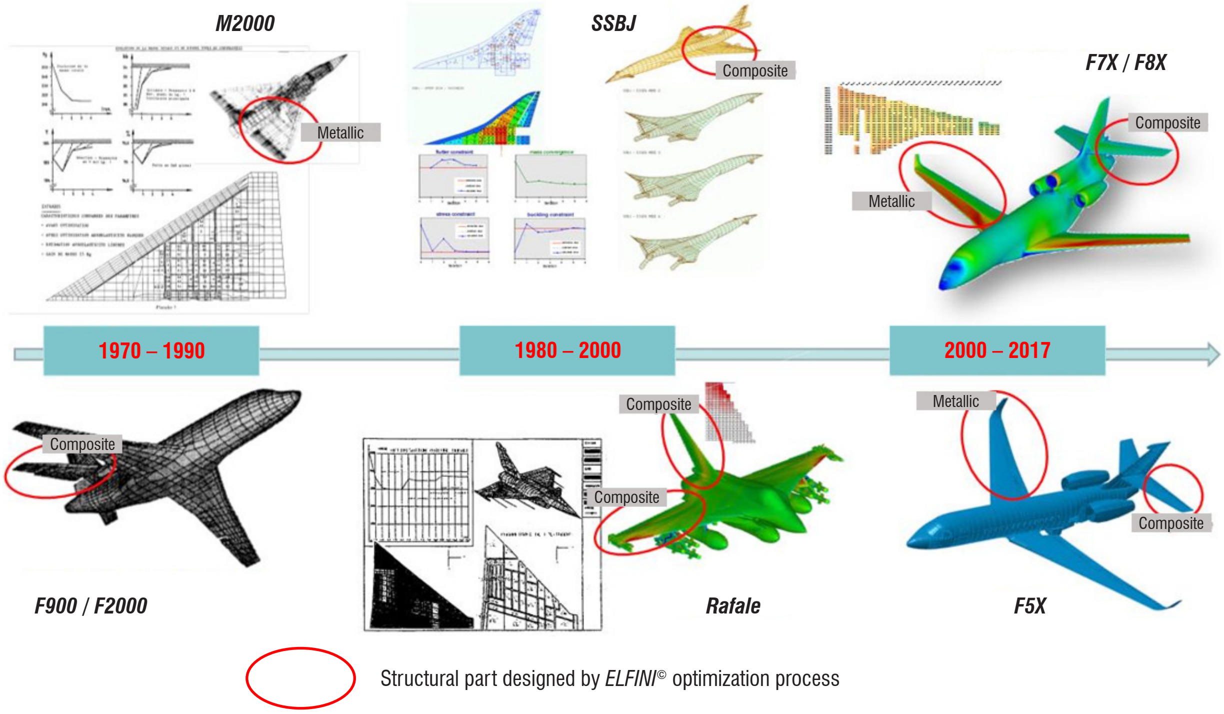


Figure 18 – Applications of *ELFINI*© aero-structural optimization on Dassault Aviation aircraft

Aerostructural Optimization

The means to analyze aeroelasticity that have just been presented in the previous chapters are of great use for the analysis and verification of a specific airframe drawing. However, the complexity of the aeroelastic phenomena is such, that no simple and rational rules can be given that would enable the designer to offer solutions that satisfy both the aeroelasticity criteria and the other design constraints. Despite the analysis tools, the designer may encounter difficulties, in certain cases, in "thinking intuitively" about the right changes to make to drawings to control complex phenomena, like aerodistortion, static control surface reversal or flutter.

Historically, the aeroelastic design process could only work with a good measure of intuition and, above all, the experience of the designers. This, in itself, could be problematic and particularly limiting when it came to innovating and moving away from the experience already gained. We can specifically mention the introduction of composite materials for large structural parts (typically the wing panels for the RAFALE or horizontal stabilizers for the FALCON 900), which was a true technological breakthrough compared to the use of metal parts.

At Dassault Aviation, the need to supplement the traditional design process with more effective aerostructural optimization tools has rapidly taken hold. It was strengthened by the integration of ever more complex aeroelastic phenomena in the design, as well as increased use of composite materials in airframes (see Figure 18 above).

This type of tool has been described in great depth in [42], [43], and [44] and, more recently, in [66]. They are based on the core of *ELFINI*© finite-elements solvers and the various branches of analysis of this platform (including the "Aeroelastic" branch), which provide an exact or approximate assessment of the derivatives for the calculated quantities (load flow, critical buckling load, modal mode shapes and frequencies, control surface efficiency, flutter speeds, etc.), with respect to the "design parameters" to be optimized, which the overall structural mass depends on: in practice, the skin and stiffener thicknesses in metal structures, or the number of plies in each direction for composite-material elements. The kernel of the *ELFINI*© finite-element tool also naturally provides the influence matrix for the structural mass with respect to the various design parameters considered.

In this calculation environment, the aerostructural optimization process aims to "drive" the following global iterative process (illustrated in Figure 19 below) [43]:

- definition of design parameters on the aircraft GFEM and their initial values,
- definition of the design constraints to be respected to enable the aircraft to reach the intended levels of performance (structural strength criteria, buckling stability, minimum required flutter speeds, maximum level of aerodistortion, etc.),

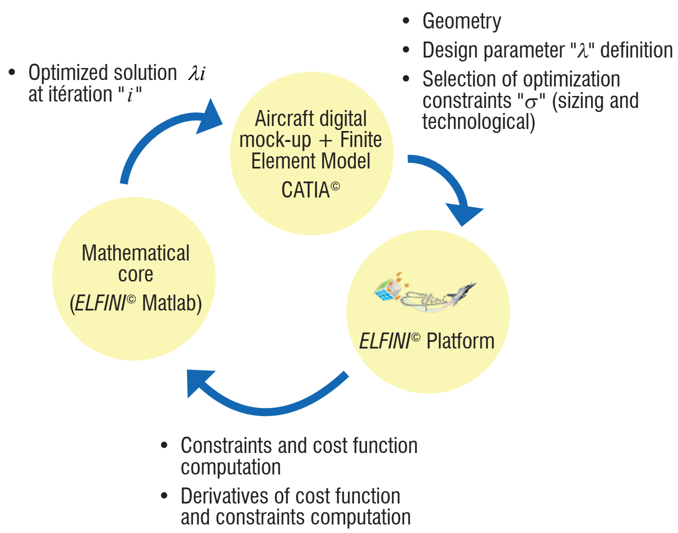


Figure 19 – Dassault Aviation global aero-structural optimization process

- definition of the "technological constraints" to be respected, so that the optimization process solution meets the design office drawing rules and constraints and can be manufactured,
- finite-element analyses (including aeroelasticity) in the structure for a given set of design parameters; calculation of the tangential derivatives of these analyses with respect to the design parameters,
- resolution of the optimization problem: minimization of the structural mass cost function under constraints and determination of the optimal design parameters. In *ELFINI*©, the algorithm used to solve this constraint optimization problem is a mathematical solver commonly used in the mathematical optimization domain, which operates by using the combined projected gradient method.

The developments over the last ten years in the field of aerostructural optimization at Dassault Aviation have mainly consisted in making the most of both the significant progress made in linearized Navier-Stokes CFD and the just as significant progress in the *ELFINI*© finite-element platform, in terms of:
- reinforcing the link with the digital mock-up and the CAD geometry definition (within the *CATIA*© environment),
- automating and facilitating elementary finite-element analyses,
- taking advantage of the increasing computing power (processor CPUs and multiple-core parallelization),
- ergonomics and specific control tools for the optimization workflow and the post-processing of results.

In comparison, the progress made in the algorithmic and methodological "mathematical core" of the optimizer has been relatively minor in nature.

In passing, we highlight once again the benefit of using linear CFD, which greatly facilitates the use of the latest generation of "high-fidelity" aerodynamic modelling (*i.e.*, the Navier-Stokes AETHER code at Dassault Aviation) in an aerostructural optimization process. The aeroelastic optimization process, as performed at Dassault Aviation, therefore uses the same level of structural and aerodynamic modelling as the rest of the aeroelastic analyses.

Once the aerostructural optimization process has been industrialized in the *ELFINI*© calculation tool platform, there are many optimization "sub-products" that offer an array of benefits. Take the example of the automatic plotting of response surfaces in Figure 20, which gives the evolution of an optimization constraint according to one, or several, design parameters.

At Dassault Aviation, the latest evolutions of the aerostructural optimization tool concern the introduction, within the framework of structures with composite materials, of new technological constraints linked to the optimization of a single lay-up table, as illustrated in Figure 21 [45]. We can also cite the introduction of geometric design parameters alongside structural design parameters in the optimization process [6]. This most recent evolution toward a future full topological-optimization capability is facilitated by the now very close links between the parameterized geometric definition (as proposed by the CATIA CAD tools) and the pre-processing tools for the finite-element codes.

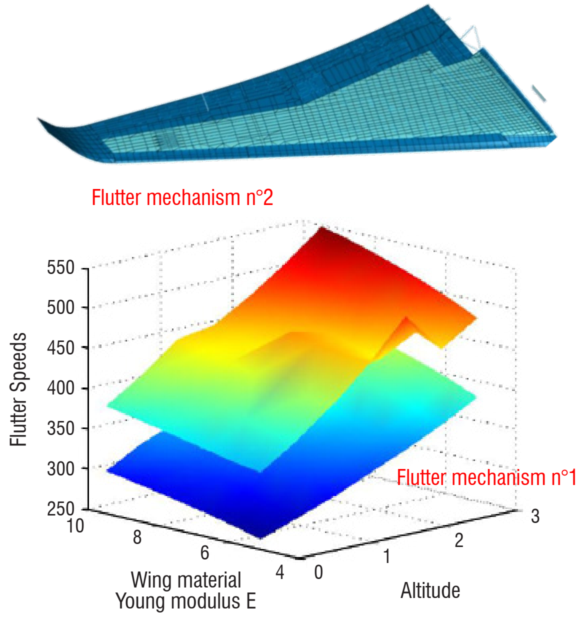


Figure 20 – Example of automatic response surface generation: flutter speed as a function of the wing stiffness.

