Tutorial on the Needs to Incorporate Aeroelastic Aspects into the Conceptual Design Process

(Received: Dec 2, 2012. Revised: Dec 14, 2012. Accepted: Dec 14, 2012)

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Abstract
The paper gives an overview on potential impacts from aeroelasticity on the definition of global aircraft design parameters, on the vehicle's mass properties and on performance data, as well as inverse views from aircraft design requirements and global configuration design parameters on the possible magnitudes of aeroelastic impacts. Some examples are shown, where aeroelasticity was essential for the success or failure of projects. This also includes a review of engineering methods to identify and quantify aeroelastic effects and their interactions with other disciplines. The last sections deal with the difficulties to establish the proper analytical models and generate the required input data for aeroelastic analysis at the start of a new project.

1. Introduction

Long before the expression aeroelasticity was created, its steady and unsteady effects resulting from the interactions of structural flexibilities, aerodynamic forces, and inertia forces were investigated by some of the pioneers. Otto Lilienthal carefully studied bird flight to build and improve his gliders. Among others he was also in correspondence with Alois Wolfmller, the buyer of his second production glider "Normal-Segelapparat" (common soaring apparatus) in 1894 about improving the performance and manoeuvrability by actively controlling the structure's deformations [1, 2]. Based on these ideas Wolfmller built and tested his own airplanes, like the "Gleitflugapparat" in Figure 1, which is today on display at the "Deutsche Museum" in Munich (collection at the Flugwerft Schleiheim). This design allowed the pilot to control elevator, rudder, and moveable leading edge devices on the lower wing via a chest harness. In addition, he could manually change the wing camber.

Probably the most famous and widely published examples for beneficial or disastrous aeroelastic impacts on flying vehicles are the "wing warping" concept for roll control on the Wright Flyers and the unfortunate attempts by Samuel P. Langley at the same time with his Aerodrome vehicle. Whereas the Wright Brothers' success can be attributed to their skills in light weight design from building bicycles and the intentional exploitation of aeroelastic servo effects on a flexible structure to create control forces, the Aerodrome's structure failed twice in the catapult launches from the roof of a house boat after the design had been scaled up from a successful smaller design, which was steam powered and unmanned. According to most authors this failure can be attributed to structural divergence of the wings because of insufficient torsional stiffness (which could however not be confirmed in some analytical studies), because of buckling instability (caused by aeroelastic load amplification?), or an initial failure in the substructure because of touching an obstacle at take- off ([3, 4, 5, 6]. Looking at the picture of the scaled model of the Aerodrome in Fig. 2 implies another possible reason for the disintegration: missing stiffness of the fragile fuselage structure between the twin wings.

Some years later, during the First World War, Anthony Fokker had to experience how the increase of safety concerns by certification authorities can result in the opposite effect because of aeroelasticity. As he described it in his biography "The Flying Dutchman" [8], the military authorities had asked for a

