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Airplane Aeroelasticity: Practice and Potential

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A perspective on the practice, issues, and potential of aeroelasticity is presented. The issues of cycle time reduction and improvements in the fidelity of aeroelastic analysis need to be emphasized for aeroelasticity to support adequately the airplane configuration development and configuration decisions. The introduction of fly-by-wire control systems has increased the complexity as well as the fidelity requirements for the aeroelastic analysis. The business cost of inaccuracies in loads and dynamics predictions can be seriously high. Therefore, innovative approaches should be encouraged to address these issues. Aeroelasticity has an opportunity to contribute to airplane design by evolving to become a more integrating discipline. Although many of the methods and processes in different subdisciplines are in place already, others need to be developed further for improved usability, efficiency, fidelity, and integration. The most challenging problems in realizing the full potential of aeroelasticity are not just technical but are also organizational in nature. The organizational issues are related to management of multidisciplinary teams in a lean engineering environment. Thus, to realize the multidisciplinary integrating potential of aeroelasticity and its contributions to the configuration decisions, technical and management foresight, leadership, and vision are required.

Nomenclature

$C_{N_{\mathrm{MAX}}}$	=	maximum normal force coefficient
V_A	=	design maneuvering speed
V_B	=	design speed for maximum gust intensity
V_C	=	design cruising speed
V_D	=	design diving speed
V_F	=	design flap speed
$V_{\mathrm{MO}}/M_{\mathrm{MO}}$	=	maximum operating limit speed
V_R	=	rotation speed
V_S	=	stalling speed or the minimum steady flight speed at which the airplane is controllable
V_{S1}	=	stalling speed or the minimum steady flight speed obtained in a specific configuration

I. Introduction

THE primary objective of this paper is to present the author's perspective on the practice of aeroelasticity from a vantage point in the Boeing Commercial Airplane, Loads and Dynamics organization. The secondary objectives are to share the author's personal views on the challenges faced by the aeroelasticity practitioners in design and certification of large transport airplanes and the potential opportunities offered by the challenging environment. In many of the points discussed here, the author draws freely upon the long and distinguished aeroelasticity heritage of the legacy Boeing and the contributions of many former and current Boeing aeroelasticians, most of whom are generally unknown outside of Boeing. In discussing new ideas, the author draws upon the collaborative development effort by several creative individuals carried out mainly with internal Boeing funding. Because many of the comments are based on unpublished work, it is not possible to cite references in many cases because the materials exist only in internal Boeing documents.

The paper examines the concept of aeroelasticity and discusses basic ideas rather than detailed methods. The term "loads" is used here in a broad sense to include static loads, dynamic loads, as well as the flutter and aeroservoelastic disciplines. This reflects a typical usage within Boeing. The paper is written with the hope that it would stimulate a dialogue and encourage airing of different opinions within the larger community of aeroelasticians. The views presented herein are solely the author's own interpretations and do not represent a Boeing position on any of the topics discussed.

II. Aeroelasticity at Boeing—The Beginning

Bisplinghoff et al. in their classic text[1] provide a historical background of aeroelasticity going back to the failure of Samuel P. Langley's monoplane in 1903 caused by what now seems like wing torsional divergence. The subsequent success of the Wright Brothers biplane and the lack of understanding of static divergence delayed the introduction of high-performance monoplane design. In 1930, Boeing created the revolutionary Monomail (Fig. 1) (data available online at http://www.boeing.com/companyoffices/history/boeing/), which made traditional biplane construction a design of the past. The Monomail wing was set lower, was smooth, made entirely of metal, and had no struts (cantilevered construction). The retractable

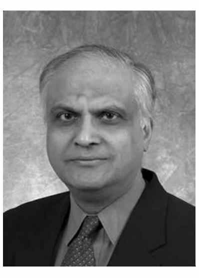

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Fig. 1 Boeing Monomail (1930).

Fig. 2 Boeing B-47 Stratojet (1947).

Fig. 3 Boeing B-52 (1952).

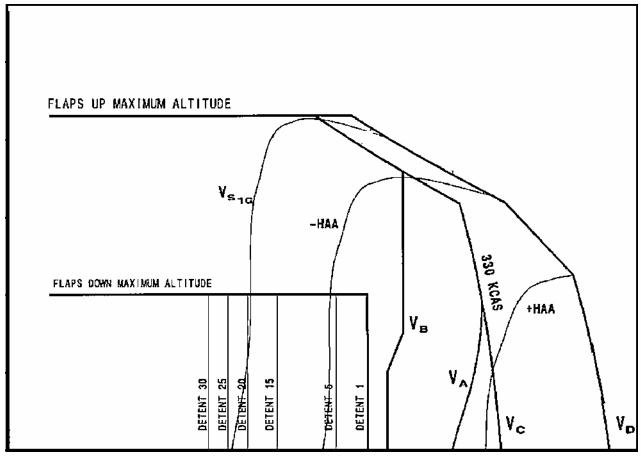

Fig. 4 Speed–altitude envelope for a weight condition.

landing gear, the streamlined fuselage, and the engine covered by an antidrag cowling added up to an advanced, extremely aerodynamic design. This was the forerunner of the airplanes to come after it.

The early cantilevered wing design progressed rapidly to evolve into the Boeing Model 247 (1933), B-17 (1935), Model 314 Clipper (1938), Model 307 Stratoliner (1938), B-29 (1942), and C-97 Stratofreighter and Model 377 Stratocruiser (1947). The B-17 had the newly designed autopilot system. The Clipper was the “747” of its day with a range of over 3500 miles; the Stratoliner had the first pressurized fuselage, etc. These advances were accompanied by intense competition from the other manufacturers with their own improved designs. It was a lively era where Boeing won many contests but also lost some with DC-2 and DC-3 being the prime examples of Boeing losing the lead for a time to erstwhile Douglas. In 1947, Boeing introduced the revolutionary B-47 (Fig. 2) inspired by the WWII German wind-tunnel data on swept-wing jet airplanes. The recently completed Boeing High Speed Wind Tunnel was used to develop and design the XB-47, with its slender, 35-deg swept-back wings.

