6. ANKARA INTERNATIONAL AEROSPACE CONFERENCE AIAC-2011-054
14-16 September 2011 - METU, Ankara TURKEY

OPTIMIZATION OF AN HELICOPTER ROTOR FOR MINIMUM VIBRATORY LOADS

Aykut TAMER[1]
Turkish Aerospace Industries
Integrated Helicopter Group
and
Middle East Technical University
Department of Aerospace Engineering
Ankara, TURKEY

Yavuz YAMAN[2]
Middle East Technical University
Ankara, TURKEY

ABSTRACT

In this study, the helicopter rotor optimization was studied for the purpose of achieving minimum vibratory loads. The minimization was achieved for critical vibratory hub loads. The dynamic analysis was performed by CAMRAD JA rotorcraft comprehensive analysis tool. A gradient based optimization tool, CONMIN, was used to evaluate the design variables and constraints. The design variables included the blade bending and torsion stiffness distributions and the mass distribution. The constraints were applied on blade mass, auto rotational inertia and blade natural frequencies. The analyses were conducted on a light utility helicopter.

INTRODUCTION

The main rotor provides the essential functions to a helicopter which are the lift to overcome the gravity, thrust to overcome the drag and the necessary control forces for trimmed flight and maneuvers. As opposed to fixed wing aircraft, all main functions are provided with a rotating aerodynamic surface which involves strong aerodynamic, dynamic and elastic interactions. The effective design of a rotor is therefore extremely critical in order to produce competitive rotorcrafts.

Helicopter vibrations are the main problem which strongly affects service life, ride qualities and maximum flight speed [3]. The detrimental effects on the crew health are also well known [6]. Additionally, the excessive level of vibration leads to the increased maintenance frequencies which in turn increase the operational costs [22]. 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 lower vibration levels.

The main source of vibration in a helicopter is the main rotor [11]. 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

[1] Design Engineer, Email: aytamer@tai.com.tr
[2] Prof. in Aerospace Engineering Department, Email: yyaman@metu.edu.tr

coupling of blades induce loads 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 $n\Omega$ 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 fuselage and the other frequencies are cancelled at the rotor hub [5]. These frequencies can be expressed as $kN\Omega$ where N is the number of blades and k is an integer starting from 1. Therefore if the loads occurring at the multiples of rotor angular speed can be kept at lower levels, the fuselage vibrations can be greatly 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 $N\Omega$ frequencies while neglecting higher harmonics of $kN\Omega$ hub loads [11]. The reason of this consideration is the tendency of the reduction in oscillatory aerodynamic load amplitudes at higher harmonics. Therefore the loads at the $N\Omega$ frequency dominate the vibrations transmitted to the fuselage from the main rotor [3]. Then the attempt of reduced vibration levels should start from the reduction in the hub loads at the $N\Omega$ frequency. Generally these $N\Omega$ rotor frequencies are expressed in non-dimensional form so that the *N/rev* is the preferred representation of $N\Omega$ frequencies.

The vibration levels are relatively low at hover and increases with forward flight velocity and reach to significant levels with maximum flight velocity [11]. There may be high-level of vibration at some specific conditions such as the transition from hover to cruise flight but since the helicopter operates most of its time at cruise conditions, these specific conditions were excluded and in this study only vibrations arise in high speed cruise flight were analyzed. Because of this reason 145 knots flight speed was selected for the analysis 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 [13]. Peters and Cheng performed optimization of rotor blades for combined structural, performance and aeroelastic characteristics [15]. Friedmann and Celi investigated the optimization of rotor blades with straight and swept tips which are subject to aeroelastic constraints [14]. Similar procedure was applied to rotor blades for minimum weight by Chattopadhyay and Walsh [17]. Lee implemented genetic algorithm to multidisciplinary optimization [10]. Glaz et al used multiple surrogates together with neural networks in blade vibration reduction [2].

The aim of this study was to couple an optimization process with a comprehensive analysis tool for minimum vibratory loads and implement the procedure on a light utility helicopter. Apart from the studies which worked on the isolated rotor problems, trim of the whole body was included in addition to the aeroelastic rotor 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 which was chosen because of availability of flight test data and detailed information about the helicopter [16]-[20]. 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 [18]-[19]. Optimization was performed by CONMIN algorithm [1].

METHOD

Optimization Procedure

Figure 1 gives the developed analysis and optimization procedure by using CAMRAD JA and CONMIN programs.