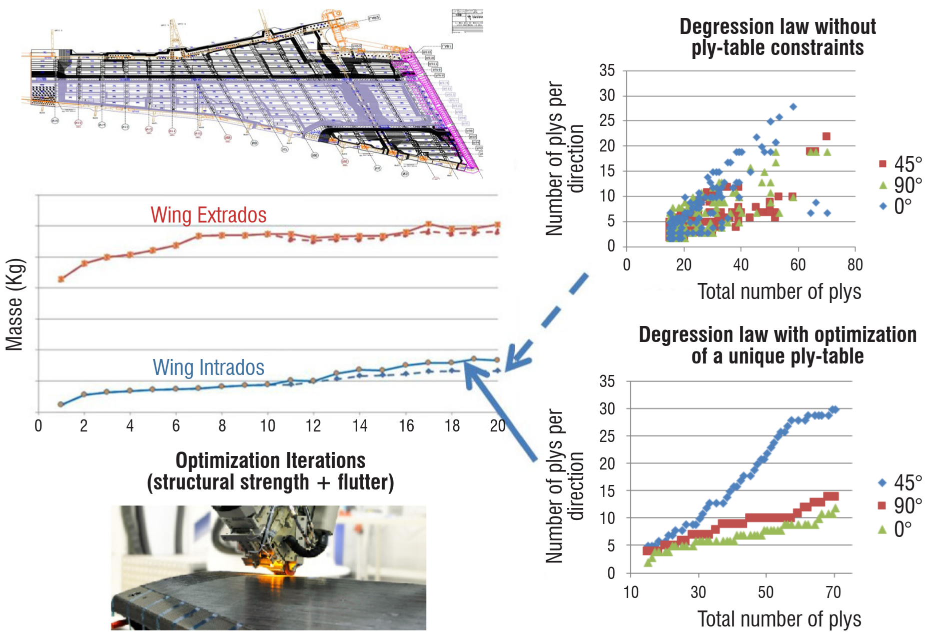


Figure 21 – Example of a composite wing optimization (static strength and flutter) with a single optimized ply-table

Experimental Validations and Model Calibration Methods

As we have seen in the previous sections, the use of aeroelastic tools and theoretical predictive models in the context of a military or civilian program is very challenging, in terms of risk and cost control. This challenge cannot be met if progress is not also made in parallel with the experimental techniques and adjustment tools that will be used to validate the methods, adjust the computational procedures and calibrate the associated models.

In the domain of experimental validation, the strategy currently adopted at Dassault Aviation is generally as follows:

- *With regard to aeroelastic method validation:* use of flexible mock-ups in wind-tunnel tests for the validation of CFD methods, CFD to CSM coupling procedures, tools and computational processes used for aeroelastic analyses.

- *With regard to aeroelastic certification model validation:* use of full-size ground and flight tests on aircraft, and calibration tools for the adjustment of the aeroelastic models used within aircraft projects.

Note that those 2 types of validation are recommended (or required) in the certification process for military and civilian aircraft ([86] for example).

Another important aspect that needed to be covered at Dassault Aviation was the training of young aeroelasticity engineers, and the renewal of the experience. Thirty years after the explosion of numerical aeroelastic modelling techniques, the generation of great experts who brought aeroelasticity to life, nurtured it, and participated in the aeroelastic design of famous aircraft such as the MIRAGE F1, RAFALE or the FALCON 900 (J. C. Hironde, C. Petiau, J. P. Brevan, B. Schneider, C. Geindre, G. Menard) have gradually taken leave from the professional world. Major efforts needed to be made (and must continue) to preserve the aeroelasticity techniques. The test specification on real structures, whether in a wind tunnel or in flight, and the monitoring of these tests and their correlation with theoretical calculations, has proven to be a key vector in training young aeroelastic engineers, which has actively contributed to a widened sphere of knowledge and the development of skills and creativity.

Experimental Validation of Aeroelastic Methods and Computational Procedures using Wind-Tunnel Tests on Flexible Mock-Ups

Since the beginning of aeroelasticity, the use of wind-tunnel tests on flexible mock-ups has proven to be a major factor in the aeroelastic analysis strategy for aircraft structures. Between the 1960s and the 1980s, these tests were mainly performed on flexible mock-ups that were "dynamically similar" to the aircraft being designed, mainly to validate the flight envelope for this aircraft with respect to aeroelastic instability phenomena before the flight tests. See Video 2 of a typical flutter test on a "MIRAGE F1 with a dynamically-similar flexible mock-up".

With the ramp-up in numerical aeroelastic analysis methods, the ultimate aim of these tests has changed at Dassault Aviation. The main objective is now to validate new aeroelastic methods and the associated calculation procedures. The difficulty is no longer to dynamically represent a specific aircraft through "similarity" using a mock-up and to study its aeroelastic behavior in the wind tunnel, but rather to design a flexible mock-up that highlights certain "generic" phenomena that may be encountered on the aircraft. The mock-up is therefore designed as a real "demonstrator of aeroelastic phenomena"; its instrumentation is defined to control the tests to be performed, with to the aim of maximizing the ability to observe the phenomena studied and collecting as many measurements as possible, which will be correlated with calculation previsions. We have clear evidence from the past that the use of results from real tests have made it possible to move forward and validate analysis techniques and methodology, by identifying difficulties that could not be detected in the case of purely numerical validations.

Over the last 20 years, this type of wind tunnel test on flexible mock-ups have enabled Dassault Aviation to validate, calibrate and develop aeroelastic analysis tools and methods in the following domains:

- **Steady and unsteady CFD aeroelasticity tools,** whether in the military domain [47] or civilian domain ([20], [21]). For this purpose, flexible mock-ups with flutter mechanisms, typically studied during the aircraft development phases at Dassault Aviation (*i.e.*, mechanisms that couple the bending/torsion modes of lifting surfaces or lifting surface bending/control surface rotation modes), were designed and heavily instrumented then tested in

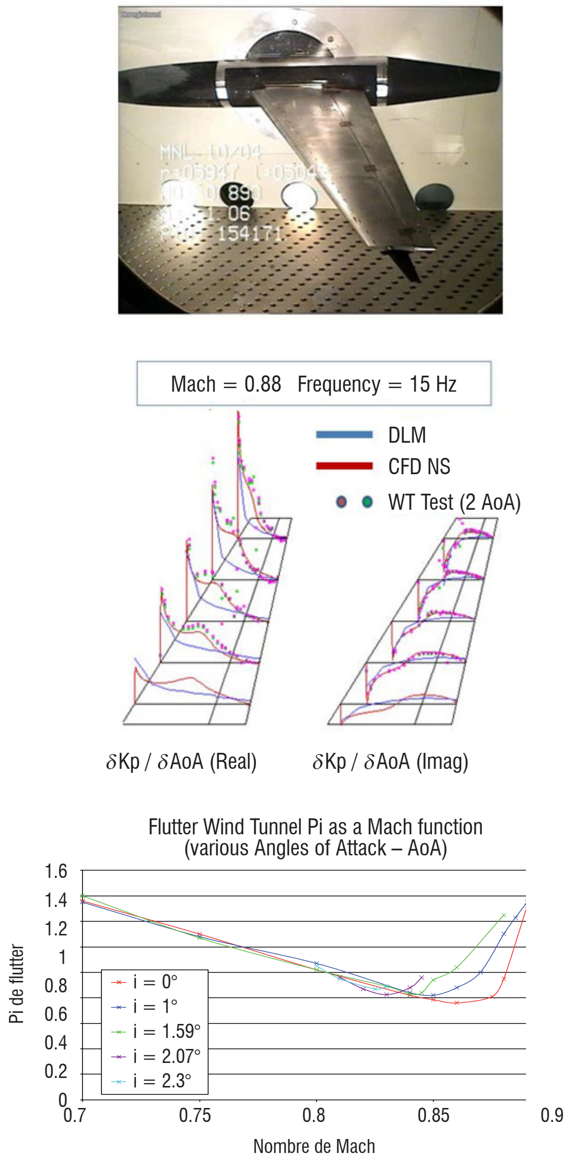


Figure 22 – Example of a wing flexible mock-up tested in ONERA S2-Modane (steady / unsteady aerodynamic + flutter tests) in subsonic and transonic regimes for aeroelastic methods validation

the ONERA S2 Modane wind tunnel under subsonic and transonic conditions in 1995 and 2005, as seen in Figure 22 ([46], [48]). Figure 23 shows an example of the pressures and flutter speed measured during WT testing, compared with the previsions obtained by the latest version of the Dassault Aviation linearized Navier-Stokes tools, with and without linearized turbulence.

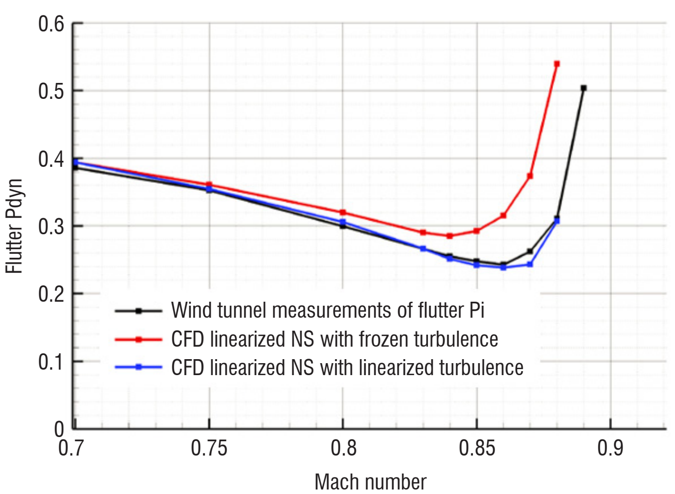
- **Non-linear aeroelasticity in the presence of mechanical free-plays and contacts ([46], [53]).** Based on a flexible mock-up representing the planform of a horizontal stabilizer and integrating an elevator, the aeroelastic behavior of this mock-up in the presence of mechanical free-play in its control surface kinematics was measured in the ONERA Modane S2 wind tunnel (see Figure 24). The stability and instability areas could thus be observed in the wind tunnel, together with the conditions leading to LCO phenomena. In this second case, the amplitude of the LCO was measured and correlated with provisional calculations [53] (see Figure 24).

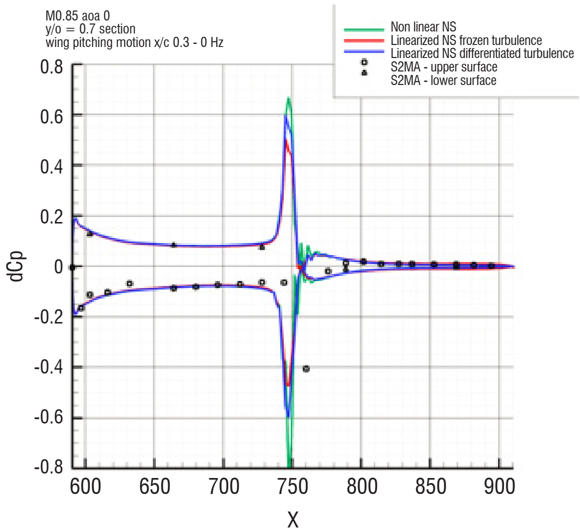
- **Aeroelasticity in complex or non-conventional aerodynamic configurations.** In the military domain, a flexible wing mock-up integrating a missile on the wing tip and two large under-wing stores was designed and measured in the ONERA Modane S2 wind tunnel in the subsonic and transonic domains in 2005 [47], [48] (see Figure 25 left and Video 3 of a wind-tunnel flutter test on a military wing in complex configuration near the flutter point, before and after the flutter instability is detected and the automatic security system activated). In the civilian domain, a flexible mock-up of an innovative configuration for a U-shaped stabilizer (see Figure 25 right), that could also represent a wing configuration with a very large winglet, was tested in 2016 at the S2 Modane in the subsonic and transonic domains [49], [50], [51]. The main aim of these tests was to validate unsteady linearized CFD tools for flutter applications on complex and innovative configurations with large aerodynamic interactions. Figure 26 presents some calculation results compared with the measurements taken. They show a satisfactory correlation between the calculations and the tests. Since tests on the U-shaped stabilizer mock-up are recent (end of 2016), they continue to be subject to work in progress [50].

