Design and Testing of Flexible Aircraft Structures

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Preface

The work presented in this doctoral thesis was carried out at the Department of Aeronautical and Vehicle Engineering, Kungliga Tekniska Högskolan, between March 2000 and April 2004. The work was financially supported by the Commission of the European Union (EU) and by the Swedish National Program for Aeronautics Research (NFFP).

I would like to express my gratitude to my supervisor professor Ulf Ringertz for believing in me as a graduate student and for the excellent support I have received during these years. Also, I would like to thank my two advisers, in order of appearance, Jakob Kuttenkeuler and Dan Borglund. Jakob really helped me out in my early days at the Department and he also shared his remarkable sense for experimental strategies. Dan has guided me a lot along the road. His comprehensive knowledge has widely improved my technical insight and also my writing skills.

My time at work would not have been as joyful without all the great people at the Department *Far & Flyg*. I particularly recognize my friends at the Division of Flight Dynamics. You are all an invaluable source of support, inspiration, and great fun!

During my first three years of work with this thesis, I had the privilege to meet several creative and skilled partners in the EU-funded project “Multi-Disciplinary Design and Optimisation for Blended Wing Body Configuration” (MOB). I learned a lot during our meetings and work-shops, but also during our fruitful discussions around the evening dinner table. Thank you all! A special thanks goes to professor Otto Sensburg, who acted as the opponent at my licentiate thesis presentation and also gave me a lot of constructive criticism.

I also take this opportunity to thank the helpful people in the NFFP research group at Saab AB: Anders Karlsson, Bo Nilsson, Karin Ståhl-Gunnarsson, Hans Söderberg, and Bengt Winzell (today at FOI). In particular, I express my appreciation to Torsten Bråmå for his generous support and valuable feedback with respect to both the EU and NFFP funded research projects.

I am very grateful to my beloved family and friends for your enthusiasm and for always being there when I need you the most. Finally, all my love goes to Ingrid and our lovely daughter Rebecka. You have made the recent years to the happiest time of my life. Still, I believe that the best is yet to come!

Stockholm in April 2004

Martin Carlsson

Abstract

Methods for structural design, control, and testing of flexible aircraft structures are considered. Focus is on nonconventional aircraft configurations and control concepts. The interaction between analysis and testing is a central topic and all studies include validation testing and comparison between computational and experimental results.

The first part of the thesis is concerned with the design and testing of an aeroelastic wind-tunnel model representing a Blended Wing Body (BWB) aircraft. The investigations show that a somewhat simplified wind-tunnel model design concept is useful and efficient for the type of investigations considered. Also, the studies indicate that well established numerical tools are capable of predicting the aeroelastic behavior of the BWB aircraft with reasonable accuracy. Accurate prediction of the control surface aerodynamics is however found to be difficult.

A new aerodynamic boundary element method for aeroelastic time-domain simulations and its experimental validation are presented. The properties of the method are compared to traditional methods as well as to experimental results. The study indicates that the method is capable of efficient and accurate aeroelastic simulations.

Next, a method for tailoring a structure with respect to its aeroelastic behavior is presented. The method is based on numerical optimization techniques and developed for efficient design of aeroelastic wind-tunnel models with prescribed static and dynamic aeroelastic properties. Experimental validation shows that the design method is useful in practice and that it provides a more efficient handling of the dynamic aeroelastic properties compared to previous methods.

Finally, the use of multiple control surfaces and aeroelastic effects for efficient roll maneuvering is considered. The idea is to design a controller that takes advantage of the elasticity of the structure for performance benefits. By use of optimization methods in combination with a fairly simple control system, good maneuvering performance is obtained with minimal control effort. Validation testing using a flexible wind-tunnel model and a real-time control system shows that the control strategy is successful in practice.

Dissertation

This doctoral thesis consists of a brief introduction to the area of research and the following appended papers:

Paper A

M. Carlsson and J. Kuttenkeuler. Design and Testing of a Blended Wing Body Aeroelastic Wind-Tunnel Model. *Journal of Aircraft*, Vol. 40, No. 1, pp. 211-213, 2003.

Paper B

M. Carlsson. Control Surface Response of a Blended Wing Body Aeroelastic Wind-Tunnel Model. Presented at the *41st AIAA Aerospace Sciences Meeting*, Reno, Nevada, 6-9 January 2003. *AIAA Paper 2003-450*. To appear in *Journal of Aircraft*, 2004.

Received the "Outstanding Paper Award" from the American Institute of Aeronautics and Astronautics (AIAA) Ground Test Technical Committee.

