The 15th International Conference on Machine Design and Production
June 19– 22, 2012, Pamukkale, Denizli, Turkey

THE VIBRATORY LOADS OF AN OPTIMIZED HELICOPTER ROTOR AT OFF-DESIGN CONDITIONS

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ABSTRACT

The off-design vibratory loads of a helicopter rotor were studied for the purpose of achieving lower level of vibratory loads. The minimization for critical vibratory hub loads at a specified flight speed was achieved in a previous study. As a continuation to that study the analyses were conducted on the same light utility helicopter for the off-design conditions. The vibratory loads of the optimum blades and the original blades were analyzed at the off-design flight speeds and results were compared.

Keywords: Helicopter Structural Dynamics, Rotor Blade Optimization

1. INTRODUCTION

Helicopter vibrations cause problems which strongly affects the service life, ride qualities and maximum flight speed [Kvaternik, 1989]. The detrimental effects on the crew health are also well known [Harrer, 2005]. Additionally, the excessive level of vibration leads to the increased maintenance frequencies which in turn increase the operational costs [Veca, 1973]. Furthermore more serious problems like the undesired failure in flight and possible accidents should also be avoided. Therefore, the vibration levels should be carefully analyzed and rotorcraft should be designed for possibly lower vibration levels.

The main source of vibration in a helicopter is the main rotor [Johnson, 1994]. The excitation due to the aerodynamic loads and aeroelastic responses of the rotor cause vibrations on the rotor. The aerodynamic environment is quite complex for a rotor and the aerodynamic loads pose unsteady characteristics. Cyclic pitch, blade vortex interactions, shock waves, blade stall and aeroelastic coupling of blades induce loads at the rotor blades at different frequencies. For a rotor, the fundamental frequency is the rotor angular velocity (Ω) and these different excitation frequencies are the multiples of rotor angular speed. This can be stated as nΩ where n represents the blade harmonics starting from 1. But, for an equally spaced identical blades, which is the case in main rotor, the rotor acts as a filter and only those frequencies which are at the integer multiples of the number of blades pass to the fuselage and the other frequencies are cancelled at the rotor hub [Bielawa, 2005]. These frequencies can be expressed as kNΩ where N is the number of blades and k is an integer starting from 1. Therefore if the critical loads occurring at the integer multiples of the rotor angular speed can be kept at lower levels, the fuselage vibrations can consequently be reduced and the rotorcraft can approach to a jet-smooth flight. The relevant problem can then be stated as to design the blades in order to minimize these critical loads.

The vibration reduction applications usually consider the loads at NΩ frequencies while neglecting higher harmonics of kNΩ hub loads [Johnson, 1994]. The reason of this consideration is the tendency of the reduction in oscillatory aerodynamic load amplitudes at higher harmonics. Therefore the loads at the NΩ frequency dominate the vibrations transmitted to the fuselage from the main rotor [Kvaternik, 1989]. Then the attempt of reduced vibration levels should start from the reduction in the hub loads at the NΩ frequency. Generally these NΩ rotor frequencies are expressed in non-dimensional form so that the N/rev is the preferred representation of NΩ frequencies in helicopter studies where Ω=1/rev.

The main rotor induced vibrations are relatively low at hover and increases with forward flight velocity and reach to significant levels with maximum flight velocity [Johnson, 1994]. There may be high-level of vibration at some specific conditions such as the transition from hover to cruise flight and full power operation of the engine at hover but since the helicopter operates most of its time at cruise conditions, these specific conditions were excluded from the current study and only main rotor induced vibrations arise in mid speed and high speed cruise flight were analyzed. Because of this reason 0.35 advance ratio which is equivalent to 145 knots flight speed was selected for the optimization analyses which was high enough to see the significant N/rev vibratory loads.

The solution involves the optimization and comprehensive rotor analysis stages. The comprehensive analysis is an essential tool for rotorcraft design and it has widely been coupled with optimization algorithms in order to reach more effective designs. Adelman and Mantay performed an extensive work for integrated multi-disciplinary optimization of rotor from aerodynamics to blade structures [Adelman, 1989]. Peters and Cheng performed optimization of rotor blades for combined structural, performance and aeroelastic characteristics [Peters, 1989]. Friedmann and Celi investigated the optimization of rotor blades with straight and swept tips which are subject to aeroelastic constraints [Friedmann, 1989]. Similar procedure was applied to rotor blades for minimum weight by Chattopadhyay and Walsh [Chattopadhyay, 1988]. Lee implemented genetic algorithm to multidisciplinary optimization [Lee, 1995]. Glaz et al used multiple surrogates together with neural networks in blade vibration reduction [Glaz, 2009].