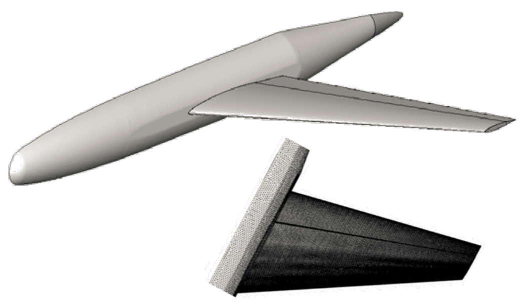
Even though each mock-up is subject to specific instrumentation, they have all been equipped with a large number of steady and unsteady pressure sensors (a few hundred or so), to enable an in-depth correlation between the CFD calculations and the measurements and to gain a better understanding of the aerodynamic phenomena encountered in the wind tunnel. Similarly, these mock-ups are equipped with accelerometers, strain-gauges and optical equipment to obtain the structural behavior from the point of view of steady and unsteady flexible displacements and internal loads. In general, these tests are carried out in two parts [49]:

- The first part, mostly oriented towards the "aerodynamic domain", in which we measure aerodynamic data (mainly by pressure sensors), on the basis of steady and unsteady globally-rigid (or partially-rigid) displacements of the mock-up (angle of attack, sideslip, control surface deflection), in a configuration where the mock-up is not subject to flutter for the various aerodynamic regimes studied.

- The second part, oriented towards the "flutter domain", where we vibrate the mock-up for variable aerodynamic regimes (Mach and dynamic pressure) in configurations, in which the







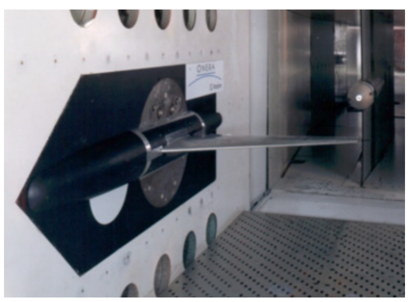


Figure 23 – Example of unsteady CFD validation for flutter prediction by wind-tunnel tests on a flexible mock-up (steady / unsteady aerodynamic + flutter tests).

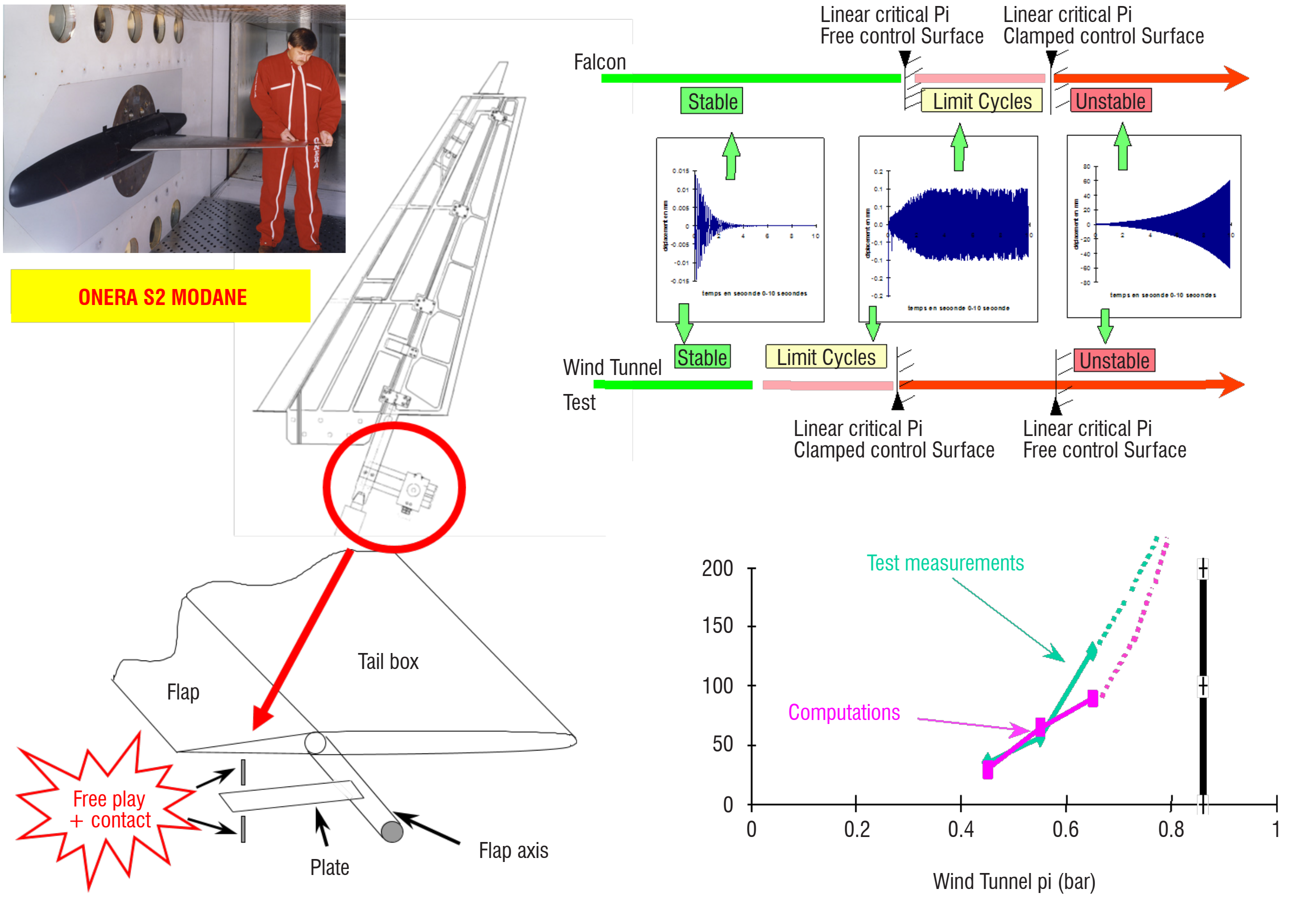


Figure 24 – Wind-tunnel validation of non-linear aeroelastic methodologies in the presence of mechanical free-plays (instability regions + LCO)

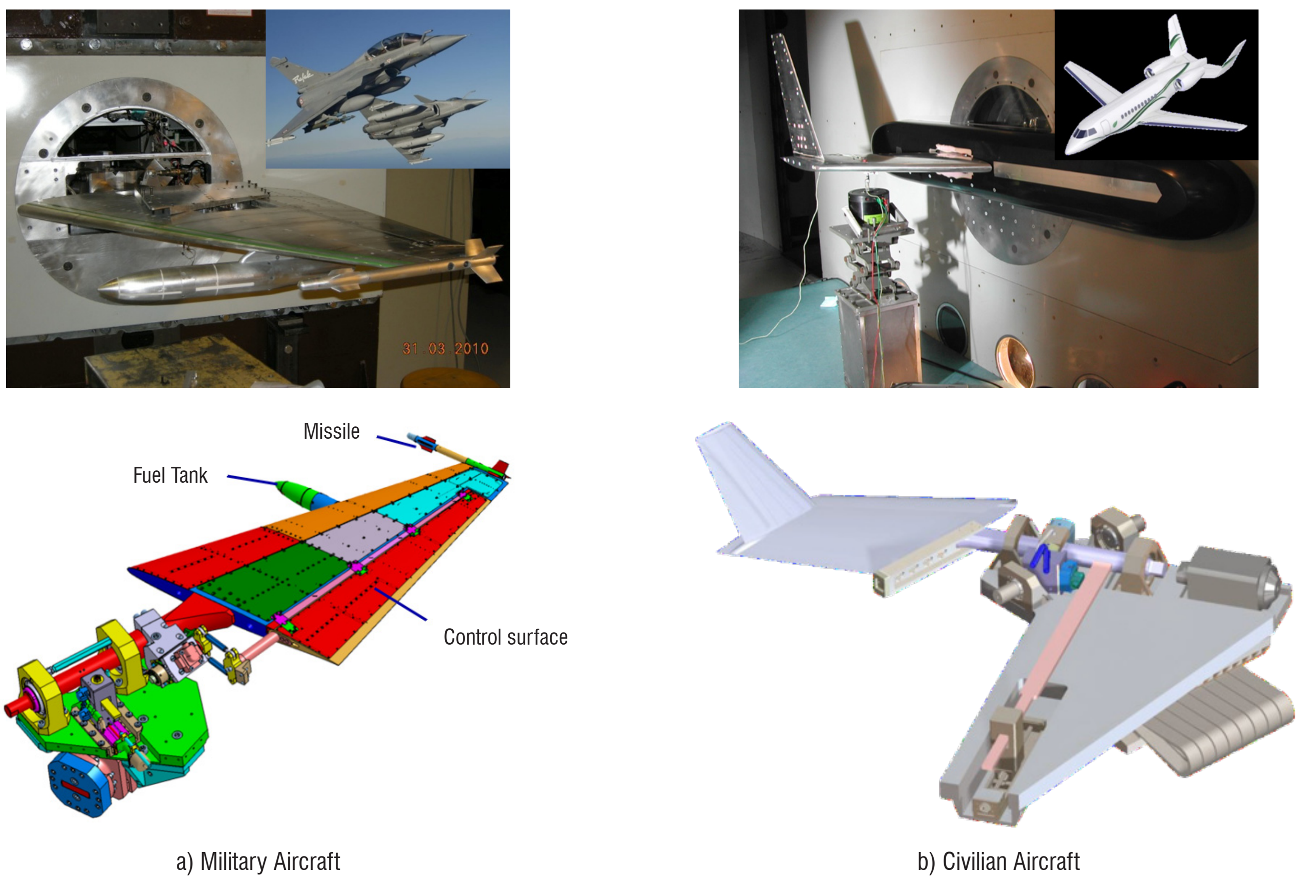


Figure 25 – Wind-tunnel validation of unsteady NS CFD applied to aeroelastic complex configurations: Test setup.