The modern era of aeroelasticity can be said to have dawned with the design and introduction of the B-47. Every large transport jet aircraft today is a descendant of the B-47. The evolution of modern transport airplane aeroelasticity also coincided with the need to predict loads and aeroelastic stability of an airplane with a large, high-aspect-ratio, swept-wing design. The need grew with the design of B-52 (Fig. 3), Dash 80 and 707, 747, 767, and 757. Lessons from this vast legacy went into the design of 777, which is the first Boeing, all fly-by-wire airplane. The B-47 and B-52 can be considered to be the two airplanes with the most influence on aeroelasticity.

III. Aeroelasticity at Boeing—The Practice

The aeroelasticity practice at Boeing-Commercial is directed at airplane design and certification and therefore is naturally much more comprehensive and detailed than what can be found at a typical university or even a large research institution. In a university or research environment dynamics and flutter in particular seem to receive most of the attention. Although flutter is crucial for airplane design and certification, the general design philosophy is to avoid as much as possible, adding any structural stiffness to satisfy dynamics requirements. Using the strength design as a baseline, the goal is to eliminate or minimize any flutter weight increment. Thus, static loads predictions for strength design tend to get more attention particularly during the early preliminary design phase.

Static aeroelastic methods for the complete airplane were developed at Boeing around 1950 and are published in a classic NACA report.[2] The document includes reduction of wind-tunnel aerodynamic data to obtain sectional force and moment coefficients free of model flexibility effects and simultaneous consideration of fuselage and nacelles effects on the wing spanwise loading using a closed-form aeroelastic solution. Several programs to deal with various aspects of loads certification evolved internally at Boeing from the basic approach described in TN-3030. Most of the Boeing large airplanes were designed using these programs. The method is still fresh today and is being used with some updates for derivative airplanes. Figures 4 and 5 show a typical speed-altitude chart and a V-n diagram used to define conditions for an aeroelastic analysis. Figures 4 and 5 provide a perspective on the number of design conditions required for airplane certification. Design loads as well as dynamic responses are functions of the mass condition (payload and fuel), Mach number, altitude, and load factor. The conditions cover both flaps down as well as various combinations of deployed control surfaces. The total number of load conditions required to certify an airplane can be in the neighborhood of 5000 to 10,000 conditions even when attempting to reduce the number of load conditions. The results for these conditions are analyzed to determine critical design conditions provided to the stress/design engineers for structural sizing and design. There is therefore some iteration between stress and loads when the sizing modifies structural stiffness, which in turn affects loads. In this context it is easy to see that the use of computational-fluid-dynamics (CFD) data requires the ability to predict aerodynamic pressure distributions through the full flight envelope at various Mach, flight parameters (e.g., angle of attack), and control settings.

The unsteady aerodynamics used for flutter predictions was based on a modified formulation of strip theory by Theodorsen[3] until it was replaced by the doublet-lattice method.[4] The strip theory usage followed the TN3030 philosophy in that the induction effects were included, and steady sectional data were used to modify the theoretical aerodynamics. The analytical flutter models used were beam models with various factors and artifices to account for interactions not possible to represent by beams. The best example of such an interaction is the typical wing-body joint. Beam models were also ideal for branch mode analysis[5] along with the assumed modes for the nacelles and control surfaces. These models are simple and ideal for parametric studies. Much of the flutter beam analysis approaches were made efficient by automating the creation of the models in ATLAS.[6] There is a need to create the simple but powerful and elegant capabilities of the beam-based analyses in the finite element model based analyses and design approaches.

The Boeing dynamic flight loads methods were systematically organized in DYLOFLEX.[7] The structural models used for dynamic analysis were also branch modes models from ATLAS. One of the major differences in the flutter and dynamic loads analyses is the extra care in modeling the aerodynamics for rigid-body degrees of freedoms in the equations of motion of the complete free-free airplane used for dynamic loads.

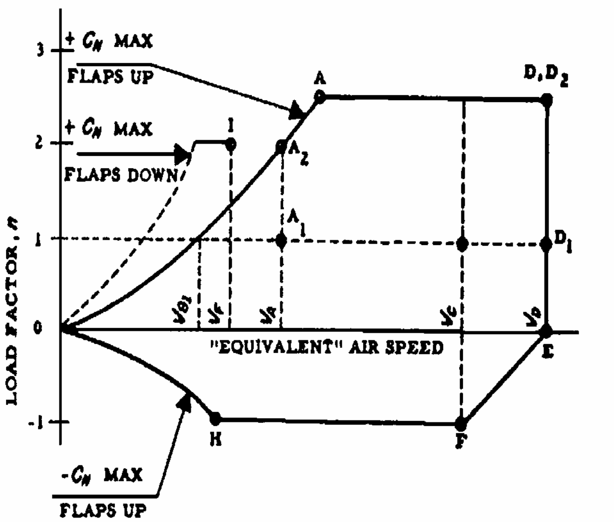

Fig. 5 V-n diagram for a specified Mach number and a weight condition.

The evolution of the airplane fly-by-wire control systems has improved airplane handling and ride qualities but has increased the potential for aeroservoelastic interactions. Fly-by-wire systems are characterized by increased frequency bandwidth with high gains of the augmented control laws/system utilizing angular-rate and acceleration sensor feedbacks. The increased bandwidth results in control law interactions with structural modes, and the high gains make these interactions significant. Strong aeroservoelastic interactions have required extensive coupled aeroservoelastic closed-loop analysis for stability as well as dynamic responses.

Typical control laws analyzed include yaw dampers, stability augmentation systems, modal suppression systems, autopilot control, and structural mode control. Since augmentation systems have become more critical for flight operations, the control system architecture has increased redundancies to deal with potential system failures. Thus the analysis conditions have increased significantly to include system failures in addition to structural failures. Figure 6 illustrates a typical schematic of the control law architecture for yaw axis control for an airplane.

