

Optimizing Tuning Masses for Helicopter Rotor Blade Vibration Reduction and Comparison with Test Data

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This article describes the development and validation of an optimization procedure to systematically place tuning masses along a rotor blade span to minimize vibratory loads. The masses and their corresponding locations are the design variables that are manipulated to reduce harmonics of hub shear for a four-bladed rotor system without adding a large mass penalty. The procedure incorporates a comprehensive helicopter analysis to calculate the airloads. Predicting changes in airloads due to changes in design variables is an important feature of this research. The procedure was applied to a one-sixth, Mach-scaled rotor blade model to place three masses and then again to place six masses. In both cases the added mass was able to achieve significant reductions in the hub shear. In addition, the procedure was applied to place a single mass of fixed value on a blade model to reduce the hub shear for three flight conditions. The analytical results were compared to experimental data from a wind-tunnel test performed in the Langley transonic dynamics tunnel (TDT). The correlation of the mass location was good and the trend of the mass location with respect to flight speed was predicted fairly well. However, it was noted that the analysis was not entirely successful at predicting the absolute magnitudes of the fixed-system loads.

Nomenclature

C_T	= coefficient of thrust
f	= objective function
I	= number of constrained frequencies
J	= number of tuning masses
K	= number of harmonics of shear included in the objective function
M_j	= j th tuning mass
NP	= frequency or loading at N times the rotational speed of blade
S_k	= amplitude of k th harmonic of shear
X_j	= location of j th tuning mass
β_k	= scalar design variables appearing in the objective function and constraints
μ	= advance ratio (ratio of forward flight speed to tip speed)
Ω	= rotational speed of rotor blade
ω_i	= i th natural frequency
$\bar{\omega}_i$	= ω_i/Ω
ω_{li}	= lower bound on $\bar{\omega}_i$
ω_{ui}	= upper bound on $\bar{\omega}_i$

Introduction

SINCE helicopter vibration is transmitted from the rotor blade to the fuselage through a time-dependent shear force at the hub, methods for reducing vibration through reduction of hub shear have long been a subject of study. An example of this is vibration reduction of rotor blades through passive control. For instance, pendulum absorbers,¹ active isolation devices,² additional damping,^{2,3} and vibration absorbers which create antiresonances^{4,5} have all shown promise

in reducing blade vibratory response. Historically, frequency placement has been the principal technique for passively reducing blade vibration.⁶ Another form of passive control is to alter the mass and stiffness distributions of the blade. These modifications tailor the mode shapes to achieve orthogonality to the airloading, thereby reducing the generalized force and response of the blade.⁷ This is generally done in a late stage of the design process.

The current trend in engineering design of aircraft is to incorporate critical requirements from all pertinent disciplines into an early phase of the design process to avoid costly modifications after a problem has been detected.⁸ In the preliminary stage of design, a large number of design variables are free to be chosen in order to satisfy important multidisciplinary considerations. It is in this stage that passive control of vibration can play an important role. The design process is a labor-intensive effort, however, mathematical optimization techniques allow for efficient and thorough searches of the design possibilities while satisfying a large number of conflicting design requirements from many different disciplines. For example, Ref. 9 used optimization methods to study the interaction of structural properties with airload distributions in designing blades for low vibration. The structural properties included mass and stiffness distributions. The airload distributions included higher harmonic lift components and aerodynamic pitching moments which are the primary sources of vibration in helicopter rotor blades. Comparison of the vibration characteristics from three analytical design strategies showed the benefits of using an automated structural optimization procedure with a coupled aeroelastic analysis. Another example where optimization was successfully applied to the design of low vibration rotor blades was reported in Refs. 10 and 11 where several alternative optimization formulations were investigated and their benefits revealed. Reference 11 validated the design procedures from Ref. 10 by showing that the optimized designs had lower vibration levels than the baseline designs. The design procedures described in Refs. 10 and 11 did not include an aerodynamic analysis for airload calculations, nor did the results include validation by direct comparison between analytical and measured vibration levels. Reference 12 described an optimization procedure for designing a low-vibration rotor blade. Wind-tunnel tests of the rotor showed that the design had lower vibratory response

Received March 11, 1992; presented as Paper 92-2376 at the AIAA/ASME/ASCE/AHS 33rd Structures, Structural Dynamics, and Materials Conference, Dallas, TX, April 13-15, 1992; revision received Aug. 24, 1992; accepted for publication Aug. 25, 1992. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

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than a rotor designed using the traditional approach of frequency placement. A comparison between the analytical results and test data was performed and revealed that the trends and reductions in load levels were predicted well, but the absolute values of the loads at given airspeeds were predicted less accurately.