The aim of this study was to analyze the reduction in the vibratory hub loads of a previously optimized helicopter blade [Tamer, 2011] at off-design flight conditions. Apart from the studies which worked on the isolated rotor problems, trim of the whole body was included in addition to the rotor aeroelastic analysis. Inclusion of the whole body is believed to have the advantage of finding more realistic rotor control angles as compared to the isolated rotor analysis. This in turn leads to the better oscillatory load and response prediction. For this purpose Aerospatiale Gazelle SA349/2 helicopter was chosen as the platform to study because of the availability of extensive flight test data and detailed information about the helicopter [Yamauchi, 1986-1988]. The analysis model included main rotor, tail rotor and fuselage. The helicopter trim, aerodynamic loads and dynamic response calculations of the helicopter were solved by CAMRAD JA [Johnson, 1988]. Optimization was performed by CONMIN algorithm [Vanderplaats, 1973].

2. METHOD

The key step of this study is building CAMRAD JA comprehensive analysis model and evaluating the vibratory loads at different flight speeds. The model consisted of main rotor, tail rotor and fuselage including blade aerodynamic parameters, inflow and wake models, blade dynamic model, fuselage aerodynamic characteristics and fuselage rigid degrees of freedom. The helicopter was expected to operate in trimmed condition which was achieved by CAMRAD JA trim analysis and the vibratory loads were evaluated at the trimmed flight. That model was used in evaluating the vibratory loads at the off-design speeds.

In the previous work [Tamer and Yaman, 2011] where blades were optimized, CAMRAD JA model was coupled with CONMIN optimization code in order to achieve the reduced vibratory loads. The advance ratio of the optimization was 0.35 which was the high speed cruise of the corresponding helicopter. Optimization algorithm evaluated the gradients of objective function and constraints from CAMRAD JA outputs. Based on the evaluated gradients, CONMIN provided new guesses on design variables to CAMRAD JA and the values of objective function and constraints were updated until the values of the objective function do not change within a prescribed limit for consecutive iterations. Since the aim of the previous study was to minimize the vibratory loads, the amplitudes of N/rev hub forces and moments were considered. Among all N/rev load components, the N/rev vertical hub force was selected since it is generally the primary vibratory load [Pritchard, 1992]. The constraints were applied on the blade natural frequencies, blade auto-rotational inertia and blade mass. Two approaches of the blade optimization were performed. In the first approach, the cross sectional mass, flapwise bending, in-plane bending and torsion stiffness distributions were optimized for minimum 3/rev vertical hub force. This approach was referred to as “full cross section optimization” and took the design of the whole cross section into account with structural and non-structural components like cross section dimensions, blade material properties and non-structural mass. In the second analysis, the critical vibratory loads were tried to be minimized by the addition of non-structural masses which was referred to as “non-structural mass optimization”. The non-structural mass has tuning function and it primarily changes the mass per unit length [Watkinson, 2004]**Error! Reference source not found.**. In this respect its effect on the blade stiffness was neglected as compared to the structural elements. For both analyses satisfactory results were achieved while keeping constraints at their prescribed limits. For the first approach 55% reduction in 3/rev vertical hub force was obtained whereas for the second approach the reduction was 44%. An extensive information on the optimization analyses can be found in [Tamer, 2011].

In the current study the N/rev vibratory main rotor loads were evaluated for the off design conditions for the same helicopter. The helicopter models with the optimized blades of the two previously conducted approaches and the initial design were analyzed by CAMRAD JA at the off-design flight speeds. The results were compared for the effect of the optimization on the off-design N/rev vibratory loads.