As is well known in the case of transport jets with their multitude of low-frequency modes, including coupled wing, fuselage, engine, and tail motions, significant uncertainties can arise in early aeroelastic model predictions as a result of modeling difficulty in the structural dynamics and unsteady aerodynamics characteristics. The fidelity of aeroelastic models, then, has to be improved using ground, wind-tunnel, and flight-test results.

Flutter analyses have been performed mostly in frequency domain using an enhanced version of the *p-k* method developed at Boeing.[8] The Boeing *p-k* method based process includes automatic identification of the unstable roots/modes in the flight spectrum, using the match point process. Also, a large number of parameter variations, both for structural parameters such as control-surface frequency as well as system parameters such as gain/phase, can be performed in a single computer run. The process is used to include complex and high-order control laws. Gain and phase margins can be obtained using bode response plots or by the use of flutter parametric solutions. However, the computation time/cost for closed-loop aeroservoelastic flutter process can be significant depending on the size of the problem.

For generating time-domain solutions, rational function approximations for unsteady aerodynamics are used to develop a state-space

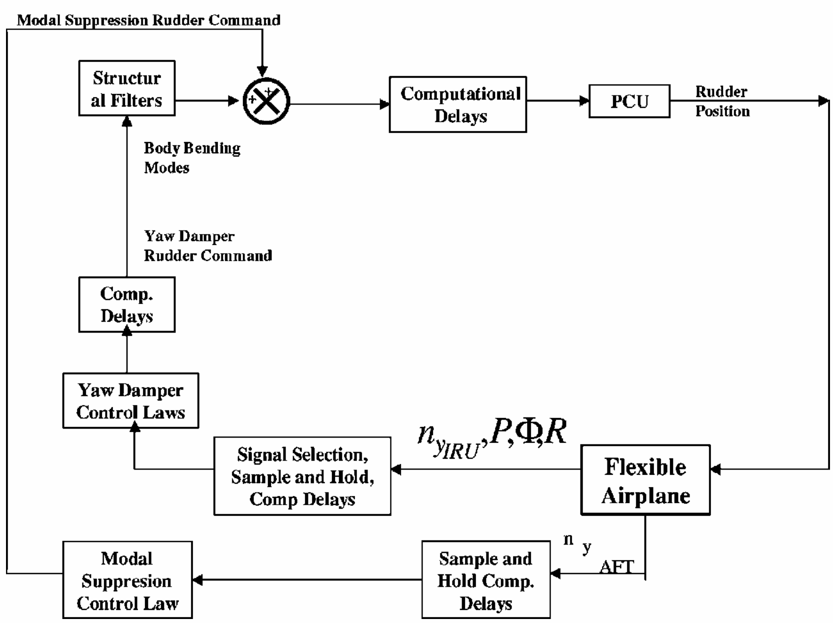

Fig. 6 Typical block diagram for yaw control.

representation of the aeroelastic system. The equations of motion are described in the s-plane using the Roger approximation[9] for the generalized aerodynamics. The Roger approximation was developed at Boeing for the B-52 active controls studies. An example of the work performed on B-52 was documented in 1967 (Ref. 10).

The equations of motion in the s-plane are primarily used for dynamic analysis, and their use for stability analysis has been somewhat limited. In dynamic flight loads the time-domain responses to atmospheric turbulence are evaluated using the closed-loop s-plane equations of motion. The frequency-response analysis uses a hybrid method where the open-loop second-order equations of motion are coupled with the state-space description of control laws. The responses to control-surface oscillatory failures are determined in a similar manner.

The preceding summary does not discuss nacelle loads, ground loads, landing loads, controls-surface loads, and other miscellaneous loads. Lomax has included a more complete description of loads analysis based on his many years of experience at Boeing in Ref. 11.

Boeing has since moved to a finite element based, more integrated loads and dynamic analysis approach using the CATIA-ELFINI (Ref. 12) and ELFINI Aeroelasticity (Ref. 13) from Dassault Systems. The potential advantages of Catia-Elfini are increased integration with the stress and structural design engineers. The flutter and dynamic loads solutions are performed outside ELFINI using the Boeing's enhanced *p-k* method and the EASY5/MAT (Matrix Algebra Tool) (Ref. 14), respectively. MAT is an interactive language-based tool for advanced numerical computation. It consists of a high-level language for writing algorithms, a multiwindow graphical user interface, and several libraries of numerical functions. MAT is designed specifically to be used in conjunction with EASY5 to perform control system design, data analysis, model data preparation, and postprocessing of EASY5 analysis results. Even though commercial off-the-shelf tools are available to do the basic aeroelasticity, in-house processes are required to perform the required certification analyses in an efficient manner. Therefore, each major airplane manufacturer probably has commercial tools embedded in a proprietary process to suit their specific needs. These tools and processes are assessed from time to time, and improvements and changes are made to improve the airplane design and certification process.

IV. Aeroelasticity Practice—The Issues

There are two primary issues with the practice of aeroelasticity in an airplane development environment. The first issue is the flow time and resources required to perform the aeroelastic analysis and evaluations at each stage of design cycle, that is, to determine design loads and stiffness requirements. The second issue is the increased need for predictive accuracy and elimination of revisions to design loads and stiffness requirements once they have been established. In the following section each issue and its implications are examined.

The time and resources required for an aeroelastic analysis are excessive both for the preliminary and detailed design cycles. During the preliminary design cycle, aeroelastic analysis cannot currently keep up with configuration development. As a consequence, static loads and strength analysis get emphasized, and the dynamic and aeroservoelastic analyses are delayed until the configuration development has progressed to center around more or less a converged configuration. This increases the likelihood that the relevant aeroelastic inputs are not available for the decision-making process to select the most promising candidate configurations for further study. During an airplane certification cycle, aeroelastic analysis can take several months. The loads analysis is a significant contributor to the long cycle time required for design and certification of an airplane. Because the loads are required for detailed design of every part of the airplane structure, any delay or revision to loads can be expensive. A revision to detailed design in itself can be expensive, but it also can contribute to expensive program delays.