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doi:10.3293/asdj.2012.22

Figure 1: Alois Wolfmller's Gleitflugapparat

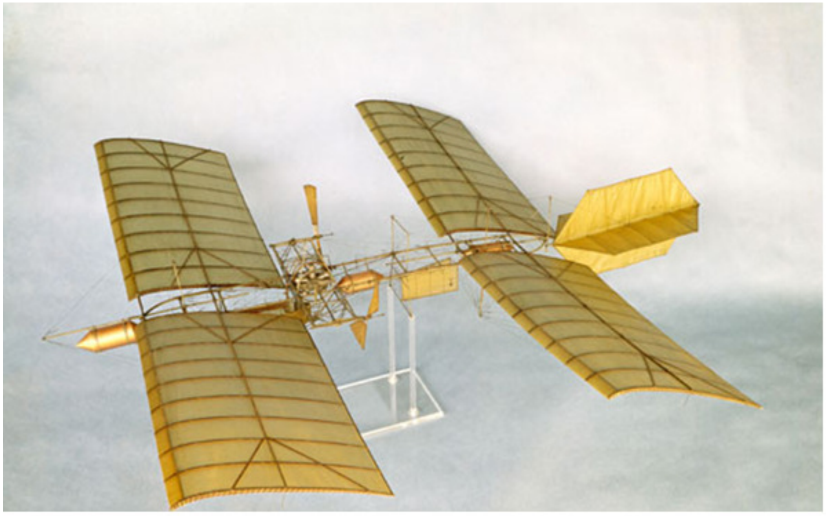

Figure 2: Aerodrome scaled model

fail-save re-design of the wing attachments to the fuselage for the D-VIII model, which was solved by a reinforcement of the rear spar. The result was a shift of the elastic axis, causing the wings to diverge at high speed and killing several pilots before this effect was uncovered by load tests on the ground.

Aileron reversal as another basic aeroelastic effect is described by Prof. Hodges in [9] as a serious problem on the Bristol Bagshot, Figure 3, in 1927. The problem was analysed and solved by Cox and Pugsley from the Royal Aircraft Establishment, who also proposed the name "aeroelasticity" for the first time for this kind of phenomena. The issue was solved in this case by a single-spar wing design, as reported in [10]. It is typical for these early years that such phenomena were only analysed after more or less serious incidents and accidents had happened. These findings were then "translated" into design guidelines and handbook methods.

Once the theory was better understood, based on experiments and simple models for the structure and the aerodynamic forces, the challenge in the following decades was that the required computing power for sophisticated analytical models did not yet exist, especially for the efforts to predict the structural dynamic characteristics (Eigenmodes and –frequencies), and, even more than that, for the unsteady aerodynamic forces which are created by the oscillations of the structure in these modes at various speeds of flight.

Figure 3: Photograph of the Bristol Bagshot

It was more or less mandatory or at least "best practise" in the following years to build aeroelastic wind tunnel models as early as possible in the design process to improve the design and avoid bad surprises. Dr. William P. Rodden, the author of the most recent and most comprehensive book about Aeroelasticity [11] once told the author of this paper that this common practice was ignored for the design of the Convair Coronado jet aircraft. When the need for an aeroelastic wind tunnel model was finally uncovered to resolve the flutter problems it was already too late for a successful participation in the new market of passenger jet aircraft.

Finite Element Methods for structures and similar numerical aerodynamic analysis methods (Vortex Lattice, Doublet Lattice) were developed more or less in parallel with the development of digital computers, Starting in the 1960s, the availability of computers, appropriate software, and then also the introduction of composite materials with directional stiffness properties paved the way to perform aeroelastic analysis in early project phases. This enabled the designers to include aeroelastic effects already very early in the design process and minimize "aeroelastic weight penalties" by means of "Aeroelastic Tailoring" [5], or even to exploit aeroelastic effects again like the Wright Brothers and other pioneers had done it before Among others, this was demonstrated on the experimental aircraft X-29 with a forward swept wing [5], and in the X-53 Active Aeroelastic Wing (AAW) program [12], where an early version of the F-18 wing was uses to demonstrate the creation of control forces by actively twisting the wings. The initial F-18 wings had been too flexible and required structural reinforcement and other modifications to achieve the required roll rates at high speed.

Although analytical tools were already in a very mature status in the 1990s, the lack of careful analysis during the design caused the cancellation of the Dark Star UAV program because of a dynamic instability which still existed 26 months after the crash in the second flight [13]. This was one of the reasons that the Global Hawk was finally the winner for the HALE UAV programme in the USA. Improper or too late aeroelastic analysis for new design even seems to happen more often today than some 20 or 30 years ago. The following chapters will help to identify some of the reasons for this situation, and show some approaches that help to improve this situation.

