AN EXAMINATION OF THE RELATIONS BETWEEN ROTOR VIBRATORY LOADS AND AIRFRAME VIBRATIONS

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Abstract

Harmonic rotor hub loads and airframe interactions in steady flight are reviewed, with regard to the objective of achieving lower airframe vibration by modifying blade root loads.

Flight test and wind tunnel data are reviewed, along with sample fuselage response data. Trends which could provide a generalized approach to the above objective are found to be very limited.

Recent analytical and corresponding experimental blade tuning modifications are reviewed and compared. Rotor vibratory load modification and substantial vibration changes were achieved over a wide range of rotor operating conditions.

It is still concluded that improvement of blade tuning has the potential for reduction in airframe vibration. Current analytical methods are found not accurate enough to confidently predict effects of blade tuning on vibration.

Test-based development of favorable blade configurations is shown to be feasible, and will also generate data to guide further development of analytical methods.

Introduction

Reduction in helicopter airframe vibration enhances crew and passenger effectiveness and comfort, and reduces vibration-related problems with the airframe structure and installed equipment. Higher speed operating regimes are planned for future helicopters, which will create a strong tendency for increased vibration. Furthermore, vibration levels even lower than those of presently operational helicopters are desired in these higher speed regimes. Therefore, the development of improved vibration control measures is receiving continued attention.

Analytical investigations such as those presented in Reference 1 have predicted that substantial reductions in helicopter rotor vibratory hub loads may be obtained by modifying the distributions of structural properties such as blade bending stiffness and mass, with little or no penalty in blade weight or structural complexity. The implied corresponding reduction in airframe vibration was verified by coupled rotor-airframe aeroelastic analysis.

This method of reducing vibration is quite attractive, since it can reduce or eliminate the need for other vibration control measures such as vibration absorbers or higher harmonic control. These other measures are effective, but entail additional cost, added parts, weight, and maintenance.

This paper examines the trending of rotor hub loads as indicated by various flight and wind tunnel test programs, and the typical airframe vibratory response to these loads, to assess the possibility of creating a generalized recommendation for modification of hub loads. Some recent analytical and corresponding experimental efforts to exploit the blade tuning concept are reviewed. These results of these attempts are diagnosed, and an assessment made of the feasibility of applying the concept analytically, through complete system experimentation, or from separate dynamic model and airframe testing.

Background

The reduction of helicopter blade vibratory elastic response in forward flight has long been intuitively recognized as a potential means of reducing vibratory hub loads and their consequent airframe vibration. Historically, this objective has been addressed during the design stage simply by providing blade designs whose elastic natural frequencies were well-separated from resonances with the harmonics of the rotational frequency.

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The development of sophisticated analytical models and the computer programs to implement them provided a means for further understanding of the complex phenomena involved in the motions of a helicopter blade and the resulting forces transferred to the fuselage. The helicopter rotor math model described in Reference 2 is an example of a number of such tools available.

Analytical and experimental work described in References 3 and 4 indicated that passive tuning of the normal blade structural parameters was worthwhile pursuing. Reference 5 is a concise analysis of blade bending mode response to harmonic loadings. The traditional resonant amplification factor was considered; in addition, a Modal Shaping Parameter was developed which considered the modal generalized mass, the modal inertial shear integral, and the modal aerodynamic generalized force. The product of the resonant amplification and the Modal Shaping Parameter provided a quantity which reflected the response of a given blade mode root shear to a given harmonic. It was shown that the modal shaping parameter is at least as important as the natural frequency in determining the root shear for a given mode and harmonic forcing frequency.

The work of Reference 1 exploited the availability of advanced rotor and airframe mathematical modeling to pursue further refinements in rotor blade dynamic tuning. A detailed consideration of the various factors involved in the harmonic forcing of the individual blade modes was conducted, along with the influence of these factors on blade root shears for each harmonic. This analysis led to recommended design improvements aimed at reduction in the amplitude of modal root shears. These design improvements were the removal of blade mass from blade midspan, an increase in blade mass at the tip, moving the mass center of gravity forward at the blade tip, and increasing the blade edgewise stiffness. Rotor-airframe coupled response calculations with the method of Reference 2 verified a substantial decrease in airframe vibration, amounting to better than 50% reduction for the higher amplitude vibration components.

Scope of Present Considerations

This paper considers the hub loads and airframe interactions of an articulated four-bladed rotor. The rotor is in steady flight, and has identical blades. The blade hinge and rotor shaft hub loads considered are shown in Figure 1. Explicit consideration of blade pitch control loads and lag damper loads are ignored, as is the effect of hub motion on the rotor loads. These restrictions do not result in the exclusion of any fundamental concept, and permit a simplification of the discussions to follow. The discussions herein are centered on the blade tuning concept, they do, however, have more general application to other means of altering blade vibratory responses or hub loadings.

Basic Relationships

The fundamental relationships that exist between the blade hinge loads and the vibratory response at an airframe point are reviewed in this section.

Transfer of Loads Between Rotor and Fuselage

The resolution of vibratory loadings between the turning rotor and the airframe has the well-known result presented in Table 1. The rotor applies vibratory loadings to the airframe at the blade passage frequency only (the rotational frequency times the number of blades). These airframe loadings are caused by vibratory loadings in the rotor system at frequencies equal to the blade passage frequency, the blade passage frequency minus the rotational frequency, and the blade passage frequency plus the rotational frequency. In the case of the four-bladed rotor, the four per revolution airframe loadings are caused by three, four, and five per revolution loadings in the rotor.

Generalizations related to the reduction in airframe loads and vibration that can be drawn from the relationships in Table 1 are limited. The vertical force FZ4 has a straightforward relationship with the A4 vibratory hinge force, so that a reduction in A4 has a corresponding reduction in FZ4. All the other airframe load components have the possibility of beneficial cancellation among the constituent components. Therefore, a reduction in the load component H3C, for example, may result in an increase in the in-plane loads FX4 and FY4. A generalized decrease in in-plane hub loads will result if all the radial and tangential 3 and 5 per revolution hinge load components are reduced in the same proportion. Another obvious generalization is that the hinge offset distance e controls the magnitude of the in-plane and torsional vibratory moments, and the relative importance of the vertical 3 and 5 per revolution hinge forces which give rise to them.

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Airframe Vibratory Response to Loads

A presentation of representive vibratory responses of an airframe point to the rotor load components is provided in Figure 2. This figure shows the cosine and sine response of the cockpit floor at the pilot location in the vertical direction for a set of rotor load components. A graphical vector addition of the components is shown, along with the resultant pilot vertical vibration. These data are purely analytical, but do illustrate the manner in which the various component responses combine. The vibratory response at a point is generally dependent to some degree on beneficial cancellation between various components. In the example of Figure 2, a reduction in vertical vibratory force would cause very little change in the vibration level at the pilot floor. Furthermore, a reduction in in-plane moments (dependent on vertical hinge forces) would cause an increase in vibration at that point. Note that this example is purely illustrative; other points in the same aircraft, different aircraft, and actual test data would show different response results. One general modification that can be applied to the vibratory rotor load components that will result in a reduction in vibratory response is to reduce all of them in the same proportion. An increase in the number of blades provides a generalized decrease in the amplitudes of the loads and this decreases airframe vibration.

Review of Hub Load and Fuselage Response Data

Survey of Vibratory Hinge Load Test Data

In this section, a collection of measured hinge load data will be presented and examined, with the objective of searching out any evident general tendencies which could be useful in the development of guides or judgement for the application of beneficial blade tuning.

A total of six sources were used in preparation of this collection of data, which is presented in Figures 3 and 4. These are briefly described as follows:

(1) Unpublished data from the 1977 test of a prototype 4-bladed S-76 rotor in the Ames Research Center 40x80 foot Wind Tunnel. Hinge load data were obtained from calibrated strain gage readings of hub and shaft bending.

(2) Data from the Reference 6 report of a 5-bladed S-61F rotor flight test. Hinge load data were obtained from differences between strain gage readings of blade bending moments at two stations near the blade root. Corrections were applied in accordance with hinge motions, cyclic pitch, and blade mass distribution in the root area.

(3) Data from the Reference 7 report of a 6-bladed CH-53A rotor flight test. Data were obtained essentially in the same manner as for Reference 6.

(4) Unpublished data from a 1983 test of a specialized 4-bladed set of model blades with adjustable mass distribution. Hinge load data were obtained from a superposition of blade modal hub shears. Blade bending mode amplitudes were obtained from a least squares fit of the blade mode shapes to the measured blade harmonic vibratory bending moment distribution.