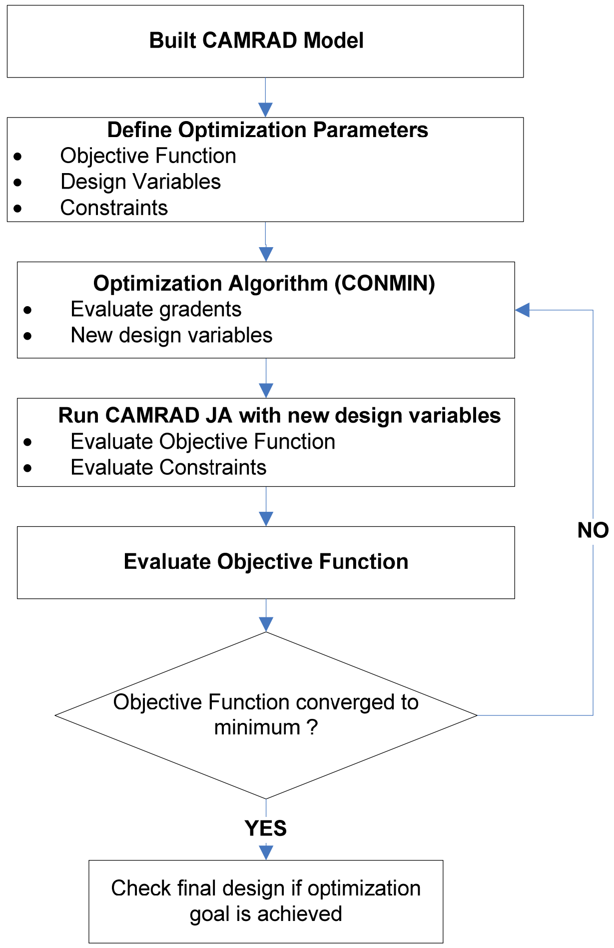

Figure 1: Design Procedure for Reduced Vibrational Level

The CAMRAD comprehensive analysis model of the rotor was built. The model consisted of main rotor and tail rotor parameters like blade aerodynamic parameters, rotor configuration, 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.

Then, the optimization problem was defined with objective function, constraints and design variables. The objective function was the model output which was aimed to be minimized; the constraints were selected in order to avoid the likely occurrences of possible unrealistic results and the design variables were the proper model inputs which were the most sensitive to the optimization problem.

Since the aim of this study was to minimize the vibratory loads, the amplitudes of *N/rev* hub forces and moments were considered. There is no need to minimize all the *N/rev* vibratory loads since the importance of each component are not of same importance. Among all *N/rev* load components, the *N/rev* vertical force is generally the primary vibratory load [12]. Therefore *N/rev* vertical force was selected as the critical hub load whereas other load components of the analysis results were also controlled for their possible significance.

The vibratory hub loads are dependent on blade oscillatory aerodynamic loads and blade response to these loads. In this study, the aerodynamic properties of rotor blades unaltered but the blade mass, flapwise bending stiffness, chordwise bending stiffness and torsional stiffness distributions were considered as the design variables.

The blade design was constrained by putting limits to design variables, blade mass moment of inertia and blade natural frequencies. The blade mass moment of inertia was not allowed to be lower than the original design in order to preserve the kinetic energy of the rotor in the case of a possible engine failure [4]. The aerodynamic excitation occurs at frequencies which are the integer multiples of rotor angular speed (n(1/rev)=n/rev, n=1,2,3…) which are called the rotor harmonics [5]. Any coincidence of these aerodynamic excitations and the blade natural frequencies causes excessive vibrations on the blades, rotor and fuselage [11]. Hence in order to avoid that possibility, an offset of 0.15/rev was chosen in this study so that blade natural frequencies could not be closer than that. Since centrifugal forces dominate the fundamental flap mode, that mode is very close to 1/rev irrespectively of the mass and stiffness distributions. Because of this reason the optimization analyses are not expected to affect the fundamental flap mode and therefore it was not included in natural frequency constraints. Additionally, since a significant increase in blade mass reduces payload and/or maneuvering capacity the blade mass was also limited.

As detailed in Figure 1 the CAMRAD JA model was coupled with CONMIN optimization code in order to achieve the reduced vibratory loads. CONMIN is a FORTRAN program which is applicable of solving the linear and non-linear constrained optimization problems by using the method of feasible directions [21]. CONMIN can either evaluate gradients by using finite differences method or in a user provided manner. In this study, finite difference equations of CONMIN were used. 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.