2. The classical conceptual design process

Conceptual design for airplanes starts with an empty sheet of paper and some inputs from operational research. The objective is to deliver a design that meets all requirements and needs no re-iterations during or after the preliminary design phase. The probably most important quantities in conceptual design are:

1. wing area loading (m/A) or (W/A),

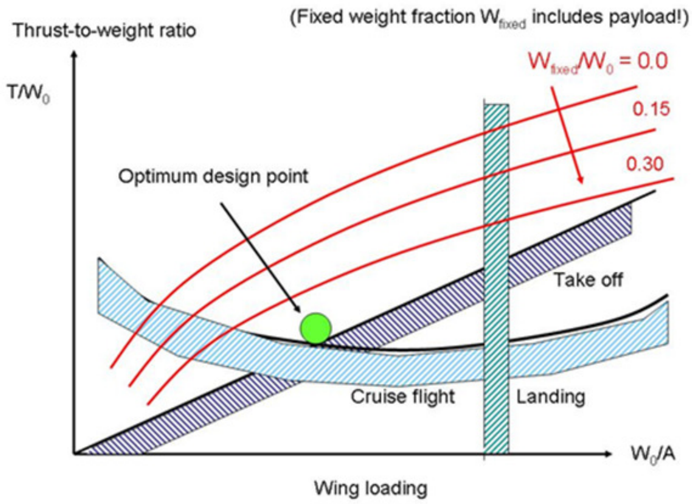

Figure 4: Typical example for sizing optimization diagram

2. thrust-to-weight ratio (T/W).

These quantities describe the relations between the essential forces acting on an airplane at equilibrium conditions: lift and weight in vertical direction, and aerodynamic drag and thrust in horizontal direction. The mass m (or weight W) is usually based on the maximum take-off weight (MTOW) and A is a theoretical wing reference area. The T/W ratio is usually taken at cruise conditions. Although it is not visible these quantities already include a lot of aerodynamic assumptions and "optimization" for the best basic geometry parameters of the vehicle, especially for the wing and for the total aircraft size and shape. On the other hand these aerodynamic quantities also include effects from the required mass of the vehicle. This is for example the case for finding the optimum flight speed for minimum aerodynamic drag, or, if approached from an already preselected cruise speed (dynamic pressure), to find the proper geometry parameters (and vehicle mass) to achieve optimum aerodynamic conditions.

The optimum values for T/W and m/A are found by first assuming the mass ratios for the fixed and variable masses, and then, if the initial assumption for the structural mass is not met in the initial aircraft sizing process, to re-iterate these data with a new assumption for the total mass. But it should always be kept in mind that this as all based on simple assumptions, where the "required" structural weight is found by means of statistical data for the same type of airplanes, by semi-empirical methods, or by handbook data. This process does not include any analysis for the real loading conditions on the structure for sufficient strength capacity, or for the required stiffness to meet aeroelastic requirements.

A typical example for a sizing optimization diagram is depicted in Figure 4. It should be noted that the location of the optimum strongly depends on the already preselected wing geometry parameters which define the aerodynamic characteristics, and that these parameters also have strong impacts on the required mass – from static loads as well as from aeroelastic stiffness requirements. Aerodynamic quantities for these equations can be rather easily generated in the early design phase - by simple handbook methods as well as by more or less refined numerical methods (CFD), and it is also common practice to confirm them very early by wind tunnel tests. But there is a huge gap in capabilities to assess the required structural mass by analysis, and to quantify aeroelastic impacts on the aerodynamic characteristics and on stability and control needs.

Although books on conceptual design like the one from Raymer [14] mention essential impacts from aeroelasticity on performance, stability & control,

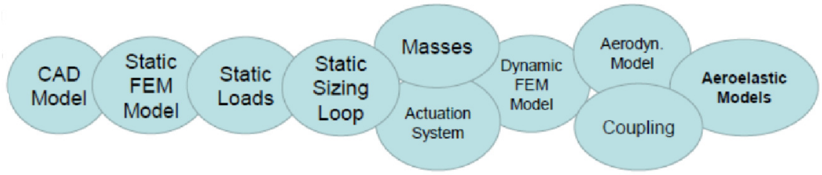

Figure 5: Aeroelastic model creation steps

with typical values ranging from zero aileron roll control effectiveness (aileron reversal), and losses in the pitch and yaw stability derivatives as high as 50 percent, the required efforts to quantify these effects early in the design process are still ignored today in many cases. The reason for this is usually that adequate analytical models are not available, and no proper tools exist to create them.

