Physics Based Modeling of Maneuver Loads for Rotor and Hub Design

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ABSTRACT

A Hybrid Navier-Stokes Free-Wake Computational Fluid Dynamics (CFD) methodology, coupled with a multi-body dynamics analysis code, has been applied to the UH-60A rotor to study the loads developed during selected revolutions of a severe diving turn maneuver at a mean advance ratio of 0.388 and a mean load factor of 1.48. Loosely coupled CFD/CSD simulations were performed for the first 15 revolutions of the maneuver that are characterized by maximum blade structural and pitch-link loads. Time histories of sectional normal loads and pitching moments, blade structural loads, and pitch-link loads for these revs have been examined. Harmonic content of structural loads for a representative revolution are presented and discussed. Results indicate that the current methodology gives an accurate prediction of harmonics 1P-3P, but under-predicts harmonics 4P-6P.

INTRODUCTION

The helicopter is one of the most complicated vehicles to design because of the myriad flight modes that need to be considered and the complex multidisciplinary coupling of various physical phenomena. Helicopters experience a wide range of aeroelastic phenomena that stem from the fact that rotor blades are long, slender and elastic. Helicopters in maneuvering flight, in particular, are affected by complex transonic and dynamic stall phenomena to varying degrees. Manuevers are characterized by high load factors and are critical points in rotor and hub design. Modeling rotorcraft aeromechanics using accurate and efficient, high fidelity computational tools is therefore of great importance to the rotorcraft community.

The strength and durability of the rotor hub components is contingent on the accurate prediction of peak-to-peak structural loads at the blade root. Accurate knowledge of control loads is important for sizing the swash-plate components, and for characterization of the fatigue. The sizing of these components is generally dictated by the large loads which occur during extreme flight conditions. Rotor components may need to be redesigned if the loads associated with extreme maneuvers fall outside of the design load spectrum. If the components are not adequately sized, they will be plagued by a short lifespan. Frequent repairs and replacement of components may also result. Peak-to-peak loads in the fixed system are dependent upon the harmonic content of rotating system loads. For example, the 4P swash-plate servo loads (fixed system) are dependent upon the 3-5P pushrod loads (rotating system). Accurate prediction of the peak-to-peak pushrod loads is necessary for sizing the pushrod, and the harmonic content of pushrod loads must be accurately predicted to capture the 4P servo loads. Incorrect estimation of the fatigue load spectrum for rotor components can be detrimental to an aircraft design program. Vibratory loads are not only important from a passenger comfort and safety perspective. Therefore, the next-generation state-of-the-art rotor design tools must be equipped to accurately predict mean, peak-to-peak loads as well as harmonic content of structural and aerodynamic loads. Maneuvering flight introduces additional challenges that need to be addressed by the rotor and hub design tools; aperiodic rotor airloads and structural response, and dependence of rotor response on vehicle dynamics.

Over the last several years, computational tools have been extensively developed for improving the prediction of rotorcraft aeromechanics (Ref. [7]-[19]). In the current study, a right turn diving maneuver at 140 knots tested in the NASA-Army UH-60A Airloads Program (Ref. [4]) is
studied using these tools. The UH-60A Airloads Program provides a highly repeatable and accurate set of flight test data that includes pilot input, vehicle attitudes, blade airloads and structural loads. A number of steady and maneuvering flight conditions were flown as a part of the NASA-Army UH-60A Airloads Program (Ref. [4]). Out of them all, the right turn diving maneuver counter 11680 with a banking angle of 60 deg, has been ranked the most severe based on the highest loads for pitch-link force, torsion moment at 0.3R and root chord bending moment at 0.113R (Ref. [4]). The flap root bending moment at 0.113R has been ranked fifteenth most severe.

**NUMERICAL METHODOLOGY**

**GT-Hybrid CFD Methodology**

The CFD methodology used in this study is GT-Hybrid (Ref. [5]). GT-Hybrid is a three-dimensional unsteady viscous compressible flow solver. The flow is modeled by first principles using the Navier-Stokes Methodology. GT-Hybrid solves the three-dimensional unsteady Navier-Stokes equations in the transformed body-fitted coordinate system using a time-accurate, finite volume scheme. A third-order spatially accurate Roe scheme is used for computing the inviscid fluxes and second order central differencing scheme is used for viscous terms. The Navier-Stokes equations are integrated in time by means of an approximate LU-SGS implicit time marching scheme. The flow is assumed to be turbulent everywhere, and hence no transition model is currently used. The solver accepts a user defined table of blade geometric and elastic deformations and deforms the computational grid. The temporal change in computational cell volume is accounted for, by explicitly satisfying the Geometric Conservation Law (GCL). GT-Hybrid currently has the capability to use advanced turbulence models such as SA-DES and KES to compute the eddy viscosity.