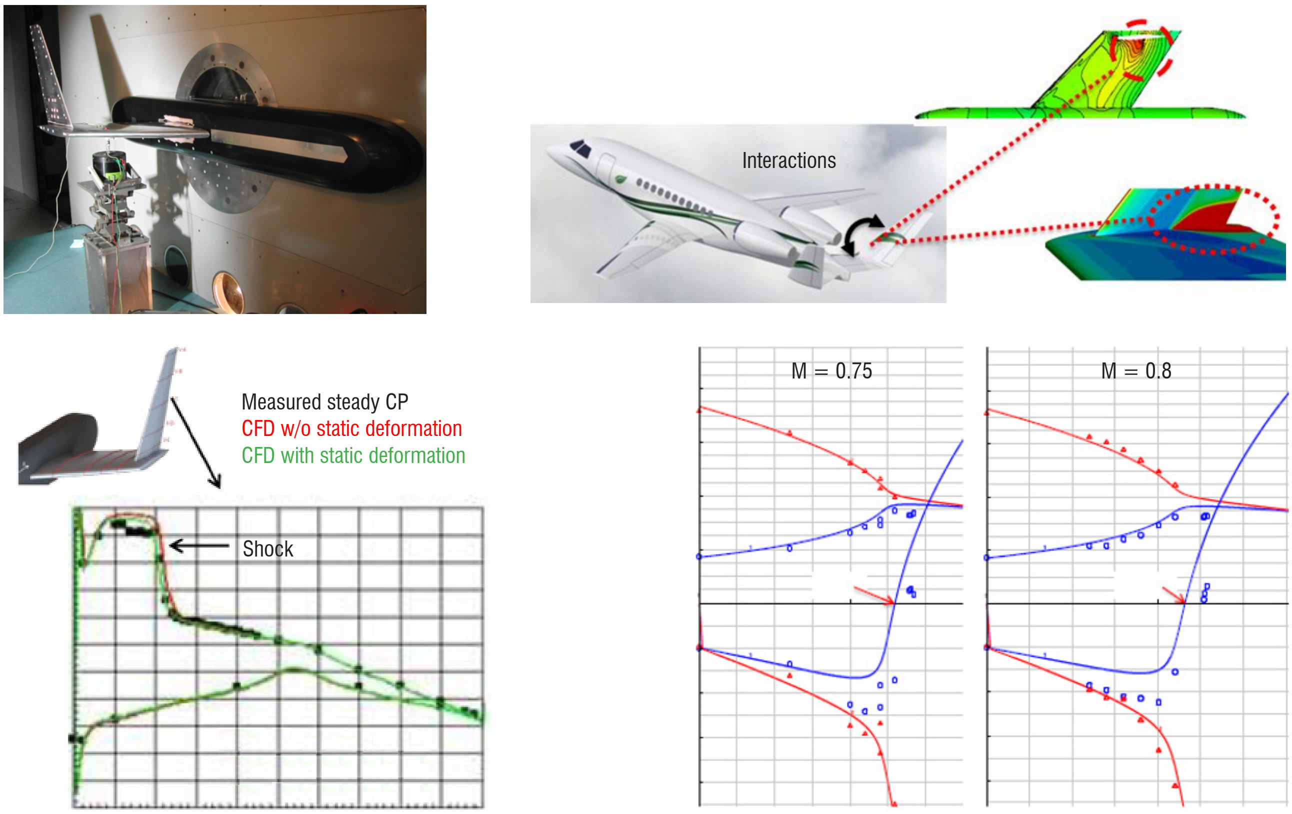


Figure 26 – Wind-tunnel validation of unsteady NS CFD applied to aeroelastic complex configurations: measurement / computation comparisons.

mock-up is subject to flutter. We measure and identify its aeroelastic modal behavior in the wind using techniques similar to those used during ground or flight vibration tests on aircraft [53]: identification by measuring the frequencies, damping and mode shapes of structural modes coupled with aerodynamics. During these "flutter tests", the measurements from the entire aerodynamic installation (pressure sensors, mainly) are also acquired, synchronously to with the structural measurements, for an improved correlation between the aerodynamic fields measured, the consequences of these fields on the aeroelastic behavior of the mock-up and the provisional calculations.

It is important to note that all of these mock-ups are equipped with a safety system that makes it possible to approach flutter points in complete safety in the wind tunnel (without running the risk of destroying the mock-up) [49]. In this manner, we can maximize the observations and measurements taken on the mock-up when the instability phenomenon is truly in place, and check that the critical flutter speeds calculated do indeed correspond with those observed in tests. All of this is not possible in real life during flight testing for aircraft programs, unless there is a major technical contingency or a highly-specific research program [54].

Finally, it must be emphasized that all of these test campaigns in wind tunnels on flexible mock-ups, which have given rise to significant advances in the field of aeroelasticity, would not have been possible without a close collaboration between Dassault Aviation and ONERA and the latter's know-how in terms of design, instruments and the implementation of this type of mock-up and testing.

ONERA, a key partner of Dassault Aviation for this type of study, is also in charge of the structuring, documenting, traceability, provision and data logging of the experimental databases that were built following these test campaigns. This is an important point and a crucial challenge for the future, given that these tests and the large volume of data that they generate (*i.e.*, dynamic phenomena over a large number of sensors) can lead to years of exploitation with a lot of feedback back and forth between the tool-development and validation activities and the measurement post-processing.

Lastly, we note that these wind-tunnel tests, which are intended to be methodological validations (and therefore, very well instrumented), are very costly and it is difficult for a single industrial manufacturer to bear such costs alone. These tests were made possible thanks to the support from the DGA, DGAC and the European community (the Clean Sky program in particular), as well as cooperation between the industrial players (Airbus, ONERA, RUAG, etc.).

Aircraft Ground and Flight Tests

These tests are used to calibrate and validate the aircraft aeroelastic models used during new military or civilian programs, for certification and substantiation purposes. The tests are performed on selected aircraft configurations, chosen from among the basic and most critical configurations. It is then accepted that the aeroelastic model, when calibrated, can represent other configurations that are not ground or flight tested.

Aircraft ground tests (static or vibration) are designed to calibrate the aircraft GFEM (*i.e.*, the "elastic part of the aeroelastic model") by measuring the strain gauge responses for a given set of static load conditions and by identifying the modal characteristics (frequencies and shapes) of the complete aircraft for dynamic excitations such as shaker forces, hammer impacts or control surface sine-sweep, or white noise excitation (as illustrated in Figure 27). They are also one of the inputs needed to open the flight envelope to facilitate monitoring by flight-test engineers and thus ensure the aircraft safety: the Ground Vibration Test (GVT) is, in some senses "seen" as the first flight point measured for the entire flight envelope. The fact that GVT is very well instrumented and that it allows "clear pictures" of the frequencies and mode shapes to be identified means that it is possible to keep only a minimal onboard Flight Test Instrumentation (FTI) in the aircraft to monitor the rest of the points in the flight envelope. Moreover, aircraft ground tests (static or vibration) are a means of compliance, as required by the CS/FAR 25, to determine the accuracy of the aircraft GFEM and validate its use in calculating loads and flutter.

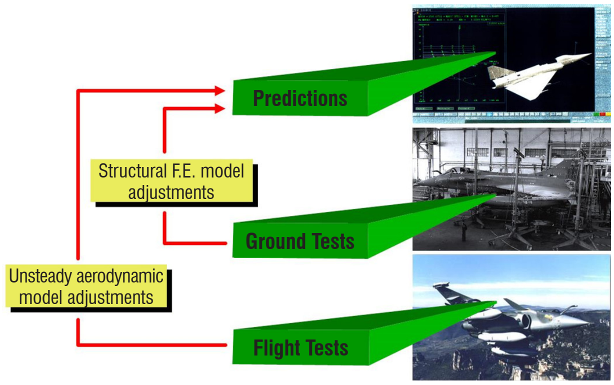


Figure 27 – Ground and flight test strategy to adjust aeroelastic models

Given that these tests are on the critical path for the first flight authorization of the first "prototype", there is a lot of work that needs to be done to adapt the ground test methods and organization, in order to reduce the time spent on the aircraft, achieve the required measurement precision, and prepare the future work on the correlation between all data obtained during those tests and the theoretical models. One of the major advances made by Dassault Aviation over the last decade was to propose a fully-integrated test team that reinforces the synergy between the test provider (SOPEMEA for Dassault Aviation), flight-test engineers, aeroelastic engineers and digital FBW control engineers, in areas such as experimental analysis tools, aircraft operations, result databases, pre- and post- processing, etc. (see Figure 28 for a typical installation). Studies are also in progress relating to the methods used to identify aircraft modal properties (on the basis of the Phase-Resonance Method [55] or the Phase-Separation Method [56]), to try to reduce their costs at iso-precision, and create hybrids of them using theoretical models or identification techniques that will be used also for flight tests.

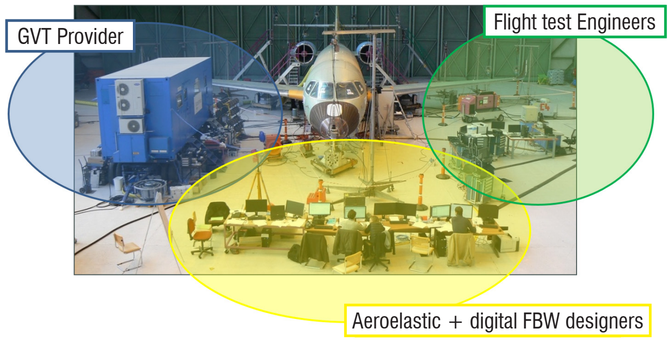


Figure 28 – Ground Vibration Test typical collaborative installation

Flight tests (maneuvers and control surface sine-sweep or white noise excitation) are used to calibrate the "aerodynamic part" of the aeroelastic model (as illustrated in Figure 27), by measuring the flight parameters, global aircraft parameters and aircraft structure responses (strain gauges and accelerations). They are a necessary means of compliance for the certification process of new military or civilian aircraft. The progress made at Dassault Aviation over the last decade in terms of aeroelasticity flight testing has mostly concerned Flight Test Instrumentation (FTI), the recording and onboard telemetry equipment and the post-processing of measurements, mainly with a dual objective:

- **During flights:** to allow flight-test engineers to improve their ability to analyze the aeroelastic behavior of the aircraft in real time, and to authorize progress in the flight domain during the flight tests, without having to land the aircraft for additional analyses and interrupt the flight. The progress made in this field has made it possible to drastically reduce the number of flights needed to open the flight envelope for aspects related to loads, flutter and aeroservoelasticity. Among the means implemented: Dassault Aviation's ability to run "light" aeroelastic models in real time in flight-monitoring rooms. These models are enriched by and recalibrated in real time with measurements taken during the previous flight points, which allow the flight-test engineers to have a real-time adjustment of the 'best prediction' of the aeroelastic behavior of the aircraft for the remaining flight points. As an illustration of this point, Figure 29 gives the flight forecast for the