3. Some easons for the lack of structural and aeroelastic analysis in the conceptual design process

Although very accurate and realistic looking computer aided design (CAD) models are created and refined during the conceptual design process, there is no confirmation that the external geometry, the structure, and the basic equipment, which are shown in these 3D drawings, will finally be able to meet the requirements, or that the chosen essential design parameters actually have their optimum values - because no adequate coupled structure – flight physics analysis is performed. Reasons for this gap can be:

1. It is common practice today to create analytical models for the structure from CAD models, usually by means of powerful pre-processor tools. But the more refined the CAD model is already, the more time and efforts will be required to create the analytical model.

2. Once the complex analytical model finally exists no-one wants to change it any more.

3. The complexity of these analytical models is so high that it is impossible to create or use them within the typical time and budget constraints for conceptual design efforts.

4. These high efforts have created a "first time right" mentality for the creation of analytical models, which unfortunately results in a much too late detection of deficiencies.

5. The "official" processes for the creation of aeroelastic models is today often based on a strictly linear approach, as indicated in Figure 5. Each sub-process, which is required to create the "official" aeroelastic model, will only start after the previous sub-process is completely terminated.

The last bullet above also indicates that this approach easily creates a Catch-22 situation for the performance of aeroelastic analysis and for feeding back its results into the design process. This can easily be seen only by looking at the mass data, which is required to create analytical structural dynamic and aeroelastic models. The first set of mass data, which is required to build the aeroelastic model, must be created by a structural sizing loop for sufficient strength. In order to do this, a complete set of "official" design load cases and input data for them must exist. In order to create the loads data for structural sizing, the "official" mass data must already exist, and so on. This shows that a "first time right" approach is not possible, and that it is also not desirable at all at the conceptual design level of project maturity.

4. Some examples why aeroelastic effects are essential for the global design concept

4.1 Static aeroelastic impacts on the required empennage size and mass

As already mentioned above the loss of longitudinal and lateral static stability from structural flexibilities of the empennage itself or from the fuselage can be considerable. If this is detected too late the size of the tail surface or the moment arm from the centre of gravity must be increased. This will increase the mass of the tail and shift the centre of gravity and require a relocation of the wing. This in turn reduces the moment arm again, or it requires to counterbalance the additional mass by the relocation of equipment. If this is not possible anymore, dead balance mass must be added in the nose of the airplane.

To increase the stiffness of the structure in order to achieve the required tail effectiveness by structural "sizing" optimization also requires additional mass, and, if the desired effectiveness is too high, it can have an asymptotic behaviour. It is. a great advantage to know these sensitivities and add the geometric stiffness of the external geometry to the available design variables.

4.2 Optimum wing span, spanwise lift distribution and loads interaction with the required wing mass

The "optimum" wing span is usually determined very early in the conceptual design process, however without the impacts from the required structural mass, and without taking loads interactions with structural deformations into account. Also the optimum aerodynamic load distribution along the span for minimum drag is usually determined by aerodynamic considerations only. As it is widely known, the elliptic distribution will have the lowest lift-induced drag. This is however only valid, if the span is already fixed. If the span and the required structural weight are also taken into account, a higher span with higher load on the inboard section and lower load in the tip region will result in less drag. This fact was already published by Ludwig Prandtl in 1932[15], but it is still often forgotten or ignored today. Aeroelastic load redistribution effects resulting from the basic wing geometry (sweep angle) or from the chordwise location of the (virtual) elastic axis along the wing span can have considerable impacts here too - intentional and beneficial, if taken into account early in the design process, or unintentional and unpleasant, if the effect is discovered too late.