Paper C

D. Eller and M. Carlsson. An Efficient Aerodynamic Boundary Element Method for Aeroelastic Simulations and its Experimental Validation. *Aerospace Science & Technology*, Vol. 7, No. 7, pp. 532-539, 2003.

Paper D

M. Carlsson. Aeroelastic Model Design Using an Integrated Optimization Approach. Earlier version presented at the *CEAS/NVvL/AIAA International Forum on Aeroelasticity and Structural Dynamics*, Amsterdam, The Netherlands, June 2003. To appear in *Journal of Aircraft*, 2004.

Paper E

M. Carlsson and C. Cronander. Efficient Roll Control using Distributed Control Surfaces and Aeroelastic Effects. TRITA-AVE 2004:09, Department of Aeronautical and Vehicle Engineering, KTH, 2004. Submitted for publication.

Contents

Appended papers

Introduction

All aircraft structures are flexible to some extent. Structural mechanics, aerodynamics, and flight dynamics are all disciplines included in the truly multidisciplinary science called *aeroelasticity*. Aeroelasticity covers the interaction between the flexibility of the structure and the aerodynamic loads that depend on, and in turn also affect, the structural deformations. Figure 1 shows an illustration of the aeroelastic interaction and the first fourth generation fighter aircraft, the Saab JAS 39 Gripen. This interaction strongly couples to flight mechanics because the stability and control properties of the aircraft are highly dependent on the aerodynamic load distribution.

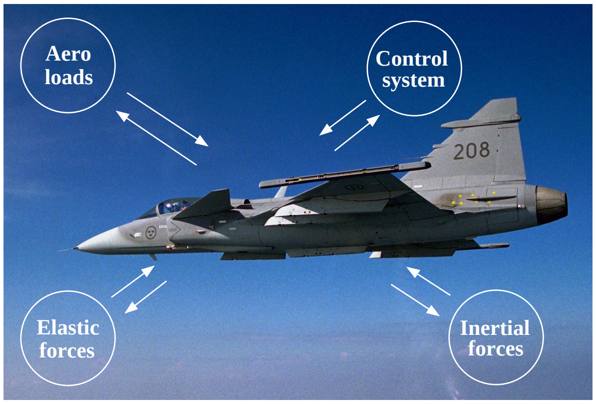

Figure 1: The aeroservoelastic system (courtesy of Saab AB).

The stability and control of many modern airplanes depend on advanced control systems. The control system including sensors, control algorithms, and actuators is a complex dynamic system itself, but also interacts with the aeroelastic properties of the aircraft. The term *aeroservoelasticity* may therefore describe the area of research better since it emphasizes that the control system usually has to be considered in aeroelastic analysis and design. However, the notation *aeroelasticity* is used in this introduction, although control considerations sometimes are included.

Background

The aeroelastic interactions in Figure 1 lead to a number of classical phenomena. In the following, some of the most common aeroelastic phenomena that are considered during aircraft design are briefly described.

Static aeroelastic deformation

During flight, the aircraft is subjected to aerodynamic loads that deform the flexible structure. For some aircraft, substantial aeroelastic deformations are to be considered, which to a large extent affects the flying qualities. The significant deformation of the eta high performance sailplane during flight is shown in Figure 2. To obtain the optimal inflight wing shape sometimes means that the shape during manufacturing (jig-shape) is very different from the shape of the structure when flying. Large deformations are not necessarily a problem, but have to be considered during the design process to ensure high performance.

Figure 2: The eta sailplane (courtesy of eta Aircraft).

Divergence

Divergence is a static aeroelastic instability that may lead to abrupt structural failure. It can be described as a buckling type phenomenon, and is caused by the fact that the aerodynamic forces overcome the restoring elastic forces of the structure. During aerodynamic loading, the structure deforms in a way so that the aerodynamic loads further increase. At a certain critical airspeed, the self-amplifying deformation ends in structural failure.

Forward swept wings, like the wings of the Grumman X-29 shown in Figure 3, are known to be very prone to aeroelastic divergence. It is however possible to tailor the structure of forward swept wings to avoid this phenomenon. The tailoring concept of a forward swept wing is illustrated in Figure 4. If the primary stiffness axis (composite fiber main direction) is parallel to the sweep axis of the wing (wing A), positive wing loading will cause the wing to twist nose up (called wash-in behavior). This results in a very low divergence speed.

Figure 3: The Grumman X-29 (courtesy of NASA).