OPTIMIZATION of SA349/2 ROTOR BLADE for REDUCED VIBRATORY LOADS

Vibratory loads are multidisciplinary in nature and correct calculation requires reliable models which can solve aeroelastic behavior of the rotor. Since the model results affect the design directly, the reliability of the analysis model has major importance. The best way of checking the reliability of the model is to compare with test data. For this purpose, the *N/rev* vibratory loads of the CAMRAD JA model were compared with those of flight test at 145 knots flight speed. The SA 349/2 rotor has three blades and the 3/rev hub loads were included in comparison. The 3/rev hub forces included longitudinal (H), lateral (Y) and vertical (T) components and 3/rev hub moments included rolling (M_x), pitching (M_y) and yawing (M_z) components. The comparison is presented for the force components in Figure 2 and for the moment components in Figure 3.

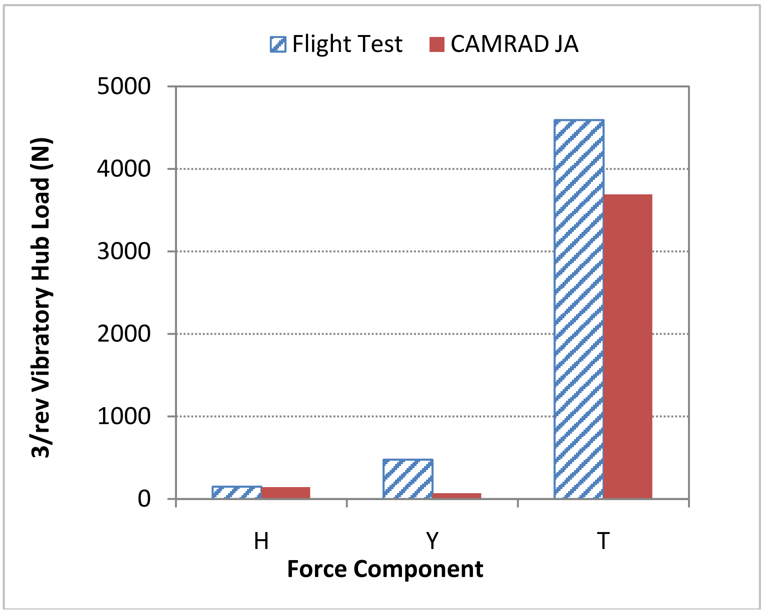

Figure 2: Flight Test and CAMRAD JA Results for 3/rev Hub Forces of SA349/2 Helicopter

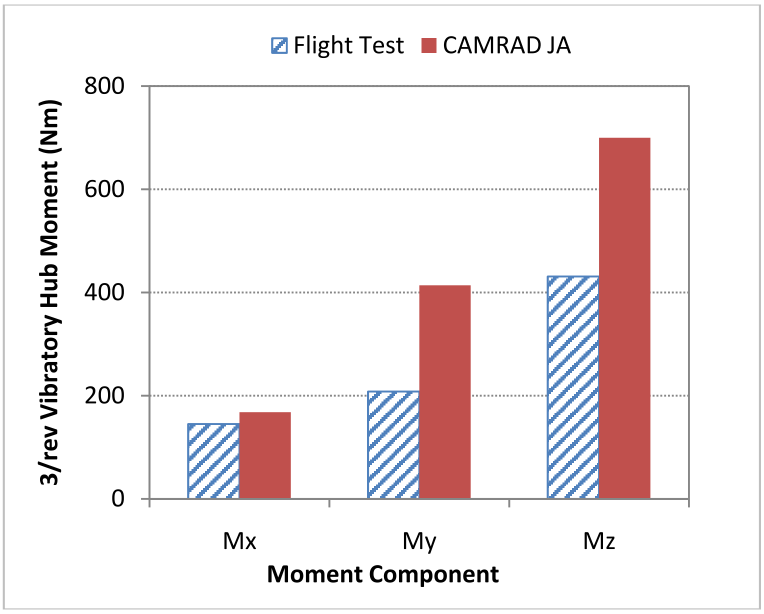

Figure 3: Flight Test and CAMRAD JA Results for 3/rev Hub Moments of SA349/2 Helicopter

According to the flight test data of Figure 2, the critical 3/rev hub force was determined as the vertical hub force (T) which has approximately 4500 N magnitude. This value was approximately 20% of the weight of the helicopter studied. The longitudinal (H) and lateral (Y) components were negligible as compared to the vertical hub force (T). All the moment components given in Figure 3 were small as compared to the main rotor torque of 10000 Nm torque and were not considered as critical. Since the CAMRAD 3/rev vertical force was close to that of flight test data and the hub moments were calculated within the same order of magnitude, the model was considered as reliable within the scope of optimization analysis.