GT-Hybrid CFD solver utilizes a hybrid methodology where the flow field near the blade is resolved through the Navier-Stokes solution, whereas the influence of the other blades and of the trailing and shed vorticity in the far field wake are accounted for by modeling them as a collection of piece-wise linear bound and wake vortex elements, as shown in Fig. 1. The near wake is captured inherently in the Navier-Stokes analysis. The use of such a hybrid Navier-Stokes/vortex modeling method allows for an accurate and economical modeling of viscous features near the blades, and an accurate “non-diffusive” modeling of the wake in the far field. The vortex model is based on a Lagrangian wake approach where a collection of vortex elements are released from the rotor blade trailing edge and are convected downstream by a combination of the free-stream velocity and the bound and wake vortex element self-induced velocities. The strength of the vortex elements is based on the radial and temporal gradients of the bound circulation and the number of spanwise wake elements and wake time step increment chosen by the user. The influence of these vortices on the blade aerodynamics from the wake model is computed by appropriately specifying the vortex-induced velocities at the far field boundary of the Navier-Stokes domain, neglecting the contribution of the elements within the CFD volume grid released from the blade.

**Computational grid**

For this work, the computational grid over each blade has 131*65*45 nodes in chordwise, spanwise and normal directions respectively. The blade surface has 90 chordwise points and 50 spanwise points. The far field boundary is located nine chords away from the blade surface. The normal grid spacing at the blade surface is about $10^5c$, where $c$ is the reference chord length. The grid is clustered near the tip and near the leading and trailing edges to handle regions of high gradients. The grid is based on a C-H grid topology.

![Fig. 1: Schematic of Hybrid methodology](image1)

![Fig. 2: Multiple trailer representation of wake model located uniformly along the spanwise direction](image2)
DYMORE CSD Methodology

DYMORE (Ref. [6]) is a computational structural dynamics (CSD) solver used in this study. It is a multi-body finite element code for arbitrary non-linear elastic systems. The multi-body models are constructed by connecting basic structural elements; the data for these elements are stored within an element library. Each of these elements has its own system of equations which when integrated create larger and more complex equations. The structural elements include beams, rigid bodies, cables, springs, dampers and various structural linkages. The code incorporates robust and efficient time integration algorithms for integrating the resulting large scale, nonlinear, differential or algebraic equations. The rotor blades are modeled as elastic beams with geometrically exact composite beam finite element formulation. DYMORE belongs to a class of solvers known as rotorcraft comprehensive codes. These solvers typically include an internal lifting line based aerodynamic model and auto-pilot algorithm which can be used to perform a fully trimmed aeroelastic simulation of an isolated rotor configuration. A four bladed UH-60A rotor model is used for the simulations. The model includes blade, lag damper, push rod, rotor hub and swashplate. A lifting line based 2-D table lookup aerodynamics with dynamic wake model is used for computing airloads internally.

Coupling Methodology

The coupling between fluid dynamics and structural dynamics solutions may be performed in two ways. The first method, often referred to as loose coupling (LC), involves transfer of information between the structural dynamic analysis and CFD analysis at periodic intervals, usually at the end of each blade revolution. The second method, which is the tight coupling (TC) approach, involves a simultaneous time integration of the structural dynamic and fluid dynamic equations, so that information is exchanged between the aerodynamics and structural dynamics equations after each time step. In this study, CFD and CSD methodologies are coupled in a loosely coupled manner, primarily to estimate trim settings for steady flight regions and to provide preliminary estimates of control settings for maneuver simulations in a tightly coupled manner.