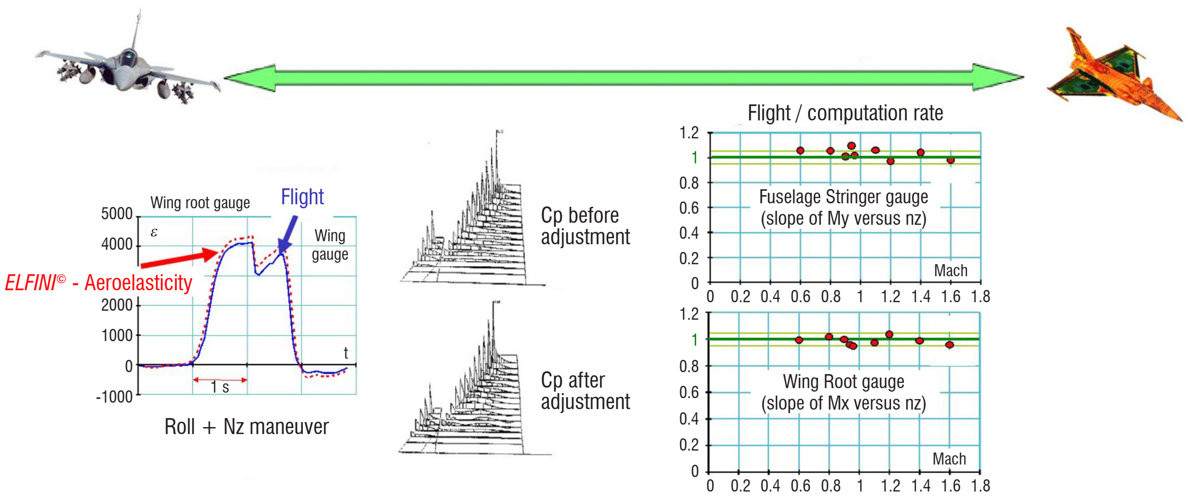


Figure 29 – Wing root load computed and measured during a combined "Roll + G" manoeuver on the RAFALE

RAFALE wing root loads during a combined "roll + G" maneuver superimposed in real time, in a flight-monitoring room, with the aeroelastic model forecast.

- **Once the flights are over:** to allow the flight-test engineers, in collaboration with the design engineers, to gain more confidence in the measurements taken, to identify trends and, above all, to understand the origin and the physics of the aeroelastic phenomena observed in flight on the aircraft. For this, the latest technologies in deformation measurement sensors (mainly optical sensors), load gauges and steady and unsteady pressure gauges were deployed on the most recent Dassault aircraft (F8X/F5X/nEUROn and RAFALE), which made it possible to noticeably increase the amount of information collected during flights. A specific "OCTAVE©" tool, whereby one of the modules is specialized in the analysis of aeroelastic vibrational phenomena and structural loads, was also developed internally at Dassault Aviation to process all measurements from flight tests. In addition to proposing a vast array of measurement processing functions, modal identification and post-processing tools specific to aeroelasticity, this tool makes it possible to easily compare many calculation results taken from the *ELFINI*© database with the test results, in an environment specific to aeroelasticity (see Figure 30).

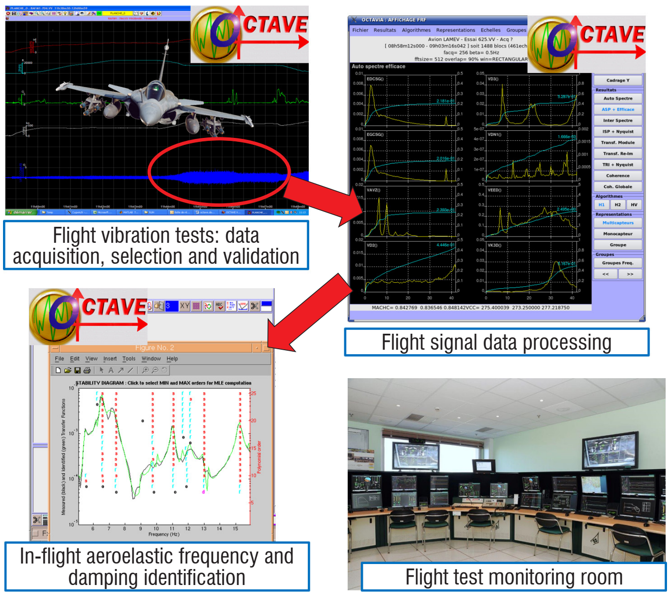


Figure 30 – Dassault Aviation OCTAVE© tool for flight-test vibration measurement processing (real-time and delayed-time)

Mathematical Calibration and Adjustment of Aeroelastic Models Based on Ground and Flight Tests

For the elastic and dynamic structural parts of the aeroelastic model, the adjustment techniques and tools were developed and fully integrated into *ELFINI*© during the 1980s for adjustment of the aircraft GFEM based on the strain-gauge information collected during static-calibration tests or on the vibration modes identified during GVT. An example of the application of such tools on a MIRAGE III/NG is given in [58]. In this case of structural finite-element model adjustments, the tuning parameters are physical characteristics of the structure through their representation in the finite-element model: thickness and area of structure-element sections, interface stiffnesses, material characteristics, etc.

During the 1990s, the main efforts at Dassault Aviation have been concentrated on tools to adjust the steady aerodynamic parts [57] to flight-test measurements and, more, recently the unsteady aerodynamic parts ([60], [61]) of aeroelastic models.

The mathematical "core" of the adjustment method that is used is an original identification technique [58], [59], which is based on "searching" tuning parameters "λ" (unknowns of the adjustment problem) as close as possible to their nominal (or presumed) values given by the theoretical aeroelastic model, with the requirement that the measurements be met by the model at a given accuracy "ε".

Applied to aerodynamic model adjustments in the scope of aeroelasticity (Figure 31):

- The adjustment parameters λ are either generalized steady or unsteady aerodynamic forces, or are directly the steady and unsteady components of the pressure field on the aeroelastic grid.
- The cost functions to be met are the model restoration with a given precision ε of the measured strain gauges during maneuvers or the aeroelastic modal frequencies and damping factors measured during flight vibration sequences.

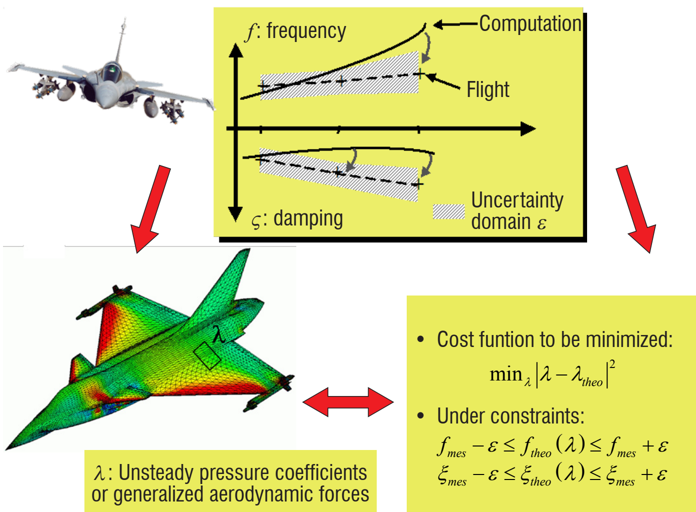


Figure 31 – Unsteady aerodynamic adjustments using flight-test data (aeroelastic frequency and damping values identified during flight tests): theoretical principles

This problem is then solved by a sequence of quadratic optimization problems.

Unlike the classic least mean square methods that solve minimization problems for cost functions, which is the distance between the aeroelastic model outputs and measurements, this approach has the considerable advantage of being "insensitive" to parameters under observation and trying to "stick" as close as possible to the "physics" of the theoretical aeroelastic model. If the bias of the model is too great, there is a clear statement by the method that it is impossible to reconstruct measurements by the model.

The true value of this method lies in the ability to detect potential critical flight envelopes or maneuver situations, far removed from the "quiet" calibrated test points. It has been proven that this procedure leads to a drastic reduction in the number of flight tests, as well as improvements in their safety.

To illustrate the application and the results obtained with this method for steady pressure field adjustments on the aeroelastic grid, an example of the adjustments made after a flight-test campaign on the RAFALE is given in Figure 29 above.

Another example of the application of this adjustment method for flutter analysis is illustrated through the adjustment of unsteady aerodynamic forces on the MIRAGE F1. This case study is well known at Dassault Aviation: it is currently used as a benchmark to validate new methods in the field of aeroelasticity. It should be noticed that, for the purposes of this case study, the dynamic elastic model is completely derived from an experimental modal base identified during a dedicated GVT, and then believed to be perfectly correlated with the elastic dynamic behavior of the "real" aircraft.

Historically, theoretical flutter predictions in the transonic domain ($M = 0.9$) were made for this aircraft using the traditional Doublet-Lattice method. The flutter results are given in the left-hand side of Figure 32 hereafter, and compared with the flight-test results:

As can be seen, theoretical flutter analyses give a critical speed that is substantially greater than the speed for the test. To improve the situation, the frequency and damping measurements for the first three flight points, for which the speeds are substantially below the critical flutter speeds, are used to adjust the steady and unsteady aerodynamic forces of the aeroelastic model. Flutter analysis using this adjusted aerodynamic model is shown in the right-hand part of Figure 32 hereafter. It is noted that the critical speed calculated with the adjusted model is now superimposed on the one approached during the flight tests.

Industrial Future Areas of Focus in Aeroelasticity R&D

The future areas of focus in R&D aeroelasticity at Dassault Aviation are primarily aimed at fostering innovation in all design and manufacturing domains (participating in the development of future technologies to better respond to customer and market needs), improve aircraft quality (performances, costs, safety, etc.) and to increase the reliability and efficiency of the calculation processes and methods used in design and certification. These areas of focus are strategic for a company such as Dassault Aviation and cannot easily be described in detail in an article of this kind.