(5) Unpublished data from 1983 flight testing of an S-76 aircraft with modified main rotor blades. These modifications were increased edgewise stiffness and the addition of a 10-lb tip weight. Data obtained by the same method as for item (4) above.

(6) Data from Reference 8. A 4-bladed model rotor was provided with a specially instrumented hub for the measurement of blade hinge loads.

In Figure 3, the 3, 4, and 5 per revolution hinge loadings per blade are presented in non-dimensional form by dividing by rotor lift and plotting against advance ratio. Hinge loading phase angles are also presented for the more important of the hub loadings. Perhaps the most prominent trend visible is the relatively large magnitude of the 3 per revolution vertical load response A3. Most of the model and full-scale data for this parameter are reasonably consistant. Exceptions are the data from the flight testing with the edgewise stiffened S-76 blades, and the adjustable mass model blades. Adding tip mass to the stiffened S-76 created large A3, while the stiffened blades without tip mass had small A3. These changes in A3 itself, however, are believed to have had little effect on airframe vibration because of the relatively small hinge offset and consequent small in-plane moment. Note that the behavior of the A3 load will be of greater importance with 4-bladed hingeless rotors with larger virtual hinge offset.

Generalized trends which apply to the other loading components are not immediately evident, beyond the tendency of all load amplitudes to rise steeply after an advance ratio of .3. Some of the edgewise load data display a tendency toward lower amplitudes at moderate advance ratio, similar to rotor power required loadings. Data from the individual rotors does show individual trending as a result of increasing advance ratio. Except for the A3 amplitudes, however, the data vary widely between the various rotors.

Figure 4 presents a crossplot of the same hinge load data against the ratios of the natural frequencies of the various blades to various harmonics. The objective of this figure is to exhibit the extent to which the hinge loadings depend on resonance with harmonic frequencies.

In general, it appears that blade resonance with harmonics is a significant factor in the hinge load component magnitudes. It can also be seen that other influences are significant. The A3 loadings for the S-76 wind tunnel and flight test configurations appear to be responding to classical resonance with 3 per revolution airloadings. The earlier S-61F, CH-53A, and Reference 8 model data have, however, have relatively high A3 load response for their conventional flatwise frequency placement, suggesting that the aerodynamic spring effect discussed in Reference 1 may be active in moving the aeroelastic flatwise modal frequency closer to 3 per revolution for these rotors. As mentioned previously, the A3 load in itself does not strongly influence airframe vibration for 4-bladed articulated rotors with conventional hinge offsets. Further examination of Figure 4 shows that other influences such as the modal shaping effects discussed in Reference 1 are apparently influencing the response of the individual hinge loads to a greater extent than the resonance effect. The H5 loadings, for example, become smaller for the adjustable mass and the S-76 flight blades even though the tuning attempts resulted in edgewise mode natural frequencies closer to 5 per revolution.

General tendencies which appear in Figures 3 and 4 may be summarized by stating that the 3 per revolution flatwise load is by far the largest, and this may dominate for larger virtual hinge offset rotors and airframes sensitive to in-plane moment forced vibration. The other load components range from very small up to about one-half of the 3 per revolution flatwise loading. Trends of amplitude with forward speed are upward beyond an advance ratio of .3, but other details such as phase angle are peculiar to the individual blade configurations. Some evidence of resonance with harmonic loadings is present, but it is also clear that other phenomena have an important contribution.

Variability in Airframe Dynamic Response

In this section, a limited sample of calculated and test airframe dynamic response data will be reviewed, in order to present the extent to which variability occurs in the airframe response to dynamic loading components, and show a sample of the predictive capability of current finite element methods.

Figure 7 presents the cosine and sine parts of the pilot vertical response due to a 1000 lb vibratory hub force at the 4 per revolution frequency in the longitudinal direction. The contours are formed as the frequency is varied to reflect rotor rotational speed variations between 90 and 110% of normal. Calculated data are shown for three aircraft. Also shown is a data point available from an S-76 shake test for a normal 4 per revolution frequency. From data of this nature, one can conclude that the phase response of an airframe point can be anywhere in the sine/cosine plane. The corresponding calculated data from finite element methods has at best a rough order of magnitude correspondence with the shake test data.

Review of Experimental Blade Tuning Results

The foregoing generalized considerations show that the application of blade tuning involves some uncertainty. Various loading components, as well as various blade aeroelastic effects have opposing effects on vibration. Therefore, reduction in a load component or components is not a sufficient condition for the reduction of airframe vibration level. Nevertheless, analytical results showed that reduction in blade mode harmonic response or a generalized reduction in the hub shears would usually lead to a reasonable reduction in the airframe vibration. Therefore, it was worthwhile to attempt experimental verification of the blade tuning concept.

Mass-Tuned Model Blade Wind Tunnel Test

A dynamically scaled model blade set was provided to NASA/Langley by Sikorsky Aircraft under Contract NAS1-12671 in 1976. The blade set was specially designed with removable and replaceable counterweight segments, such that a variety of blade mass and chordwise center of gravity distributions could be provided for testing of their effect in the wind tunnel. The blade set is a traditional 4-bladed, untwisted, articulated design of 4.58 ft. radius. The blades were constructed with forward and aft counterweight tubes along the blade span. Up to 80 counterweight segments, each 1/2 inch long, may be inserted in the tubes and removed or replaced as desired by disassembling the blades from their cuffs. Alternate tungsten and aluminum segments are available to provide a variety of spanwise and chordwise distributions. The detailed physical properties of the blade set are described in Reference 9.

The design analysis used to provide favorable mass distributions for the model blade utilized the Reference 2 mathematical model as its major element. It was applied to the dynamical system comprised of the adjustable mass model rotor system coupled to a modal representation of the model rig and its support system. An objective function to be minimized was defined as the sum of the squares of the individual hub load components (i.e., the three forces and three moments - the moments were divided by twice the hinge offset distance). It was noted that the moment components had a relatively small contribution to the objective function. It was felt that this was a reasonable situation for the articulated model rotor.

A baseline configuration was defined with essentially constant mass distribution and quarter-chord center of gravity over the mass-adjustable portion of the blade. The mass-adjustable portion of the blade was divided up into eight spanwise zones, each including a forward and an aft counterweight increment, for a total of sixteen design variables.

At a defined rotor operating condition, uniform mass increments were added in turn to each of the sixteen counterweight zones. The change in the objective function was noted and a finite difference partial derivative formed with respect to each of the design variables. The favorable mass distributions were formed by adding or subtracting mass to the counterweight zones in proportion to the negatives of the objective function partial derivatives. The amount of mass that could be added or subtracted was constrained by the physically available counterweights. Favorable mass distributions were derived in this manner for a total of three operating conditions. The first of these dictated the removal of mass from the midspan region to the blade tip, with the blade center of gravity forward at the tip. The second was essentially the addition of tip mass. These distributions were constrained when a physical limit was reached at any one counterweight zone. The third distribution was practically the same as the first, so this was modified by adding or subtracting mass in the favorable direction in each zone until the physical limit was reached. Figures 8 and 9 show the spanwise mass and center of gravity distributions resulting for the baseline and the number 3 mass distribution. It was noted that this mass distribution was qualitatively similar to the favorable mass distribution resulting from the Reference 1 study, with mass removed from blade midspan and placed at the tip, and with the center of gravity moved forward at the tip.

When the tuning mass distributions were defined by the above analytical procedure, they were input to the coupled rotor-airframe analysis to confirm that an improvement had actually been obtained. Samples of the analytical results are provided in Figures 10 and 11. The large in-plane loadings are reduced by about 25%, and the vibratory response at the hub is reduced by a much larger percentage. In a purely analytical framework, the blade tuning optimization was shown to be successful.

