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AIRCRAFT AEROELASTICITY AND STRUCTURAL DYNAMICS RESEARCH AT THE NASA LANGLEY RESEARCH CENTER-SOME ILLUSTRATIVE RESULTS

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Abstract

Highlights of nine different research studies are described. Five of these topics relate directly to fixed-wing aircraft and range from flutter studies using relatively simple and inexpensive wind-tunnel models to buffet studies of the vertical tails of an advanced high performance configuration. The other four topics relate directly to rotary-wing aircraft and range from studies of the performance and vibration characteristics of an advanced rotor design to optimization of airframe structures for vibration attenuation.

Introduction

The Langley Research Center of the National Aeronautics and Space Administration (NASA) and its predecessor organization, the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics (NACA), have a long and rich history in aircraft research and development.(1) For almost seventy years Langley scientists and engineers have been conducting research on a variety of topics ranging from structural dynamics to material science to performance aerodynamics. The depth and breadth of recent work is easily seen by examining a typical annual report of the Langley Research Center.(2)

The purpose of the present paper is to present some illustrative results from recent research at Langley in aeroelasticity and structural dynamics. Langley has an extensive research program in these areas as attested to by the summary material presented in references 3, 4, and 5. In this paper representative topics of both airplane and helicopter (rotary wing) research are discussed. In selecting topics to be included herein the authors have undoubtedly been biased by their own experiences and interests. Consequently, a large portion of the subject matter presented directly resulted from or was closely related to wind-tunnel tests in the Langley Transonic Dynamics Tunnel which is the premier wind-tunnel facility in the United States for aeroelastic research. In all, nine different research investigations are described. The format used in the discussion is the same in each instance, namely, a description of the purpose of the study, followed by a description of how it was conducted, and then a discussion of illustrative results.

Airplane Research

In this section five topics relating to fixed-wing aircraft are discussed. All of these are related to experimental wind-tunnel model studies that have been conducted in the Langley Transonic Dynamics Tunnel (TDT).(6) This facility is a closed circuit, single return wind tunnel with a large slotted-wall test section (16-feet-square). It is equipped to use either air or Freon* as the test medium. Tunnel pressure is continuously controllable from near vacuum to atmospheric pressure. The Mach number (M) may be varied continuously to a maximum of 1.2. The TDT is used almost exclusively for aeroelastic and structural dynamics research.

The topics discussed range from very simple model studies that are in the basic research category to very complex studies that were initiated to support the development of advanced designs.

Some Effects of Speed Brakes on Wing Flutter

Speed brakes, spoilers, and other devices that are extended from the surface of a lifting surface have been used effectively in many stability and control applications in aeronautics. One use that has not been studied, however, is their use as a flutter suppressor. The purpose of this study was to obtain some parametric results of the effects of speed brake size and deployment angle on wing flutter.(7) A relatively simple, paddle-type flutter model was equipped with a speed brake that could be deployed over a range of angles by adjusting a mechanical mechanism. In addition, the model

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could be fitted easily with different-sized speed brakes. A photograph of the model is shown in Figure 1. This multiple exposure shows the speed brake at several angles. That portion of the model exposed to the flow was "rigid." Model stiffness was determined by dimensions of the flexible "paddle handle" that was behind the splitter plate which was used to place the wing root outside the wind-tunnel wall boundary layer. The bending and twisting of the paddle handle provided the wing with flapping and pitching degrees of freedom. The handle was shielded from the flow by a fairing. The model was ballasted so that the mass and inertia did not change as speed brake parameters were varied, thus, the natural frequencies remained the same. Consequently, changes in flutter characteristics between different speed brake configurations could be directly attributed to speed brake aerodynamic effects.

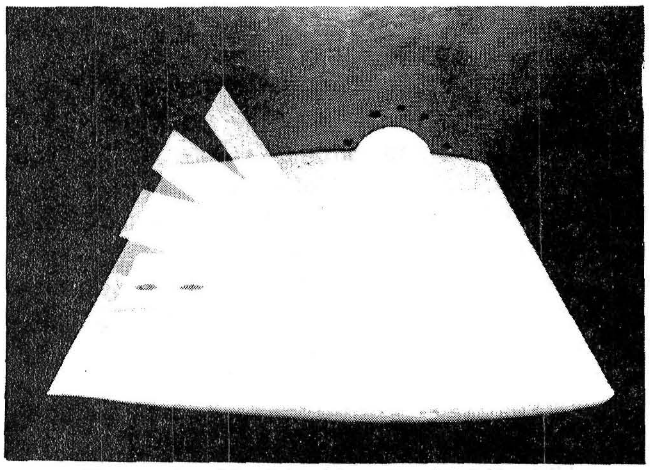


Figure 1. Model with speed brakes.

Experimental flutter results were obtained at M=0.80 for variations in speed brake deployment angle for a constant speed brake size and for variations in speed brake size for a given deployment angle. These results are shown in Figures 2 and 3 as the relative variation of flutter dynamic pressure with the respective speed brake parameter. These results show that the flutter dynamic pressure is increased by increasing either deployment angle or size but that a significant deployment angle is required before the flutter speed changes significantly. Further, the data show that size has a stronger effect on flutter than does deployment angle over the range of variables studied. These data provide an initial basis to evaluate the effects that the deployment of speed brakes have on suppressing wing flutter.

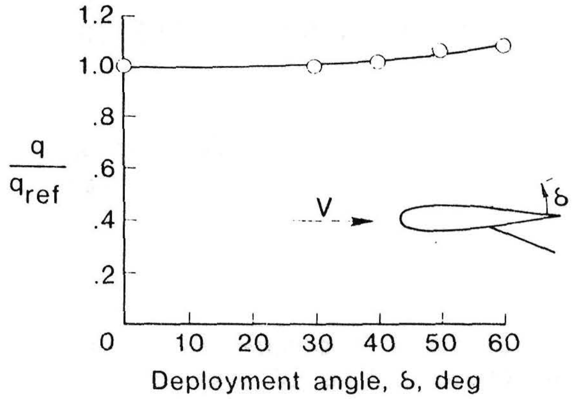


Figure 2. Deployment angle effects for brake area/wing area=0.047.