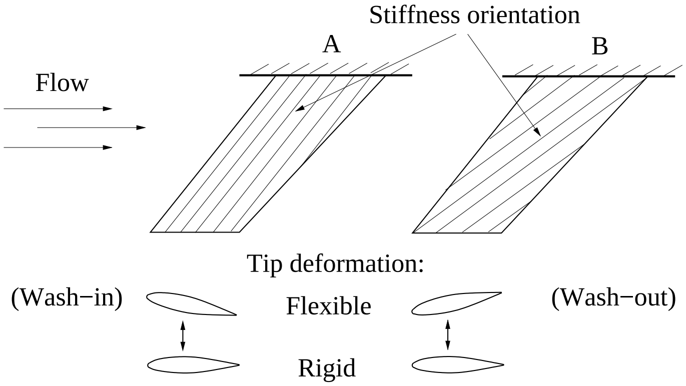

Figure 4: Aeroelastic tailoring of forward swept wing.

Rotating the stiffness axis, as illustrated by wing B, gives a bending/torsion stiffness coupling that makes the wing twist nose down during loading. This reduces the elastic efficiency of the wing somewhat but increases the critical divergence speed of the wing significantly [1]. An aft-swept wing behaves in the opposite fashion and normally shows wash-out behavior. Hence, aft-swept wings are rarely prone to divergence instability.

Reduced control surface efficiency

The reduction of control surface efficiency at high speed caused by structural deformations is one of the major concerns for high performance aircraft. The efficiency of an outboard trailing edge aileron is strongly coupled to the torsional stiffness of the wing. At high speed, the twist moment caused by the deflected aileron results in wing twist that affects the lift and reduces the aileron efficiency significantly. At the reversal speed, the effect of the aileron vanishes and beyond the reversal speed the effect is a rolling moment in the opposite direction. Obtaining an acceptable efficiency of a trailing edge aileron at high speed can be solved by stiffening the wing, but this is usually associated with substantial increase in structural weight.

For aircraft with very slender wings, like the GlobalFlyer shown in Figure 5, a reduction in outboard aileron efficiency due to the highly flexible wing is most likely. However, aileron efficiency is a major concern also for relatively stiff fighter aicraft. The original wing design of the early prototype F-18 was for example modified due to severe problems with reduced aileron efficiency at high speed [2]. Major stiffening of the production wings was therefore performed. Later, the original wing has been used to demonstrate the feasibility of active aeroelastic wing technologies as will be discussed in more detail later.

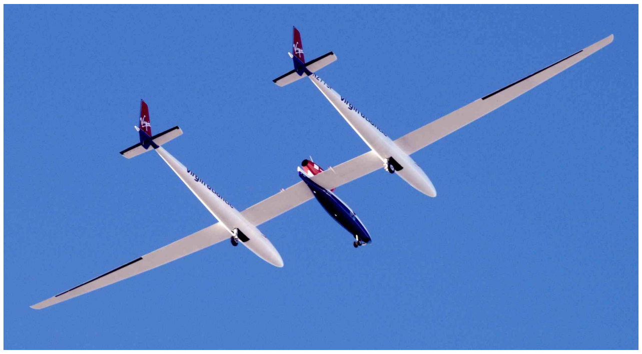

Figure 5: The GlobalFlyer (courtesy of Jim Sugar & Brian Lawler).

Flutter

One of the most well known aeroelastic phenomena is flutter. The aeroelastic system exhibits dynamic properties that during some conditions lead to oscillations. Flutter is a dynamic instability of the aeroelastic system and often leads to exponentially growing oscillations and structural failure.

In the 1950s, the desire to improve performance in terms of speed and range, resulted in aircraft with aft-swept high aspect ratio wings and thin airfoils, see the Boeing B-47 in Figure 6. During the development of this breakthrough design concept, much research with respect to aeroelastic matters was required [2]. Divergence was avoided by the aft-swept wing geometry and flutter was prevented by mounting the engines somewhat in front of the wing (mass balancing). However, aileron efficiency was still a problem with the configuration. The B-47 is sometimes called the ancestor of all modern jet transports, because this type of configuration is still used for almost all airliners. For example, compare with the Airbus A380 in Figure 7.

Figure 6: Boeing B-47 (courtesy of NASA).

Stability and control

Aeroelasticity and flight mechanics are very tightly connected although sometimes claimed to be separate disciplines. Significant coupling between rigid body motion of the aircraft and elastic structural motion is often present [3]. For aircraft with high aspect ratio wings loaded with fuel, such as the GlobalFlyer in Figure 5, the elastic frequencies of the structure are relatively low and the frequency separation from typical rigid body motion of the aircraft is small [2]. For tailless aircraft with relatively low pitch inertia, like the Blended Wing Body (BWB) aircraft in Figure 8, this coupling can be even more evident.