DIVING TURN MANEUVER, 11680

Diving turns are characterized by high-speed and high-load factor turns where the available potential and kinetic energy is drawn upon to provide the power required to maintain a constant load factor on the helicopter. There is significant vibration. The high speed, diving turn is characterized by non-zero angular rates but nominally zero angular accelerations. This maneuver extends well beyond the static stall limit (McHugh lift boundary) for steady flight counters which is seen in Fig. 5.
This condition results in severe pitch link loads and represents design conditions for the military aircraft (Ref. [1]). The pushrod loads experienced during severe maneuvers are about 2.5 times greater than the loads in maximum speed flight (Ref. [4]).

Fig. 6(a) shows the time history of angular rates for the dive turn maneuver based on rotor revolutions. While the yaw rate is relatively constant throughout the maneuver, the pitch and roll rates change considerably. At the start of the maneuver, the helicopter has a high pitch rate of 10.34 deg/sec. As seen in Fig. 6(a), the vehicle experiences a peak pitch rate in Revs 8-11 with a peak average pitch rate of 11.1 deg/sec in the ninth revolution. Fig. 6(b) shows peak load factor which occurs 2 revolutions later at Rev 11 with an average load factor of 1.9. Fig. 6(c) shows oscillatory pitch-link loads lagging the load factor time history by approximately a revolution with the peak pushrod loads occurring at Rev 12. The oscillatory pitch-link loads (half peak-to-peak) during the dive turn maneuver gradually increase starting from the first revolution. Peak pitch-link loads are developed at about Rev 11. Following revolution 14, the rotor thrust represented by load factor starts to decrease gradually and the pitch-link loads suddenly decrease until Rev 20. Lowest half peak-to-peak pitch-link loads are found at the completion of the maneuver.

The advance ratio for this maneuver has an average value of 0.388 and a maximum of 0.404 (Ref. [4]). During the maneuver, the rotor RPM is fairly constant with a value of 255 RPM. The gross weight of the aircraft is approximately 16400 lbs. Because of the high advance ratio combined with an average diving rate of 5324 ft/min, the flight test data is has considerable amount of noise in the normal load factor and angular rates data. Furthermore, there are possible sources of error in the static pressure measurements because of the effects of the fuselage on the air-stream.

The rotor thrust was not directly measured during the UH-60A Airloads Program, and therefore it is not possible to directly evaluate the accuracy of the calculated rotor thrust. There are three ways to estimate thrust, first from the normal load factor, second from the integrated blade pressure measurements of flight test data and third is estimation from flight dynamics simulation. From preliminary estimation, it appears that the fuselage and horizontal tail lift contribution is significant. The fuselage and tail force would be equal to the difference between the total vehicle force and the rotor force. For the purpose of simulations, the thrust produced by the rotor was taken to be approximately 92% of the gross weight, in order to account for the lift generated by the fuselage, the horizontal stabilizer and the component of lift force produced by the tail rotor thrust. For a flight dynamics simulation, a steady-level turn at an advance ratio of 0.4 and an equal banking angle produces far less values of rotor thrust within the lift boundary estimated as per the wind-tunnel tests of McHugh as seen in Fig. 5.

**MANEUVER SIMULATION**

In the present loosely coupled CFD/CSD simulations of the maneuver, each revolution of the maneuver is treated as a separate case and the thrust, airspeed, pitch rate etc., are assumed to be represented by data averaged over one revolution. The rotor is trimmed for the required hub pitching and rolling moment and the target thrust averaged over each of the revolutions. The measured hub linear and angular velocities were added to grid motion in the CFD solver. However, the linear and angular accelerations at the hub were not included in the DYMORE model.

![Angular rates of hub](Image)  
Fig. 6. (a) angular rates of hub (b) normal load factor, (c) oscillatory pitch link loads for the first pushrod during the diving turn maneuver, 11680
The present hybrid CFD simulation accounts for the effects of the trailing wake as well as the shed wake. A multi trailer wake model is used and four revolutions of shed wake on the Navier-Stokes domain are included. The effects of turbulent mixing are modeled using the Spalart-Allmaras-Detached Eddy Simulation (SA-DES) turbulence model because of its simplicity and ability to predict massively separated flows. No transition model has been used in the current simulations. The induced velocity due to shed and trailing wake outside the Navier-Stokes domain is computed once every 5 degrees of azimuth and imposed as velocity boundary conditions.