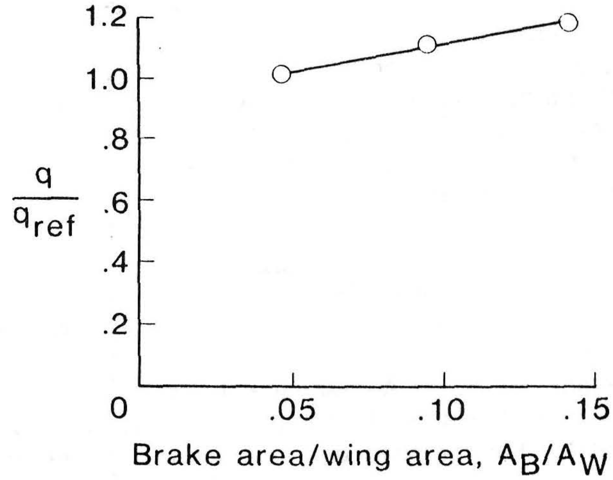


Figure 3. Speed brake size effects for deployment angle=40°.

Arrow Wing Flutter Study

A resurgence of interest in supersonic cruise flight has rekindled interest in providing a better understanding of the flutter characteristics of such supersonic transport configurations. This has been a subject of considerable interest to Langley researchers, and a modest aeroelastic research program has been underway for some time.

That portion of this program which consists of a series of parametric wind-tunnel flutter model tests accompanied with companion analytical studies is described in this section.(8) This flutter research consists of determining the effects of several parameters considered important to flutter on a generic arrow-wing design representative of a supersonic cruise configuration. A listing of the parameters being investigated is presented in Figure 4. A photograph of one of the model configurations mounted in the wind tunnel is shown in Figure 5. A typical model consisted of an aluminum alloy plate which was covered with end-grain balsa wood to provide the desired parabolic airfoil section. Cutouts in the plate were used to simulate an arrangement of spars and ribs.

- **STRUCTURAL ARRANGEMENT-WING TIP REGION**
- **MASS DISTRIBUTION-WING TIP REGION**
- **GEOMETRY-WING TIP REGION**
- **FUEL LOADING**
- **UPPER SURFACE MOUNTED WING FIN**
  - **ON/OFF**
  - **STIFFNESS**
  - **MASS EQUIVALENT**
- **ENGINE NACELLE-ON/OFF**
- **ANGLE OF ATTACK (LIFT)**

Figure 4. Arrow-wing study parameters.

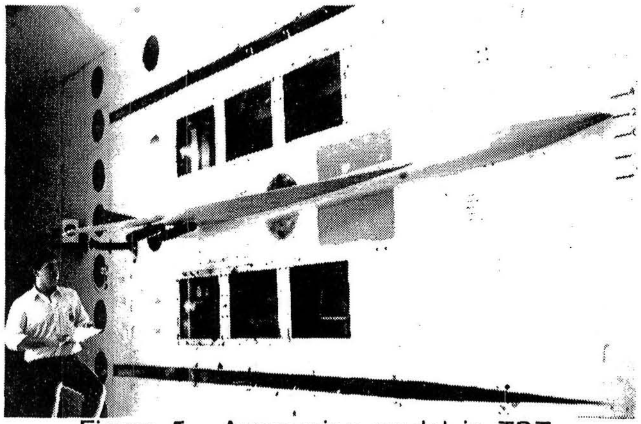


Figure 5. Arrow-wing model in TDT.

Some illustrative experimental flutter results are presented in Figure 6 as the variation of dynamic pressure with Mach number. Data are presented for four configurations, namely, the basic wing, the basic wing to which had been added an upper-surface-mounted fin, the basic wing with two simulated nacelles mounted near the trailing edge on the lower surface, and the basic wing with both the fin and two nacelles. The flutter boundaries shown are typical of those that have been observed for a variety of configurations. (The suppressed origin in the figure tends to exaggerate the transonic dip.) The boundaries for the two "with nacelles" configurations are similar and exhibit a considerably more pronounced transonic dip than do the boundaries for the basic wing and wing-with-fin configurations. The addition of the fin to the wing has a favorable effect on the flutter boundary.

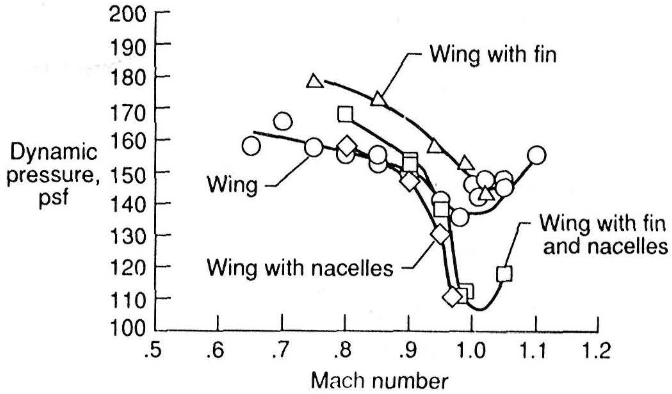


Figure 6. Arrow-wing flutter boundaries.

<u>Unusual Instability Boundary For Transport Wing Configuration</u>

The purpose of this research was to investigate further an unusual transonic instability encountered in a previous test in the TDT of a wing model representative of an advanced transport configuration. A photograph of the model mounted in the wind tunnel is shown in Figure 7. During the previous test what appeared to be a wing first-bending mode instability was predicted by using a subcritical response technique to occur at dynamic pressures well below the analytically predicted conventional flutter boundary.(9) This instability appeared to occur at constant M=0.90, to cover a relatively large range of dynamics pressures from about 50 psf to above 300 psf, and to be sensitive to changes in wing angle of attack. Because this instability exhibited characteristics similar to a phenomena that has become known as shock induced oscillations (SIO), it is a concern to designers of advanced transport configurations. Therefore, a second test was conducted using the same model to explore the apparent instability in more detail.(10,11)

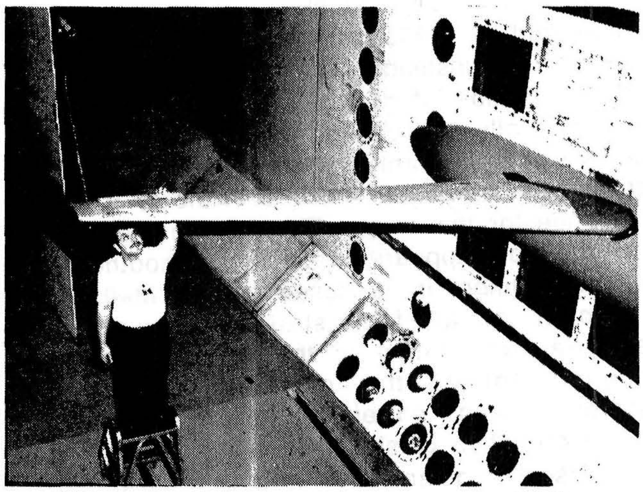


Figure 7. Transport wing model in TDT.