A large number of load cases are required for airplane design to determine loads for all parts of the airplane and to cover all relevant flight conditions. The number of conditions for a design loads analysis tends to be in the range of 5000–10,000 cases. Therefore, even though linearized methods are used for most of the aeroelastic analysis, it involves a lot of detail and effort. The trend of increasing number of load conditions is driven by several factors. The first is the desire not to miss any critical conditions even by a small margin so as to avoid any redesign of the structure. The second and a related factor is to maintain increasingly tight margins so as not to add unnecessary weight to the airplane. The other factors contributing to this trend are the perception that a large number of load cases should not contribute any significant cost increase because of the advances in the computer technology. Often not considered are the implications of the large volumes of data on the overall computing system including storage and retrieval of the data and the cost of downstream use of data. But most important is the risk to the development of intuitive abilities of the young loads engineers to discern critical design cases in an environment where they might easily get buried in the volumes of data with increased reliance on a computer to run a large number of cases and extract the critical conditions.

Once the external loads have been computed, the transfer of loads from an external loads model to a more detailed internal loads or a stress finite element model is necessary. Because an internal loads model is usually finer than an external loads model, an accurate loads transfer can be challenging and requires extensive verification. Added to this complexity is the need from the stress engineers to get distributed loads on the airplane structure. Because the linear aerodynamic methods used in the loads analysis do not produce accurate detailed pressure distributions directly, the wind-tunnel pressure data are used to arrive at the final distributed loads. If reliable and affordable (in time and cost) CFD methods were available, some of the loads input data preparation could be simplified, but such is not the case currently.

The introduction of fly-by-wire systems and increased emphasis on handling and ride qualities has increased the scope of the closed-loop analyses and iterations with flight controls. Of concern is the practice in the flight-controls community to design control laws particularly for the autopilot, assuming a rigid airplane or at best a quasi-static aeroelastic airplane. For large, flexible airplanes the structural modal frequencies are in the range where they can have an adverse interaction with the handling qualities. Even though these issues are recognized, there is an understandable reluctance on the part of control law designers to include structural dynamics effect in the control law design because of insufficient fidelity of current structural dynamics models particularly during the early design phase. The control law designers in many cases like to or have to fine tune the control laws by extracting the structural dynamics models during flight test using system identification techniques. The revisions to control laws can require extensive rework, and this rework is difficult to plan in advance. The analysis model fidelity requirements are more stringent for aeroservoelastic analysis than for the traditional aeroelastic analysis. There is plenty of room for improvements in how we manage the aerodynamics-structures flight-controls interfaces and interactions.

The issue of predictive accuracy is important in its own right, but it also affects the time and resources required for loads analysis. The airplane has to meet the guarantees to the customer as well as meet all of the regulatory requirements for certification. In either case if the predictions fail to match the flight or other test data, airplane guarantees and/or certification can become an issue. In such a case the resolution of the problem must take precedence over many other tasks, and therefore the unplanned activities necessary to resolve the problem cause disruption in other tasks. It is obvious that there is a potential for serious business consequences for any serious discrepancy between predictions and actual performance.

Structural sizing methods of the past used to be conservative. With the ability to use large finite element models and improvements in calibrated stress methods, structural predictions have become quite accurate (within a very small percent) for the specified design ultimate loads. Simultaneously, aerodynamic designs have become more aggressive to improve airplane performance, and therefore the challenge of improving fidelity of loads predictions has become more difficult. Although some inaccuracy in loads predictions of the past was compensated by conservative structural sizing practices, this is not the case any more. Unfortunately, progress in the application of CFD methods to flight regimes where design loads are critical has been disappointing until recently. When extended to full flight envelope, CFD codes perform well in certain regimes and not so well in other regimes. For example, the most commonly used Navier–Stokes codes seem to do well as long as the flow is attached or mildly separated. This should allow for the use of CFD codes for a significant portion of the design loads predictions. However the use of CFD codes has been limited by the challenges of efficient grid generation and the cost of computing. The long flow time required for grid generation and execution of the large number of cases required for loads analysis coupled with the high cost of computing has impeded the introduction of CFD in loads analysis. The application of the CFD methods for unsteady aerodynamics for flutter and dynamic response is even more difficult not just because of the cost of computing for time-accurate solutions but also because of the limited validation of the CFD codes for unsteady aerodynamics.

The current practice is to rely heavily on the wind-tunnel-based methods. Aerodynamic pressure data are collected from wind-tunnel tests for many conditions. Different linearizations are used to address different flight regimes for different subdisciplines. The wind-tunnel data are adjusted for flight Reynolds numbers using a limited number of CFD cases. The current practice at Boeing of using common wind-tunnel models for aerodynamics and loads is the right approach and helps foster a closer collaboration between the two disciplines. Closer collaboration between aeroelasticians and aerodynamicists promises to improve airplane design practice. A consequence of such collaboration is the increased use of CFD in both aerodynamics and loads. The hope is that someday when the process for CFD predictions is more efficient and reliable and the computing costs are much more affordable than today, the need for the wind-tunnel testing will be reduced significantly.

There is a tendency to presume that most of the errors in an aeroelastic analysis are caused by inadequate aerodynamics. However, there are sufficient indications that the structural representation and mass distribution for aeroelastic analysis, and in some cases assumption of linear structural behavior, contribute significantly to the mismatch between predictions and flight test. Various subdisciplines in aeroelasticity have a tradition of using separate analytical models. For example, it was not unusual for static loads, dynamic flight loads, and flutter to have separate analytical models. Each of these models in turn can be different than the structural models used in the internal loads and stress analysis. It is not an easy task to keep these models consistently updated through the course of an airplane program. In the end all of these analytical models should be updated to correlate with the static ground vibration and flight tests. Therefore there is a potential for duplication of effort and confusion regarding differences in the models. Recent improvements in the CAD tools, closer integration of analysis software with CAD, the use of single source of geometry data, and improved design and analysis management software tools are expected to improve the consistency of different analytical representations.