**RESULTS AND DISCUSSION**

In this section, the sectional loads are shown and discussed in the time domain. The blade structural loads, including bending and torsional moments are discussed next in both the time and frequency domain. Finally, the pitch-link loads are discussed. Accurate estimates of the mean values, peak values, peak-to-peak variations and harmonic content of structural loads are all important for adequate sizing of the blades and the hub. Aeromechanical loads prediction was carried out for the first 15 revolutions of the maneuver, since it comprises of the most severe part of the maneuver, in terms of normal load factor and peak-to-peak of pitch-link loads.

**Sectional Airloads**

Blade sectional airloads consisting of sectional normal loads and pitching moments for the first 10 revolutions are shown in Figs. 8-11. The mean loads as well as the waveform are captured reasonably well for this extreme maneuver. The stall characteristics for each revolution remain the same except for differences in magnitude of the loads. It is observed that although the inboard stations give accurate loading results at the 0 and 180 (nose) azimuth positions, stations from 0.675R to the tip have a phase difference between simulated and flight test data.

Representative time histories of non-dimensional sectional normal loads for Rev 12, characterized by a high load factor of 1.89, have been obtained as shown in Fig. 12. Although strictly speaking the diving turn is a transient maneuver, the waveform is repeated between one revolution to the next, indicating that this is a relatively slow maneuver. For this reason, loose coupling CFD/CSD analysis is deemed applicable to a study of this maneuver.

In Fig.12, at 0.675R location, the first occurrence of stall is seen at 210 deg with another stall occurring at 270 deg in the flight test data. Azimuthal locations of stall events for this radial location have been marked in grey in Fig. 12. At the inboard stations 0.225R and 0.4R, there is a stall occurring at 170 deg azimuth over the nose of the vehicle likely due to increased angle of attack resulting from flow over the fuselage. Although mean loads are predicted reasonably well, the peak loads especially at the 0.675R and 0.775R are not adequately captured. Lift stall is observed beginning in the fourth quadrant, continuing into the first quadrant at radial locations between 0.675R and 0.865R. This stall has been predicted with a phase lag of about 12 deg compared to flight test data.

For the same representative revolution (Rev 12), pitching moment data with the means removed have been plotted in Fig.13. Moment stall for this flight condition is observed at almost all the radial stations. At 0.225R, moment stall occurs between 140 and 160 deg as indicated by flight test data, whereas there is a phase lag of about 15 deg observed in the simulated results shown on the same plot. At 0.4R moment stall is observed at about 170 deg in both measured and predicted data. At the outboard locations of 0.675R to 0.775R, moment stall associated with first dynamic stall cycle is seen in the flight test data near 210 deg. This first dynamic stall cycle lags the test data by 4-5 deg. This stall event is three-dimensional in nature, over a narrow azimuth 0.675R-0.775R, as seen in Figs. 12, 13. A second stall cycle is apparent from 0.675R to 0.92R. The third dynamic stall vortex sheds from a location with pre-dominant supercritical flow over the front of the airfoil. This complex interaction between the supercritical flow and dynamic stall vortex has not been captured by the CFD/CSD simulations. There is also a fourth stall cycle present in the flight test data in the first quadrant at 0.92R location in the pitching moment data, as seen in Fig. 13, which is also not captured by the CFD/CSD prediction. It may be inferred that the dynamic stall events in the first quadrant occur quickly since they occur over a small range of azimuth of five to ten degrees.

In Ref 1, Bousman makes an observation that “torsional dynamics of the rotor controls determine where the dynamic stall may occur, while the flight condition and the resulting aerodynamic inflow determine whether it will occur.” Thus, if a dynamic stall is not predicted at a particular location as expected, there may be an inconsistency in either torsional dynamics or inflow distribution at that location or both. The dynamic stall events are sensitive to the blade sectional angle of attack which is in turn dependent on control pitch angle, the elastic torsional response as well as induced flow angle. The induced flow angle is dependent upon the wake of the blade, the inflow induced by the other blades and the flow induced by the fuselage. These angles are not easily captured due to the complex interaction between flow features in a severe maneuvering flight condition.
Blade Structural Loads

The diving turn at an advance ratio of 0.4 and a 60° roll angle is ranked the most severe maneuver in the UH-60A Airloads database based on the highest torsional moment at 0.3R and the highest pitch-link loads that have been recorded. Normal bending moments at 0.3R and 0.5R blade sections for the first 10 revs have been plotted in Fig. 14. The peak-to-peak and mean values of the normal bending moment have been captured reasonably well. The time histories of normal bending moments are captured well in magnitude and phase. At 0.3R location, there is a spike observed in normal bending moment time history at the beginning of every rotor revolution. This may possibly be due to over-prediction in lift coefficient at this azimuthal location (ψ=0). The waveform and peak-to-peak normal bending moments at 0.5R are captured well and the prediction results are consistent with flight test data at this radial station.

