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Dynamics of an Optimized Rotor Blade at Off-Design Flight Conditions

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Introduction and Background

SINCE vibration has been a major source of problems in helicopters, its alleviation plays an important role in the rotor blade design process. Because of the importance of the problem there has been a considerable amount of research aimed at reducing vibration, primarily at the blade level, as shown in Refs. 1–6. In some of these work, dealing with optimum blade designs for reduced vibration, the aerodynamic loads on the blade were either not considered[1–3] (i.e., blade in vacuum) or prescribed airloads were used[4,5] and the effects of the design changes, during optimization, on changes in the blade airloads were not included. A first investigation at integrating some of these disciplines is reported by Chattopadhyay et al.[6] where the integration of aerodynamic loads effects and the dynamic aspects of blade design was addressed by coupling a comprehensive helicopter analysis code, CAMRAD,[7] to an optimizer consisting of the nonlinear optimization algorithm, CONMIN[8] and an approximate analysis technique. A combination of the blade root 4/rev vertical shear and the blade weight was minimized with constraints on coupled lead-lag and flapping frequencies, blade autorotational inertia, and centrifugal stress. The use of the program CAMRAD permitted the design of the blade with calculated airloads and its presence in the closed-loop optimization procedure allowed the inclusion of the effects due to changes in these airloads with changes in design variables. The paper demonstrated a significant reduction in the 4/rev vertical shear and blade weight, which were objective functions, along with overall reductions in the amplitudes of the oscillatory vertical airloads, azimuthally and radially, for the optimized blade, when compared to a baseline ("reference") blade. As a by-product, it was shown that optimization also reduced the total power required by the rotor while maintaining the same C_T/σ, and C_X/σ, C_T being the rotor thrust coefficient, C_X the propulsive force coefficient, and σ the thrust weighted solidity of the blade.

The optimization in Ref. 6 was performed for the rotor in forward flight at a particular advance ratio μ, subject to a reasonable but limited set of design constraints. For example, only 4/rev vertical shear was involved and no constraint was imposed on the total rotor thrust, although the C_T/σ was held constant between the reference and the optimized blades. This led to an overall reduction in blade thrust after optimization due to reduction in the solidity of the optimized rotor. It was of interest, now, to determine how well a blade designed for one flight condition and a limited number of constraints would perform for other conditions and to assess performance with respect to criteria not included in the design process. In this paper, the dynamic behavior of the optimized blade design obtained in Ref. 6 is investigated in detail.

The Optimized Blade

A brief description of the optimized blade along with the basis for obtaining it is presented in this section. The optimization procedure developed in Ref. 6 was applied to a "reference" blade. The reference blade was a modified version of a wind-tunnel model of an advanced rotor blade. The reference and the optimized blades are articulated with rigid hubs and have linear twist distributions. The blade was optimized for minimum weight and minimum 4/rev vertical root shear. Constraints were imposed on the following: 1) upper and lower bounds on first four elastic coupled blade natural frequencies, 2) lower bound on blade autorotational inertia, and 3) upper bound on centrifugal stress on each blade segment. The design variables were the blade bending and torsional stiffnesses, nonstructural masses, chord, radius of gyration, and taper ratio. Blade radius R, rotor angular velocity Ω, airfoil distributions, and hinge off-sets were fixed during optimization. A comparison of the optimized and the reference blade is presented in Ref. 6, which shows that the reference blade has a rectangular platform whereas the optimized blade is tapered with a taper ratio $\lambda = 1.33$.

Study Description

The intent of the present note is to investigate the vibratory loads on the optimized rotor over a wide range of operating conditions and for a large number of rotor characteristics than those considered in the design process, in order to assess the design. This is accomplished by 1) studying the dynamic performance criterion of the rotor blade, optimized at a prescribed flight condition, at "off-design" flight conditions and 2) investigating the behavior of the optimized blade with respect to the dynamic performance criteria that were not included in the optimization formulation.

The program CAMRAD is used for calculating the vibratory airloads for the optimized and the reference blades. In CAMRAD, the blade response is computed using rotating, free-vibration modes, equivalent to a Galerkin analysis. Ten bending modes, of which seven are flapping (one rigid and six elastic), three are lead-lag (one rigid and two elastic), and one is a rigid-body torsion mode, are calculated. Main blade resonances up to eight per revolution are included and therefore, eight harmonics of the rotor revolution are retained in

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the airloads calculation. The blade loads are generated using the isolated rotor model in CAMRAD. The code is run using the same aerodynamic assumptions used in the optimization study. These assumptions include uniform inflow, yawed flow on the rotor, unsteady aerodynamics, and no dynamic stall. It is recognized that some of these assumptions will produce an inaccurate picture of the rotor aerodynamic environment (particularly the inflow assumption); however, the authors feel that it is more appropriate to retain the same model for the purpose of this theoretical study.