V. Aeroelasticity—The Potential

When the aeroelastic process and its interactions with the airplane design process are considered, cycle time reduction becomes a critical issue. The efficient, timely, and cost-effective practice of aeroelasticity is an important segment in "minimizing" the overall airplane ownership cost because it has the potential to contribute significantly towards reduction of product development time. To achieve a near-optimum cycle time, it is necessary to have an aeroelastic process with the following characteristics: 1) a single, defined preferred process and defined alternatives, if any; 2) a seamless process from preliminary design through detailed design; 3) a robust process; 4) an efficient process; 5) a process with acceptable accuracy; and 6) an integrated process across as many disciplines as feasible at any given time for a given project.

It is easier to make a rational choice regarding technical approaches necessary for aeroelastic design when viewed from a broad cycle reduction perspective. An aeroservoelastic analysis and design using state-of-the-art methods was performed during the 1990s for the NASA-Boeing High Speed Civil Transport (HSCT) project. A supersonic airplane and its well-known aeroelastic problems[15] provided a fertile ground for implementation and demonstration of many of the approaches believed to be essential for improving the practice of aeroelasticity. The fact that the HSCT was in a preliminary design phase allowed deviation from the traditional approaches that have proven to be much more challenging to change in the traditional airplane organizations at Boeing, where ongoing project pressures make it difficult to deviate from existing methods.

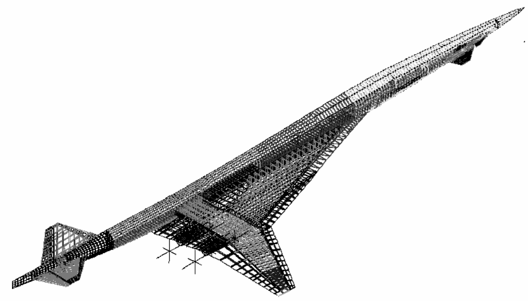

Fig. 7 HSCT common finite element model.

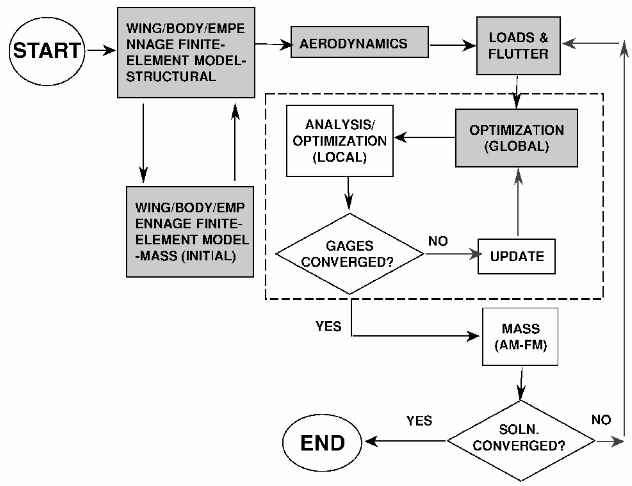

Fig. 8 Aeroelastic analysis and structural optimization.

During the HSCT development, an attempt was made to minimize the cycle time and eliminate redundant models. A single, common model for static loads, dynamic loads, and flutter analysis was used. The same model was used for structural sizing using the same tools used by the stress engineers. Figure 7 shows a typical HSCT finite element model used for aeroservoelastic analysis. A collaborative closed-loop analysis was performed with flight controls using again the same dynamic model. The collaborative analysis was used to modify the flight control laws to eliminate adverse impact on flutter characteristics.

The total time required at the end of the project for a complete preliminary design aeroelastic cycle was about 3–4 months. The aeroelastic cycle included definition of structural layout and geometry; creation of the finite element model and the associated mass model, steady and unsteady aerodynamic models, and loads and flutter analyses; and setup for structural optimization with strength, buckling, flutter, end loads, design and manufacturing constraints, implementing structural sizing iterations using optimization, and ultimately weights. Figure 8 illustrates the flow diagram for aeroelastic analysis and structural optimization. The optimization problem had about 2000 design variables, 20 load conditions, 10 flutter conditions, and over a million total constraints of which less than 10,000 were active at any step.

The important issue of fidelity of aeroelastic models deserves significant attention. The four main sources of errors in an aeroelastic model are 1) structural modeling, 2) mass modeling, 3) aerodynamic modeling, and 4) control law modeling. The structural

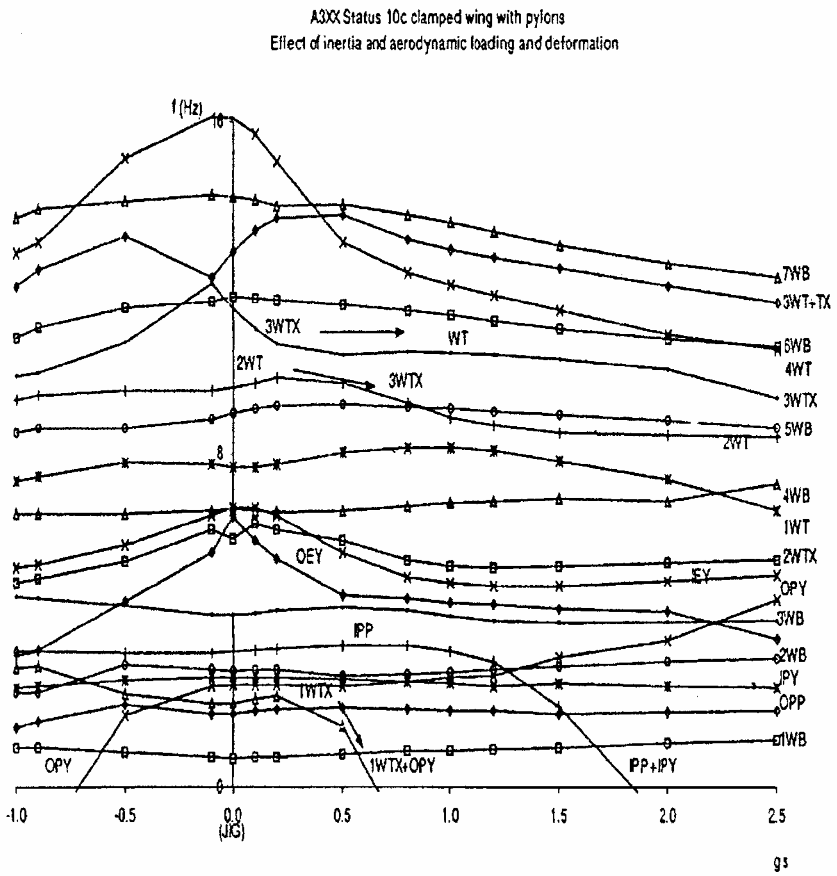

Fig. 9 Effect of inertia, aerodynamic loading, and deformations on clamped wing with engine pylons on normal modes in hertz.[17]