4.3 Aileron size, shape, location, and structural stiffness

The Active Aeroelastic Wing (AAW) research programme [12] successfully demonstrated the exploitation of aeroelastic load redistribution for enhances rolling moment effectiveness at high dynamic pressures. Whereas an aileron which is located at the trailing edge of the wing has a clear advantage over a leading edge surface for rigid conditions (or at low speed), the leading edge surface location shows benefits with increasing speed from the favourable deformation of the main wing, whereas the aileron at the trailing edge will always show decreasing effectiveness at higher dynamic pressures. In the case of the AAW demonstrator aircraft X-53, additional leading edge surfaces were used for roll control and the trailing edge aileron was used beyond the reversal speed by reversing the sign in the flight control laws.

It is rather well known that a conventional outboard aileron is more prone to aileron reversal than an inboard control surface. If a trailing edge control surface is designed to extend along the whole span of a wing, this knowledge may lead to the conclusion that it is better to use a control surface shape with a high inboard and a small outboard chord length. Fact is however that if the control surface chord length is increased at the outboard location, the chord length(and the area) of the fixed part of the wing in front of the control surface, which twists in the opposite direction gets smaller and has therefore a smaller detrimental effect. This fact was for example used in the early phases of the Eurofighter programme to achieve better rolling moment characteristics by increasing the outboard flap chord.

The possible impacts from Active Aeroelastic Wing technology on conceptual design were demonstrated in a classic paper by Flick, Love, and Zink in 1999 [16]. If properly applied to a conceptual design, the complete vehicle size and mass can be reduced considerably by snowball effects.

4.4 Required flight control actuation power

It is a requirement to avoid aileron reversal within the flight envelope. In order to reduce the required actuation power it is advisable to design the airframe for a higher aileron effectiveness because this will reduce the hinge moment and therefore reduce the power demand for the actuators. This will not only help to keep the mass of the actuation system small but can reduce the size of fairings for the actuators external to the wing surface and therefore reduce the aerodynamic drag.

It is also an advantage to know the required actuator dimensions early to avoid aerodynamic losses from the dimensions of the required actuator fairing at a later phase in the project.

4.5 Additional vertical tail design aspects

Static aeroelastic effectiveness has an essential impact on the required size of the vertical tail and rudder. The loss of effectiveness results from deformations of the tail surface but also from the flexibility of the fuselage. A good trade-off between reinforcement of the structure and changing the size and shape of the tail surface is therefore essential already at the beginning of the project. In addition to a horizontal tail surface, the vertical tail effectiveness is also reduced by the fuselage torsion stiffness.

Vertical tail buffeting is another essential design consideration for highly manoeuvrable airplanes. This applies to the decision for a single or twin tail design as well as to the position of the tail relative to the vortices that separate from the wing fuselage intersection. Besides the structural loads, these vibrations can also have severe impacts on equipment mounted on the tail surface. This applies to simple equipment like position lights as well as to antennas or other sensor systems. Any additional mass near the tip will increase the buffeting vibration levels.

4.6 Positioning of equipment on or in aerodynamic surfaces

The position and mass of any equipment at or near the tip of any aerodynamic surface can have very essential impacts on the flutter stability – detrimental as well as beneficial. In general, a forward position will be better than a rear location. This should be kept in mind when making decisions for the location of equipment on any surface.

4.7 Engine and external store location impacts

The integration of engines and external stores on a wing has even more important aeroelastic aspects than internal equipment. Because of the higher mass and their position outside of the wing's planar surface, the high mass moment of inertia about the wing's elastic axis will not only cause changes to basic Eigenmodes and frequencies of the wing It will also introduce additional modes that will reduce the flutter stability. The knowledge of these characteristics will help to find the optimum positions for minimal impacts on the required additional mass to increase the wing's stiffness.