Reference 13 described a procedure for placing and sizing tuning masses at strategic locations along the blade span to tailor the mode shapes. This procedure used formal mathematical programming techniques in conjunction with a finite element program to model a simplified blade and calculate the dynamic response. The airloads used in the analysis represented a set of harmonics typical of a four-bladed rotor system,⁷ but the loads did not vary with changes in the masses or their locations. The purpose of this article is to describe the enhancement and validation of the method described in Ref. 13. The enhancements include the incorporation of a comprehensive helicopter analysis CAMRAD/JA¹⁴ into the optimization procedure which yields a more realistic blade model and the incorporation of calculated airloads inside the optimization loop. The validation is accomplished by comparing the analytical results with experimental data from wind-tunnel tests.

Problem Definition and Formulation

The design goal is to find the optimum combination of masses and their locations (Fig. 1) to reduce the vertical hub shear. The method entails formulating and solving an optimization problem in which the tuning masses, M and corresponding locations X are design variables that are manipulated to minimize the objective function. Equation (1) defines f , which is a combination of vertical hub shear and added mass:

$$f = \left(1 + \sum_{k=1}^K \beta_k \right) \sum_{j=1}^J M_j \quad (1)$$

The objective function includes additional design variables β_k which also appear in the constraints as "upper limits" on the shear harmonic amplitudes S_k :

$$S_k/\beta_k - 1 \leq 0 \quad k = 1, 2, \dots, K \quad (2)$$

By convention, a constraint is satisfied if its value is less than or equal to zero. Consequently, the optimizer will tend to decrease the values of β_k to minimize the objective function, but will also tend to increase the values of β_k to satisfy the constraints. This results in a compromise on the values of β_k which forces a reduction in the values of S_k , thus reducing the hub shear harmonics while incurring the smallest possible mass penalty. Additional constraints include upper and lower bounds on the natural frequencies of the blade to avoid resonance, as shown in Eq. (3)

$$\left. \begin{aligned} \bar{\omega}_i/\bar{\omega}_{ui} - 1 &\leq 0 \\ 1 - \bar{\omega}_i/\bar{\omega}_{li} &\leq 0 \end{aligned} \right\} \quad i = 1, 2, \dots, I \quad (3)$$

Analyses

The analyses that are used in the procedure are the comprehensive helicopter analysis code, CAMRAD/JA,¹⁴ the op-

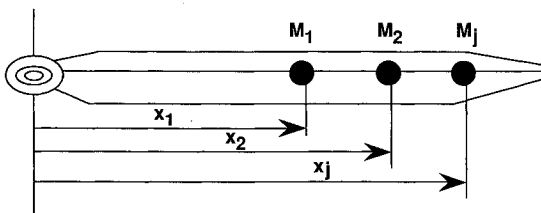


Fig. 1 Design variable definition for optimizing magnitudes and locations of tuning masses.

timization code, CONMIN,¹⁵ and an approximate analysis to reduce the number of CAMRAD/JA analyses during the iterative process. CAMRAD/JA calculates rotor performance, loads, vibration mode shapes and frequencies, aeroelastic stability and response. In this study, CAMRAD/JA was used to calculate frequencies, airloads, and hub loads. The structural model of the rotor is based on engineering beam theory for rotating wings with large pitch and pretwist. The frequencies and mode shapes are computed using a modified Galerkin analysis. The rotor aerodynamic model is based on lifting-line theory and uses steady two-dimensional airfoil characteristics provided in tables of section lift, drag, and pitching moment vs Mach number and angle of attack. The analysis includes unsteady aerodynamic forces from thin airfoil theory, and the induced velocity is obtained from either a uniform inflow model or a vortex wake model. A detailed description of the theory is given in Ref. 14.

CONMIN is a general purpose optimization program that uses the method of feasible directions for constrained function minimization and the conjugate direction method of Fletcher and Reeves for unconstrained minimization problems. The approximate analysis uses a linear Taylor series expansion to approximate the objective function and constraints for the iterative portion of the optimization procedure to save computational effort.