representation should represent all major load paths to allow the finite element model to simulate the behavior of the airplane structure. Similarly the mass model should faithfully represent the mass distribution on the underlying structure. Without a proper structural representation it would be very difficult, if not impossible, to adjust an analytical model to match ground-vibration test (GVT) or flight test responses. Correlation and model correction methods have made significant progress to be considered for inclusion in the regular arsenal of aeroelasticians. An example of application of the modern correlation methods to space station is presented in Ref. 16.

One aspect of structural representation that deserves more attention is the effect of large deflections on the static and dynamic characteristics of the structure. This is particularly important for large, flexible airplanes. For static loads analysis an attempt is made to account for changes in external load vectors caused by large deflections. However, the effect of large deflections for dynamic characteristics is usually not considered. Analytical results were recently published showing the effect of large deflections on a large, flexible airplane.[17] Figure 9, taken from Ref. 17, illustrate the effects of large deflections on frequencies of a clamped wing.

The effect of large deflections is more pronounced without the aerodynamics. Comparing the effect of large deflections with and without aerodynamic loading, the authors note that the outboard pylon yaw mode and the second wing torsion modes have significant differences between the 1-g analysis conditions corresponding to GVT and flight test. The chordwise bending modes are more sensitive to the large deflections than the vertical bending modes. This can be significant for configuration with winglets.

The general practice in aeroelasticity is to model the airplane in its jig shape. This practice needs to be examined to determine its effects on modal correlation during flight test. This is particularly important for large, flexible airplanes with a fly-by-wire control system, where requirements for the accurate response predictions might be more stringent than requirements for dynamic loads or flutter. As had already been discussed, inaccuracies in the coupled aeroservoelastic model make it challenging to design reliable active control laws. In many cases flight-test measurements are used to refine the analytical models and modify the control laws during flight test. There are obviously improvements needed in the accuracy of the structural dynamics predictions and the design of robust control laws.

In considering the use of CFD in aeroelasticity, it is apparent that the full nonlinear CFD analyses are not practical for thousands of design conditions required in an aeroelastic analysis. Breakthrough improvements in geometry preparation, grid generation, predictive accuracy in full flight envelope, and cost reduction will be needed to make the CFD use practical on a large scale or in a fully nonlinear solution environment. For now the CFD usage must be limited to mostly a linearized formulation for aeroelastic analysis and a limited number of nonlinear applications.

A three-stage process has been suggested by the author for practical application of CFD for design loads analysis. In the first stage CFD is used as a substitute for the wind-tunnel, and a limited number of CFD runs are executed. The CFD data are linearized for a traditional loads analysis, and a large number of load cases ($O10^3$) and the corresponding deflected shapes are determined from a linearized aeroelastic analysis. The loads results of stage 1 were examined for potential critical loads conditions and selected load conditions and associated deflected shapes defined ($O10^2$) for a stage 2 analysis The airplane geometry is adjusted to create deflected geometry for each of these conditions, and CFD is used to create a linearized aerodynamic database. A linearized loads analysis for the conditions is repeated using the new aerodynamic data directly for the reference condition and the linearized aerodynamic data to account for aeroelastic effects. The stage 2 loads analysis can be used for design after verification of the critical design conditions by a stage 3 analysis. The stage 2 analysis can account for large deflections approximately or more precisely if the analysis is iterated. In stage 3 selected conditions ($O10^1$) can be verified by directly coupled aeroelastic analysis with reference to the results obtained during stage 2. Figure 10 illustrates the three stages and their usage during different design phases.

It was estimated that to use even the first stage of the three-stage process requires massively parallel computers. A minimum grid size of 10 million points is needed to obtain an adequate Navier–Stokes solution for a complete airplane. To calculate CFD solutions for

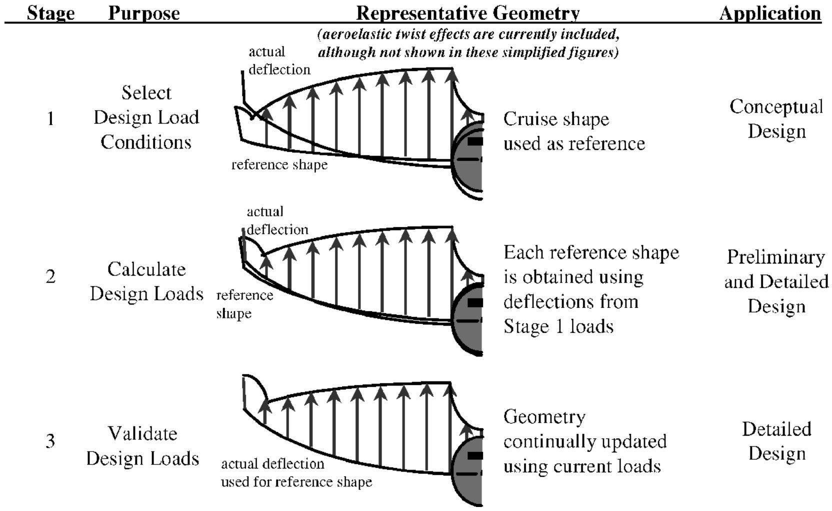

Fig. 10 Three-stage process.