The model blade set was mounted on the Sikorsky Aircraft Basic Model Test Rig, and tested in the United Technologies Corporation Main Wind Tunnel. A number of duplicate flight conditions were tested for the baseline and each of the three "optimized" mass distributions. Sample test results are shown in Figures 12 through 14. Figure 12 shows the response of a certain accelerometer on the model rig, indicating the blade passage frequency lateral vibration component amplitude as a function of advance ratio and nondimensional rotor lift. The blade tuning had a fairly substantial effect which extended over a wide range of flight conditions. The effect of the blade tuning, however, was to worsen vibration instead of improving it. Figure 13 shows the vibration level from the same accelerometer as a function of mass distribution and advance ratio. The baseline distribution had essentially constant mass versus span and a quarter-chord center of gravity over the mass-adjustable portion of the blade. The number 1 distribution removed mass from the blade midspan, increased mass at the blade tip, and moved the center of gravity forward at the tip. The number 2 distribution added mass to the tip area. The number 3 distribution was based on number 1, with further mass increments added or subtracted in each of the local zones where this was possible. Figure 13 shows an orderly relationship between the different mass distributions, which extended over a reasonable range of flight conditions. Figure 14 shows the effects of blade tuning on harmonic hinge load amplitudes, as estimated from a summation of bending modal shears. The various bending mode amplitudes were estimated from a least-squares fit of the experimental blade bending moment distributions. The vertical 3 and 5 per revolution loads were raised, but this is not considered to have had a large effect on the rig vibration. The in-plane 3 per revolution hinge load was raised, while the 5 per revolution load was lowered. The loss of phase information during data processing is presently precluding a full diagnosis of the manner in which experimental hinge load components changed to create higher vibration. It is reasonable to expect the completion of data processing will show that the 3 and 5 per revolution in-plane loading are the source of increased vibration.

Figure 15 presents a comparison of test and analytical blade bending moment coefficients for pertinent harmonics and as a function of mass distribution, with the objective of evaluating the rotor aeroelastic analysis as a tool for determining favorable blade tuning adjustments. In the flatwise sense, the qualitative trending of the vibratory bending moment is quite faithfully predicted by the analysis, but the amplitude level is underpredicted by a factor of about one-half. In the edgewise sense, the loadings are also generally underpredicted, and the trending of the 3 per revolution and the 5 per revolution amplitudes is reversed. A detailed quantitative analysis of the results of these differences on the predicted hinge loadings has not been conducted. It is sufficiently evident from consideration of the relationships shown in Table 1 and Figure 2 that much greater accuracy will be needed from the analysis before it can be considered a reliable design tool for use in blade tuning.

Tuned Blade Flight Test

The success of analytical blade tuning considerations such as those described in Reference 1 also provided rationale for a flight evaluation of the concept conducted in the same time frame as the model test described above.

The main rotor blades of an S-76 helicopter were modified by adding a 10 lb tip weight at approximately the 92% radius. The edgewise bending stiffness was also increased by approximately 77% by adding boron strips to the trailing edge. This stiffness change raised the first edgewise bending frequency of the blade from 4.73 to 5.24 cycles per revolution. These modifications represented practical modifications to the existing blades which approximated the findings of Reference 1 with regard to favorable mass and stiffness changes. These specific modifications were also investigated with the blade aeroelastic analysis with the results shown in Figure 16 for hub loadings.

A sample of the flight test results appears in Figure 17. The aircraft vibration was generally increased rather than decreased by the analytically favorable blade modifications.

Figure 18 presents the effect of the tip weight on the vibratory hub load amplitudes for the stiffened S-76 blades only. The addition of tip weight significantly increased the 3 per revolution loadings, the 4 per revolution edgewise loadings, and decreased the 4 per revolution vertical and 5 per revolution edgewise loadings. These hinge loads were obtained from the blade modal fit and shear superposition method described earlier. Baseline aircraft blade bending moment data were not available to develop comparative data. It appears that the tip mass modification did create a substantial change in the blade response, although in the unfavorable direction. Common trends of tip mass addition and mass-tuned model blade distribution number 3 include increases in the 3 per revolution flatwise and edgewise loadings and a decrease in the 5 per revolution edgewise loading.

Figure 19 presents a comparison of flight test and analytical bending moment coefficients for the stiffened blades. Agreement between full scale analysis and test is lacking, especially the large increase in 3 per revolution loadings caused by the addition of tip mass.

Figure 20 presents test data for fixed system hub loads from the stiffened S-76 blades with tip weight on and off. These data are supplied by a resolution into the airframe system of the rotating system hinge loads from the blade modal fit and shear superposition method. The addition of the tip weight creates a substantial increase in lateral shear load and in-plane moments, but decreases the vertical shear loads.

Figure 21 compares the analytical and flight test hub loads applied to the airframe. It can be seen that there is no agreement between analysis and test that would allow reasonable use of the analysis as a tool for blade tuning to decrease airframe vibration.

Figures 22 and 23 are vector addition diagrams which illustrate the manner in which hub load component responses combine to create the resultant vibration amplitude at a point in the airframe. The various vector contributions are labeled with their corresponding force components. The factors p, q, m, and n represent transmissibility factors. The data used to construct these diagrams was obtained from S-76 airframe shake test results at the pilot seat, for in-plane vibratory force inputs at the rotor head. The shake test results showed an insensitivity to the vertical force, so this was not included in the vector diagrams. These shake test data also do not include the effects of the main rotor bifilar absorbers and the nose absorber which were active during the tuned blade flight testing. Despite this, the flight test data shows qualitative agreement with these figures.

Inspection of Figures 22 and 23 and use of Table 1 show that even for the simplified case considered here, wherein the radial force amplitudes are small, both the H3 and H5 force components are involved in the development of the resultant vibration level. Furthermore, Figure 18 shows that the 3 per revolution and the 5 per revolution in-plane load components are of the same order of magnitude.

This highlights a potential difficulty of making a straightforward choice of blade tuning modifications for vibration reduction. A modification of blade mass distribution which, for example, reduces the 3 per revolution amplitude response, may create an unfavorable change in 3 per revolution response phase angle, or in the 5 per revolution response amplitude and phase.

It appears that an attempt to predict even the qualitative result of a proposed blade tuning modification must consider the airframe response to the hub load combinations, unless the modification creates a profound reduction in all the hub load components which have a significant effect on airframe vibration.

Application of Blade Tuning Modifications

In common with other vibration control methods, the effects of blade tuning modifications have been found to be poorly predicted by analytical means. It is technically feasible, however, to arrive at a favorably tuned blade configuration by conducting an organized set of experiments. An improved mass distribution based on the mass-tuned model experiments is presented in this section. In terms of full-scale aircraft application, this would correspond to a series of flight tests with trial blade configurations. As an alternative to this flight development stage experimentation, it may be advantageous to develop a favorable configuration by combining dynamic scale model wind tunnel experimental data with airframe shake test data as described below. This latter method would also yield a more organized body of detailed data on rotor loads response to blade modifications and of airframe dynamic response. These data could be used for the improvement of the analytical methods, with the ultimate objective or improving them to the point where they could be used early in the design process.

Development of Favorable Mass Distribution from Model Test Results

The current series of model tests are the basis of an improved vibration-tuned mass distribution for the mass-tuned model discussed earlier. Note that these results are, strictly speaking, peculiar to the model and its support system itself, and the mass distribution derived may not be suitable for any particular full-scale aircraft.

The process of developing a favorable vibration configuration started with the selection of a performance index. In the case of the model, a single accelerometer reading was sufficient, namely the top lateral accelerometer response presented earlier herein. Application to a full-scale aircraft could use a performance index comprised of the weighted sum of the amplitudes of a number of accelerometers at various points in the aircraft.

Each of the three mass distribution modifications tested had been scaled by the constraint of the maximum counterweight change which physically could be accommodated. The change in the accelerometer response from baseline for each distribution at a certain flight condition was then considered as a partial derivative with respect to that distribution. A combined distribution was formed by subtracting the three test distributions times a multiplier in proportion to their partial derivatives but also such that the total removed met the physical constraints of possible counterweight removals. It was assumed that magnesium counterweights could be manufactured to facilitate this.

The distribution resulting from this method is presented in Figures 24 and 25, compared with the baseline distribution. As one might expect, the distribution change from the baseline is similar to the inverse of the analytically derived number 3 distribution shown in Figures 8 and 9. To date, this new distribution has been neither tested nor investigated with analytical methods. It should be noted, however, that the Reference 3 analytical study of the effects of added mass reported some trends that agree with the findings of this model test, such as an increase in 3 per revolution flatwise response when tip weight was added.

Alternative to Complete System Experimentation

Application of the above method of blade tuning to the full scale aircraft development process would imply flight testing the aircraft with a number of experimental blade configurations. This is feasible technically, but a means of arriving at the favorable tuning configuration earlier in the development process would certainly be desirable. Dynamic model test data for the blade configuration selected and airframe shake test data could potentially supply this earlier, and guide the choice of a starting point for flight testing of blade tuning. When a completely new aircraft is in development, the rotor design has been essentially frozen when the airframe becomes available for shake testing, so any blade tuning modifications would be limited. Therefore, the procedure outlined below should be most acceptable when an improved rotor system is to be developed for an exisiting airframe.