Some illustrative results from this second test are shown in Figure 8. These tests showed that the previously identified instability boundary could be penetrated without the amplitude of oscillations diverging, thus indicating the absence of a "hard flutter" condition. However, significant oscillatory response was observed. The data in the figure show that the wing tip motion begins to increase rapidly at about M=0.85, reaches a maximum near M=0.93, and then decreases rapidly. Illustrative autospectra results, not shown in the figure, indicated that the response was primarily in the first bending mode which had a wind-off frequency of about 8.2 Hz. The response was effected by changes in angle of attack, but no consistent pattern was observed. The response at a given angle of attack was proportional, but not linearily so, to the dynamic pressure. Tufts installed on the wing surface during the test indicated large regions of flow separation on both upper and lower surface above M=0.90.

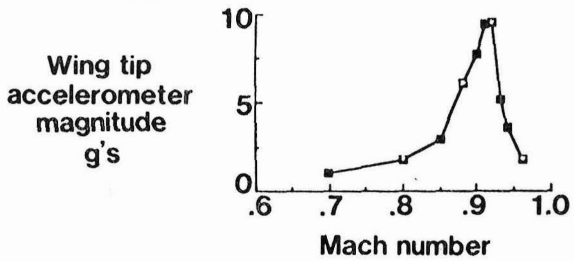


Figure 8. Wing-tip response.

In addition to the response measurements, some unsteady pressure measurements were made. Some of these pressure results are shown in Figure 9. Pressure time histories at four chordwise locations at about ninety-percent span are shown for four Mach numbers. At M=0.80 some unsteadiness is apparent in the flow, most noticeable at station 1. At M=0.88 the flow is smooth at station 1, and is considerably unsteady at station 2 on the upper surface and at stations 3 and 4 on the lower surface. This unsteadiness is believed to be due to the formation of strong shocks on the wing which typically for configurations such as the one here begin to form at Mach numbers near the drag rise Mach number which is in the M=0.81 to 0.83 range for this wing. The data in the figure show the flow appears to become smoother as the Mach number is increased until at M=0.96 it is smooth at all four stations shown. A qualitative examination of the response of the wing in light of the pressure fluctuations indicates a strong correlation between response and the formation of shock waves that are likely to be oscillating and the attendant boundary layer separation.

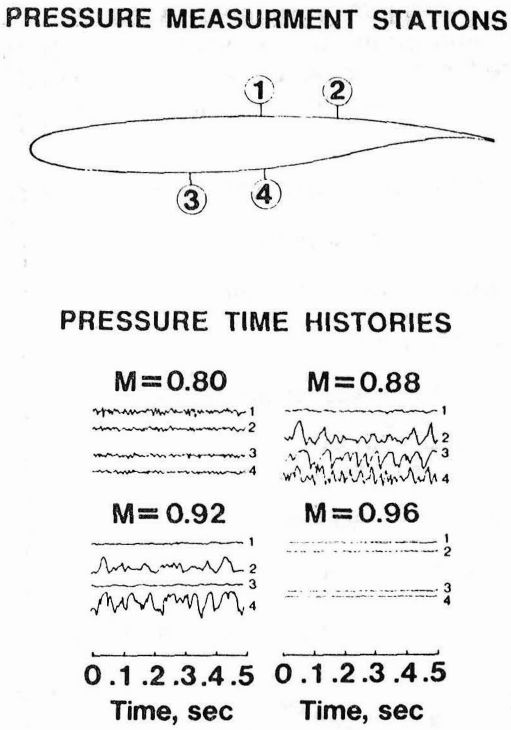


Figure 9. Unsteady pressure time histories.

<u>Flutter Characteristics of an Advanced Wing Design with External Stores</u>

As part of the development process of a new wing design for an attack type airplane a 1/4-size dynamically scaled aeroelastic model was tested to determine the flutter characteristics of the wing with and without external stores.(12) A photograph of the semispan model mounted in the wind-tunnel is shown in Figure 10. The aerodynamic effects of the fuselage on the wing were accounted for by using a rigid fuselage fairing. The model wing was attached to the wall through a fixture that simulated the wing-fuselage attachment flexibility. The store configurations studied were selected from those expected to be used most commonly and to have the most impact on wing flutter characteristics.

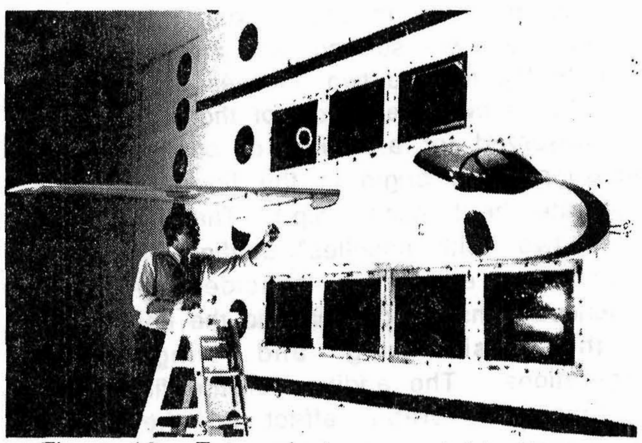


Figure 10. External stores model in TDT.