The torsional moments for the first 10 revolutions are shown in Fig. 15. Torsional moments at a particular location are both a function of elastic response at that station as well as the torsional loads acting on the blade outboard of that station. Although peak-to-peak is being captured efficiently, torsional moments at 0.3R show that the waveform is not predicted accurately at the 210 deg azimuth position. It is interesting to note that this inconsistency is not observed at 0.5R which follows the waveform more accurately.

It is also interesting to note that the waveform of the torsional loads at 0.3R is quite similar to the waveform of the pitch-link loads developed during the maneuver, as seen in Fig. 16. There is an over-prediction of compressive push-rod loads in the third quadrant between ψ = 180° and ψ = 225°. Harmonic content for the pitch-link loads has been plotted in Fig. 17. While 1P, 2P, 3P magnitude and phase of pitch-link loads are predicted reasonably well, 4P, 5P and 6P magnitudes are under-predicted.

The harmonic content (magnitude) of the normal bending moments of a representative revolution (Rev 7) has been plotted in Fig. 18. The variation of each harmonic vs. radial station has been plotted for flight test and predicted data. The over-prediction in normal bending moment at 0.3R, as seen in Fig. 14, may be attributed to the incorrect prediction of 4P harmonic at this radial location, as seen in Fig. 18. Since the magnitude of harmonic content at 0.5R are predicted close to flight test results, the time history results at this station are consistent.

Examining the harmonic content of the torsional loads at 0.3R and 0.5R, as seen in Fig. 19, shows that there is inconsistency in the prediction of 4P harmonic at 0.3R location by the CFD/CSD model. However, the harmonic 4P is predicted well in magnitude at 0.5R location. To certain extent, this explains the difference in prediction quality of time histories of Torsional Moments (Fig. 15) at 0.3R and 0.5R locations. In particular, the wake model being used for these simulations is one that uses uniformly spaced wake trailers, whose vorticity is based on the strength of the bound circulation in the Navier-Stokes domain (Fig. 2). Alternate wake models that better represent the wake developed during diving turn maneuver are expected to shed some light on the under-prediction of 4P harmonic.

The harmonic content (magnitude) of pushrod loads for the first 12 revolutions has been plotted in Fig. 20. The first harmonic 1P is over-predicted by approximately 700 lb, and the 2P component is over-predicted by 300 lb. The harmonic 3P is predicted well in magnitude, while 4P, 5P and 6P are under-predicted. The 7P harmonic and higher harmonic content are consistently predicted in magnitude.

CONCLUSIONS AND RECOMMENDATIONS

A Hybrid CFD based CFD/CSD methodology was used to study a severe diving turn maneuver for UH-60A. This maneuver was characterized by highest structural loads namely torsional moment at 0.3R and pitch-link loads, in the UH-60A Airloads Program. The airloads and structural loads for Revs 1-15 of the maneuver have been analyzed and encouraging preliminary results were obtained. The following conclusions are drawn to summarize the findings in this effort:
1. The mean and waveform of sectional normal loads and pitching moments were captured moderately well despite the severity of the maneuver. In particular, the peak-to-peak sectional airloads at inboard locations are modeled reasonably accurately.

2. Due to the combination of high advance ratio (0.4) and high normal load factor (1.8), there is extensive occurrence of dynamic stall phenomena. The interaction of dynamic stall vortex with supercritical flow is critical for this maneuver, and crucial for the prediction of the advancing side third stall event at 0.675R to 0.775R radial locations. This was not captured by the current simulations.

3. The peak-to-peak structural loads and the mean loads are accurately predicted. The harmonic content of structural loads with harmonics 1P to 3P is well-captured.