A famous phenomenon in flight mechanics and control is so-called pilot induced oscillations (PIO). This phenomenon is normally caused by the interaction between the pilot inputs, the rigid body dynamics, and the control system of the aircraft [4]. For very large aircraft, such as the Airbus A380 shown in Figure 7, the frequencies of the first elastic modes are very low (about 1 Hz) and there is a possibility that the pilot inputs also will interact with the elastic motion of the structure.

Figure 7: Airbus A380 (copyright Airbus - computer graphics by i3m, with permission).

Although the structural frequencies of the aircraft are well separated from the rigid-body frequencies, static aeroelastic effects may have a major impact on the stability and control properties of the aircraft. For example, the wash-in/wash-out effect of swept wings discussed earlier affects the longitudinal stability properties. Moreover, large elastic bending of slender wings during flight increases the effective dihedral of the aircraft, which is known to affect the flying qualities, see Figure 2.

Traditional analysis

In the very early days of aviation, aircraft were often aeroelastically designed using rules of thumb and experimental investigations [5, 6]. In the 1930s, methods for analyzing aeroelastic stability phenomena like wing divergence and flutter were developed [7]. The analysis was at that time usually restricted to isolated slender beam-type aircraft components. During the 1960s and 1970s, the finite element method for structural analysis and panel method, or lifting surface, aerodynamics [8, 9, 10] were developed. These methods made it possible to analyze the aeroelastic behavior of complete aircraft configurations [3].

In the past, aeroelasticity was usually associated with problems and aeroelastic effects were something to be avoided. The analysis was often performed as a final check when a new design was nearly completed or when problems appeared during flight testing. Problems were traditionally solved by stiffening the structure and/or by mass balancing. The aeroelastician was hence the, sometimes unpopular, engineer whose field of knowledge “added” weight to the aircraft structure.

Today, aeroelastic analysis is often performed at a much earlier stage and sometimes the focus is instead on how to utilize the aeroelastic interactions for performance benefits. Being an aeroelastician may still be a challenge because you have to communicate with, and understand, the experts of the various disciplines involved. However, in the future, the knowledge of the aeroelasticians will likely be exploited to increase the performance of the aircraft.

Towards improved performance

Improved performance in terms of speed, altitude, range, payload etc has always been strived for in aeronautical engineering. Today, much effort is also concentrated on reduction of emissions and noise from the steadily increasing number of air vehicles. Regardless of which performance criteria are considered, lower weight of the aircraft structure in general gives better performance. Low structural weight leads to higher loading capacity, less aerodynamic drag, less fuel consumption and so on.

When it comes to the demand for increased air transportation capacity in the future, larger passenger transport aircraft is one possible solution. The new Airbus A380 (Figure 7) represents the largest civil passenger aircraft ever built [11]. According to Airbus, the A380 will enter airline passenger service in 2006. Although very large, the A380 configuration is fairly conventional. Development of a new aircraft is a long-term project and research is already ongoing with respect to future successors of the A380.

New configurations

It is sometimes claimed that the conventional transport aircraft is approaching its evolutionary potential [12]. Research effort is today put on finding alternative configurations with larger potential for efficient future air transportation. One of the concepts receiving much attention is the so-called Blended Wing Body (BWB) aircraft shown in Figure 8. The potential advantages of the BWB configuration have been the objective for several recent research projects [13, 14] including the European MOB-project [15, 16].

Figure 8: Blended Wing Body conceptual aircraft.

The BWB concept aims at combining the advantages of a flying wing [17] with the loading capabilities of a conventional airliner by creating a wide body in the center of the wing to allow space for passengers and cargo. Especially, for very large transport aircraft, the BWB concept is often claimed to be superior compared to conventional configurations in terms of higher lift-to-drag ratio and consequently less fuel consumption [18].

There are still many challenges with the BWB concept. For example, the lack of a stabilizing tailplane puts additional requirements on the control system. To reduce the trim drag, the longitudinal stability margin of the BWB has to be very small or negative. As a consequence, the BWB has to rely on a digital control system for stability and control [19]. The aircraft performance will most likely be constrained by aeroelastic considerations such as control surface efficiency and critical flutter speed.