Some illustrative flutter results are shown in Figure 11 as the variation of flutter dynamic pressure with Mach number. These data are for a single store mounted on the outboard pylon. Flutter data are presented for three configurations, namely, the wing with simulated 300-gallon fuel tank, the wing with simulated 400-gallon fuel tank, and the wing with pencil store that had the same mass and inertia characteristics as the 300-gallon fuel tank. The fuel tanks were streamlined bodies with a fineness ratio of about eight; the pencil store was a small rod-like configuration with a fineness ratio of about 33. The arrows on the figure show the approach path to the flutter boundary during the test. The Mach number trends of the boundaries for the fuel tank configurations were similar, almost constant dynamic pressure with increasing Mach number. The flutter boundary for the 400-gallon-tank configuration was the lower of these two boundaries. The flutter dynamic pressure for the pencil-store configuration was the highest of the three configurations and had a different trend with Mach number, decreasing to a minimum value near M=0.90 and then increasing with increasing Mach number, the typical transonic dip, or bucket. This difference in flutter characteristics is a clear indication that store aerodynamic effects play a significant role in the flutter characteristics of this wing with external stores.

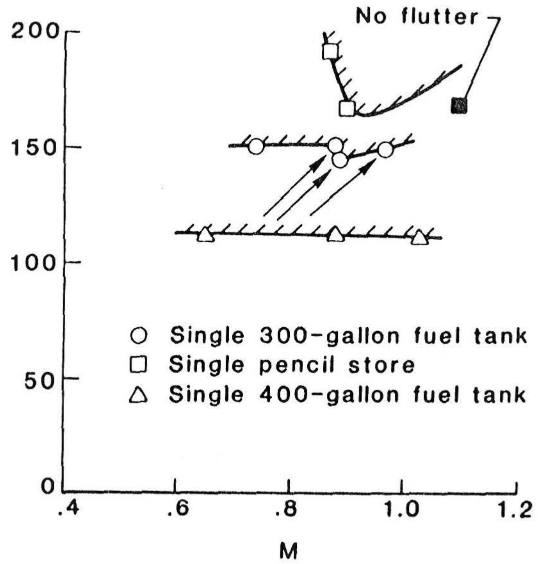


Figure 11. Store effects on flutter boundary.

<u>Effects of Mach Number on Buffet Response of a Twin Vertical Tail Airplane Model</u>

Recent experiences from the operational use of high performance, twin vertical tail airplane configurations have shown that relatively large dynamic response of the tail structure occurs at certain often encountered high angle of attack flight conditions. These buffet like responses may be larger than those anticipated in the structural design and can have an adverse effect on service life. This study was undertaken to obtain data that can be used to better understand the characteristics of these undesirable responses. A full span, "rigid," sting mounted model of a high performance twin vertical tail airplane was equipped with an elastic vertical tail and buffet tested over a range of angles of attack and Mach numbers.(7) A photograph of the model mounted in the wind tunnel is shown in Figure 12. Although the elastic tails did not precisely scale the dynamic characteristics of a specific full scale design, their stiffness and mass were chosen so that the dynamic characteristics were representative of full-scale values.

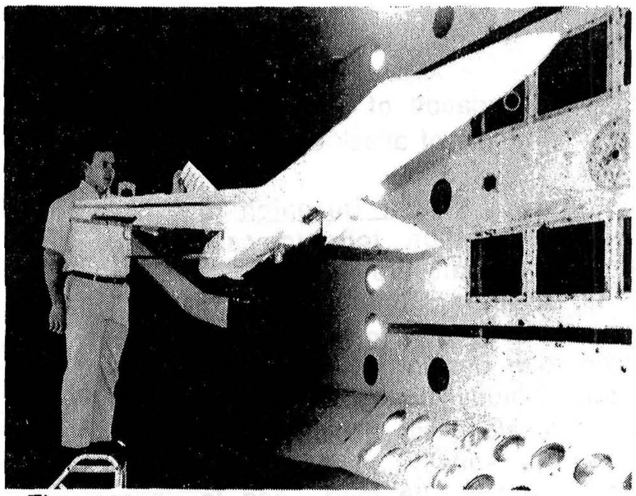
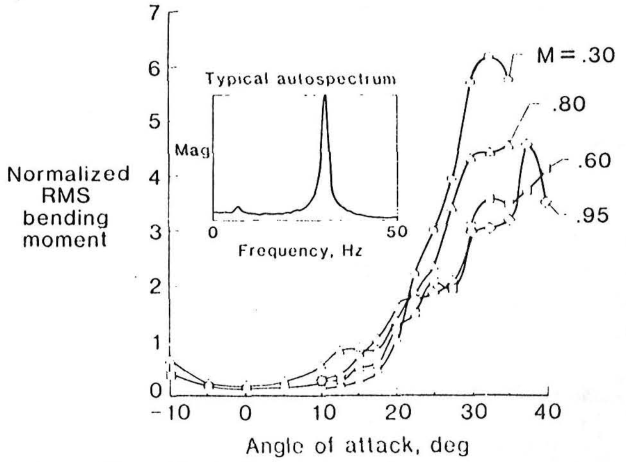


Figure 12. Twin-tail buffet model in TDT.

Some of the experimental buffet response data that were obtained are shown in Figure 13 as the variation of a normalized root-mean-square bending moment response parameter with angle of attack for several different Mach numbers. The commonly used response parameter is the one derived from using generalized harmonic analysis considerations. In normalizing the data it was assumed that the aerodynamic damping was very small compared to the structural damping, a reasonable assumption here because the tails were at near zero lift during the test. The response of the tails was primarily in one structural mode as shown by the typical autospectrum included on the figure. The data for all Mach numbers are similar in that the bending moment is small and relatively constant up to an angle of attack of about 15^0, where a relatively sharp increase in bending moment begins to occur. Although the details of the data are different at the various Mach numbers, it does appear that the peak response occurs in the neighborhood of about 30 to 35 degrees angle of attack. The magnitude of the maximum values, however, appears to be a function of Mach number. Data such as those presented here provide a basis for assessing the Mach number effects on the buffet characteristics of twin vertical tail airplane configurations.



Figue 13. Variation of buffet response with angle of attack and Mach number.

Rotorcraft Research

In this section four topics relating to rotary wing aircraft are discussed. The first topic is a pure helicopter study of the performance and vibration characteristics of an advanced rotor design. The second topic is an optimization study that used the design of a helicopter fuselage for minimum vibration as a focus, but is equally applicable to fixed-wing designs as well. The third and fourth topics address tilt-rotor aircraft. The first of these two is a wind-tunnel model study and companion analytical study of a advanced tilt-rotor airplane design. The fourth topic, the second one on tilt-rotors, is an optimization study employing extension-twist coupling concepts to develop a rotor design that satisfies both hover and forward flight requirements.