(1) Through relationships such as those in Table 1, the hub forces $\{F\}$ may be developed as a function of the hinge or blade root loads $\{H\}$:

$$\{F\} = [R]\{H\}$$

(2) The fuselage accelerations $\{X\}$ due to the hub forces are assumed to be accurately known from a well-implemented airframe shake test; the matrix $[A]$ may include corrections for the influence of the rotor itself on hub motions:

$$\{X\} = [A]\{F\}$$

(3) A suitable performance index $\{Q\}$ is developed to reflect the response of the aircraft at all the critical locations:

$$Q = \lceil X \rfloor [W]\{X\}$$

(In the above, $\{\}$, $[\,]$, and $\lceil\,\rfloor$ denote column, rectangular, and row matrices respectively.)

(4) Run a dynamically scaled wind tunnel test for a baseline blade. Obtain baseline blade hinge or root loads $\{H0\}$. Use the above relationship to develop a baseline performance index $Q0$.

(5) Define a set of n distinct modifications, such as mass distribution, stiffness distribution, trailing edge reflex tab distribution, tip sweep, and the like. Scale these changes to a common portion (say 50%) of the allowable change.

(6) Run wind tunnel tests for the n modified blade sets and obtain n corresponding sets of hinge or blade root loadings. $\{H1\}$, $\{H2\}$, - - - $\{Hn\}$. Use these data to get corresponding performance function values $Q1$, $Q2$, - - - Qn.

(7) Examine $Q1-Q0$, $Q2-Q0$, - - - $Qn-Q0$. Apply the various modifications to the model blade in proportion to their favorable effect. Apply to the model and retest to verify the combined effect.

Execution of the plan outlined above would, in addition to providing a benefit to the subject aircraft, supply a body of data to support future applications and the development of analyses, which could ultimately allow the introduction of blade tuning refinements at an early stage in the design process.

Concluding Remarks

1. Helicopter harmonic vibration at an arbitrary local point in the airframe is affected by a number of distinct blade root load components and distinct airframe shaft load to vibration transmissibility components. In general these create reinforcement and cancellation effects which make the vibration change outcome of a change in blade root loads uncertain. The reduction of the amplitude of one or a number of blade root load components is not a sufficient condition to cause a reduction in airframe vibration.

2. A survey of some existing experimental blade root 3, 4, and 5 per revolution articulated rotor loadings has been conducted and examined for trends which could be helpful in developing lower vibration levels for helicopters with four blades. The three per revolution vertical force was the largest and had similar trends among several conventional model and full scale rotor configurations. Specialized tuned configurations were notably different from the conventional rotor trending for this load component. Other force component amplitudes were similar in size, and had no common trend beyond an increase at the higher speeds. There appears to be no specific modification in blade root loads which would be of generalized benefit, beyond a reduction of all components by a common factor.

3. Simple resonance of blade natural frequencies with harmonic loadings appears to have an effect on the blade root loads.

Analytical considerations and blade tuning experiments indicate that other important effects are present. These include aeroelastic or modal shaping influences on the aerodynamic forcing of the blade.

4. The response of an airframe to harmonic hub forces is highly variable with respect to frequency, location, and airframe. There appears to be no analytical prediction or characterization of this response beyond a rough estimate of the order of magnitude.

5. Modification of blade structural properties to alter blade response, root loads, and airframe vibration has been accomplished successfully within an analytical framework.

6. Model and full-scale experiments were successful in demonstrating that practical changes in blade structural properties could create substantial blade root load and airframe vibration changes. These changes were consistent over a reasonable range of flight conditions and were typically 20% to 60% of a baseline level. Individual load component reductions of this magnitude were achieved by tuning attempts, and therefore, vibration reductions of corresponding size are considered potentially available.

7. Experimental attempts to modify vibration by blade structural changes resulted in increases rather than the analytically predicted decreases in vibration.

8. Rotor aeroelastic response analyses and airframe dynamic response analyses do not generally provide an accurate prediction of the effects of blade structural changes on vibration. Some trends of individual response components are predicted correctly. Opposing and reinforcing interactions between a number of response components magnify the effects of predictive errors.

9. It appears that a series of organized experiments could be utilized to define favorable blade structural property distributions for reduced vibration.

10. Experimental determination of blade structural properties favorable for reducing the vibration of a specific aircraft could be based on a series of flight tests with experimental rotor blade configurations.

11. Experimental determination of blade structural properties favorable for reducing vibration might also be based on rotor flight test or wind tunnel data, combined with airframe shake test data.

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Table 1.
CORRESPONDENCE OF AIRFRAME LOADS AND BLADE HINGE LOADS

Airframe Loads	Blade Hinge Loads
FX4C =	2(R3C+H3S+R5C-H5S)
FX4S =	2(R3S-H3C+R5S+H5C)
FY4C =	2(-R3S+H3C+R5S+H5C)
FY4S =	2(R3C+H3S-R5C+H5S)
FZ4C =	4(A4C)
FZ4S =	4(A4S)
MX4C =	2e(-A3S+A5S)
MX4S =	2e(A3C-A5C)
MY4C =	2e(A3C+A5C)
MY4S =	2e(A3S+A5S)
MZ4C =	4e(H4C)+4MD4C
MZ4S =	4e(H4S)+4MD4S

Nomenclature:

As shown in Figure 1.
3, 4, 5: 3d, 4th, 5th harmonics
C,S: cosine, sine parts
R: radial
H: horizontal
A: axial
e: hinge radial offset

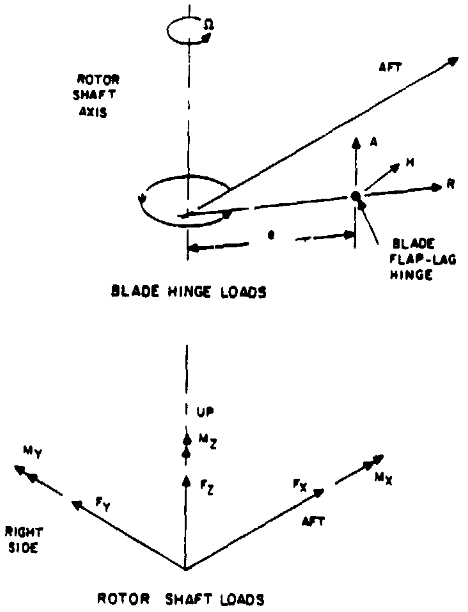


Fig. 1. Hinge and shaft loads.