Another example of a nonconventional configuration is the GlobalFlyer shown in Figure 5. This aircraft is designed for long endurance flight and is meant to fly around the world in 80 hours without refueling. The extremely high fuel fraction of about 80% and the flexible slender wings with tailbooms make the aircraft very interesting from an aeroelastic and handling qualities point of view. The first flight was performed on March 5, 2004 and good flying qualities were reported [20]. The first test flight was performed with very little fuel onboard and the handling will most likely be more challenging when heavily loaded with fuel. Very good insight in the aeroelastic behavior of an aircraft of this type is crucial to get satisfactory performance and handling qualities.

Active aeroelastic concepts

Currently, much research is performed in the area of so-called active aeroelastic concepts [21]. The basic idea is to take advantage of the structural deformation to increase performance. In the ongoing European research project “Active Aeroelastic Aircraft Structures” (3AS), different active aeroelastic concepts are evaluated with respect to potential performance benefits [22]. One example is to use spanwise distributed control surfaces to control the deformation of flexible wings during flight. By using this approach, the spanwise lift distribution can be optimized with respect to the actual flight condition and the lift-induced drag can be reduced [23, 24]. A very small reduction of the induced drag can give a substantial reduction in fuel consumption during long endurance flights.

As mentioned earlier, the original wing design of the F-18, shown in Figure 9, was stiffened to achieve acceptable aileron efficiency. However, the original and very flexible wing has been re-used during the Active Flexible Wing (AFW) and the subsequent Active Aeroelastic Wing (AAW) flight research programs [25, 26]. By active use of leading edge control surfaces, in addition to conventional trailing edge surfaces, satisfactory roll maneuverability can be achieved despite a very flexible wing [27, 28, 29, 30]. Hence, the weight penalty associated with increased wing stiffness can be avoided.

Figure 9: The F-18 AAW research aircraft (courtesy of NASA).

Figure 10 shows a schematic illustration of the roll moment efficiency versus airspeed for different control surfaces of the BWB aircraft. The outer trailing edge surface (denoted TEO) is very efficient to use at low speed. The inner trailing edge surface (TEI) is not as efficient as the outer at low speed since the moment arm to the roll axis is smaller. The leading edge surface (LE) has low efficiency at low speed since the wing does not deform very much at low dynamic pressures.

As the airspeed and dynamic pressure increase, the flexibility of the structure starts to play a more important role for maneuvering. The TEO surface efficiency is significantly reduced with airspeed and the effect vanishes completely at the surface reversal speed denoted u_{rev}. The TEI surface also loses efficiency, but not as fast as the TEO surface. The LE surface efficiency increases instead significantly with airspeed since the surface produces a positive twist moment that deforms the wing in a favorable manner. At high speed, the LE surface is very efficient to use. Also the TEO surface may be used for roll maneuvering, but must be actuated with opposite deflection compared to below the reversal speed. The TEI surface is not very efficient at the highest speed, because the surface produces only negligible roll moment.

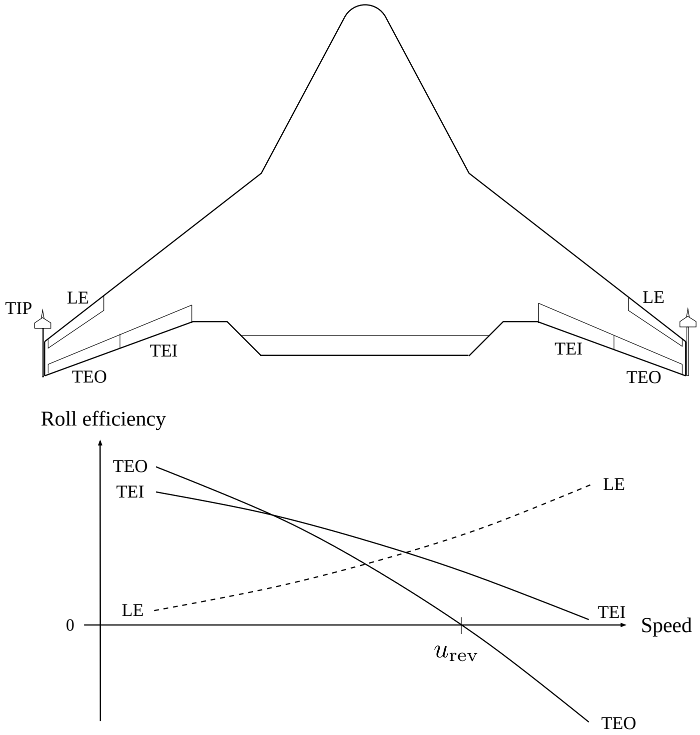

Figure 10: Control surface efficiency versus airspeed for a BWB aircraft.