Performance and Vibration Characteristics of an Advanced Rotor Design

An advanced helicopter design developed by engineers at the U. S. Army Aerostructures Directorate colocated at NASA-Langley appears to offer significant improvement in hover and forward flight performance as compared to blades designed for the same mission by more conventional methods. The present design was accomplished by using technology which optimized blade planform, airfoil section, twist, and solidity. To validate the improvements predicted analytically a Mach-scaled set of model rotor blades was designed, fabricated, and wind-tunnel tested in the TDT.(13) A photograph of these blades mounted on the Aeroelastic Rotor Experimental System (ARES) in the wind-tunnel test section is presented in Figure 14. The ARES is a system that includes the necessary instrumentation, controls, and other features necessary to test a variety of different rotor blade models. The geometry of the advanced blades is characterized by a highly tapered portion near the tip.

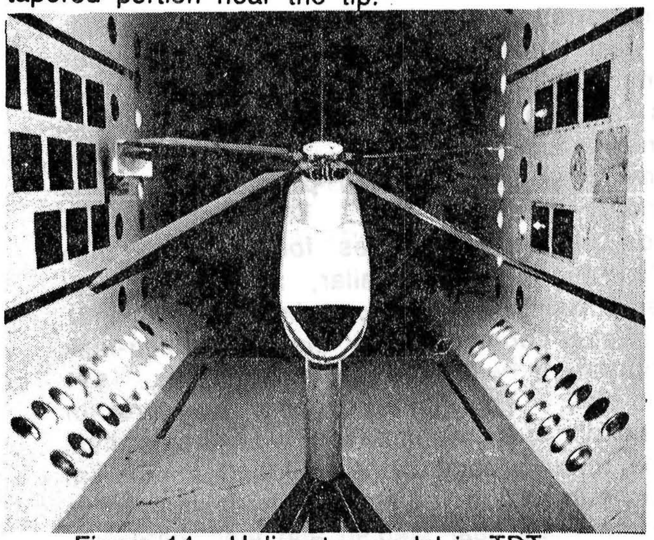


Figure 14. Helicopter model in TDT.

The model blades were tested over a range of forward speeds for several simulated gross weight conditions. Also tested for comparative purposes were model rotor blades of conventional design for the same mission requirements. These conventional blades provided a baseline for comparison purposes. Because of the close coupling of performance and vibration characteristics for rotor blades, both performance and vibration data were obtained.

Some illustrative performance data are presented in Figure 15 as the variation of rotor power required with advance ratio (in effect the variation of horsepower required with forward flight velocity) for a simulated full scale gross weight of 18,500 lbs. These results are typical of those obtained for other gross weights in that the performance of the advanced blades was always better than that of the baseline blades, although the relative degree of improvement was shown to be a function of gross weight.

Some illustrative oscillating pitch link loads (a measure of the vibratory load transmitted from the rotating blades to the control system) are presented in Figure 16 for the same gross weight for which performance data were presented. These data show that the loads produced by the advanced design are higher than those produced by the conventional blades.

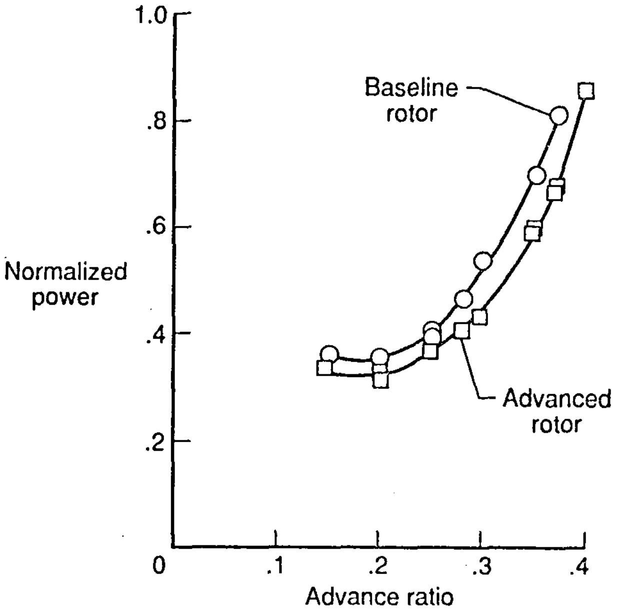


Figure 15. Variation of normalized power with advance ratio.

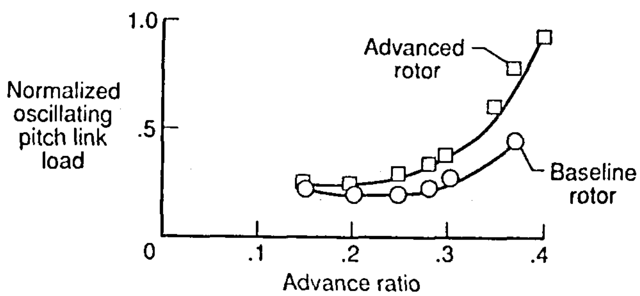


Figure 16. Variation of oscillating pitch-link loads with advance ratio.

It should be pointed out that for some conditions the oscillating pitch-loads for the advanced design were lower than those of the baseline design. However, data presented in the reference (not included here) show that four-per-rev vertical fixed-system loads (a measure of vibratory load transmitted to the fuselage) produced by the advanced design are higher than those produced by the baseline design for all conditions studied. Results such as these emphasize the complicated interaction of helicopter rotor blade performance and dynamic response in that improvement of performance in one area can to lead to degradation of performance in another area.

Optimization of Helicopter Airframes to Satisfy Frequency Constraints

The problem of attenuating the vibration response of helicopter structures has been of continuing concern to dynamicists since the first practical helicopter flew in the late 1930's. Active and passive vibration control devices, design changes in the main rotor system, and design changes in the fuselage structure have all been used to eliminate, or at least reduce to a tolerable level, helicopter vibration levels. In recent years attention has focused on using optimization procedures to design out unwanted vibrations. Some work by Murthy[4,14] has focused on the application of sensitivity analysis methods in combination with optimization procedures to the design of helicopter airframes that meet specified vibration requirements. (Additional results were presented at the Work-In-Progress Sessions at the AIAA/ASME/ASCE/AHS 29th Structures, Structural Dynamics, & Materials Conf.). A large portion of this research has focused on developing practical computational procedures.