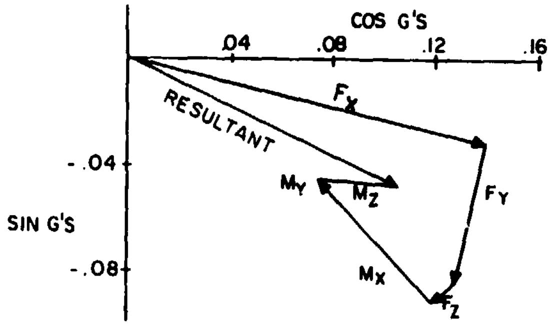
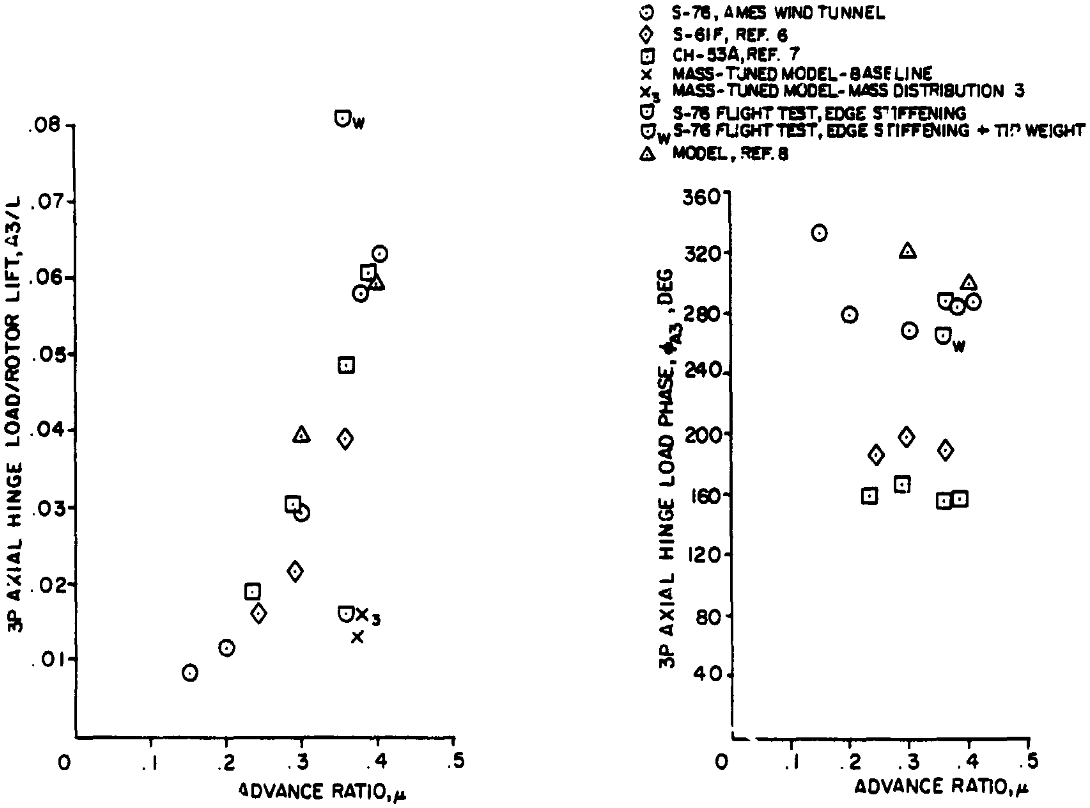
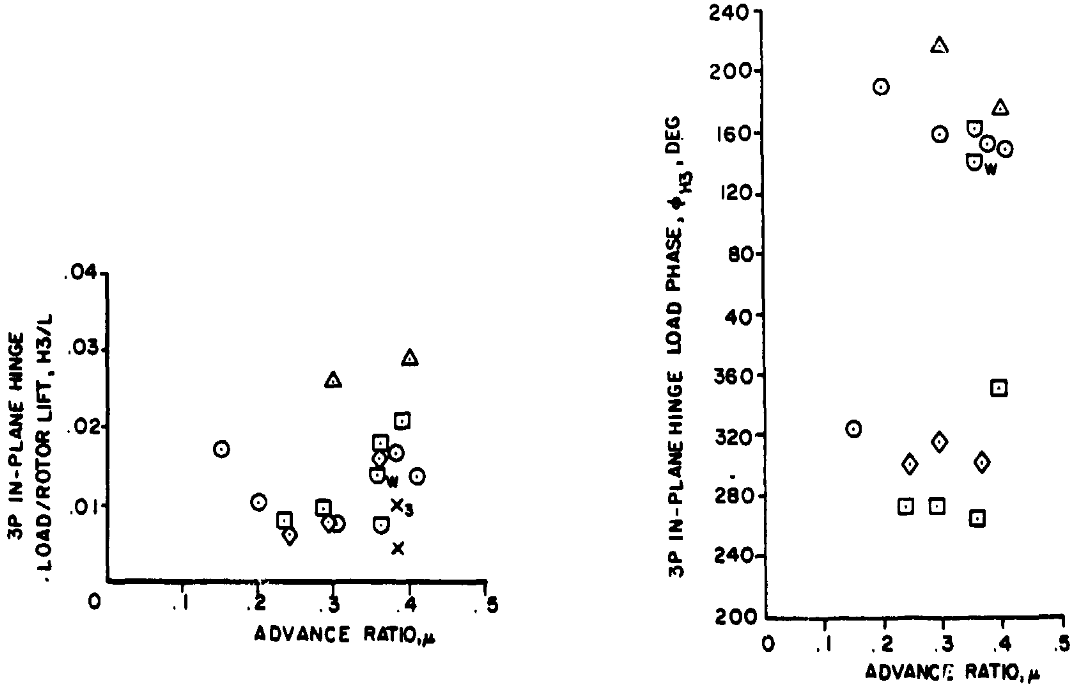


Fig. 2. Representative airframe response to rotor shaft loads.

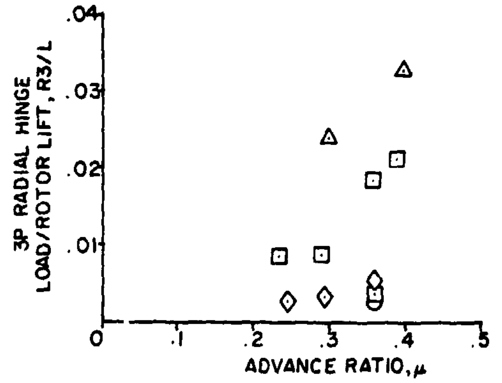


3(a) 3P Axial Amplitude and Phase



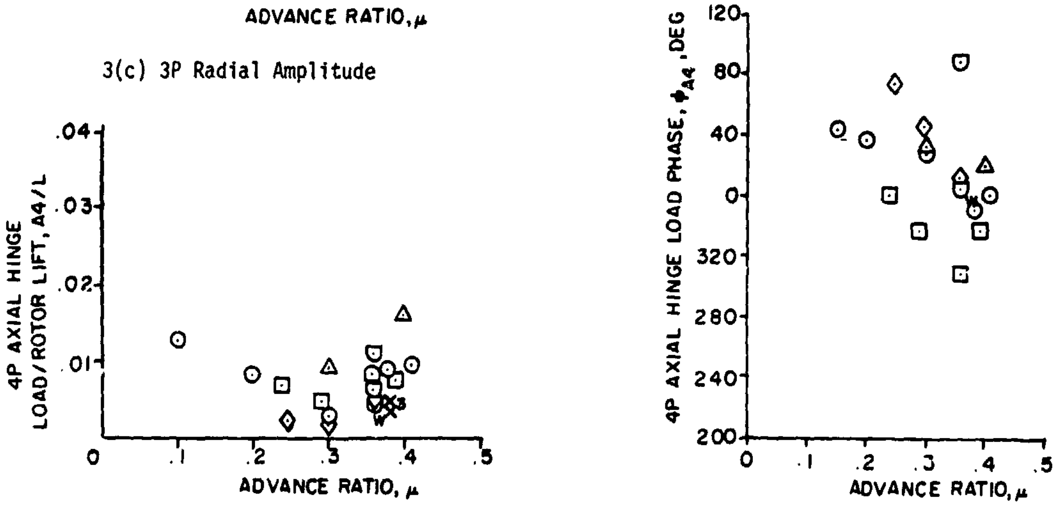
3(b) 3P In-Plane Amplitude and Phase

Fig. 3. Survey of harmonic hub load test data.

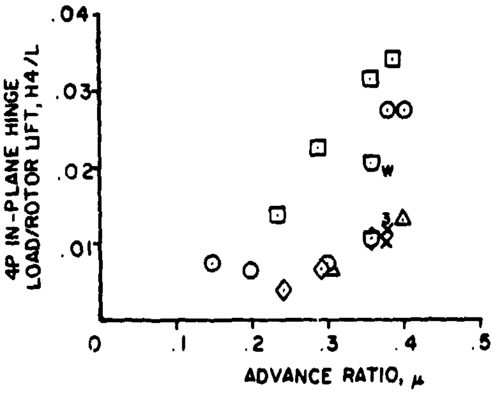


3(c) 3P Radial Amplitude

⊙ S-76, AMES WIND TUNNEL
◇ S-61F, REF. [illegible]
⊡ CH-53A, REF. 7
× MASS-TUNED MODEL-BASELINE
$\times_3$ MASS-TUNED MODEL-MASS DISTRIBUTION 3
⊡ S-76 FLIGHT TEST, EDGE STIFFENING
$⊡_W$ S-76 FLIGHT TEST, EDGE STIFFENING + TIP WEIGHT
△ MODEL, REF. 8