For a four-bladed rotor, the critical vibratory blade loads, which are transmitted to the rotor hub and therefore need to be addressed, are 1) the 4/rev vertical shear, 2) the 3/rev and the 5/rev inplane shears, 3) the 3/rev and the 5/rev radial shears, 4) the 3/rev and the 5/rev flapping moments, 5) the 3/rev and the 5/rev torsional moments and 6) the 4/rev lagging moment. The 4/rev vertical shear produce oscillatory 4/rev loads in the vertical direction at the hub. In the optimized blade, the minimization of this shear force was done at a particular flight condition, therefore, its value at "off-design" flight conditions needs to be calculated. The purpose of this study is to see whether the value of the shear force for the optimized blade remains lower than the reference blade value at other flight conditions. The 3/rev and 5/rev components of the inplane and the radial shears at the blade root are transmitted as 4/rev forces in both lateral and longitudinal directions at the rotor hub. Since they were not used as objective functions or as constraints, it is of interest to compute their values for both the optimized and the reference blades. The 3/rev and 5/rev components of the flapping and the torsional moments at blade root affect the rotor hub in the form of oscillatory 4/rev pitch and roll moments. These were not included in the optimum design process of Ref. 6, but are nevertheless critical from an airframe vibration point of view. Finally, the 4/rev blade root lagging moment, which causes oscillatory 4/rev torque at the rotor hub, is also an essential ingredient in rotor blade vibration evaluation and therefore is computed for both the rotors.

Results

For a meaningful study of the two rotors, the loads comparison will be made for two rotor tasks. Task 1 requires the optimized rotor to produce the same C_T/σ and C_X/σ as the reference rotor. Task 2 requires the optimized rotor to produce the same thrust T and the same propulsive force X as the reference rotor. Using these two tasks provides a comparison on both a nondimensional basis, for which the rotor was optimized, and a dimensional basis, for which the rotor might be expected to operate, and compares the rotor's ability to produce lift with low induced power and to produce high lift without stalling.

The optimized rotor was designed to provide minimum 4/rev vertical shear at blade root and minimum blade weight under forward flight condition at an advance ratio of $\mu = 0.30$. A study was done to estimate the 4/rev vertical shear over a wide range of advance ratio values ($\mu = 0.05$–0.40). Figure 1a presents the 4/rev vertical root shear for the reference blade and the optimized blade, operating at both rotor tasks. The figure indicates that the optimized blade has lower vertical shear than the reference blade and the reduction is more significant at higher speeds. The maximum reduction occurs at $\mu = 0.3$, the design point. The reduction in the vertical shear is partly due to the reduced thrust in task 1, where the C_T/σ is fixed and the rotor thrust reduces due to reduction in solidity after optimization. However, the optimized rotor operating at task 2 also has significant reductions in the vertical shear, over the reference rotor, for most of the speed range. Of particular interest is the smaller vertical shear in the optimized blade for task 2 than for task 1. This is because the two rotors (reference and optimized) are operating at the same T in task 2 and the optimized rotor having a much smaller σ is operating at a very high value of C_T/σ. Thus at