The initial objective of this work is to develop an optimization procedure for tuning helicopter airframes, that is, the placement of the natural frequencies of the structure at predetermined places relative to the "per rev" forcing frequencies, including harmonics, produced by the rotor system. This is illustrated schematically on the left in Figure 17. This separation of the forcing frequencies and the response natural frequencies contributes significantly to the reduction of airframe vibration levels. A block diagram of the optimization process is presented on the right in the figure. This methodology was applied to the AH-1G helicopter. A relatively simple "stick" finite-element model representation of the AH-1G helicopter was used. Sketches of the actual airframe structure and the finite-element model are shown in Figure 18.

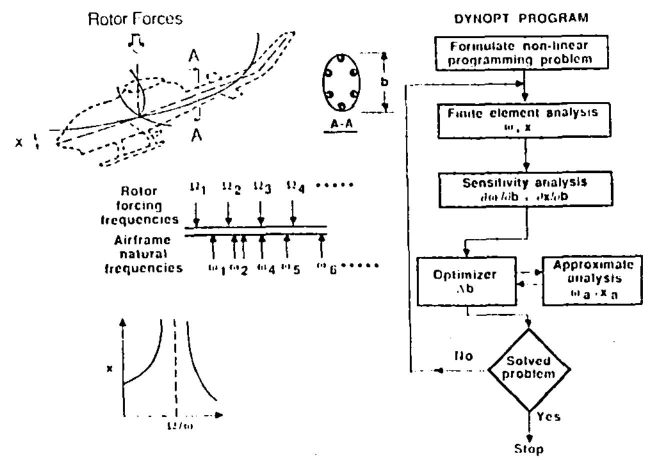


Figure 17. Optimization process.

Some results of this application are presented in Figure 19. Presented are the variations of airframe gross weight, frequency constraint parameter, and natural frequencies with iteration number. Data are shown for two pylon modes, two fuselage bending modes, and one fuselage torsion mode. For these

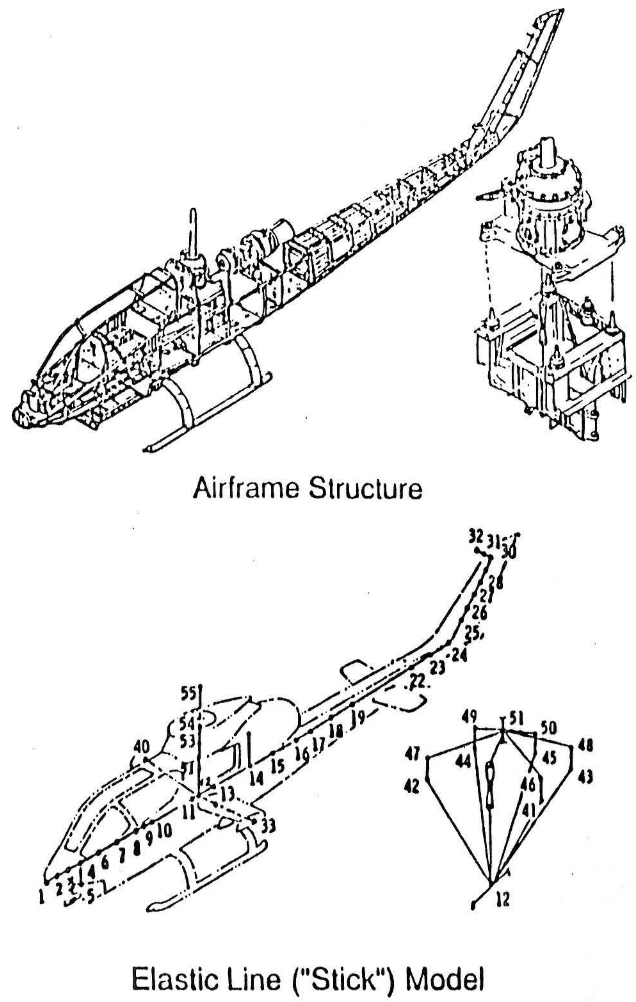


Figure 18. AH-1G structure and finite-element model.

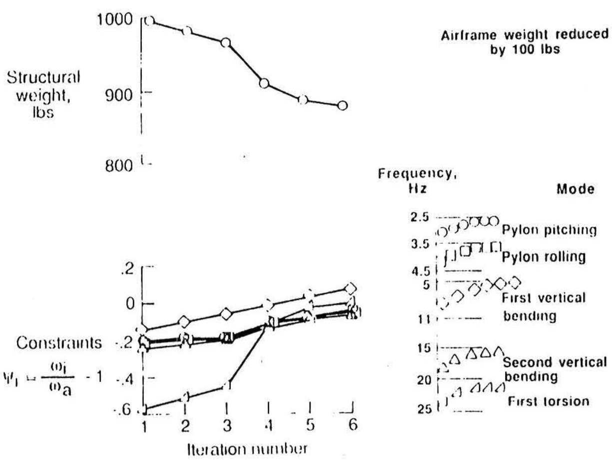


Figure 19. Optimization results.

calculations upper and lower bound constraints were applied to the natural frequencies. Results after the sixth iteration show a reduction in fuselage structural weight of about 100 lbs. Note that most of this reduction was obtained after the fourth iteration. Although this is only a small fraction of gross weight, it is about 10 percent of the weight of the primary structure. Additional work is underway to apply these methods to more sophisticated representations of helicopter fuselage structures.

Stability Characteristics of an Advanced Tilt-Rotor Design

As part of the development of a multi-mission, multi-service tilt-rotor airplane a series of wind-tunnel tests were conducted to determine the aeroelastic stability of the rotor/wing system in the high-speed airplane mode of flight and to correlate the experimental results with analysis.(15,16) A photograph of the wind-tunnel model used in this study is shown in Figure 20. During the first series of wind-tunnel tests instabilities were encountered at simulated flight conditions considerably different from those predicted by theoretical studies conducted by the aircraft developers. Of considerable concern was the fact that the calculated results were unconservative.