3. VIBRATORY LOADS AT OFF-DESIGN FLIGHT SPEEDS

The blades were previously optimized for an advance ratio of 0.35. In the current study, the vibratory loads at 0.25, 0.30, and 0.40 advance ratios were evaluated as the off-design conditions. Since the vibratory loads increase with the flight speed then in order to consider relatively higher loads moderate and high advance ratios were considered. The figures that show the 3/rev loads were plotted for each advance ratio. In the figures H, Y, and T represent longitudinal, lateral and vertical 3/rev hub forces and M_X, M_Y, M_Z represents 3/rev rolling, pitching and yawing moments. Figure 1 and Figure 2 present the force and moment components of the initial design and the optimized design for the full cross section optimization and the non-structural mass optimization for the advance ratio of 0.25. The 3/rev vertical hub force (T) which is given in Figure 1 decreased 50% for the full cross section optimization and 45% for the non-structural mass optimization. The other vibratory force and moment components given in the related figures did not show remarkable increase.

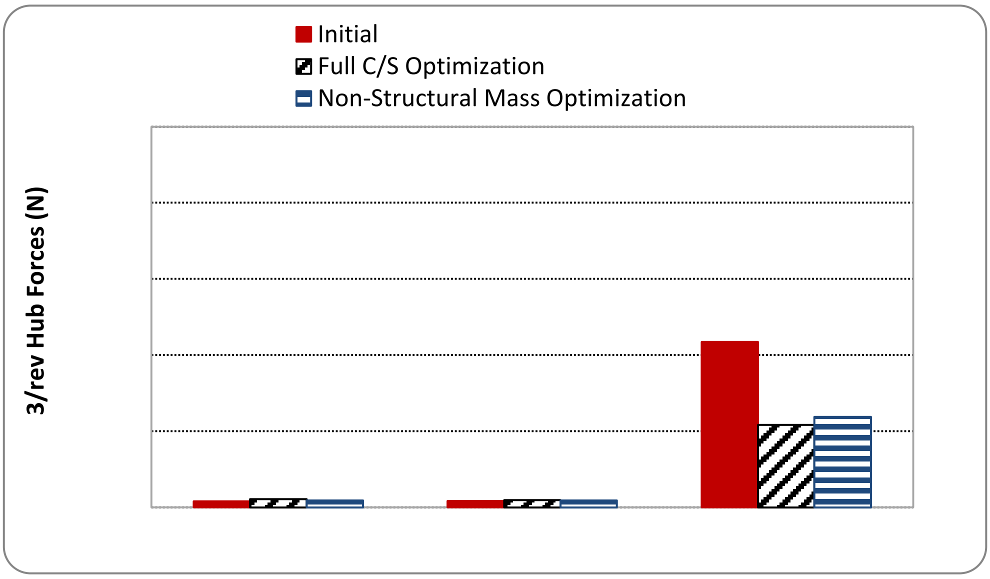

Figure 1: Comparison of 3/rev Hub Moments of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter at 0.25 advance ratio

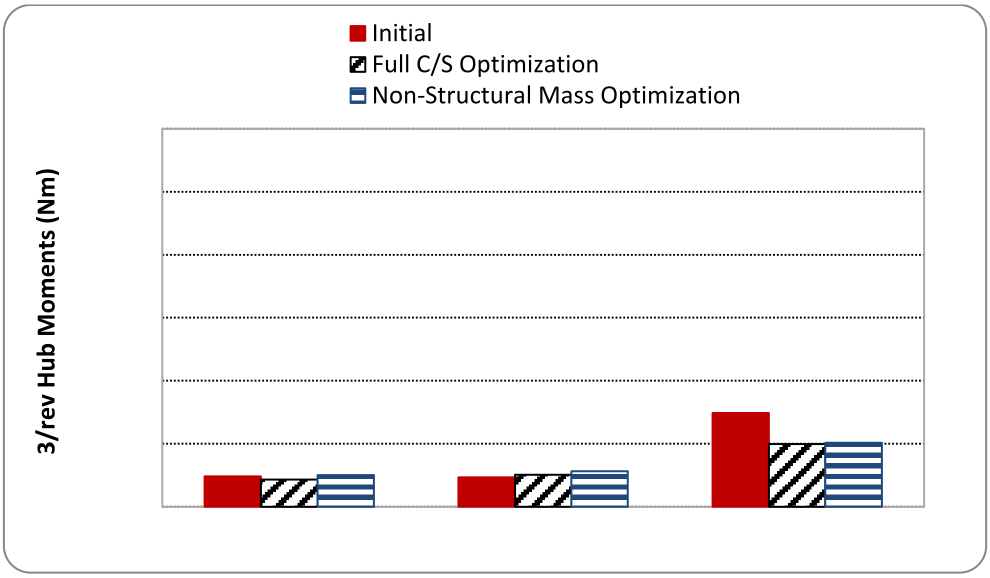

Figure 2: Comparison of 3/rev Hub Moments of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter at 0.25 advance ratio