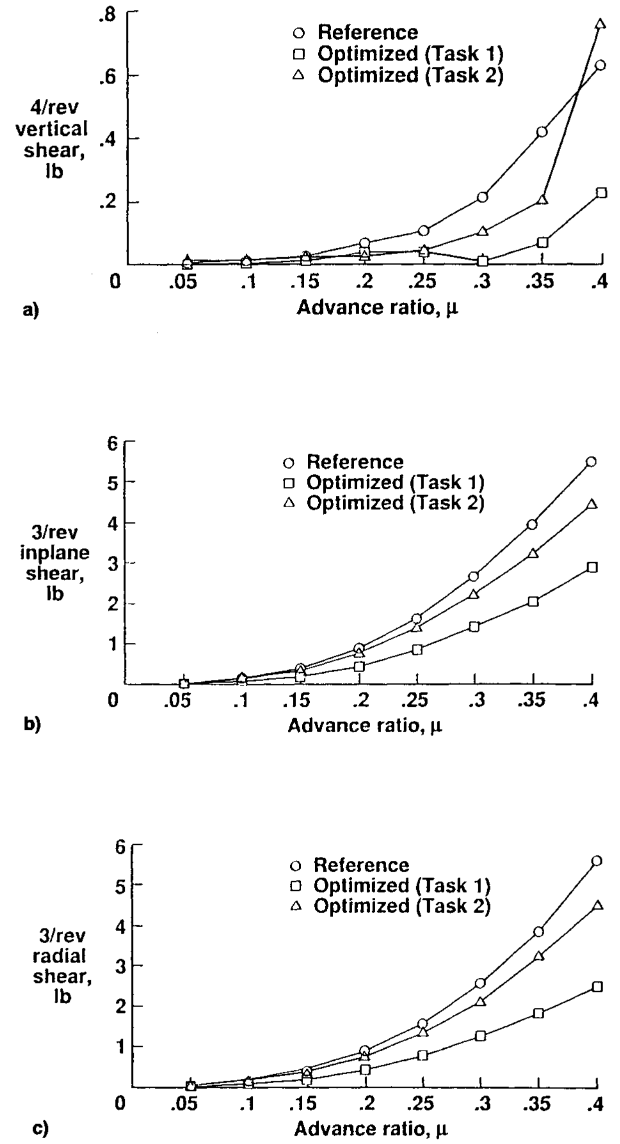

Fig. 1 Blade root critical shear forces: a) 4/rev vertical, b) 3/rev inplane, and c) 3/rev radial.

high speeds, due to higher thrust requirements that can drive the rotor to stall, there is a large increase in the vertical shear.

Critical shear forces, which were not included in the optimized blade design, are calculated for various values of μ. Figures 1b and 1c present the 3/rev components (the 5/revs components were much smaller and are not shown) of the inplane and the radial shears at the blade root. The figures indicate that the optimized blade designed for minimum 4/rev vertical shear also has lower values of the critical inplane and radial shears at both rotor tasks. The inplane and the radial shears also have very similar variations with speed. These figures also show that the differences between the reference and the optimized blade shear force values amplify with speed.

The critical root bending and torsional moments are also calculated for the same speed range. Figures 2a and 2b, respectively, present the 3/rev flapping and the torsional moments at the blade root for the reference and the optimized blade. The figures indicate reduction in these moments for the optimized blade over the entire speed range at both rotor tasks. The lowest values of course occur at task 1 when the rotor is operating under reduced thrust. It is interesting to note the nature of the flapping moment from Fig. 2a that shows occasional reductions at certain speeds, e.g., at $\mu = 0.25$ the value is lower than that at $\mu = 0.30$ for the optimized rotor under task 1. This is due to modal cancellation, i.e.,

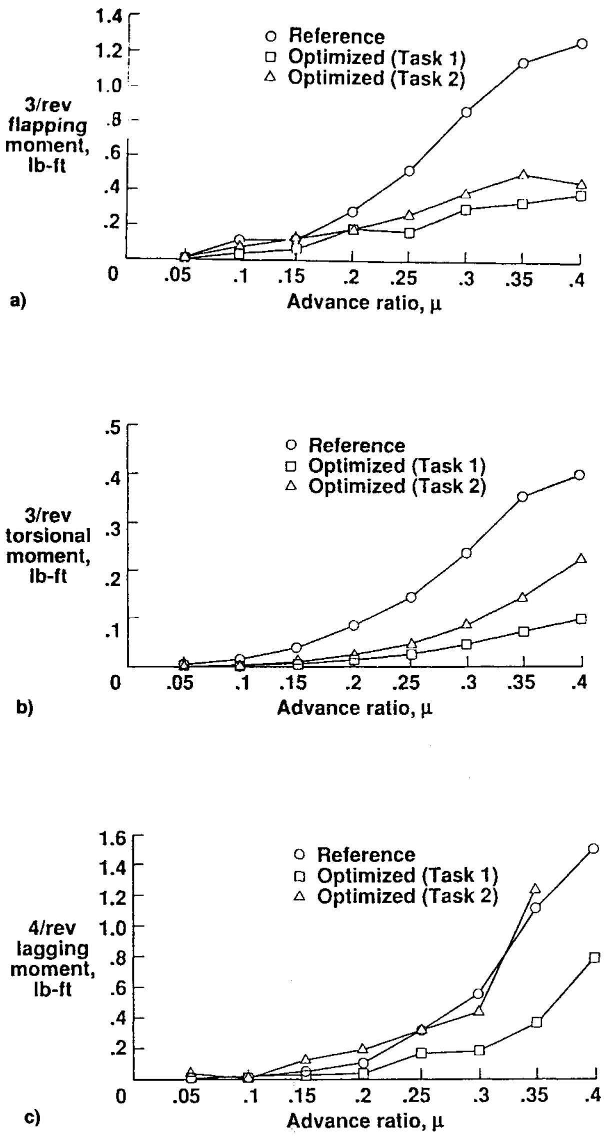

Fig. 2 Blade root critical vibratory moments: a) 3/rev flapping, b) 3/rev torsional, and c) 4/rev lagging.