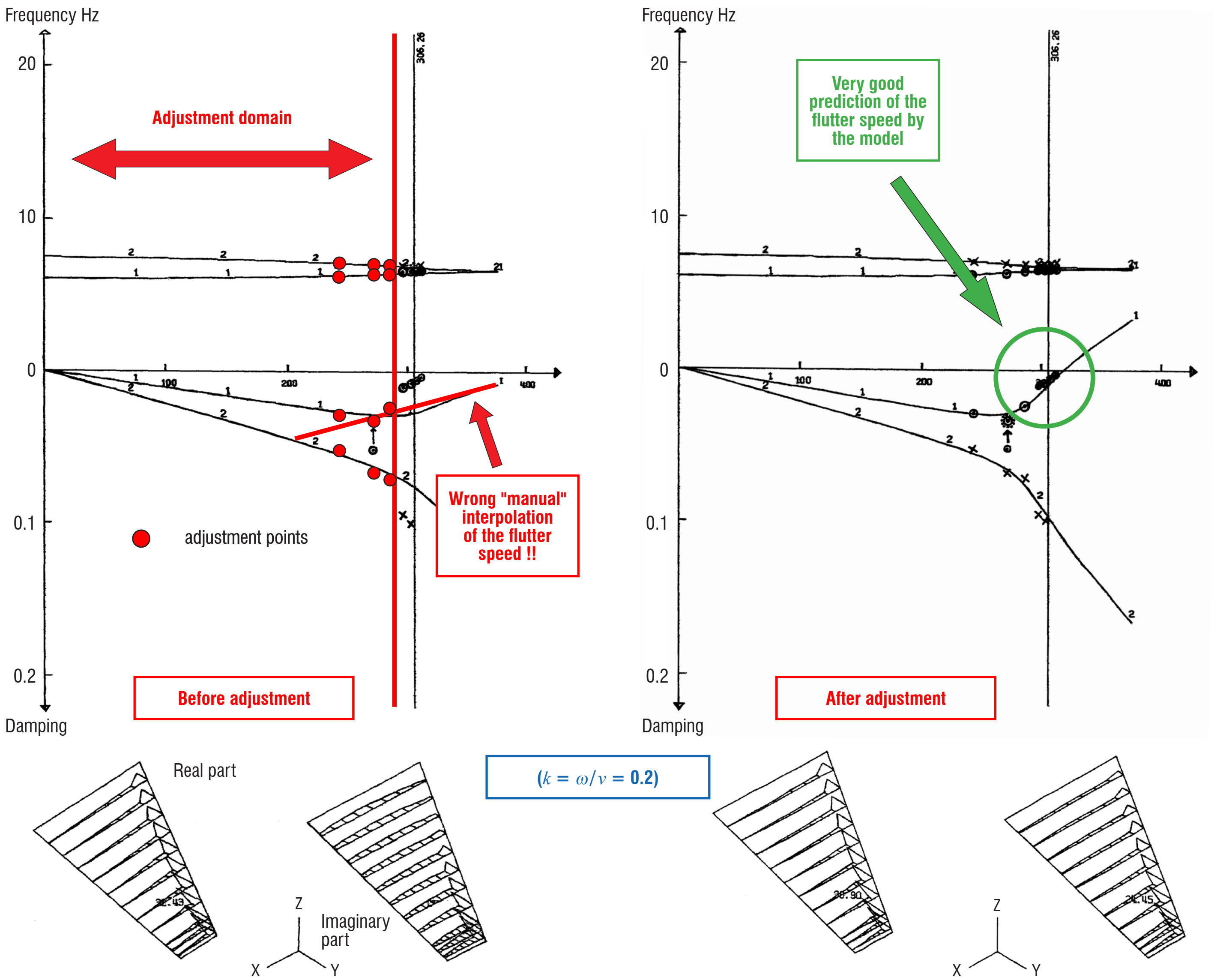


Figure 32 – Unsteady aerodynamic adjustments using flight-test data (aeroelastic frequency and damping values identified during flight tests): application to the MIRAGE F1 flutter analysis

In the following pages, a few select areas of focus in R&D are discussed in brief, and are not intended to be exhaustive. They mainly illustrate the importance of the challenges of aeroelasticity when preparing for the future.

Continuation of the CFD Development Plan for Aeroelastic Analysis

The improvements in the precision, effectiveness and applicability of the CFD aerodynamic prediction tools in the field of aeroelasticity remain THE key area of focus for future R&D developments in aeroelasticity.

While the use of Navier-Stokes CFD in aeroelastic analysis has truly taken off over the last ten years, with a host of advantages (see § "The great potential of CFD aerodynamic modelling"), a lot of work still remains to be done in understanding the characteristics of these tools and improving our use of them for real structure and industrial applications.

Many sensitivity studies (turbulence models, mesh density, etc.) have yet to be completed and summarized, based on simulations in the case of multiple applications in the civilian and military domains, or based on correlations with real test data (wind-tunnel or flight-test data). The aim is to clearly identify the areas of use and the limitations of the CFD tools in the industrial context of the aeroelastic analysis. The known limitations can give rise to additional developments to extend the applicability of CFD.

Given the "natural" increase in computing power, the ability of CFD to model complex flows around complex configurations will also be improved and therefore needs to be investigated. Non-linear aerodynamic phenomena on the angle of attack or Mach domain limits may be better captured, and this could give rise to new methodological studies and validation campaigns on the basis of real tests.

Finally, the arrival of new unsteady aerodynamic calculation codes linked to new approaches, such as the Detached Eddy Simulation (DES) [62], [63] (see Video 4 of a typical DES load computation on a Falcon with interaction between wing and horizontal tail plane at a high angle of attack) or the Field Velocity Method (FVM) [84] should give rise to a rigorous course similar to that already taken for Navier-Stokes CFD, based on their potential within the context of aeroelastic analysis (with respect to the other CFD methods). It is also the case for new turbulence models, which will continue to be enhanced and adapted for various aeroelastic computation and analysis "situations". While the potential for these new methods and models is great, they will need to be adapted to industry practice requirements in terms of aeroelasticity, so that their use in the aircraft project is industrially and reasonably permissible with respect to the calculation costs and analysis efforts.

In conjunction with these theoretical developments in the area of CFD, the in-flight measurement techniques, the calibration and adjustment techniques in the steady and unsteady aerodynamic fields must also be adapted to continue to enrich the theoretical aerodynamic predictions for real test results (wind tunnel and flight), which will be obtained through programs. However, we can reasonably assume that the improvements made to the precision of CFD tools would enable a future reduction in the number of tests needed to design and certify new aircraft.

Aeroelasticity of Laminar Wings

The integration of turbulent-laminar transition in CFD codes has been one of the key issues over the last few decades. The integration of transition in aerodynamic calculations makes it possible, firstly, to determine the drag coefficient in a rigorous manner and, secondly, to gain significant insight into the optimization of the aerodynamic design to reduce the surface friction drag on the aircraft: this is the wing concept known as laminar wings.

Nowadays, even though the design, industrialization and implementation of laminar profiles still pose a range of industrial and conceptual constraints on aircraft, there are now many demonstrators that are starting to appear (see the Clean Sky Project "BLADE" [87] or "ALFA" [88]), which are paving the way for the possible use of this technology in the future of commercial aircraft and business jets.

Recently, [64], [65] presented the results of a test campaign performed in a wind tunnel on a laminar profile. It was possible to measure the effects of the transition from the laminar flow to the turbulent flow on the aeroelastic behavior of the mock-up, and discuss and compare them with the behavior of the mock-up in a configuration in which the transition was fixed.

From an aerodynamic point of view, the measurements taken show that, in relation to the wing angle of attack, the lift coefficients have behaviors that are completely different when the transition is free (laminar wing), compared to when the transition is fixed. When the transition is free, the lift coefficients have a range of non-linearities according to the angle of attack, unlike the configuration in which the transition is fixed. The Mach evolutions of the lift polar curves are also extremely different between the cases in which the turbulent-laminar transition is free with respect to those in which it is fixed.

From a flutter point of view, these differences in aerodynamic behavior are reflected by [64], [65]:

- the appearance of additional flutter mechanisms on the "laminar" wing,
- the worsening of flutter mechanisms already present on the fixed transition wing at the "laminar" wing.

Given that these results show an atypical aeroelastic behavior of the laminar profile, we could have reason to believe that, in preparing for the future of laminar wings, improvements will need to be made with regard to:

- the predictability of CFD tools (particularly in the unsteady domain), to enable modelling of the aeroelastic behavior of these wings, which is just as robust as for "conventional" wings,
- the execution of wind-tunnel campaigns on flexible mock-ups to validate the aeroelastic calculation method for generic "laminar" profiles,
- the adaptation of the test procedures for flight-envelope opening to take into account the atypical aeroelastic behavior of these "laminar" profiles with respect to prior experience.

Analysis of the Aeroelastic Behavior in the Feasibility Phase

This important topic is given here as a reminder because it has been sufficiently discussed before in this paper in the context of the aircraft program objectives. The clear challenge here is to adapt "traditional" aeroelasticity tools and practices (*i.e.*, those that were calibrated to provide the precise quantitative data needed for aircraft commissioning, for the safety of the flight envelope opening and for drawing up certification and substantiation documents) to the "multidisciplinary" logic of the feasibility phase. In this regard, we want to prioritize the speed of analysis, the "agility" of the tools and practices in order to rapidly give trends and qualitative derivatives in "order of magnitude".

We note that this topic is closely linked to aerostructural optimization, with which it shares a certain number of objectives. In particular, the automated management of a lot of calculations with design parameter variations and their parallelization, as well as the analysis of these calculations in the form of response surfaces. This very rich multi-disciplinary environment in the feasibility phase is also a key matter in terms of the aerostructural optimization developments that we are aiming for (*i.e.*, multi-disciplinary optimization).

Aerostructural Optimization

Structural optimization is often seen as a design improvement approach which, for a given calculation cost, significantly improves a nominal drawing taken from a classic design process. When aerostructural optimization is applied to aeroelasticity, and in particular as part of the implementation of composite materials, it is a vital tool in finding a feasible optimum, without which design office know-how alone would be unable to find a solution that meets all of the specified constraints.

While optimization tools are now already industrially used at Dassault Aviation, and in fields as specialized as aeroelasticity, we are far from being able to use them without a minimal amount of understanding and practice. This also implies that, to implement these tools, the specialists in the field concerned need to be involved: design engineers and aeroelasticity engineers to formulate the problems and the detailed analyses; production engineers for their know-how; and optimization experts and code developers to build effective tools. We are still far from a "black box" process that is frozen in a recurrent application method and fully referenced: each set of problems will once again require, in the future, the implementation of adapted suitable resolution strategy and the development of reliable, and often specific tools. The optimization method must also continue to be enriched and adapted in line with the technological advances in materials and assemblies, as well as the manufacturing and machining processes. Therefore, in the future, we will need to retain a high level of agility and skills in order to develop, reconfigure and assemble the tools as per the user needs.

It is also essential to develop geometric aerostructural optimization in the future, both from an external aerodynamic shape point of view (planform variation, position and surfaces of the control surface, definition of the control surface rotational axes, winglet shapes, etc.), and from an internal architecture point of view (position and size of the main structural elements, such as ribs and stringers, for example). To do so, we could certainly take a great advantage from the ever closer links between finite-element modelling and the digital mock-up of the aircraft and the possibilities now offered by modern CAD software such as *CATIA*© in terms of geometric parameterization and the PLM database. Despite this, some technically difficult "local" problems need to be solved, such as the calculation of the steady and unsteady load sensitivity to any planform variations, and the use of geometric optimization for aeroelastic analysis, meanwhile, remains a challenge.