Two optimization analyses were conducted on Aerospatiale Gazelle SA349/2 for the reduction of the 3/rev vertical hub force. As previously discussed the other components were not found to be critical however their resulting values after optimization were discussed. In the first analysis, the cross sectional mass, flapwise bending, in-plane bending and torsion stiffness distributions were optimized for minimum 3/rev vertical hub force. This approach 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. The final blade design that is suitable for manufacturing can be achieved by post-processing such that the optimum mass and stiffness distributions of the blade are matched with cross section geometry. However, the blade cross section modeling was out of the scope of this study and a sample cross section can be found in reference [9].

In the second analysis, critical vibratory loads were tried to be minimized by the addition of non-structural masses. The non-structural mass has tuning function and it primarily changes the mass per unit length [7]. In this respect its effect on the blade stiffness can be neglected as compared to the structural elements. Since the blade stiffness was unaltered, this approach did not require a post-processing in matching the blade stiffness. Results of the two approaches were compared and discussions were made on the effectiveness and feasibility of two methods.

In both analyses the design variables were distributed at 8 equal radial stations after r/R=0.3. The design of blade root is usually dominated by limit loads and this part is quite stiffer than the outer blade. Hence, SA349/2 blade root was kept same with original design. A limit of 80 kg was defined for the blade mass which was initially 75 kg. The blade mass moment of inertia was forced to be higher than that of initial design. An interval of 0.15/rev was set such that of blade natural frequencies cannot be closer to any of n/rev aerodynamic excitation frequencies. The blade geometry, rotor dimensions, rotational speed and fuselage parameters were those of the original design. Figure 4 and Figure 5 represent the comparison of the 3/rev loads of initial and optimum designs of full cross section optimization and non-structural mass optimization approaches.

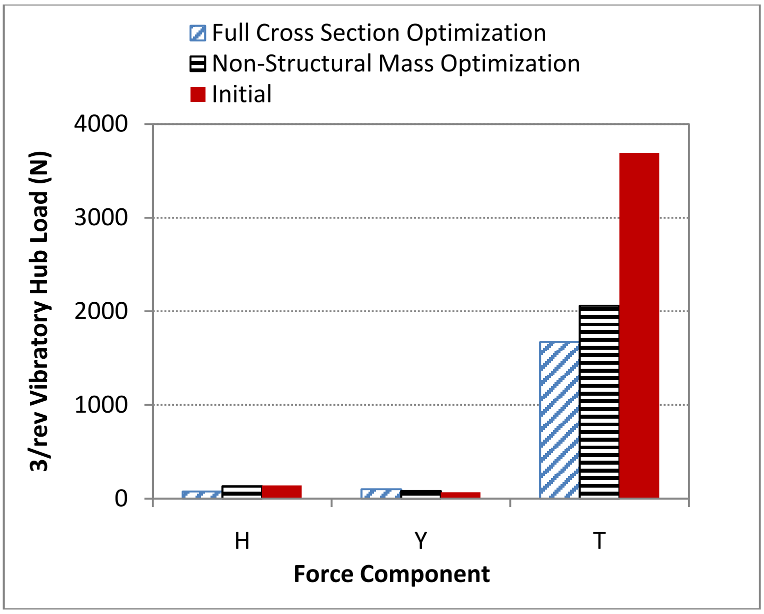

Figure 4: Comparison of Initial 3/rev Hub Forces of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter