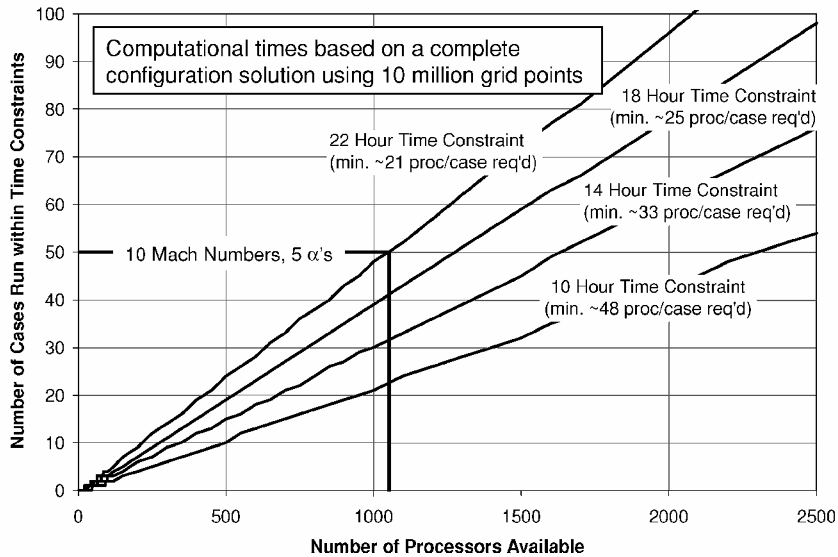

Fig. 11 CPU time for 50 CFD cases.

50 Mach number and angle-of-attack conditions in 24 hours, about 1000 processors of Origin 2000 class are required (Fig. 11). This is certainly possible today.

As the needs for the fidelity of the models and the number of cases to be analyzed increase, there is a need for a formulation that allows faster computation time. This is particularly true for state-space formulation required for closed-loop analysis. The additional lag terms required for a good fit when frequency-domain unsteady aerodynamic forces are converted to the time domain increase the size of the equations of motion. Two promising approaches to order reduction have been developed recently to achieve model order reduction. The first of these is the p-transform method,[18] which is an extension of the p-k method to transient analysis. The second method uses K-L reduction,[19] which seeks an optimal set of base vectors that will span the solution space with a minimum number of modes. A different approach to aerodynamic and structural dynamic order reduction uses the unsteady CFD solutions directly and is based upon Volterra's method.[20] It uses impulse responses to derive a reduced-order model.

Recently, we have also seen the application of unsteady Navier–Stokes codes in simulation of wind-tunnel tests. A significant body of wind-tunnel test data exists for unsteady pressures on rigid models and flutter points for scaled flexible models. Unfortunately, most of the test data are handicapped by the deficiencies in characterization of the wind-tunnel tests and in some cases incorrect simulation of tunnel boundary conditions. Design and fabrication of each wind-tunnel model and test can take many months or even years and cost millions of dollars. Therefore, in an effort to assess current CFD technology for the loads process, past wind-tunnel test results were sought for high-fidelity simulation correlation with experiments. Boeing Commercial has attempted to use the NASA-developed code CFL3D in two careful simulations. The first simulation[21] was for a rigid low-aspect-ratio wing on an oscillating table, tested in the NASA Langley 16-ft Transonic Dynamics Tunnel (TDT) during the High Speed Research (HSR) program. The second simulation[22] involved a Boeing flutter wind-tunnel flutter model representing a typical twin-engine transport wing also tested several times in the TDT. The HSR model is shown in Fig. 12, and the simulation of the twin-engine transport model is shown in Fig. 13. The steady and unsteady pressure correlation obtained for the thin, low-aspect-ratio HSR model was quite good except at high angles of attack. One of the interesting features of the analysis-test correlation was the ability of CFL3D to predict flows near and at Mach 1. The flutter correlation for the twin-engine-transport model showed that it was very important to have a high-quality grid particularly for the unsteady aerodynamic predictions, in order to avoid convergence problems. The study also highlighted the limitations of the moving grid capability. In both cases the reduced-order modeling approaches were verified and improved. The evaluation for the twin-engine-transport model is continuing, and the final conclusions have not been established as yet.

Successful simulation of the wind-tunnel tests can provide a basis for the use of high-fidelity simulations instead of some wind-tunnel tests. It is first time in the history of aeroelasticity that it is even

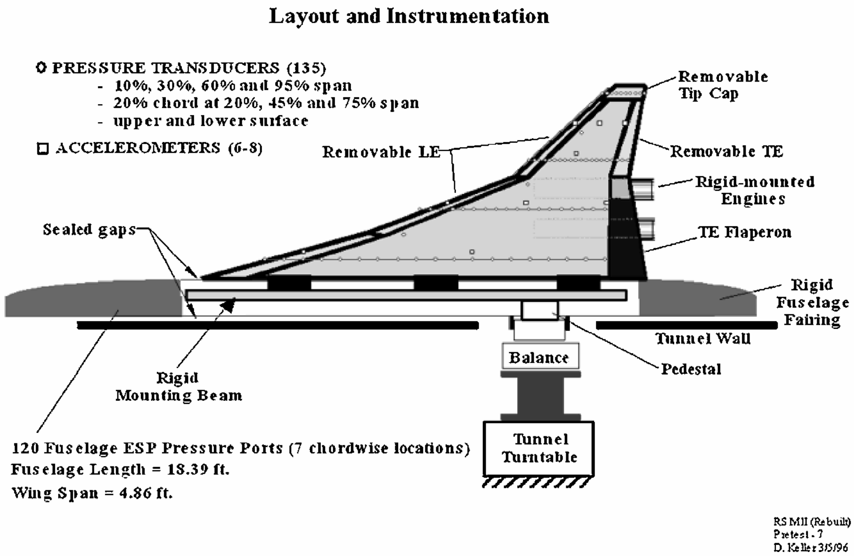

Fig. 12 Layout of the NASA HSR Rigid Semi-Span Wind Tunnel model.