Figure 3 and Figure 4 present the force and moment components of the initial design and the optimized design for the full cross section optimization and non-structural mass optimization for the advance ratio of 0.30. The 3/rev vertical hub force (T) which is given in Figure 3 decreased 49% for the full cross section optimization and 44% for the non-structural mass optimization. The other vibratory force and moment components given in the related figures did not show remarkable increase.

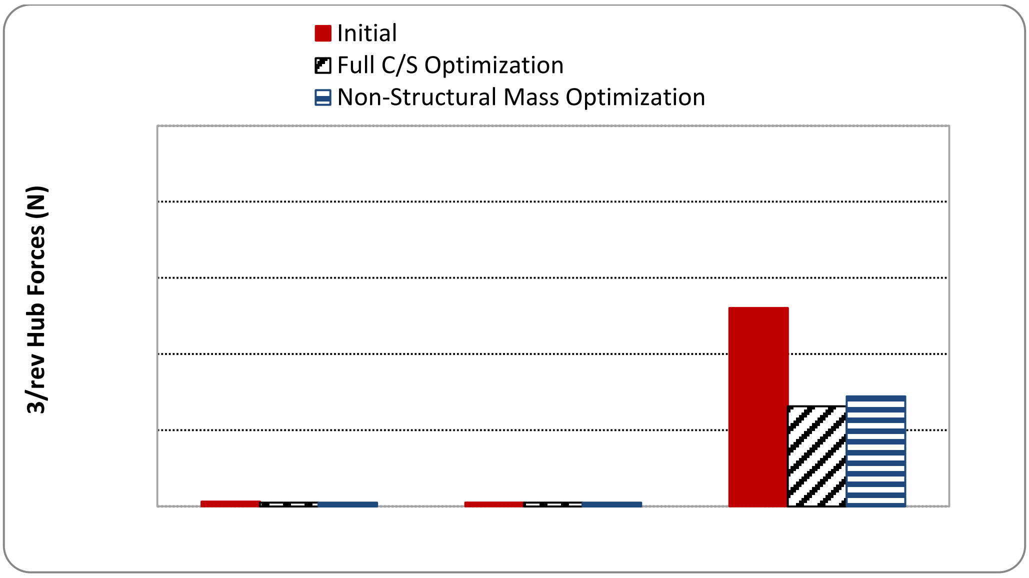

Figure 3: Comparison of 3/rev Hub Forces of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter at 0.30 advance ratio