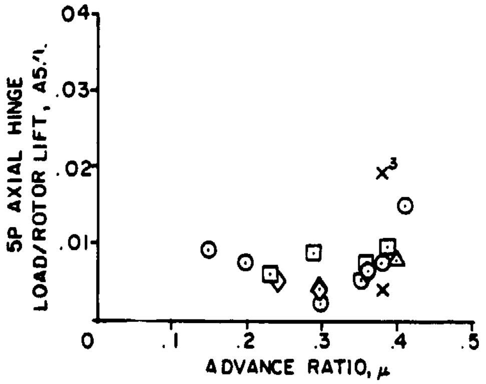


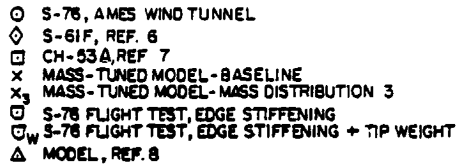
3(d) 4P Axial Amplitude and Phase



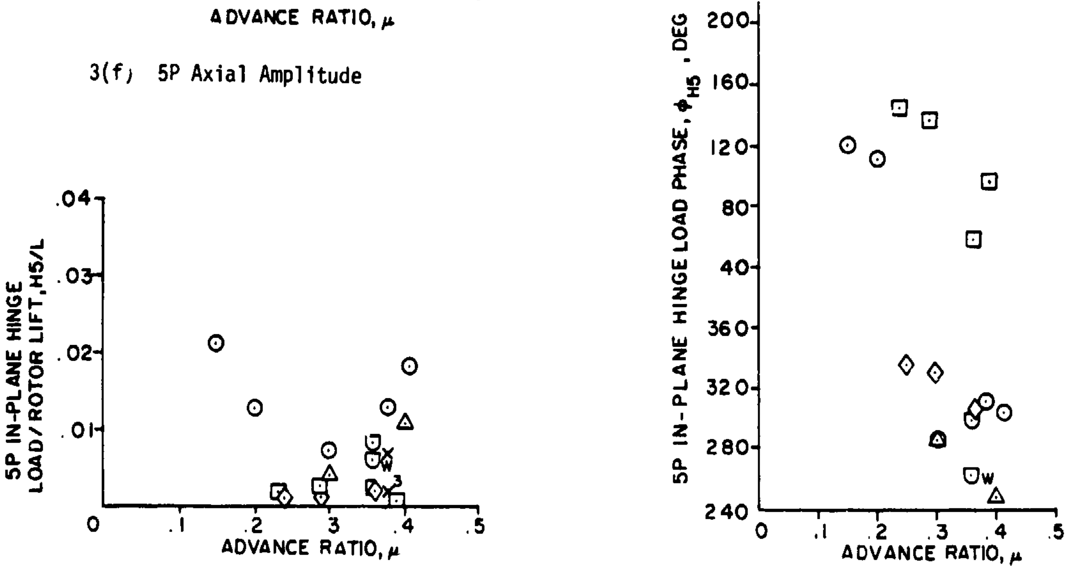
3(e) 4P In-Plane Amplitude

Fig. 3. Continued

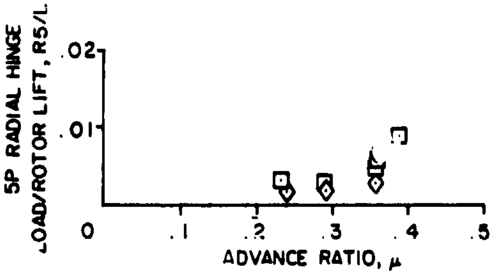




3(f) 5P Axial Amplitude



3(g) 5P In-Plane Amplitude and Phase



3(h) Radial 5/Rev Amplitude

Fig. 3 Concluded.

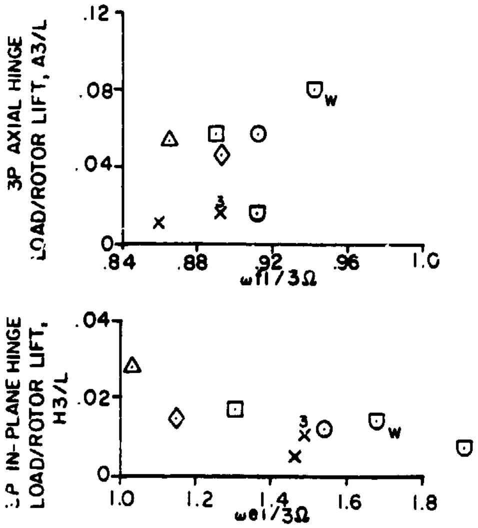


Fig. 4. Correlation of 3P Axial and In-Plane hinge loads with frequency ratio ($\mu \cong .375$)

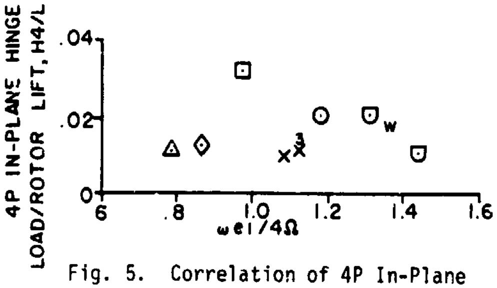


Fig. 5. Correlation of 4P In-Plane Hinge loads with frequency ratio ($\mu \cong .375$)

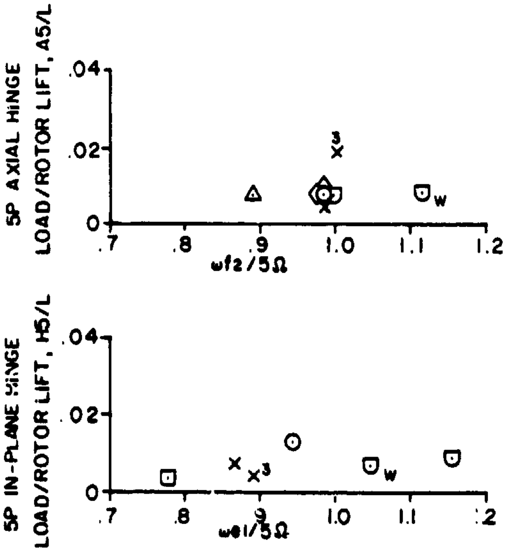


Fig. 5. Correlation of 5P Axial and In-Plane Hinge loads with frequency ratio ($\mu \cong .375$).

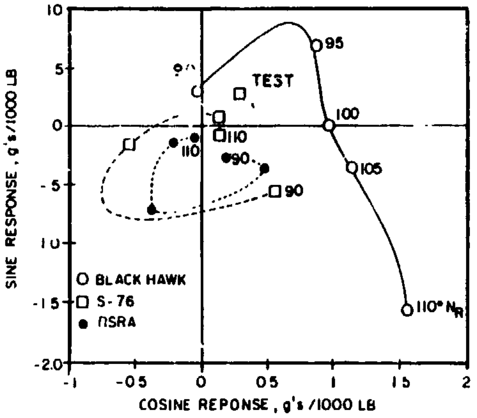


Fig. 7. Pilot station vertical vibration response.

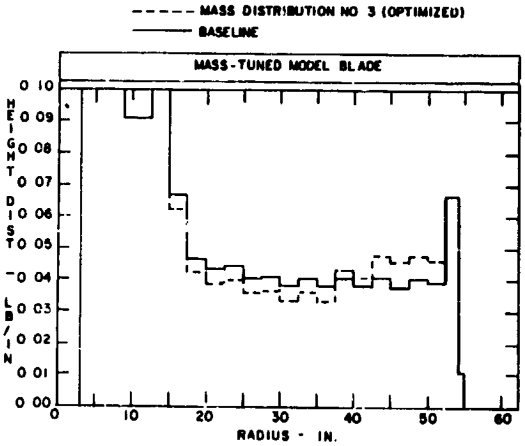


Fig. 8. Baseline and optimized mass distribution.

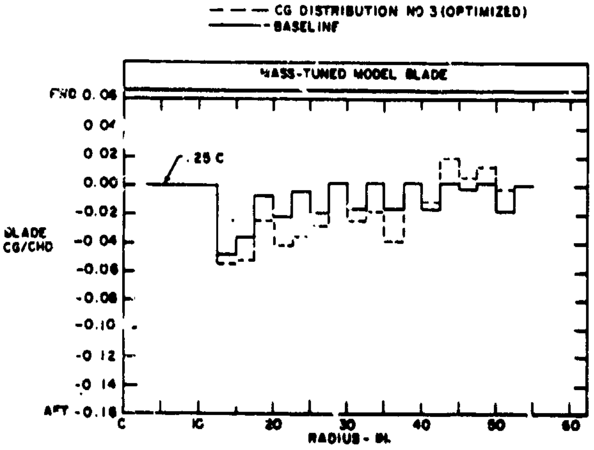


Fig. 9. Baseline and optimized center of gravity distribution.