Investigations have been made where small control surfaces mounted in front of the wing tip were used for roll control [31]. This is illustrated in Figure 10 by the surface denoted TIP. A very small surface was, by computations and flight tests, shown to give significant improvement in roll rate compared to using a conventional trailing edge aileron only.

Improved analysis and design

Panel method aerodynamics and finite element structural analysis still serve as reliable and efficient standard tools for aeroelastic analysis. Design and certification often require very efficient repetitive analysis of numerous aircraft configurations and loading conditions [32]. However, linear aerodynamic methods such as the method developed by Stark [33] and the doublet-lattice method (DLM) [10] cannot capture nonlinear effects such as shock waves and flow separation. For analysis at flight conditions where the linear assumption is not valid, such as in the transonic regime, corrections based on more involved computational fluid dynamics (CFD) or test results have to be applied [34].

The use of nonlinear computational methods such as the Euler or Reynolds-averaged Navier-Stokes methods for steady and unsteady aeroelastic simulations has increased significantly in recent years [3]. These methods utilize the best available flow models and will certainly improve the analysis and understanding of aeroelastic phenomena in the future. Also, these aerodynamic methods are a necessity to analyze aeroelastic phenomena caused by nonlinear flow effects such as stall flutter and buffeting [5]. However, the model preparation and computational cost for unsteady aeroelastic simulations is still very high.

Although linear panel methods are fairly reliable for predicting subsonic aeroelastic behavior in terms of static deformations and stability boundaries, the prediction of control surface response is still a challenge [35]. Corrections based on experience or test results often have to be considered for control system design. Development of more reliable and efficient numerical tools for aeroelastic analysis and design is very important and will pave the way for future use of aeroelastic effects for performance benefits.

Design optimization

Numerical optimization serves as a powerful engineering tool for design improvement and aeroelastic tailoring [36, 37]. In general, the objective is to determine a set of design variables $\boldsymbol{x}$, which are optimal with respect to some measure of merit described by a scalar objective function $f(\boldsymbol{x})$. The problem is often formulated as an optimization problem in the form

$$\underset{\boldsymbol{x} \in X}{\text{minimize}} \quad f(\boldsymbol{x}) \tag{1}$$

$$\text{subject to} \quad \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0}, \tag{2}$$

where $\boldsymbol{g}(\boldsymbol{x})$ is a set of functions describing design constraints and X represents bounds on the design variables. In the general case, $f(\boldsymbol{x})$ and $\boldsymbol{g}(\boldsymbol{x})$ are nonlinear functions of the design variables. In aeronautical applications, a typical objective is to minimize the weight of the structure. The design variables may be sizes of various structural elements, whereas the constraints often include strength or aeroelastic stability requirements [38, 39, 40].

Several numerical methods exist for solving nonlinear optimization problems, of which the gradient based methods are known to be most efficient if the functions considered are continuous and smooth. A very common approach is to use sequential quadratic programming (SQP) [41, 42], where the gradients of the objective and constraint functions at the current iteration are used to approximate the optimization problem (1)-(2) by a convex quadratic subproblem. Other methods such as the method of moving asymptotes (MMA) [43] are also frequently used for structural optimization in aeronautical applications [44, 45].

Robust analysis and design optimization considering uncertainties in the numerical models are today a very active area of research [46, 47, 48, 49, 50]. In particular, analysis of the flutter behavior of an aircraft is known to be very sensitive to uncertainties. Very small perturbations in structural modeshapes and aerodynamic forces may give dramatic changes in the critical flutter speed. It is also widely accepted that numerical optimization can lead to numerically feasible designs being extremely sensitive to model deviations. This can make the optimal solution infeasible in practice. To ensure that a prescribed level of performance is obtained in practice, the model uncertainties therefore have to be considered during design.

Improved testing

Although there have been substantial improvements in analysis and computational resources, experimental aeroelastic investigations will definitely maintain the position as a necessary tool for design and validation. Using wind-tunnel testing, relatively inexpensive models can be tested in an early stage of a new project. Today, there are wind-tunnels specifically designed to support aeroelastic research and development [6, 51].

The objective when testing aeroelastic wind-tunnel models may be to investigate the behavior of a full size vehicle, but often the purpose is to verify aeroelastic analysis [52, 53]. Wind-tunnel testing is in general expensive and time-consuming. Therefore, development of new efficient methods for high quality model design as well as new efficient testing procedures becomes very important.