Organization of the Procedure

A flowchart of the optimization procedure is illustrated in Fig. 2. The overall procedure consists of two nested loops. Each pass through the outer loop is referred to as a cycle which involves a full analysis and a sensitivity calculation. The sensitivity analysis includes calculating finite-difference derivatives of the objective function and the constraints with respect to the design variables. The first step is to generate the model of the blade, excluding tuning masses. The design variables (masses and locations) then determine where and how much mass should be placed on the blade. Next, the modal analysis is performed and the airloads and hub shears are computed using CAMRAD/JA, and the objective function and constraints are calculated. The inner loop consists of the optimization program CONMIN and the approximate analysis for calculating values of the objective function and constraints. Once the inner loop has converged, the next cycle begins, using updated values of the design variables. The process continues until convergence of the outer loop is achieved. The major improvement in the procedure over that of Ref. 13 occurs in the outer loop where the airloads are calculated by CAMRAD/JA. The use of CAMRAD/JA enables the change in airloads due to changes in the design variables to be taken into account.

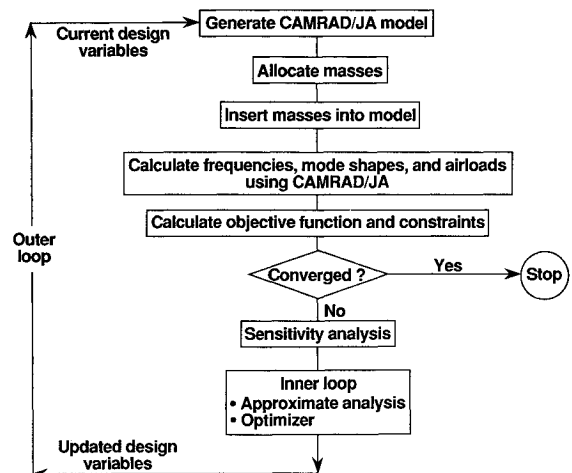


Fig. 2 Flow chart for optimization procedure.

Demonstration of the Method

The model used to demonstrate the procedure is a four-bladed, one-sixth, Mach-scaled representation of a design intended to satisfy the requirements for the "growth" version of the U.S. Army's UH-60A (Black Hawk) helicopter. Each blade (shown in Fig. 3) weighs about 1.36 kg and has three sets of advanced airfoils, RC(4)-10,¹⁶ RC(3)-10,¹⁷ and RC(3)-08.¹⁷ The planform is tapered with a -16 -deg linear twist. The calculations were performed in CAMRAD/JA using five flap/lag bending modes and two torsion modes. Each blade was modeled with 18 aerodynamic segments and 50 structural segments. The chordwise c.g., aerodynamic center, and elastic axis were coincident and located at the quarter-chord. The rotor was trimmed to prescribed values of thrust and zero flapping angles using nonuniform inflow with a prescribed wake geometry. The 4P blade vertical shear is generally the primary source of vertical loads in a four-bladed rotor configuration and the 3P and 5P blade vertical shears contribute to the hub moments. (It is customary in rotorcraft dynamics to use the notation N/rev or NP to denote frequencies or harmonics of loading at N times the rotational speed of the blade.) Therefore, these three quantities were the major focus for reduction in this optimization study. The flight condition was forward flight at an advance ratio of $\mu = 0.35$, and a thrust condition of $C_T = 0.0081$ which signifies a full scale gross weight of 8392 kg.

Table 1 shows the results obtained from applying the optimization procedure to place three tuning masses along the span of the blade model. Starting with the baseline blade (no added mass), the procedure was able to reduce the 3rd, 4th, and 5th harmonics of shear by 8, 8, and 4%, respectively, by adding 0.153 kg of tuning mass which is about 11.5% of the nominal blade weight. The mass was added between 42–52% of the blade span. The baseline blade was originally designed for low vibration so these reductions in shear from the baseline design, although seemingly modest, are considered to be significant.