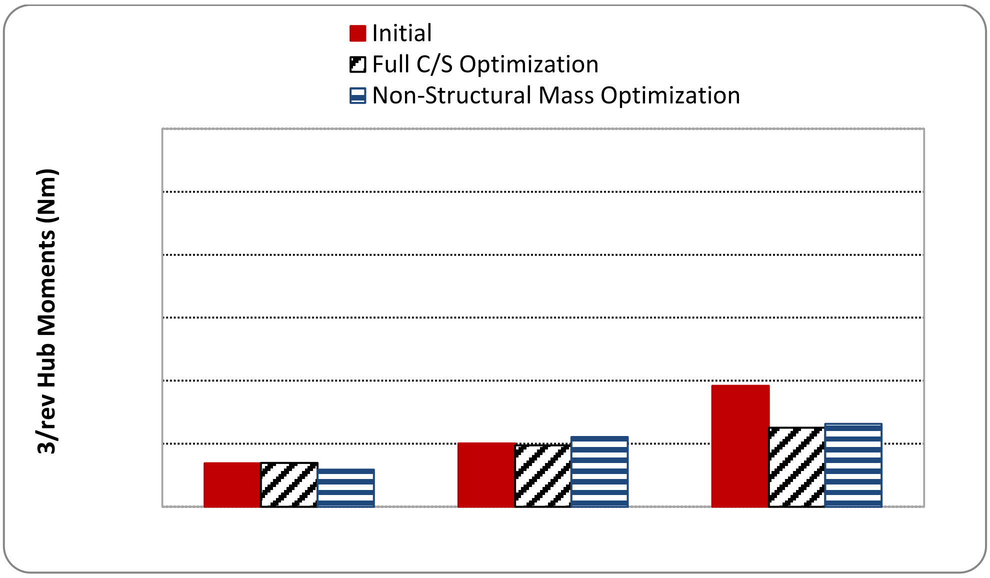

Figure 4: Comparison of 3/rev Hub Moments of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter at 0.30 advance ratio

Figure 5 and Figure 6 Figure 4present the force and moment components of the initial design and the optimized design for the full cross section optimization and non-structural mass optimization for the advance ratio of 0.40. The 3/rev vertical hub force (T) which is given in Figure 5 decreased 58% for the full cross section optimization and 46% for the non-structural mass optimization. The other vibratory force and moment components given in the related figures did not show remarkable increase. Finally, the optimization study is summarized in Figure 7 for the analyzed advance ratio range.

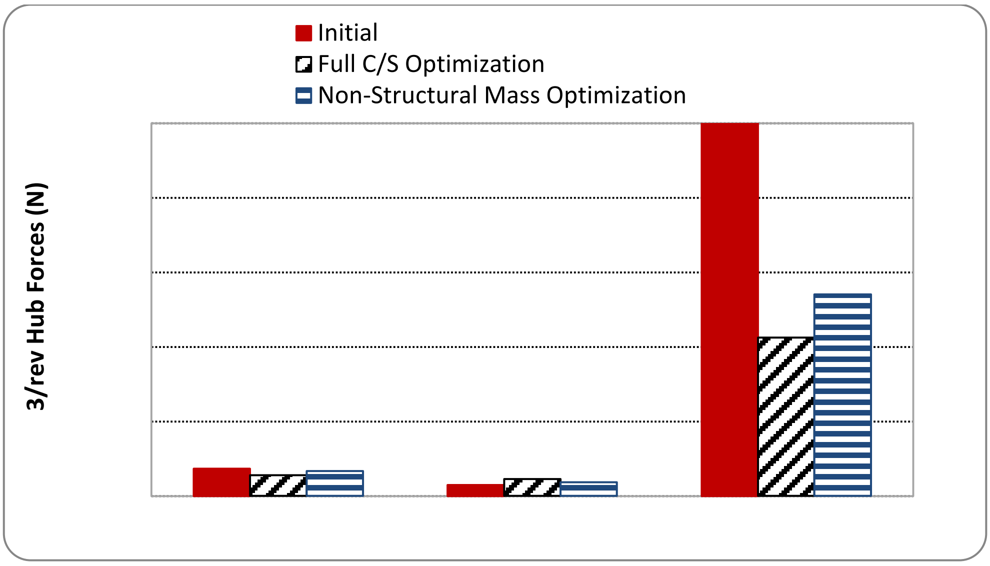

Figure 5: Comparison of 3/rev Hub Forces of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter at 0.40 advance ratio