the forcing function becoming orthogonal to one of the mode shapes. Figure 2c presents the 4/rev lagging moment variation with speed. For the optimized rotor for task 1, the lagging moment is lower than the reference blade as expected, with the differences magnified at higher speeds. However, for task 2 there is a crossover at a higher speed. In other words, the lagging moment for the optimized blade becomes higher than the reference blade at high speeds. This is because the 4/rev lagging moment is responsible for the 4/rev yawing moment at the rotor hub which increases with increase in thrust. Once again, at certain speeds, the figure shows occasional reductions of the lagging moment for both the reference and the optimized blades possibly occurring due to modal cancellation.

Concluding Remarks

An investigation was made of the dynamic performance of a helicopter rotor previously optimized for minimum 4/rev vertical shear and blade weight subject to certain dynamic and structural constraints. The program CAMRAD was used for both dynamic and aerodynamic analyses using the same modeling assumptions used to obtain the optimized blade. The dynamic behavior of the optimized rotor was compared with the reference rotor, which was used as a baseline in the optimization study. The comparisons were made over a wide range of operating conditions, including speed and thrust variations, which depart significantly from the optimum design condition. The vibratory loads at the blade root were analyzed for the reference and the optimized rotors for two rotor tasks. Task 1 required both rotors to maintain the same C_T/σ (corresponds to the design condition), and task 2 required both rotors to maintain the same thrust, T (i.e., same loading). The study yielded the following conclusions (within the context of the modeling assumptions made).

1) The optimized blade shows good dynamic performance behavior at conditions other than those for which it was designed.

2) The 4/rev vertical shear of the optimized rotor, minimized in the optimized blade at a specific forward flight condition ($\mu = 0.30$), is lower than that of the reference blade over the entire speed range studied for task 1 and exceeds the reference blade value for task 2 only at higher speed.

3) Other critical vibratory blade root forces and moments, e.g., the inplane and radial shears, the flapping, lagging and torsional moments, not considered in the optimum design, are also lower for the optimized blade, than the reference blade, for the entire speed range in task 1 and only exceeds the reference values for task 2 at high speeds. There are occasional unexpected reductions in the flapping and lagging moments of the optimized rotor with speed for both rotor tasks.

References

[1]Peters, D. A., Rossow, M. P., Korn, A., and Ko, T., "Design of Helicopter Rotor Blades for Optimum Dynamic Characteristics," *Computers and Mathematics with Applications*, Vol. 12A, No. 1, 1986, pp. 85–109.

[2]Chattopadhyay, A., and Walsh, J. L., "Minimum Weight Design of Rectangular and Tapered Helicopter Rotor Blades with Frequency Constraints," *Journal of the American Helicopter Society*, Vol. 34, No. 4, 1989, pp. 77–82.

[3]Chattopadhyay, A., and Walsh, J. L., "Application of Optimization Methods to Helicopoter Rotor Blade Design," *Structural Optimization*, Vol. 2, Springer-Verlag, 1990, pp. 11–22.

[4]Celi, R., and Friedmann, P. P., "Efficient Structural Optimization of Rotor Blades with Straight and Swept Tips," *Proceeding of the 13th European Rotorcraft Forum*, Arles, France, Sept. 1987. Paper No. 3-1.

[5]Lim, J. W., and Chopra, I., "Aeroelastic Optimization of a Helicopter Rotor," *Journal of the American Helicopter Society*, Vol. 34, No. 1, 1989, pp. 52–62.

[6]Chattopadhyay, A., Walsh, J. L., and Riley, M. F., "Integrated Aerodynamic Load/Dynamic Optimization of Helicopter Blades," *Journal of Aircraft*, Vol. 28, No. 1, 1991, pp. 58–65.

[7]Johnson, W., "A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics, Pt II: User's Manual," NASA TM-81183, June 1980.

[8]Vanderplaats, G. N., "CONMIN—A FORTRAN Program for Constrained Function Minimization: User's Manual," NASA TM X-62282, Aug. 1973.