As a matter of interest, the procedure was also applied to place six masses and results are also shown in Table 1. In this case, the optimizer placed all masses between 45–48% of the

Table 1 Comparison of baseline and optimized designs from three-mass and six-mass optimization procedures

	Baseline	Three-mass	Six-mass
Mass 1, kg	0.00	0.070	0.137
Mass 2, kg	0.00	0.013	0.127
Mass 3, kg	0.00	0.070	0.010
Mass 4, kg	0.00	—	0.027
Mass 5, kg	0.00	—	0.116
Mass 6, kg	0.00	—	0.138
Location 1, m	—	0.600	0.646
Location 2, m	—	0.671	0.668
Location 3, m	—	0.742	0.669
Location 4, m	—	—	0.681
Location 5, m	—	—	0.683
Location 6, m	—	—	0.689
S3, N	20.35	18.68	15.46
S4, N	51.15	47.15	33.23
S5, N	5.34	5.12	3.62

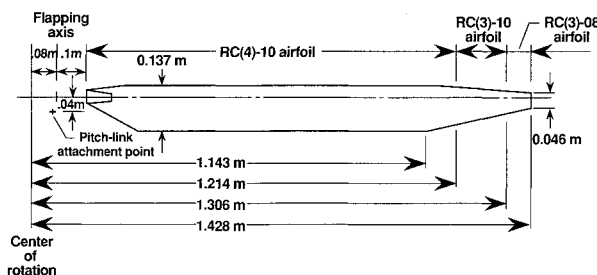


Fig. 3 Rotor blade geometry.

blade span. The procedure reduced the 3rd, 4th, and 5th harmonics of shear from the baseline values by 24, 34, and 32%, respectively, with a total addition of 0.544 kg of tuning mass. This is a sizable reduction in shear (approximately four times the reduction in the three-mass case), however, the added mass represents about 30% of the mass of the baseline blade. Consequently, this solution to the vibration problem would probably not be adopted in a practical design situation. Nonetheless, this result verifies our intuition that use of additional mass design variables improves vibration reduction, but with a significant increase in the weight penalty.

Comparison with Test Data

Reference 18 describes results of wind-tunnel tests performed in the TDT on the blade test article shown in Fig. 4. The test article, based on the model described in the previous section, was designed to study passive means for minimizing fixed-system loads and has the capability of adding nonstructural masses at various intervals of the blade span. This test provided an opportunity to validate the present optimization procedure. A description of the model, test set-up, and the reduced data are given in Ref. 18. The test involved placing a single mass of fixed value (0.123 kg) at various locations along the blade span to determine the effectiveness in reducing 4P hub shears and moments for several different flight conditions.

Reference 18 shows several data plots of 4P normal force as a function of mass location on the blade. Many of the curves are very flat and suggest that the mass location does not significantly affect the hub shear for all flight conditions. Since optimization works best for problems with well defined minimums, only selected cases were included in this study.

The optimization procedure was applied to this model for the placement of a single mass at advance ratios of 0.25, 0.30, and 0.35, and a thrust condition of $C_T = 0.0081$. Comparisons between the optimization results and the test data are summarized in Fig. 5. The measured values of the optimum locations are shown as 10% ranges of the blade span since the data was only available at 10% increments of the blade span.

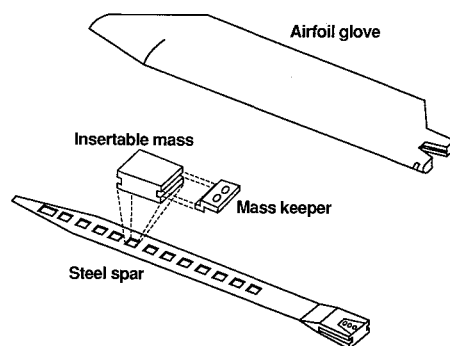


Fig. 4 Model rotor blade components.

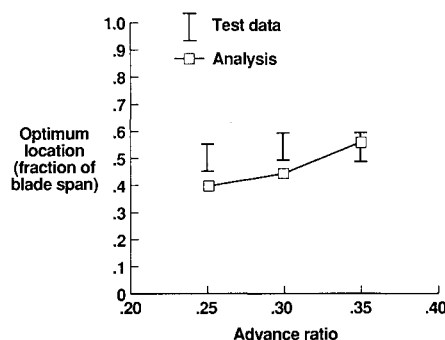


Fig. 5 Comparison of optimum location of single mass with test data.