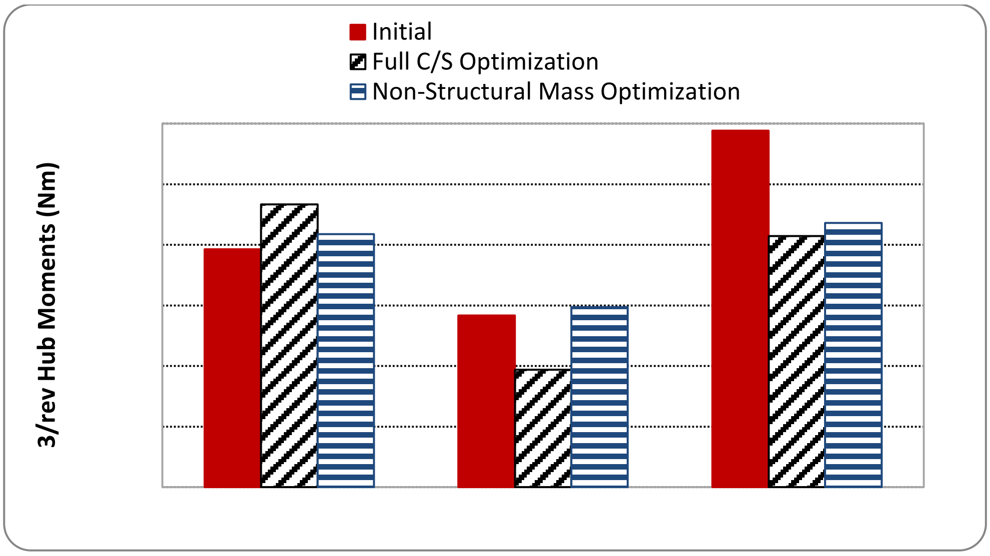

Figure 6: Comparison of 3/rev Hub Moments of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter at 0.40 advance ratio

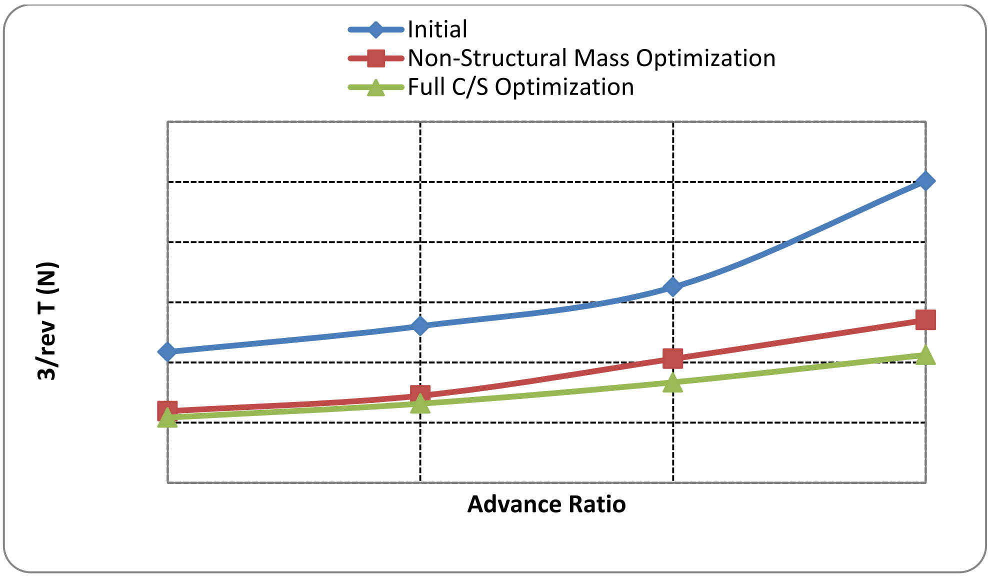

Figure 7: Comparison of 3/rev Vertical Hub Forces of Initial Design with Optimized Designs of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter for different advance ratios

It can be observed from Figure 7 that, after the optimization, the 3/rev vertical hub forces decreased significantly for the whole flight speed range. The amount of reduction increases with increasing advance ratio. Moreover, full cross section optimization yielded lower 3/rev vertical hub force as compared to that of non-structural mass optimization for the whole range of the flight speed considered.

5. CONCLUSIONS

The effect of optimization at the off-design flight speeds of a helicopter rotor was presented. For a rotor, which was previously optimized for 3/rev vertical hub force (T) at an advance ratio of 0.35, the behavior at advance ratios of 0.25, 0.30 and 0.40 were investigated. It was observed that the optimization performed for the 3/rev vertical hub force for a specific advance ratio also leaded to significant reductions in the 3/rev vertical hub force at off-design flight conditions. Additionally, the other 3/rev vibratory loads were not greatly altered. It was also determined that for the whole flight speed range considered; the full cross section optimization always yielded to lower 3/rev vertical hub force as compared to the non-structural mass optimization. Similar optimization analyses and off design performance calculations which also include the stability, strength and fatigue problems either in objective function or in constraints can also be performed with this approach.

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