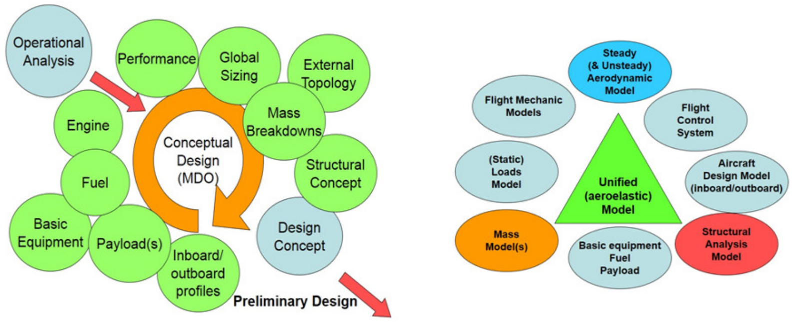

Figure 6: The different types of analytical models

4.8 Wing tip design

Any kind of special wing tip designs also create essential aeroelastic impacts. Early investigations will help to avoid bad surprises and improve the global performance. The primary objective of a wing tip design is the reduction of the aerodynamic drag. To achieve this it important to look at other aspects like the associated impacts on design loads and on aeroelastic stability. If properly designed, the design loads can be reduced by means of aeroelastic tailoring the shape of the surface or its stiffness. The same applies to the impacts on flutter stability. An out-of-plane mass of the tip surface will cause a reduced stability and a rear location of the tip's mass will have a negative impact too. On the other hand, a rear location of the tip's surface can have a beneficial effect on the load reduction as well as on flutter stability from the unsteady aerodynamic loads.

There are numerous and excellent studies on the optimization of wing tips. They are however single-disciplinary efforts in most cases, where structural aspects, if they show up at all, are only included by empirical corrections, and aeroelasticity is not considered at all. As a typical example, Ning and Kroo show in an excellent exercise [17] how the optimum C-wing configuration can be found by formal optimization efforts, including some considerations for the impacts from structural loads, but the impacts from aeroelastic effects can not be assessed and quantified.

5. Why aeroelastic models should be the starting point for conceptual design analysis and optimization

As shown above, the conventional approach to create aeroelastic analysis models takes a very long time. Today's approach is often based on the assumption that everything has to start from a CAD model which already includes all the required data for the creation of analytical models.

It is unquestionable that a good CAD model creation and update process is essential for the success of a project. On the other hand, there is no need to have a more or less complete and perfect CAD model available for the initial creation of analytical models, at least not in conceptual design. On the contrary, the analytical results should help to define the architecture and dimensions for the CAD model. Figure 6 shows the essential ingredients and activities in the conceptual design process. This picture already indicates that all these tasks contribute to a multidisciplinary design effort, and that they are also identical with the ingredients for aeroelastic analysis models. If the different types of analytical models are grouped in another picture, Figure 7, the aeroelastic model now can also be seen as the "integrator model" or a "unified model" for the different types of analysis, and as the central model for multidisciplinary analysis and optimization efforts.

6. Summary and conclusions

The early identification of aeroelastic characteristics for new designs is essential. Only the conceptual design phase offers the chance to actively exploit aeroelastic effects for potential performance improvement, or at least evaluate and quantify negative impacts and include them in performance predictions and the global aircraft sizing process.

This challenging task has several aspects:

1. short time for model preparation, analysis loops, and results evaluation,
2. appropriate architecture and size of the analytical models,
3. model creation from a very limited set of input data,
4. robustness, speed, and efficiency of formal optimization methods.

If properly done, this will reduce or eliminate the risk to re-iterate and revise important design decisions during the preliminary design phase. Besides the availability of efficient MDO tools it is essential to be able to create and evaluate a large number of alternative design variants for the internal and external topology, for major geometry parameters, the control surface architecture and their actuation system requirements, for the basic structural arrangements, as well as for the placement of equipment.

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