4. The prediction quality of harmonic content of structural loads varies with radial location. For instance, for the torsional moments, the 4P harmonic 4P is well predicted at 0.5R location, while it is poorly predicted at 0.3R location.

5. The peak-to-peak pitch-link loads were reasonably well-predicted and the time history of pitch-link loads correlates well with the time history of blade torsional moment at 0.3R. However, there is an inconsistency in the prediction of the pitch-link loads at ψ = 180°.

6. Harmonics 4P to 6P of structural loads were not accurately captured. However, the higher harmonic content (> 7P) of pitch-link loads was adequately captured.

Based on the computational studies and the conclusions drawn from them, the following recommendations are made for future research.

1. Tightly coupled simulations based on initial conditions from the corresponding loosely coupled simulations may help understand further if the inaccuracies in modeling stem from quasi-steady approximation of physics or due to omission of fuselage, horizontal stabilizer and tail load effects.

2. The poor prediction quality of sectional airloads over the outer spanwise regions of the blade may be attributed to the exclusion of hub angular velocities attributed in the structural model. The hub pitch effects will translate into vertical plunge motion of the blade over the tail boom (ψ = 0°) and nose (ψ = 180°). Studies are needed with a correct representation of structural model with a revolute joint added at the base of the hub to incorporate angular motions of the hub.

The hybrid CFD methodology is shown to efficiently predict aeromechanical loads for one of the most severe maneuvers for the Black Hawk (UH-60A). The turn-around time for each CFD/CSD loose-coupling simulation is approximately 3 days using the current methodology on a cluster of modest size consisting of 16 processors. The ease and efficiency of the current methodology make it a suitable approach for parametric studies of rotor and hub design and for sizing structural components.

In summary, aeroelastic modeling of severe maneuvers is an important step in the structural design of helicopter rotors. The predicted vibratory hub loads may be used in the structural optimization of the rotor and the hub (Ref.[20], Ref.[21]). Improving the fidelity of the Hybrid methodology so that higher harmonic content is correctly captured for a range of flight conditions will allow reliable use of these tools in conjunction with these optimization methodologies. Finally, with additional improvements to the structural solver and the wake model, the current CFD/CSD methodology may be used in estimating hub vibratory loads efficiently.

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Fig. 8. Representative non-dimensional sectional normal loads for Revs 2-5
Fig. 9. Representative non-dimensional pitching moments for Revs 2-5
Fig. 10. Representative non-dimensional sectional normal loads for Revs 6-10
Fig. 11 Representative non-dimensional pitching moments for Revs 6-10
Fig. 12. Representative non-dimensional sectional normal loads for Rev 12
Fig. 13. Representative non-dimensional sectional pitching moments (means-removed) for Rev 12
Fig. 14. Blade sectional Normal Bending Moments at 30% and 50% R

Fig. 15. Blade sectional Torsional Moments at 30% and 50% R
Fig. 16. Pitchlink loads for the first 10 revolutions

Fig. 17. Harmonic content of pitchlink loads for a representative revolution, Rev 7
Fig. 18. Harmonic content (magnitude) of normal bending moments for a representative revolution, Rev 7.
Fig. 19. Harmonic content (magnitude) of torsional loads for a representative revolution, Rev 7
Fig. 20. Harmonic content of Pushrod Loads upto Rev 12.
REFERENCES

[1] Bousman, W.G., “A Qualitative Examination of Dynamic Stall from Flight Test Data”, AHS 53rd Annual Forum, Virginia Beach, VA, 1998

[2] Kufeld, R.M., Bousman, W.G., “High Load Conditions Measured on a UH-60A in Maneuvering Flight”, AHS 51st Annual Forum, Fort Worth, TX, 1998

[3] Kufeld Robert M., Bousman William G., “High Load Conditions Measured On a UH-60A In Maneuvering Flight”, AHS 51st Annual Forum, Fort Worth, TX, 1995

[4] Bousman, William G. and Kufeld, Robert M., “UH-60A Airloads Catalog,” Aeroflightdynamics Directorate (AMRDEC), U.S. Army Research, Development, and Engineering Command, Ames Research Center, Moffet Field, California, August 2005, NASA-TM-2005-212827, AFDD/TR-05-003

[5] Rajmohan, N., “Application of Hybrid Methodology to Rotors in Steady and Maneuvering Flight”, Ph.D. Dissertation, Georgia Institute of Technology, 2010

[6] Bauchau, O. A., “Computational Schemes for Flexible, Nonlinear Multi-body Systems”, Multibody System Dynamics, Vol. 2, 1998, pp. 169-225.