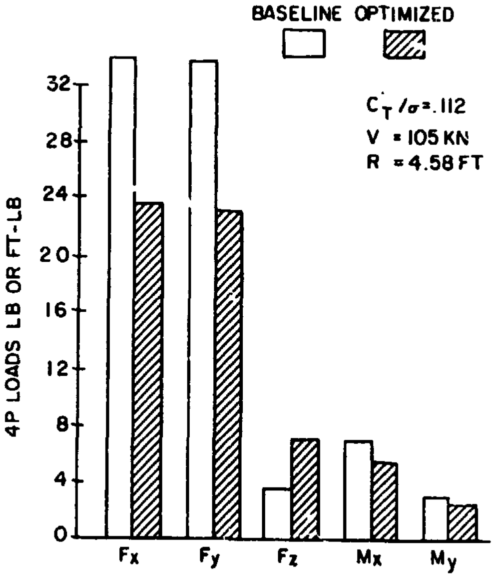


Fig. 10. Analytically predicted effects of spanwise mass distribution improvement on model hub loads.

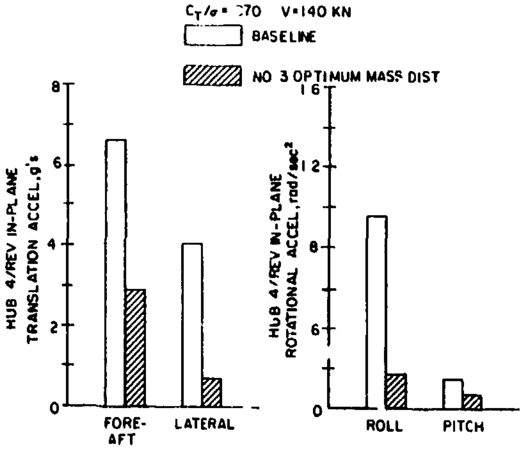


Fig. 11. Analytically predicted benefits in model rotor hub vibratory acceleration due to optimized mass distribution.

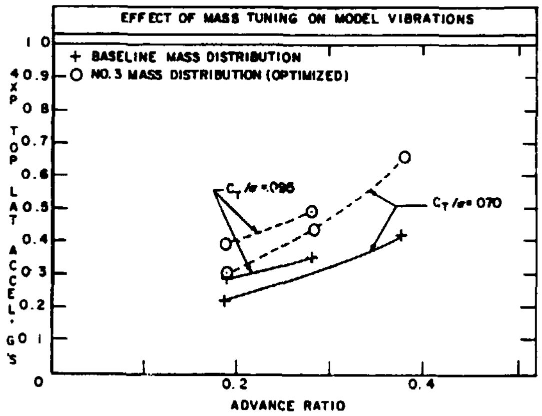


Fig. 12. Rotor support rig vibration levels as a function of flight condition.

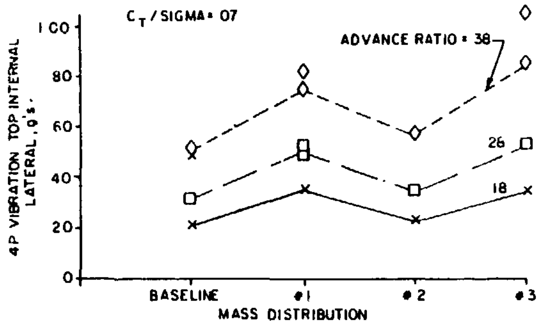


Fig 13. Rotor support rig vibration levels as a function of mass distribution.

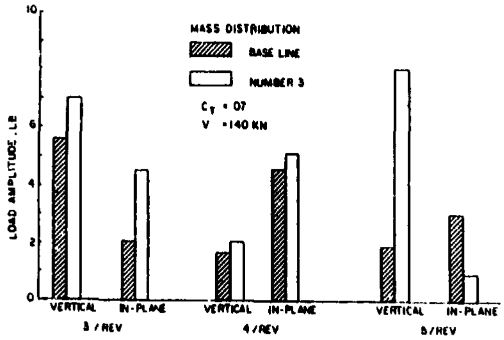


Fig. 14. Effect of mass tuning on model blade hinge load amplitudes.

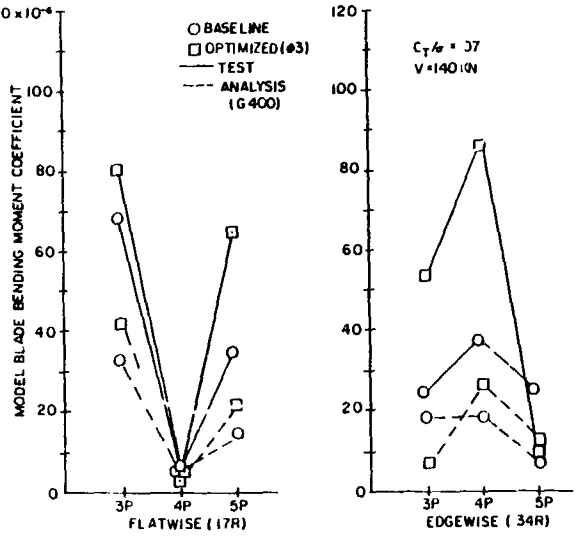


Fig. 15. Correlation of test and analysis blade bending response harmonics.

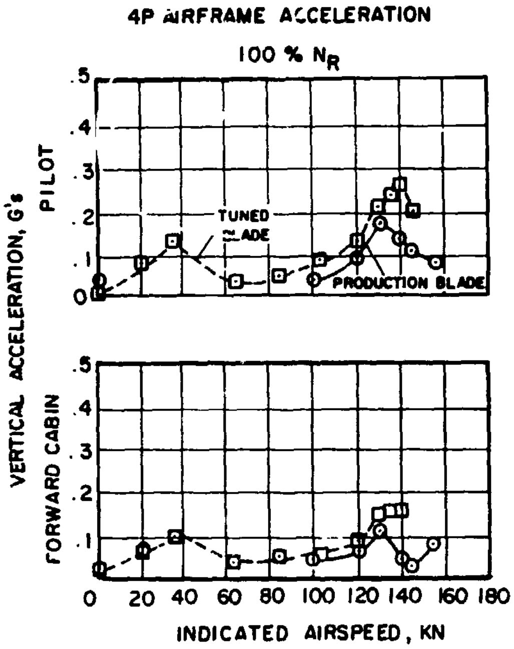


Fig. 17. Tuned blade flight test results.

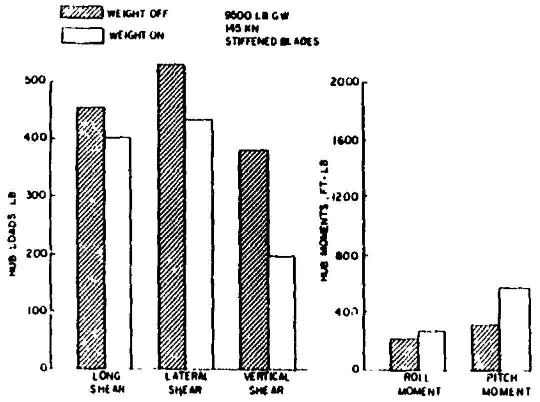


Fig 16. Effect of tip weight on analytical full scale 4P hub loads.

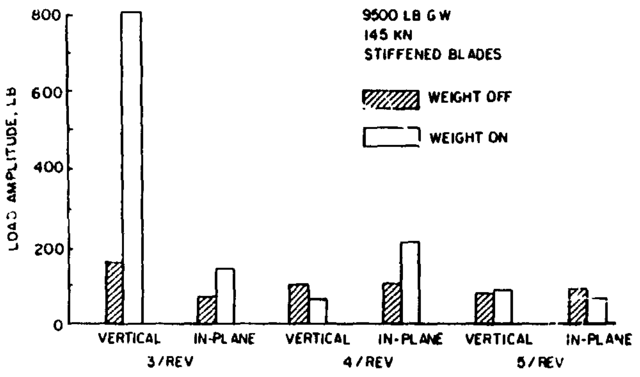


Fig. 18. Effect of tip weight on full-scale flight test hinge load amplitudes.