Aeroelastic wind-tunnel models

Elastic wind-tunnel models are structurally more complicated than rigid models. The structure of the model often has to be representative for some full size structure or show behavior that suites the particular investigation to be performed. Sometimes elastic wind-tunnel models are built by scaling all components of the full size structure to model dimensions. This approach is, due to the complexity, usually neither practical nor economical.

Sometimes, the desired model behavior can be achieved by a much more simple structure than the full size reference aircraft. A slender wing may, for example, be represented by an internal wing beam tailored to the desired behavior. By adding an outer aerodynamic geometry that does not contribute significantly to the stiffness of the model, a relatively simple design is obtained. This design is often referred to as the segmented concept [6, 54], see Figure 11.

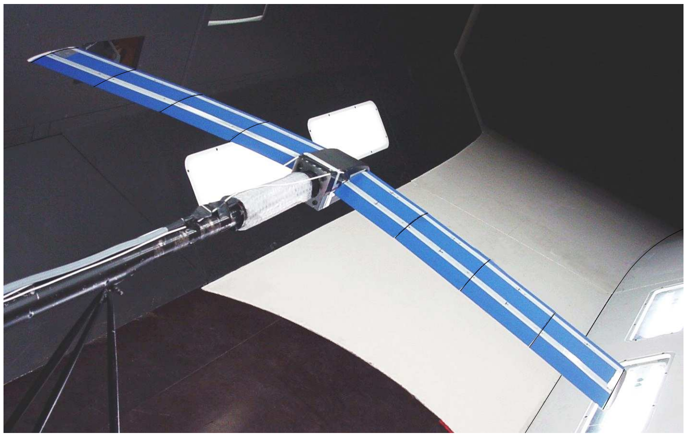

Figure 11: Segmented model in the wind-tunnel L2000 at KTH.

The design of aeroelastic wind-tunnel models is traditionally performed by very experienced craftsmen who know which structural parameters to modify to get the appropriate structural behavior in terms of stiffness, natural frequencies, and modeshapes. The interest for more straightforward procedures has increased, and methods based on numerical optimization have in recent years been proposed and evaluated [55, 56].

Measurement techniques

Wind-tunnel experiments are very sensitive to disturbances in the flow field. As a result, all measurement equipment normally have to be mounted inside the model itself or outside the flow field. Whereas load measurements are routinely performed using different types of wind-tunnel load balances, model deformation measurements are usually much more involved. In recent years, the use of optical methods based on photogrammetry for model deformation measurements has increased [57, 58, 59].

In the experiments performed in this thesis, model deformation measurements are performed using such an optical method, see Figure 12. The system consists of four CCD cameras [60] with internal flashes connected in a local area network to a standard PC. The cameras are mounted outside the wind-tunnel and view the model through openings in the tunnel walls. Each time the positions of the markers are to be determined, all four cameras acquire one frame simultaneously. Within each camera, the optical center of each marker echo is calculated. The two-dimensional (2D) positions sent from each camera are fed to the host computer, where the 3D photogrammetric calculations are performed. The system provides sub millimeter accuracy and sampling rates up to 240 Hz.

Interaction between analysis and testing

The design of a nonconventional aircraft is a very challenging task no matter if it is a small unmanned vehicle utilizing some active aeroelastic concept or a large transport aircraft like the Blended Wing Body. Numerical tools used for analysis and design are usually developed and verified with respect to conventional applications. Therefore, validation experiments are crucial in order to evaluate if the design concept is useful in practice or not. Analytical and experimental capabilities are strongly dependent on each other and must therefore be developed in

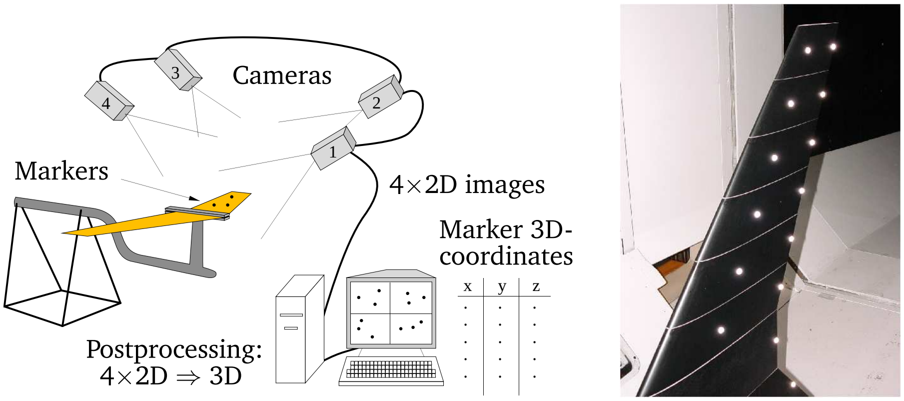

Figure 12: Experimental setup and BWB model with reflecting markers.

parallel. This will facilitate the development of innovative, more efficient, more environmentally friendly, and also more economical air vehicles of the future.