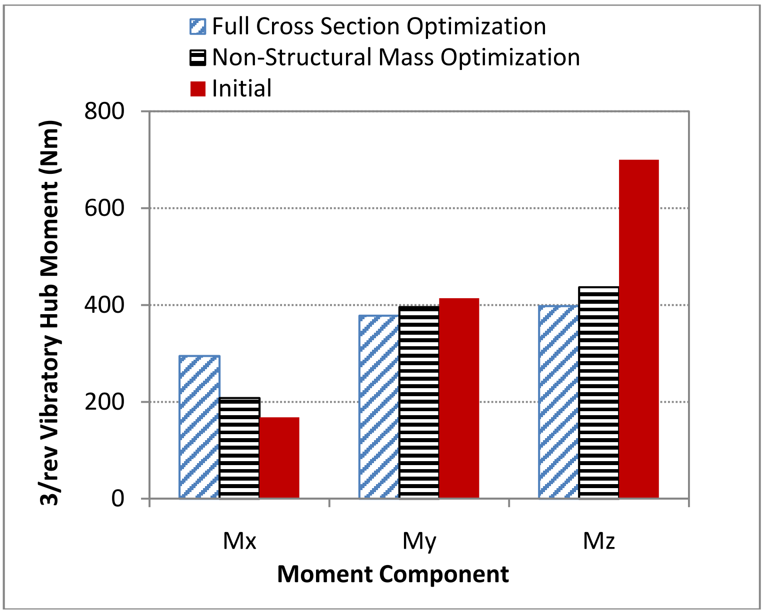

Figure 5: Comparison of Initial 3/rev Hub Moments of Full Cross Section Optimization and Non-Structural Mass Optimization of SA349/2 Helicopter

Figure 4 shows a vertical hub force (T) decrease of 55% in the full cross section optimization and 44% in the non-structural mass optimization. Due to their lower magnitudes, although the longitudinal and lateral 3/rev hub forces can be ignored as compared to vertical hub force, it was also important to see that they did not significantly increase due to the changes in blade mass and stiffness. In terms of the moment components given in Figure 5, although not significantly, only the 3/rev rolling moment increased but its value is small as compared to other moment components. Therefore both optimization analyses leaded to significant reductions in 3/rev vertical hub force.

Both optimization analyses satisfied all the constraints of blade mass, blade moment of inertia and natural frequency separation from n/rev aerodynamic excitations. Among these constraints the most important one was the blade mass because of its direct effect on the performance. Figure 6 presents the mass distributions of initial design and optimum designs.

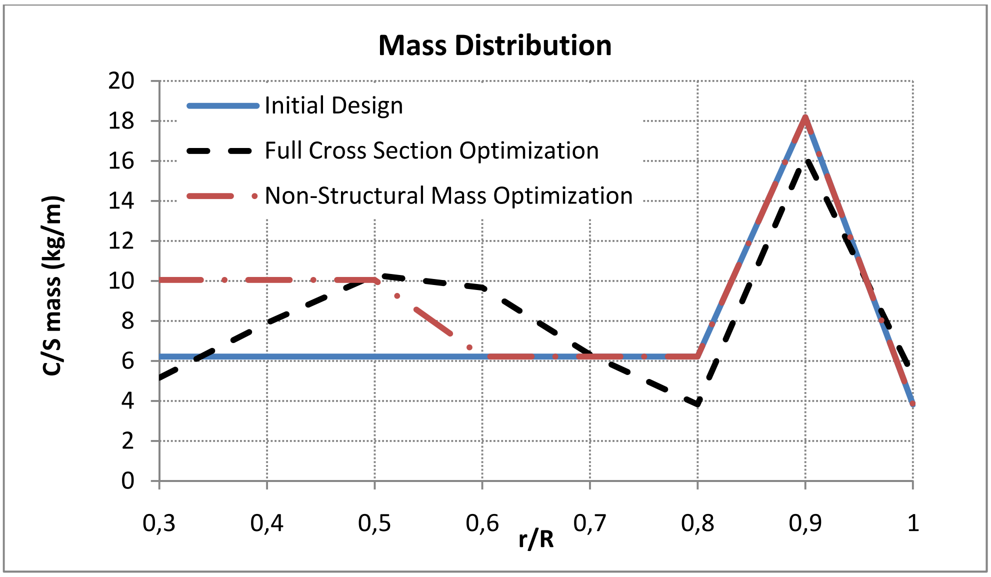

Figure 6: Comparison of Mass Distributions for Minimum Vibratory Load Optimizations of SA349/2 Helicopter

According to the Figure 6 the full cross section analysis could achieve the vibratory loads reduction with a lower mass addition than the non-structural mass optimization. In the full cross section optimization, the cross section mass was allowed both for decrease and increase. However, in the non-structural mass optimization cross section mass could only increase due to the mass addition which limits optimization capacity. This flexibility of the full cross section optimization was believed to provide better blade response characteristics which in turn yielded higher reduction in objective function with a lighter blade. In two optimization analysis, the numerical values of mass increase were found to be 3 kg and 5 kg.