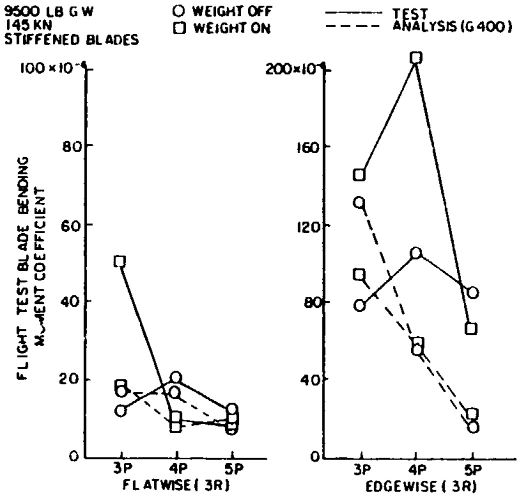


Fig. 19. Correlation of test and analysis blade bending response harmonics.

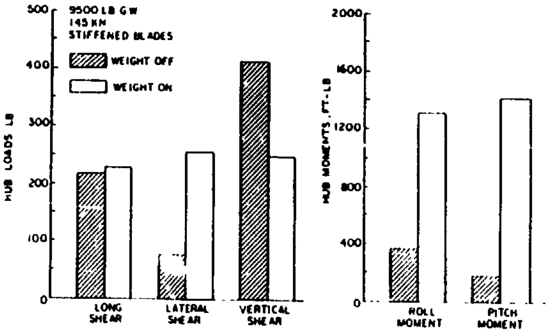


Fig. 20. Effect of tip weight on flight test 4P hub loads.

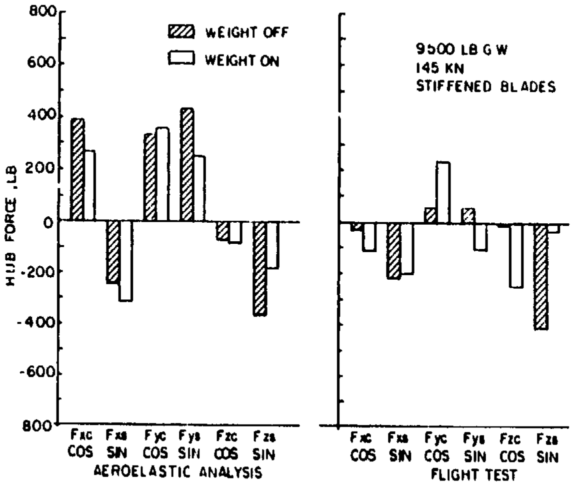


Fig. 21. Analytical and flight test in-plane hub load components.

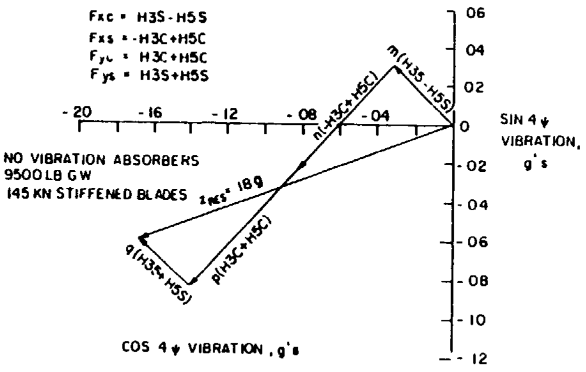


Fig. 22. Pilot vertical response to flight test in-plane shears-tip weight on.

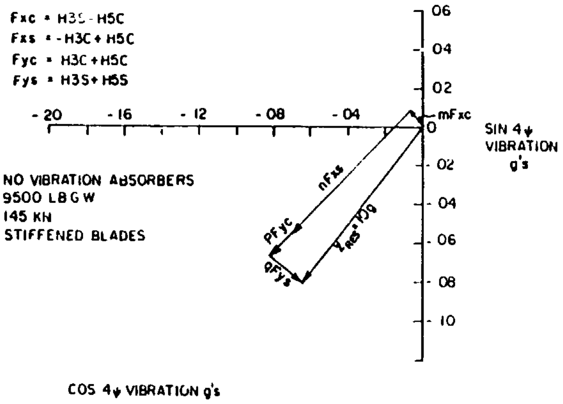


Fig. 23. Pilot vertical response to flight test in-plane shears-tip weight off.

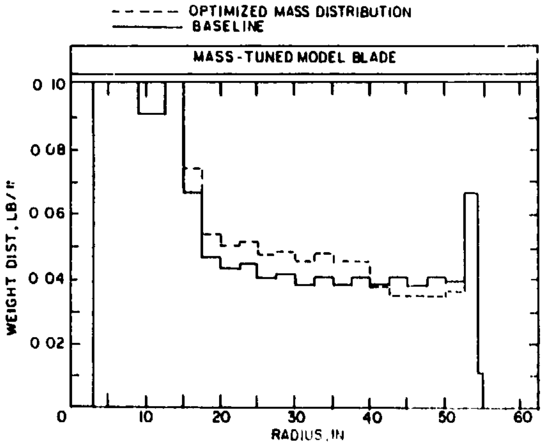


Fig. 24. Model blade mass distribution optimized from test data.

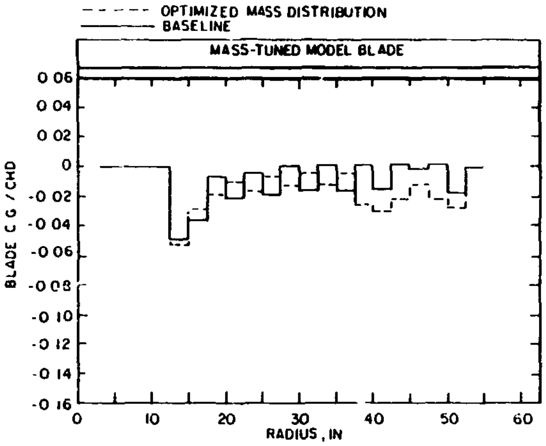


Fig. 25. Model blade mass center of gravity distribution optimized from test data.

DISCUSSION
Paper No. 19

AN EXAMINATION OF THE RELATIONS BETWEEN ROTOR VIBRATORY LOADS AND AIRFRAME VIBRATIONS

Charles F. Niebanck

Bill Weller, United Technologies Research Center: Did you verify the frequency placement on your analytical models [by] correlating with full scale or the model data prior to embarking on the optimization studies?

Niebanck: No, I didn't correlate the frequencies with model or full-scale [data].

Weller: I'd like to submit that we have problems with our analyses, but sometimes we have problems with our users. The structural data worked up may not have been the best representation. If your starting point is wrong your ending point may be as bad.

Niebanck: I can't dispute that.

Hooper: I assume it is a fair comment that the failure of the analysis was because of the failure of the aerodynamic modeling of the analysis?

Niebank: That could be part of it. I used uniform inflow and . . .

Hooper: You started off with an analysis--ours are no better than yours in this respect--which does not adequately represent the higher harmonic loading on the blades. If you draw conclusions about how to change the blades to improve the vibration it's as likely to be right as it is to be wrong.

Niebanck: Yes, I think that is a fair assessment. It seems like [from] the things that we have seen since we have been here that the unsteady aerodynamics makes a big change and [when] you look at the azimuth plot maybe that doesn't strike you as a big change, but when you do the harmonic analysis you may find a profound change in the harmonic distribution. I think that is part of the task of getting the analysis more accurate.

Dick Gabel, Boeing Vertol: I was interested in a mundane thing, Charlie, about how you measured the rotor loads. You did mention that you used modal fitting and we have tried it. We have done it routinely for the vertical, but never for the inplane. You report a lot of inplane loads that look just as good. I was curious as to how you did it.

Niebanck: It's the same way. We have a program that Bob Blackwell put together. It does this modal fit with respect to the flatwise and the edgewise loading. We think it is a fairly good assessment of what the loads are.

Gabel: Did you check it with shaft loads measurements or balance measurements?

Niebanck: They all seem to hang together fairly decently and some of them come from this modal fit method and some come from hub bending and shaft gauges and some come from strain gauges on the blade root. Especially the S-76 tunnel test; those were hub bending gauges. I see that I have relatively the same phase angle from the flight test and the wind tunnel data, so it gives me some confidence that this is working.

Bob Taylor, Boeing Vertol: I'd like to add one comment before we go on to the next paper. I'd like to second what Euan said. I think we are missing one of the most important ingredients in the problem and that is a definition of what the airloads are on the blade. We have been assuming for many years that at high speeds like 150 knots that the inflow is uniform and you can use that model for vibration predictions. I think that what Charlie has shown here indicates that is not true and we certainly need that information to go further. I might also add that I don't think the jury is in on this, it's still out and Bob Jones from Kaman will have more to say on this tomorrow in the panel sessions.