Contribution of this work

The work presented in this thesis contributes to both the design and validation testing aspects of aeroelasticity:

With respect to new configurations, Papers A and B describe design and testing of an aeroelastic wind-tunnel model representing the Blended Wing Body aircraft. A relatively simple model design concept in combination with modern measurement techniques enables efficient experimental investigations. The model is tested with respect to its aeroelastic behavior in terms of static deformations and control surface response. Experimental results are compared to different numerical predictions. The investigations indicate that well established traditional numerical tools are capable of predicting the aeroelastic behavior of the BWB aircraft with reasonable accuracy. However, accurate prediction of control surface aerodynamics is found to be a challenge.

A new method for aerodynamic analysis has been validated as reported in Paper C. The aerodynamic method developed by Eller [61] represents a method that fits in the gap between the traditional doublet-lattice approach and the much more involved CFD methods. The method offers more realistic geometrical modeling compared to the DLM thin surface modeling. Still, only discretization of the aircraft surface is required. The complexity in handling a field mesh is thus avoided. The method is also well suited for coupling to nonlinear structural models, which sometimes is desirable for analysis of nonlinear aeroelastic behavior [62].

Paper D is a contribution to the design aspect and outlines a method for efficient aeroelastic tailoring of a (model-size) wing structure. The method is based on numerical optimization and can be used to design wind-tunnel models with prescribed static and dynamic aeroelastic behavior. The method is not limited to model size structures, but can also be used to tailor the structure of a full size aircraft.

The final Paper E is dedicated to the area of active aeroelastic research and describes a method for efficient use of control surfaces and aeroelastic effects for increased maneuvering performance. Focus is on how to use multiple leading and trailing edge surfaces at various airspeeds for efficient roll control. Small surface deflections deform the flexible structure which in turn creates larger aerodynamic loads than what would be created by the surface itself. By keeping the surface deflections and deflection rates small, the requirements on the control system in terms of actuator power and speed can be reduced.

All investigations presented in the thesis highlight the importance of combining analytical investigations and new design methods with validation experiments. Often, the experiments revealed weaknesses or shortcomings in the numerical methods applied. However, minor modifications or updates often solved the problems and also contributed to further improvement of the methods.

Future work

Whereas the investigation in Paper D considers tailoring of the structural behavior only and Paper E presents control system design only, a combination where the structure and the control system are designed simultaneously would be very interesting. Substantial performance benefits may be possible if the control and structural parameters are determined using an integrated approach.

Work considering robust performance, taking uncertainties into account, is ongoing. Special focus for future research will be on how to represent the level of uncertainties of different parts of the numerical models to get a not too conservative nor too optimistic formulation. Here the uncertainty in control surface aerodynamics is a particularly important issue.

The aerodynamic boundary element method presented in Paper C is today used for active aeroelastic research in terms of induced drag reduction by optimal lift distribution. An interesting future area of research is so-called real-time drag reduction. The idea is to use measurements as complement to the mathematical model and to adjust the control surfaces during flight to achieve the optimal combination in terms of drag or airspeed. By research in the area of data acquisition and data reduction in combination with optimization methods, it may be possible to use such techniques to make flying even more efficient in the future.

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Division of work between authors

Paper A

Carlsson designed and built the wind-tunnel model with assistance by Kuttenkeuler. The authors developed and validated the numerical model in collaboration. Experiments were performed jointly by the authors whereas the data reduction and evaluation was done by Carlsson. The paper was written by Carlsson with support from Kuttenkeuler.

Paper C

The numerical investigations were performed by Eller, whereas the experiments were prepared and managed by Carlsson. Experimental data was analyzed jointly by Carlsson and Eller and the paper was written by Eller with assistance by Carlsson.

Paper E

The aeroelastic state-space model was developed by Carlsson. Cronander and Carlsson jointly designed and evaluated the controllers. Carlsson programmed the embedded controller and the experiments were conducted by both authors. The authors jointly wrote the paper.