In addition to the mass distribution, the full cross section optimization included the modifications in bending stiffness in flapping and in-plane directions and torsional stiffness values. Figure 7 to Figure 9 give the relevant stiffness distributions of initial design and optimum design after full cross section optimization.

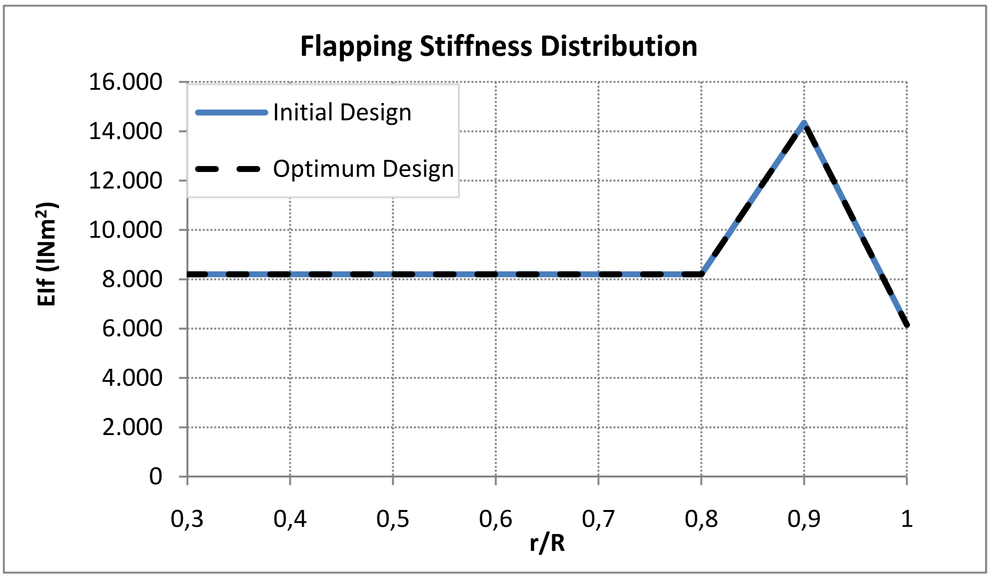

Figure 7: Flapping Stiffness Distributions of SA349/2 Helicopter of Initial Design and Optimum Design by Full Cross Section

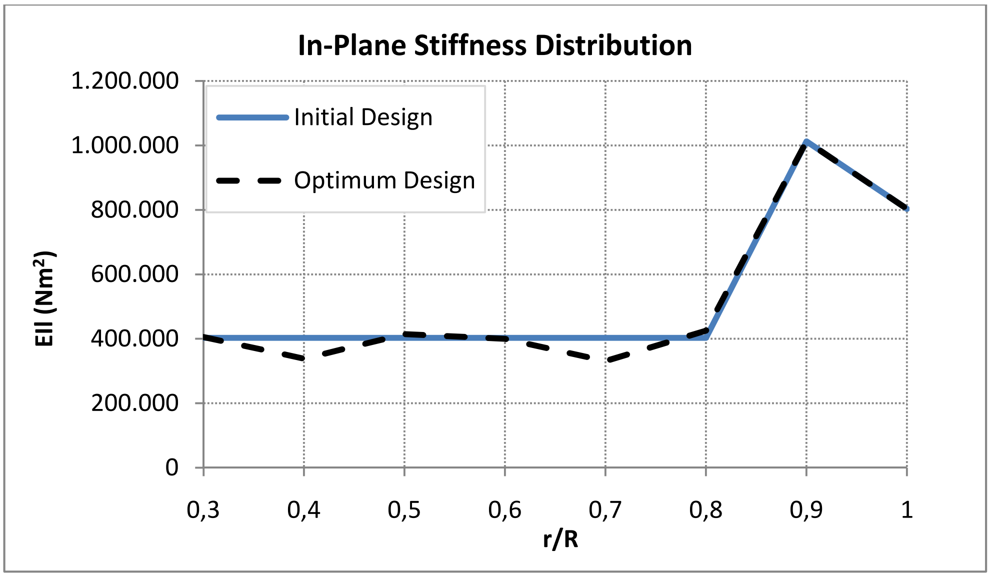

Figure 8: In-Plane Stiffness Distributions of SA349/2 Helicopter of Initial Design and Optimum Design by Full Cross Section