[7] Bhagwat, M. J., Ormiston, R. A., Saberi, H. A. and Hong, X., “Application of CFD/CSD Coupling for Analysis of Rotorcraft Airloads and Blade Loads in Maneuvering Flight,” AHS 63rd Annual Forum, Virginia Beach, VA, 2007

[8] Rajmohan N., Marpu R., Sankar L.N., Baeder J.D., Egoft T. A., “Improved Prediction of Rotor Maneuvering Loads using a Hybrid Methodology,” AHS 67th Annual Forum, Virginia Beach, VA, 2011

[9] Potsdam, M., Yeo, H., Johnson, W., “Rotor Aerodynamic Prediction using Loose Aerodynamic and Structural Coupling”, American Helicopter Society 60th Annual Forum, Baltimore, MD, June 2004.

[10] Rajmohan, N., Manivannan, V., Sankar, L.N., Costello, M., “Development of a Methodology for Coupling Rotorcraft Aeromechanics and Vehicle Dynamics to study Helicopters in Maneuvering Flight,” American Helicopter Society Annual Forum 09, Dallas, TX, May 27 – 29, 2009

[11] Duque, E., Sankar, L. N., Menon, S., Bauchau, O., Ruffin, S., Smith, M., Ahuja, K., Brentner, K., Long, L., Morris, P., and Gandhi, F., “Revolutionary Physics-Based Design Tools for Quiet Helicopters,” 44th AIAA Aerospace Sciences Meeting and Exhibit, AIAA, Reno, NV, January 2006, AIAA 2001-1068.

[12] Silbaugh, B., Baeder, J.D., “Coupled CFD/CSD Analysis of a Maneuvering Rotor Using Staggered & Time-Accurate Coupling Schemes”, AHS Specialist’s Conference on Aeromechanics, San Francisco, CA, Jan. 23-25, 2008

[13] Sitaraman J., Datta A., Baeder J.D. and Chopra I., “Fundamental Understanding of Rotor Vibratory Loads in High-Speed Forward Flight”, 29th European Rotorcraft Forum, Friedrichshafen, Germany, 2003

[14] Datta, A., Chopra, I., “Validation and Understanding of UH-60A Vibratory Loads in Steady Level Flight”, Journal of the American Helicopter Society, Vol 49, 2004

[15] Datta A., Sitaraman J., Chopra I., Baeder J. D., “CFD/CSD Prediction of Rotor Vibratory Loads in High-Speed Flight”, Journal of Aircraft, Vol 43, No. 6, Nov-Dec 2006

[16] Rajmohan N., Sankar L.N., Bauchau O., Makinen S.M., Egolf T.A. and Charles B.D., “Application of Hybrid Methodology to Rotors in Steady and Maneuvering Flight,” AHS 64th Annual Forum, Montreal, Canada, 2008

[17] Rajmohan N., Sankar L.N., Costello M., “Effect of Inflow Model on Coupling between Aeromechanics and Flight Mechanics”, 49th AIAA Aerospace Sciences Meeting, Orlando, Florida, Jan 2011

[18] Makinen S. M., Wake B. E., Daniel O., “Quantitative Evaluation of Rotor Loads Prediction Results Correlated to Flight Test Data,” AHS 67th Annual Forum, Virginia Beach, VA, May 2011

[19] Opoku, D., Makinen S. M., Wake B. E., “Investigation of Loose and Tight Aeroelastic Coupling for High Speed and High Thrust Flight Conditions,” AHS 67th Annual Forum, Virginia Beach, VA, May 2011

[20] Nguyen, K., Chopra, I., “Application of Higher Harmonic Control to Rotors operating at High Speed and Maneuvering flight”, Journal of the American Helicopter Society, Vol 35, 1990, pp 78-89

[21] Ganguli, R., “Optimum Design of a Helicopter Rotor for Low Vibration using Aeroelastic Analysis and Response Surface Methods”, Journal of Sound and Vibration, 2002