Table 2 Predicted vs measured results for single mass placement to reduce hub shear

	Advance ratio = 0.25		Advance ratio = 0.30		Advance ratio = 0.35	
	Predicted	Measured ^a	Predicted	Measured ^a	Predicted	Measured ^a
Optimum location of mass, x/R	0.40	0.48	0.44	0.52	0.56	0.52
S4 Ratio final/initial	0.94	0.93	0.92	0.90	0.90	0.92
S4 (N) Initial design mass = 0 kg	4.63	9.12	3.22	17.01	5.06	22.23
S4 (N) Final design mass = 0.12 kg	4.35	8.53	2.98	15.24	4.54	20.41

^aBased on faired curve through experimental data points.

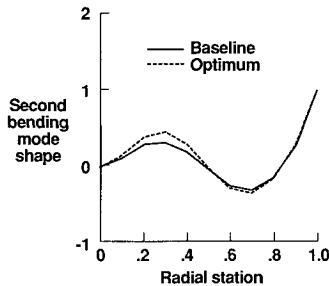


Fig. 6 Comparison of mode shapes from baseline and optimum designs.

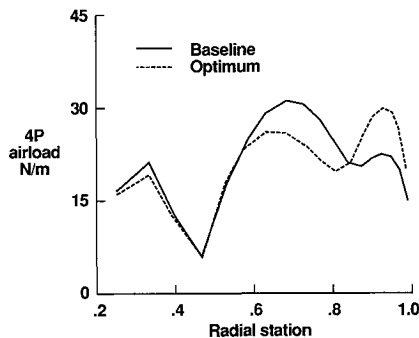


Fig. 7 Comparison of 4P airloads from baseline and optimum designs.

For the 0.35 advance ratio case, the optimization procedure predicted an optimum location within the range of the test data. The other two cases (0.25 and 0.30) were 11 and 12%, respectively, below the lower bound of the range. This is fairly good agreement considering the well-known difficulty of predicting fixed-system loads.

In order to verify the mechanism by which the hub loads are decreased, Figs. 6 and 7 illustrate examples of the changes in the calculated mode shapes and airloads, respectively, from the baseline to the optimized design. The simultaneous changes in the mode shapes and airloads result in a reduction of the generalized force, and subsequently, the hub shear. Even though the mode shape change is small, the sizable change in the airload distribution resulting from the changes in the design variables suggests that neglecting this effect would be erroneous.

Additional Details of Design Comparisons

Table 2 shows some additional details of the three results for the single mass placement optimization. The optimum location was in fair agreement with the test data, and the relative change in hub shear from the baseline to final design was also comparable between the optimization and test measurements for all three cases. However, the absolute values of the hub shear were grossly underpredicted. Unfortunately, this represents the current state of the art in prediction of fixed system loads in rotorcraft systems (e.g., Refs. 19 and 20). Although it is outside the scope of this article to either investigate the reasons for or to recommend corrective action for this shortcoming, the authors feel obliged to point out its

existence. Furthermore, we are aware of a number of efforts in progress to improve the fidelity of fixed system loads prediction. For example, some of the more fruitful approaches involve the investigations of accurate calculation of rotor airloads.^{19,21,22}

Concluding Remarks

This article describes the development and validation of an optimization procedure to systematically place tuning masses along a rotor blade span to minimize vibratory response. The masses and their corresponding locations were the design variables that were manipulated to reduce harmonics of hub shear for a four-bladed rotor system without adding a large mass penalty. The procedure incorporated a comprehensive helicopter analysis to calculate the airloads. This procedure enabled the changes in airloads due to the changes in design variables to be taken into account.

The procedure was first applied to a one-sixth, Mach-scaled rotor blade model for two cases: 1) the placement of three masses and 2) the placement of six masses. The optimized three-mass configuration reduced the 3rd, 4th, and 5th harmonics of shear between 4–8%. The optimized six-mass configuration reduced these shear harmonics between 24–34%, although four times the mass was added over a smaller region of the blade.

The optimizer was then compared to test data for placing a single mass of fixed value on a blade model to reduce the 4P hub shear for three flight conditions. A wind-tunnel test was performed in the TDT on a blade test article. The analytical results were compared to the experimental data, and the trend of the mass location with respect to flight speed was predicted fairly well. At the same time it was noted that the analysis used was not entirely successful at predicting the absolute magnitudes of fixed-system loads.

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