Introducing robustness considerations in optimization also seems of utmost importance and would involve taking into account the influence of uncertainties on optimization results. In general, the uncertainties raise questions about the appropriateness of real structures in relation to their specifications and theoretical models to reality. Converging towards an optimized drawing that satisfies the constraints in a "robust manner", while bearing in mind the uncertainties, also seems to be of key importance for the future of the aerostructural optimization field. This would imply an additional calculation cost and must, therefore, also be accompanied by a continuing research into improvements to the performance of calculation tools. The research literature is full of examples of the application of robust optimization methods for complex dynamic systems [67], which could be transposed to aeroelastic analysis in an industrial environment.

Finally, the aim is to integrate structural optimization into a wider optimized multidisciplinary design process (illustrated in Figure 33), extended to all aircraft design disciplines, for which it will be necessary to think about the most relevant strategy to exchange and integrate knowledge about the physics and constraints of interaction

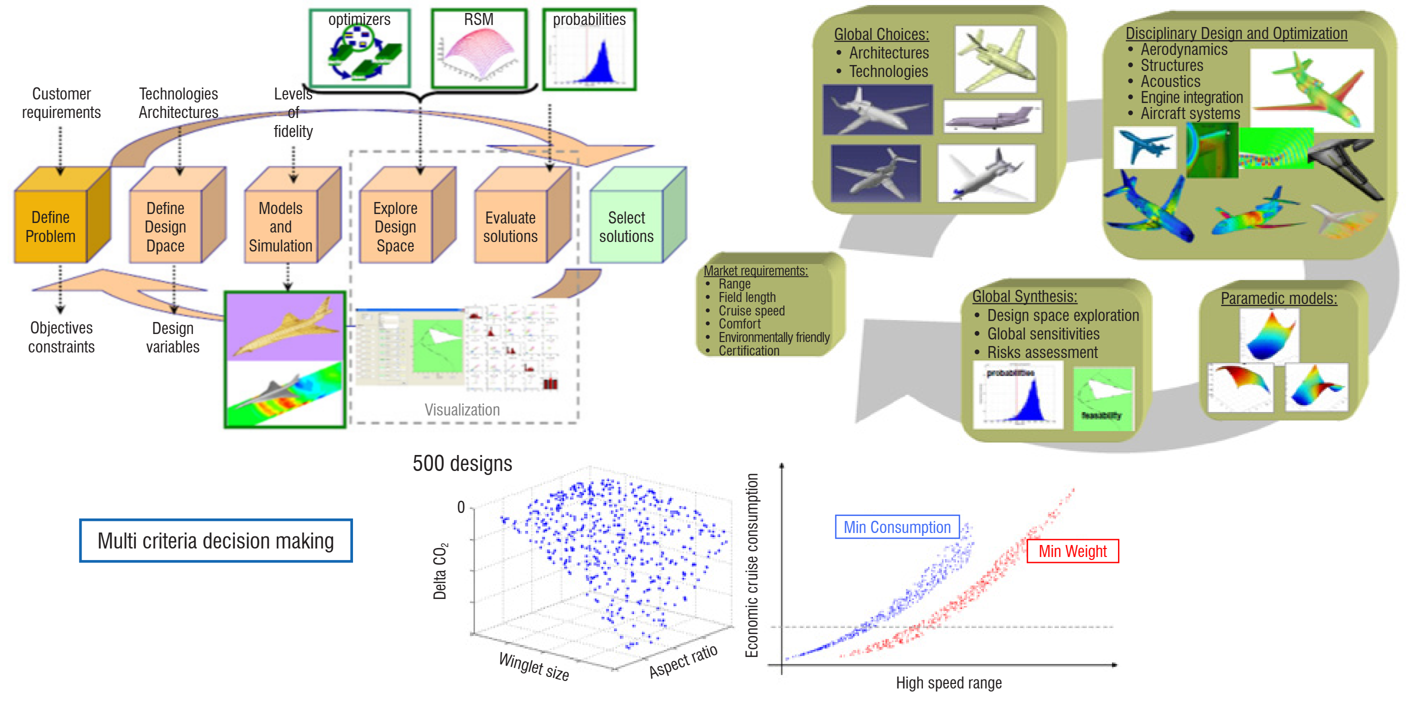


Figure 33 – Multi-Disciplinary Optimization: outline of the global process

domains: reduced models, condensed operators, meta-models ("surrogate" models), response surfaces, and so on. What should the use be? Which multi-level implementation strategies should be used? Which tools should be used to control the whole process and the convergence quality? The specialist literature is full of proposals and views for the future in this field.

Active Control of the Flexible Aircraft

As described before, the current practices in the field of aeroservoelasticity at Dassault Aviation mainly concern the design of notch-filters in the digital FBW control loops, in order to filter the flexibility information measured by the FBW sensors attached to the aircraft structure.

However, we note that the developments made over the last decade in the field of control system technology have been as important as those performed in the structural or aerodynamic domain. They concern sensor technologies, control law design/implementation methods, actuator technologies, modelling tools, etc.

This progress now offers promising perspectives for the future in fields as varied as: the "spatial" filtering of flexible modes into digital FBW control loops (when, for example, the flexible modes and the flight-mechanic frequencies overlap), the elimination of conventional lifting surfaces, load alleviation during maneuvers or when in turbulence or in discrete gust, the active aeroelastic damping augmentation system, or the improvement to the vibrational comfort when cruising. The example of the nEUROn and the lateral stabilization of this aircraft without vertical fin, using the digital FBW system, shows that some of these technologies are now attainable as part of aircraft programs.

We can reasonably think that the use of load alleviation techniques in the earliest phases of aircraft development should enable significant mass gains associated with improved performance. On aircraft that already exist, the implementation of FBW control laws to actively increase the aeroelastic damping should make it possible to avoid mass from being added that would have been necessary to stabilize the new configurations for a military aircraft heavily laden with external stores ([69, [70]) or to improve the vibration comfort during cruise or the aeroelastic stability of new version of business jets [70] to [73].

Given these potentials, Dassault Aviation has started to carry out prospective studies in the field of flexible aircraft control, with support from the DGA, DGAC and the European Community ([74], [75]). Among the challenges that were considered, the following stand out:

- The acquisition, as from the advanced phases of aircraft development, of aeroservoelastic models that are sufficiently precise and compact, and suitable for designing control laws. The readjustment of these models on the basis of ground and flight tests when these tests are available.

- The spatial filtering of flexible modes in overlap situations (or extreme proximity situations) between the aeroelastic modal frequencies of the structure and the frequencies of the flight mechanics.

- Control actuator and sensor modelling (including any non-linear or dynamic effects).

- The integration of a wide variety of flight conditions and aircraft configurations, as well as any uncertainty linked to aeroservoelastic modelling of an actively controlled aircraft; the analysis of the robustness of the envisaged control solutions regarding this variability.

- Research into new control architectures and also architectures for the corresponding equipment.

- The development of a Technology Readiness Level (TRL) ramp-up strategy, on the basis of demonstrators tested in a laboratory on digital test benches, in the wind tunnel or in flight.

- The certification methods of the implemented control technologies.

As an illustration of the first technical elements obtained, Figure 34 shows the gains attained by Dassault Aviation in a wind tunnel on an active aeroelastic damping augmentation system demonstrator whose purpose is to increase the flutter margin of a flexible wing on a heavily-armed military aircraft.

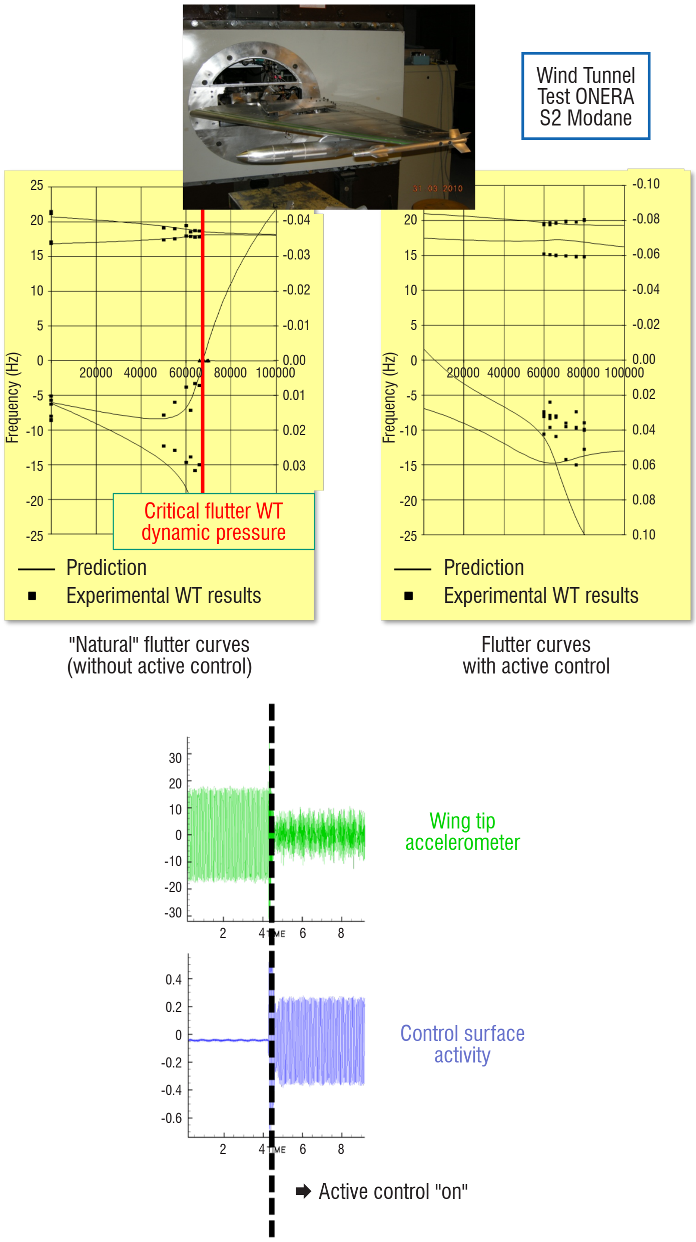


Figure 34 – Wind-tunnel demonstrator of a military wing active aeroelastic damping augmentation system

Figure 35, meanwhile, shows the reduction in pilot vibrations in the cockpit achieved during a real flight test by an active control system of a business jet using a combined elevator and aileron control system.