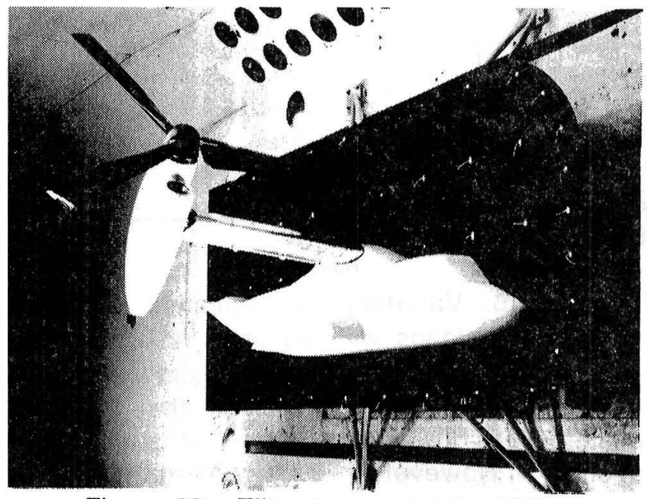


Figure 20. Tilt-rotor model in TDT.

To aid in providing a better understanding of this lack of correlation the Langley-developed Proprotor Aeroelastic Stability Analysis (PASTA), which had been used successfully in earlier tilt-rotor applications, was used to provide an independent evaluation of the analysis. PASTA is an improved version of an analysis originally documented in reference 17. This linear analysis is based on a rather simple mathematical model of a rotor with a gimballed hub. Flow through the rotor is assumed to be axial (airplane mode). The rotor is assumed to be windmilling (nonthrusting). The blade airload is represented by using quasi-steady strip-theory aerodynamics; wing airloads are assumed to be zero. The structure of the rotor is represented by beam theory; the structure of the wing is represented by a modal analysis.

Some illustrative experimental and analytical data are presented in Figures 21 and 22 as the variation of modal frequency with airspeed and as the variation of damping with airspeed, respectively. Experimental data are presented for the three lowest wing modes (beam, chord, and torsion) which are important to the stability of th rotor-wing system. In addition, calculated results for the blade lag mode are shown. The agreement between the experiment and analysis is excellent for this typical case. The analysis accurately predicts the instability at about 180 knots that is associated with the wing beam bending mode (primarily wing vertical bending). Although, on the surface at least, PASTA appears to be a relatively simple analysis method, it apparently contains all of the important aspects needed to analyze this complex tilt-rotor configuration.

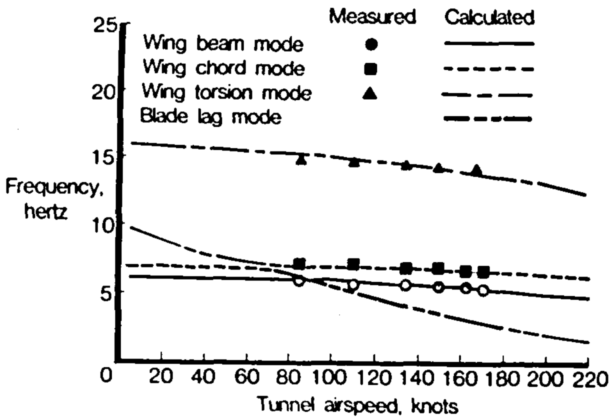


Figure 21. Variation of modal frequency with airspeed.

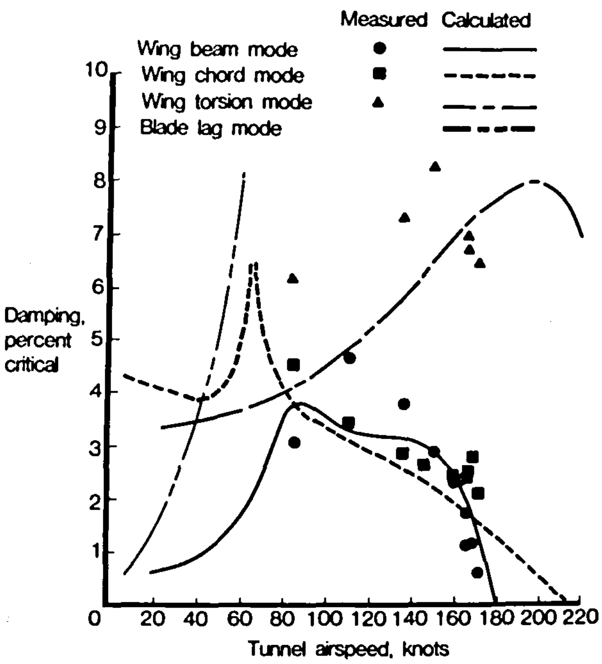


Figure 22. Variation of modal damping with airspeed.

__Extension-Twist-Coupling for Tilt-Rotor Blade Design__

Previously the design of rotor blades (or propellers, depending on one's perspective) for tilt-rotor aircraft has been a compromise between forward flight (airplane mode) and hover (helicopter mode). performance efficiencies. As illustrated in Figure 23, the blade twist distribution having minimum horsepower in forward flight is different from the twist distribution that has minimum horsepower for hover. With the advent of composite structures and structural tailoring concepts it appears that an extension-twist-coupled structure can be designed that takes advantage of the different centrifugal force fields between forward flight and hover so that the twist changes in a favorable way. Thus, the final design has near minimum power requirements for both flight modes.

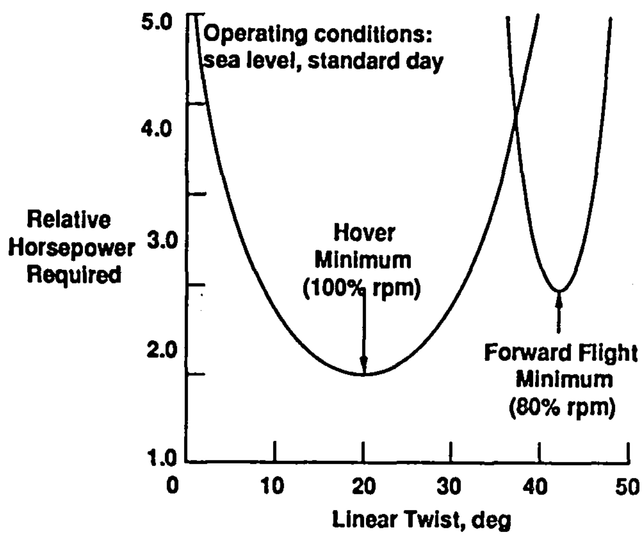


Figure 23. Linear twist performance in hover and forward flight.