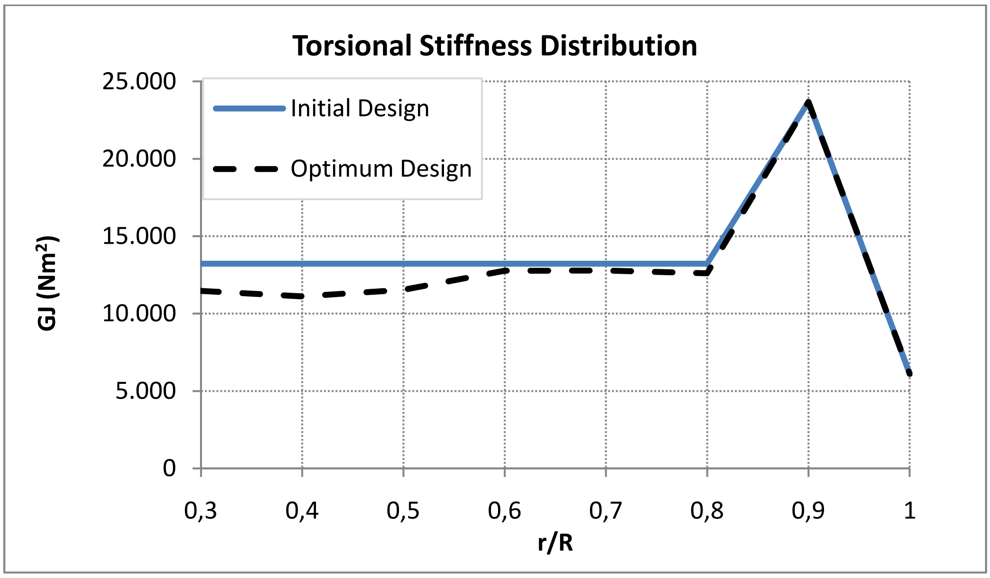

Figure 9: Torsion Stiffness Distributions of SA349/2 Helicopter of Initial Design and Optimum Design by Full Cross Section

In Figure 7 the flapping stiffness remained constant whereas Figure 8 shows that there were only slight modifications near r/R=0.4 and r/R=0.7. Finally the torsion stiffness in Figure 9 decreased significantly until r/R=0.5 and then slightly until r/R= 0.8. This reduction in torsional frequency changed the blade elastic twist distribution over the rotor disc. The change in blade elastic twist was believed to cause a more favorable blade angle of attack distribution over the rotor disc which smoothed the aerodynamic loads.

Between the full cross section optimization and the non-structural mass optimization approaches, the suitable approach can be selected according to the required blade modification. At the design phase where the cross section is strictly not determined yet, a full cross section analysis can be preferred in order to reach a more efficient design. Therefore the effects of stiffness and mass distributions are taken into account. The main requirements of this method are to use a reliable cross section model with the manufacturing capacity so that the required distributions can be matched. The optimization by non-structural mass addition is a better choice if the rotor blade cross section model does not allow any modifications. In this case, matching stiffness distribution is not required and the only possibility is to find the optimum non-structural mass distribution that would yield the reduced vibrational levels.

CONCLUSIONS

An optimization procedure was presented for the minimization of the vibratory hub loads; so that the fuselage vibrations could be reduced. The procedure was applied to a light utility helicopter. Two optimization analysis were conducted which were the full cross section optimization and the optimization by non-structural mass addition. The 55% and 44% reductions in vibratory hub loads were achieved respectively. Additionally, the full cross section optimization yielded a better design with a smaller increase in total blade mass.

This study can be further improved by identifying a blade cross section model so that the optimization can be performed on dimensional quantities. This also provides a better physical insight to the design and the optimum blade can be directly manufactured without post-processing that is necessary in matching the optimum mass and stiffness distributions. If a composite model is included; the orientation of ply angles can be optimized for reduced vibrations as well. In addition to the blade models, the modes of an elastic fuselage can be added to CAMRAD JA model so that the effect of rotor fuselage interference can be taken into account and even the reduction of the vibrational response of a specific point on the fuselage can be attempted.