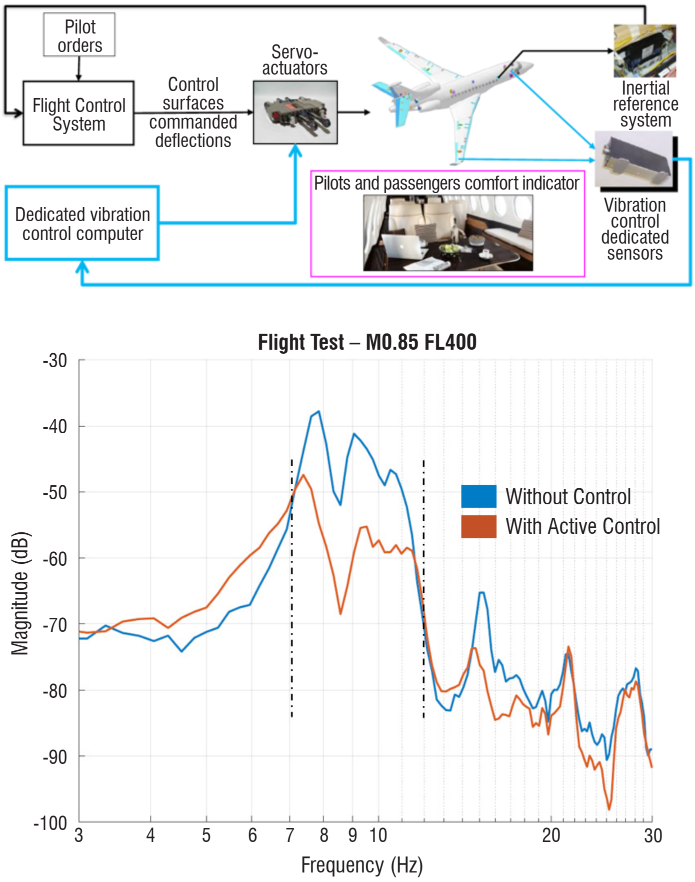


Figure 35 – Flight-test demonstrator of a FALCON active cockpit vibration control

Cooperation between universities and industrial partners is also a very important aspect to be taken into account in the field of active control for flexible aircraft, in terms of the new fundamental scientific aspects that it implies, the multidisciplinary nature of this field, and the need to effectively draw on skills existing in the academic and industrial world. The sharing of costs inherent in introducing design methods, validating them and demonstrating them on the basis of real tests in a wind tunnel or in flight is also a strong argument that speaks in favor of strengthening cooperation.

Integration of Uncertainties in Aeroelastic Analyses

It is generally acknowledged that the integration of uncertainties in aircraft design is part and parcel of "good design" rules. It makes it possible to provide rational arguments in the risk assessment and may be a pertinent guide in the decision-making for the fields of aircraft design and certification. It also contributes to the definition of a margin policy in the design method, to safeguard against complex and potentially hazardous phenomena, such as the stability of aeroservoelastic coupling or flutter.

The integration of uncertainties in the design process can also have an impact on the manufacturing quality control policy and on the maintenance procedures for in-service aircraft, to ensure minimal variation of the structural "key characteristics" from one aircraft to another (or at least to restrict these variations so that they remain within the limits considered during the design).

The notion of "robust design" (*i.e.*, less sensitive to uncertainties) is fully in line with this objective, as illustrated previously in the fields of aerostructural optimization and the active control of flexible aircraft.

When we speak of uncertainties for aeroelastic analysis, we are above all referring to the input data to build models: data that includes a scatter range either because it is naturally variable, random or misunderstood, or because it results from calculation inaccuracies in the upstream models. We can, for example, think of the material properties (particularly in the field of composites), geometric manufacturing tolerances, pressure fields, characteristics in terms of the mass, centering and inertia of external stores, the distribution of fuel in tanks and the characteristics of junction elements or assembly elements that are often non-linear and poorly understood or hard to model. Critical situations may therefore only appear for specific combinations of these parameters in this variation space. This is especially true for the flutter phenomenon [76].

Since the 1990s at Dassault Aviation, one approach for the integration of uncertainties has been to use optimization techniques and to have effective tools to automatically research potential critical configurations ("worst case configurations") in a space of uncertain parameters limited to predefined intervals [85]. In this approach, only the interval of variation limits for uncertain parameters are assumed, and there is no assumption made about the law of probability of the distribution inside these limits. The aim is to be protected against the "worst case configurations" using design actions, regardless of the probability of encountering these "worst case configurations", which may seem a highly-conservative approach.

This approach can be classified as belonging to the family of "robust" aeroelastic analysis methods, for which the μ-analysis method explained in Reference [77] is also included, and is often used in the industry for robust flutter analysis in its initial form or in a most refined one [79]. It is now industrialized and applied to the RAFALE when opening new external store configurations, or in the design of new FALCON aircraft.

One of the future areas for development in the domain of integration of uncertainties at Dassault Aviation, is to complete the methodology that is currently in place with a "probabilistic" uncertainty approach, which takes into account not only the limits of uncertain input parameter variations, but also the laws of probability of the distribution of these parameters within their interval of variations. The propagation of these laws of probability via the aeroelastic model must therefore make it possible to obtain the laws of probability for aeroelastic quantities as an output of the aeroelastic analyses.

There is a wealth of literature about the methods that could be applied in this context: Monte Carlo Simulation, Polynomial Chaos Expansion, Global Sensitivity Analysis, etc. [78], [80], [81]. The implementation of these methods within an industrial context will, of course, pose the question of obtaining laws of probability for uncertain input parameters using measured or simulated data. This is particularly the case for uncertain parameters relating to pressure fields [78], structural damping or the presence of non-linearities.

Another important topic is that of the construction of "light" metamodels using detailed aeroelastic models, in order to use uncertainty propagation methods with calculation costs that are permissible in the design cycle.

Control of Future Non-Conventional Configurations

The past and recent history of the latest developments in terms of new projects (see Figure 36) are sufficiently rich for us to readily believe that aeroelasticity will continue to play a key role in the future in promoting the design and certification of new unconventional configurations.

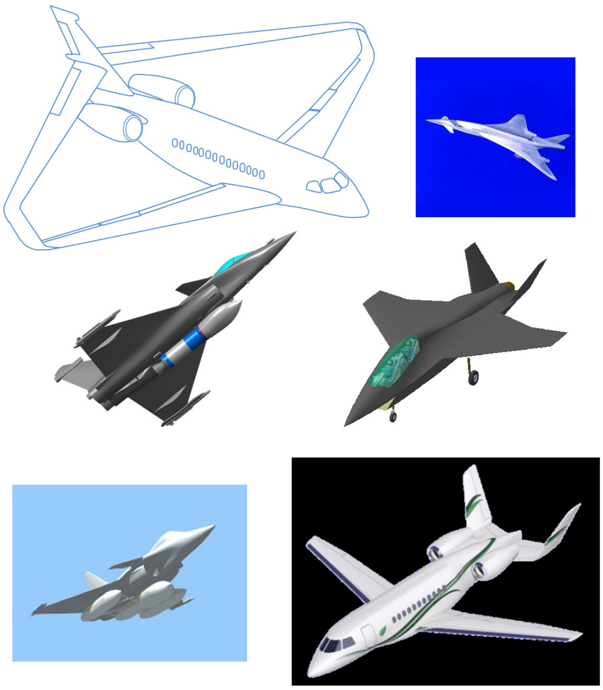


Figure 36 – Examples of future potential unconventional configurations that should be validated to check the expected aeroelastic behavior

If we want aeroelasticity to continue to play its role efficiently and not hamper innovation, then the methods, tools and procedures for numerical and experimental aeroelastic analyses will need to continue to evolve, as well as the corresponding human organization and skills. This is so that we can anticipate the technological breakthroughs being prepared in the field of materials, new structural and aerodynamic architectures, and in the field of sensors and control systems, which will be the precursor of the appearance of entirely new configurations for the aircraft of the future.

Conclusions

This paper presents a review of the industrial current practices at Dassault Aviation in the field of aeroelasticity for military aircraft and business jets.

It shows, in particular, how the issues relating to aeroelasticity have continued to take an ever more decisive role in the design process for aircraft over the last few decades, in light of the research into aerodynamic, structural and systems architectures that are more and more innovative, which has merely reinforced the potentially major impacts of aeroelasticity on the risks, costs and deadlines for new aircraft programs. Aeroelasticity is now seen as one of the main disciplines in design, and as one of the "critical" processes in the aircraft development logic.

This highly-challenging context has been the source of major and constant modifications in the field of aeroelasticity since the 1990s at Dassault Aviation. This is both in terms of industrial practices, the numerical and experimental methods used, the calculation process, model adjustment and validation strategies, as well as the human organization of skills. This paper has looked at the principles and key ideas drawn from some industrial cases of application in the military and business jet domain.

There are a few points that deserve to be highlighted given their importance:

- The time and effort required by each aeroelastic analysis loop (load determination, flutter analysis, etc.) significantly contribute to the total aircraft design and certification cycle. They stem mostly from the examination of a very large number of calculation cases. This has directed the development and introduction of new methods primarily directed towards linear or linearized methods, which help to reduce the calculation costs, facilitate the entry into a global and modular process that can be parallelized, and thus conserve maximum efficiency in the resolution of large aeroelastic analysis loops.

- The introduction and generalization of the linearized Navier-Stoke steady and unsteady CFD tool in all aeroelastic analysis branches has enabled significant gains in precision with respect to the traditional Doublet-Lattice methods, notably for complex configurations or specific aerodynamic regimes, all the while conserving the effectiveness of the global industrial analysis process. The use of CFD has massively contributed to minimizing the risks of underestimating loads, and reduces the efforts to readjust steady and unsteady pressure fields on the basis of wind-tunnel tests or flight tests on the aircraft, at a late stage in the programs.

- The growing importance of active control technologies and of the "servo" in the aero-servo-elastic domain, at each stage of the aircraft project. Introduced early in the program, these technologies should enable significant mass gains associated with improved performance in the future. On in-service military or civilian aircraft, they should make it possible to avoid mass from being added or aircraft architecture modifications that would have been necessary to stabilize new evolutions of existing configurations.

- We are now seeking to adapt the aeroelastic tools and practices to the specific environment, according to the rate and short duration of "multi-disciplinary" design loops in the feasibility phases. This is to take into account aeroelastic derivatives as soon as possible, in the early stages of the design, and to analyze the consequences for the aircraft performance and the relevance of the various architectures and trade-offs envisaged. During the upstream design phases, the use of tools such as aerostructural optimization has already proven to have many advantages.

- In parallel to the calculation processes and methods, it will be necessary to continue to develop the experimental techniques (ground, wind-tunnel, or in-flight techniques) that will continue to play a key role in the future in validating methods and models.

In the future, aeroelasticity must continue to evolve at the same rate if it is to avoid hampering innovation, and if it is to remain one of the means of innovating and seeing the technical breakthroughs of the future reach maturity.

To conclude, we must remember how important inter-industrial and academic cooperation are in the field of aeroelasticity, together with the support of Governmental or European agencies, with respect to the new scientific and fundamental aspects that they involve, the multi-disciplinary nature of this field, and the need to use existing skills effectively. The sharing of costs inherent to the introduction of new analysis methods, their validation and their demonstration on the basis of real tests in wind tunnels or during flights is also a major argument that speaks in favor of increased cooperation between industrial manufacturers ■

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