Nixon(18) applied this concept to a representative tilt-rotor design. The approach was to integrate a coupled-beam and laminate analysis with an optimization procedure to determine a structural arrangement that provided improved performance in both hover and forward flight as compared to blades designed by conventional methods. To ensure that a reasonable design was obtained the optimization process was subjected to a set of constraints that included such structural considerations as material properties and limitations on non-structural mass additions.

Some illustrative results are presented here. Shown in Figure 24 is the variation of relative horsepower required in forward flight with forward speed referred to design velocity for a blade with a -42^{0} linear twist which was the optimum linear twist for forward flight based on the parameters used in this study. Also included in the figure for comparison purposes are data for a blade designed by conventional methods which is a compromised design for both hover and forward flight considerations. The -42^{0} twist blade offers significant improvement throughout the forward flight range shown.

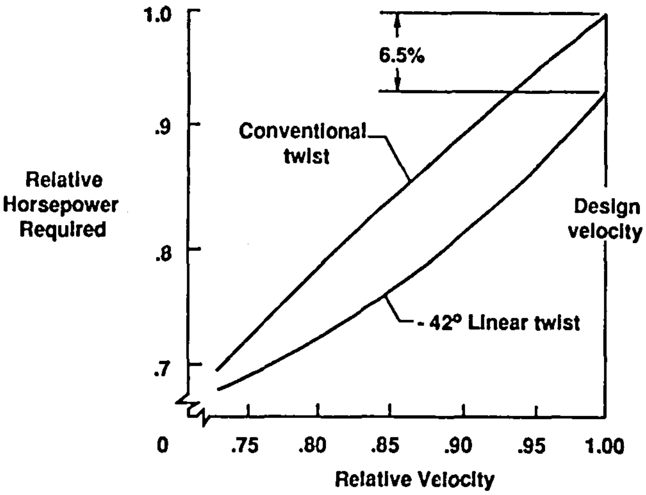


Figure 24. Performance comparison of twist design in forward flight.

Presented in Figure 25 are some hover performance data, namely, horsepower required versus relative gross weight. Data are presented for a -20^{0} linear twist blade which provided the best hover performance and for the reference blade of conventional design. Compared to the conventional design a performance improvement is obtained that could be translated into a payload increase. It is clear that if a blade could be designed to have -42^{0} twist in forward flight and -20^{0} twist in hover it would offer substantial performance improvements over a blade of conventional design.

Three different designs were studied in reference 18. The constraints applied to each design were different, primarily in the amount of non-structural mass allowed in the tip region. In each case the blades were constrained to have -42^{0} linear twist in forward flight. Therefore, the objective was to determina a structural arrangement that would maintain this twist and provide the best twist distribution for hover, which would, of course, be nonlinear. Some results are presented in Figure 26 as the relative change in horsepower

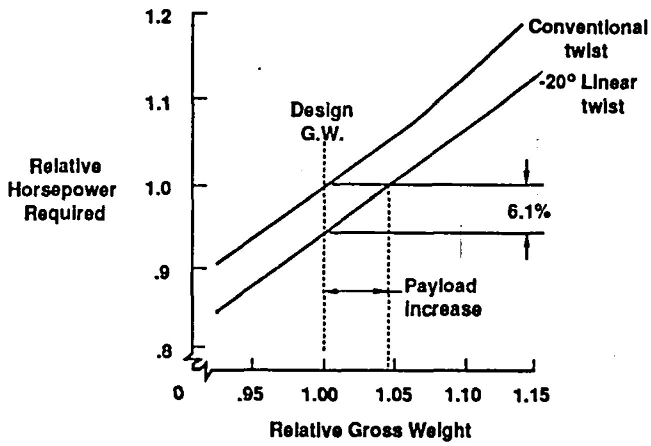


Figure 25. Performance comparison of twist design in hover.

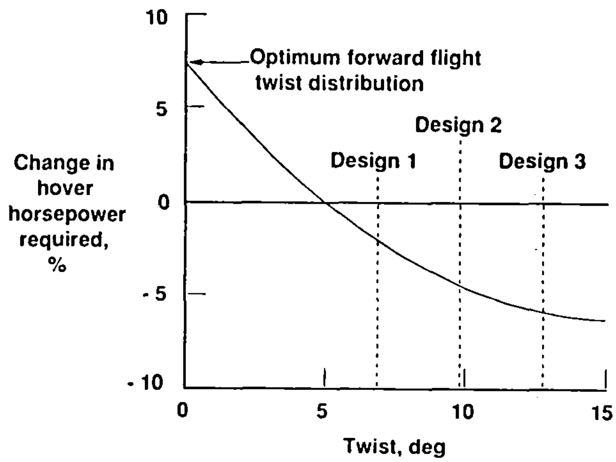


Figure 26. Hover horsepower required as a function of twist change from forward flight value.

compared to the reference blade versus twist angle which represents the twist change at the blade tip between forward flight and hover (a 20-percent difference in rpm). The data show that an improvement in hover performance was obtained for all three designs.

Although there is still considerably more work to be done in developing an automated design process that incorporates structural tailoring of composite structures to the design of tilt-rotors, the results of this study show that the extension-twist-coupling concept is structurally feasible and further indicates that substantial improvements in aerodynamic performance may be obtained by it use. Of course, in the use of these tailoring concepts careful attention must be paid to the impact of the cross-coupling on such things as aeroelastic stability.

Concluding Remarks

Nine research studies conducted at the NASA Langley Research Center in the areas of structural dynamics and aeroelasticity have been discussed. Topics discussed included research related to both fixed-wing and rotary-wing aircraft. The variety of the subjects, albeit only a small sample of the total research program, is indicative of the breadth of the research program in these areas that is in place at the NASA-Langley Research Center.

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16. Abstract

Highlights of nine different research studies are described. Five of these topics relate directly to fixed-wing aircraft and range from flutter studies using relatively simple and inexpensive wind-tunnel models to buffet studies of the vertail tails of an advanced high performance configuration. The other four topics relate directly to rotary-wing aircraft and range from studies of the performance and vibration characteristics of an advanced rotor design to optimization of airframe structures for vibration attenuation.

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