This study can be extended to include the stability, strength and fatigue problems. The high analysis capacity of comprehensive methods allows the procedure to apply to performance, stability, noise and blade loads for a wide range of rotorcraft configurations.

It is generally known that the finding local maxima rather than absolute maxima, inability to solve non-differentiable and discontinuous problems and ineffectiveness in parallel computing are the main drawbacks of gradient based optimization algorithm [8]. Hence, although this study achieved satisfactory results with CONMIN, it can be replaced with more recent optimization techniques like genetic algorithm or neural networks.

References

[1] CONMIN Source Code, http://www.eng.buffalo.edu/Research/MODEL/mdo.test.orig/CONMIN/, last visited on August 2011

[2] Glaz, B., Geol, T., Liu, L., Friedmann, P.P., Haftka, R. T., *Multiple-Surrogate Approach to Helicopter Rotor Blade Vibration Reduction*, AIAA Journal Vol. 47 No. 1, 2009, pp.271-282

[3] Kvaternik, R.G., Murthy, T.S., *Airframe Structural Dynamic Considerations in Rotor Design Optimization*, NASA Aeroelasticity Handbook Vol.2 Part 2,pp.13.1-13.13

[4] Filippone Antonio *Flight Performance of Fixed Wing and Rotary Wing Aircraft,* Elsevier, 2006

[5] Bielawa, R. L., *Rotary Wing Structural Dynamics and Aeroelasticity 2nd Edition,* AIAA, 2005

[6] Harrer, K., Yniguez, D., Majar, M., Ellenbecker, D., Estrada, N., Geiger, M., *Whole Body Vibration Exposure for MH-60S Pilots*, 43th SAFE Association Symposium, Utah, 2005

[7] Watkinson, J., *The Art of the Helicopter*, Elsevier, 2004

[8] Onwubolu G.C., Babu B.V., *New Optimization Techniques in Engineering*, Springer Publications, 2004

[9] Bramwell A.R.S., Done G., Balmford D., *Bramwell's Helicopter Dynamics,* Butterworth-Heinemann, 2001

[10] Lee, J., Hajela, P., *Parallel Genetic Algorithm Implementation in Multidisciplinary Rotor Blade Design*, AHS Technical Specialists' Meeting on Rotorcraft Structures, Williamsburg, 1995

[11] Johnson W., *Helicopter Theory* , Dover Publications, 1994

[12] Pritchard, J.I., Adelman, H.M., Walsh, J.L., Wilbur, M.L., *Optimization Tuning Masses for Helicopter Rotor Blade Vibration Reduction Including Computed Airlods and Comparison with Test Data*, NASA Technical Memorandum No. 104194, 1992

[13] Adelman, H.M. , Mantay, W. R., *Integrated Multidisciplinary Optimization of Rotorcraft: A Plan for Development,* NASA Technical Memorandum, 1989

[14] Friedmann, P.P and Celi R. *Structural Optimization of Rotor Blades with Straight and Swept Tips Subject to Aeroselastic Constraints,* NASA Technical Report N89-25152,1989

[15] Peters, D.A., Cheng Y.P., *Optimization of Rotor Blades for Combined Structural Performance, and Aeroelastic Characteristics*, NASA Technical Report N89-25153, 1989

[16] Yamauchi, G.K., Heffernan, R.M., *Hub and Blade Structural Loads Measurements of an SA349/2 Helicopter,* NASA Technical Memorandum No.100400, 1988

[17] Chattopadhyay, A., and Walsh, J.L., *Minimum Weight Design of Rotorcraft Blades With Multiple Frequency and Stress Constraints,* NASA Technical Memorandum, March 1988.

[18] Johnson W., *CAMRAD JA Theory Manual,* Johnson Aeronautics, 1988

[19] Johnson W., *CAMRAD JA User Manual,* Johnson Aeronautics, 1988

[20] Yamauchi, G.K., Heffernan, R.M., *Structural and Aerodynamic Loads and Performance Measurements of an SA 349/2 Helicopter with an Advanced Geometry Rotor*, NASA Technical Memorandum No.88370, 1986

[21] Vanderplaats, G.N. , *CONMIN – A Fortran Program for Constrained Function Minimization User's Manual*, NASA Technical Memorandum, 1973

[22] Veca A.S., *Vibration Effects on Helicopter Reliability and Maintainability,* USAAMRDL Technical Report 73-11, 1973