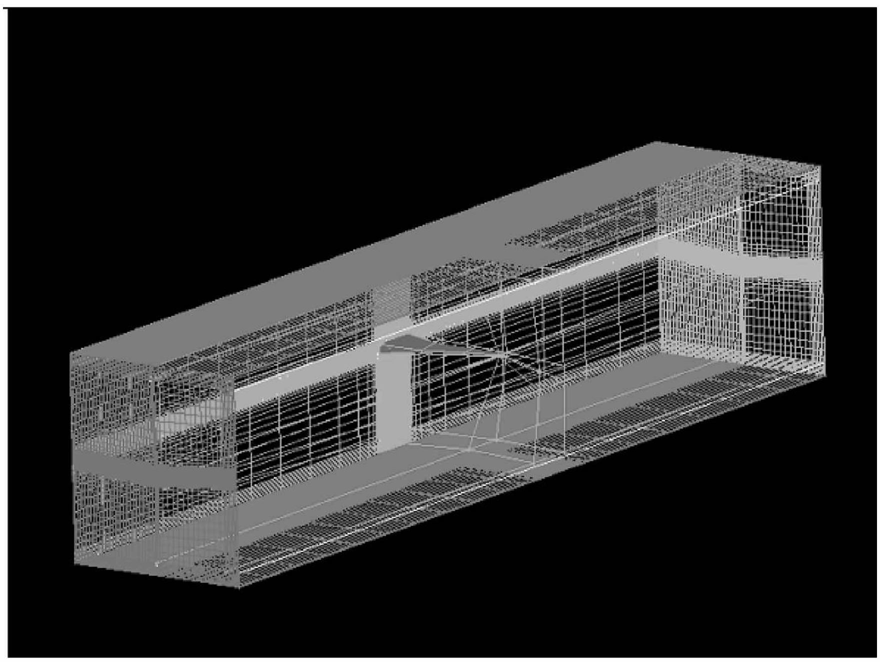

Fig. 13 Analytical simulation of the Boeing Twin-Engine Transport model in NASA TDT.

possible to think in these terms even though we are not there yet! With the rapid increase in computing capacity and affordability, it should be possible in a few years to run CFD-based simulations for selected conditions. However, we need to have significant improvements in the CFD codes to develop full confidence in them to be able to trust the results without correlating with test data. In the meantime we must continue to calibrate and correlate the existing CFD tools and provide encouragement and resources to the developers to improve the CFD simulations. At this stage it is easy to see that the CFD simulations allow us to reduce wind-tunnel testing and/or improve our understanding and utilization of the wind-tunnel test data.

The multidisciplinary effort during the HSCT project demonstrated that a small team of engineers could implement an aeroelasticity-based integrated analysis using common models. It was crucial to the success of the team to have the concurrence and access to the methodology of the stress group for sizing and to include the weights group as an integral part of the aeroelastic analysis and structural sizing team. The integrated analysis of the HSCT effort has been difficult to implant into the mainstream product development groups. Part of the reason is that the HSCT processes were suitable primarily for preliminary design (and not for certification) and in some cases were different than the processes used for conventional airplanes. There was a general acknowledgment that we needed to do things differently because of the novel HSCT configuration. In the mainstream product development groups the general feeling was that only fine tuning of the processes was required, but a complete overhaul was not necessary. In the current practice it seems that we have more elements of coordination than integration. The potential gain from the lean, multidisciplinary teams performing integrated analysis and design is too significant to ignore, and therefore we must figure out how to transition effectively to such multidisciplinary teams.

The time is ripe for a fundamental change in how aeroelastic analysis is performed. Reference 23 suggested a unified approach to modeling high-fidelity multidisciplinary interactions. The unified approach is specially tailored for application environments, where the geometry is created and managed through a CAD system. For aeroelastic analysis the unified approach offers a greater scope for automation for setting up an aeroelastic analysis with finite element method and CFD representations. The full potential of aeroelasticity will be realized when aeroelastic approaches form the core of multidisciplinary analysis and design of airplanes. The multidisciplinary heritage of aeroelasticity needs to be extended to encompass the complete airplane design and simulation. This can be achieved only if the cycle time is reduced, and acceptable fidelity appropriate for each stage of design is incorporated in the aeroelastic process. Aeroelasticity must therefore evolve by demonstrating why it should be the integrating discipline. The technical and management communities need to convince themselves that this is in the best interest of a lean airplane design process.

VI. Conclusions

A perspective on the practice, issues, and potential of aeroelasticity has been presented. The time and resources required to perform the aeroelastic analysis and evaluations at each stage of design cycle are excessive, and in particular this does not support adequately the airplane configuration development. The time and effort required to determine detailed load distributions for the large number of design cases required for an airplane certification contribute significantly to airplane certification cycle time. The introduction of fly-by-wire control systems has increased the complexity as well as the fidelity requirements for the aeroelastic analysis. The business cost of inaccuracies in loads predictions can be seriously high. It is suggested that the issues of cycle time reduction and improvements in the fidelity of aeroelastic analysis be given more emphasis than is currently given.

Recent developments in the application and verification of steady and unsteady CFD capabilities combined with the emergence of lower-cost computing provide a potential for high-fidelity flight simulations. The analytical simulations are expected to reduce the need for expensive wind-tunnel tests for configurations where the CFD has been demonstrated to provide good correlation with the wind-tunnel and flight-test results. The verification of the steady CFD applications is much farther ahead of the unsteady CFD applications because of the additional complexity and expense of the time-accurate solutions as well as the relatively more conservative tendencies of the loads community compared to the aerodynamics community. Therefore the establishment of configuration and flight parameters where unsteady CFD can be used reliably for design and prediction of dynamic characteristics is often overlooked by the CFD research community as well as the design community. Even though the unsteady CFD methods are still expensive computationally, the potential savings from reduced flutter testing is significant; therefore, investment in the significant effort required to verify that the unsteady CFD methods are accurate enough for design is justified and should be undertaken.

Aeroelasticity has an opportunity to contribute to the airplane design by evolving into a major integrating discipline. Many of the methods and processes in different subdisciplines are in place already, and some need significant additional development. But the most challenging problems in realizing the full potential of aeroelasticity are not just technical but are also organizational in nature and are related to management of teams. Thus, to realize the multidisciplinary integrating potential of aeroelasticity and its contributions to the configuration decisions, technical and management foresight, leadership, and vision are required.

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