9th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2017-163**
20-22 September 2017 - METU, Ankara TURKEY

MULTIBODY SIMULATION OF HELICOPTER ROTOR WITH FLEXIBLE BLADE

Bali Ihsan Ozturan[1]
Middle East Technical University
Ankara, Turkey

Altan Kayran[2]
Middle East Technical University
Ankara, Turkey

ABSTRACT

Most of the multibody simulation tools used for modeling helicopter rotor use beam models of the blade and the rigid rotor hub. Stress recovery in the blade and in the rotor hub are then performed by means of cross-sectional analysis tools or finite element analysis tools which use the load information obtained in the multibody simulation of the rotor. In this study, multibody model of a helicopter rotor is established using three dimensional flexible models of the helicopter blade and the rotor hub, and multibody body simulations of the rotor are performed for the hover and the forward flight load cases. The scope of the multibody simulation consists of kinematic modeling of the joints, flexible modeling of the main parts of the helicopter rotor, load application, and time response analysis with the objective of getting time history of dynamic stresses in the rotor hub and in the critical sections of the rotor blade. Preliminary results obtained showed that with the flexible rotor model the respective blade angles for the hover and the forward flight conditions can be obtained reliably. Moreover, with the flexible rotor model, it is demonstrated that the stresses in the hub can be determined for the hover and the forward flight conditions using the modal stress recovery approach for further analyses such as fatigue.

INTRODUCTION

In the design of the multibody mechanical systems, numerical simulations are powerful tool for understanding the kinematic and the dynamic behavior of the system. Simulations provide better understanding of how single components work and give chance to test whether the designed mechanism is capable of producing the desired motion or not before the manufacturing phase.

Helicopter rotor is a complex mechanical system and it consists of several parts. Therefore, several modifications are usually done in its design stage and physical testing of these modifications would require long time and high costs. Multibody simulation of such a complex mechanism provides opportunity for testing and exploring various conditions without manufacturing or setting up a physical test model. Multibody modelling and simulation tools allow the setting up of the complex multibody mechanical system in the computer environment and design modifications of the mechanical system involving mechanisms can be implemented easily. Following the design modifications, multibody simulations let the engineers to decide on the suitability of the kinematics of the mechanical system as well as the integrity of the mechanical components.

[1] MSc Student in Aerospace Engineering, METU Email: ihsan.ozturan@metu.edu.tr
[2] Professor in Aerospace Engineering, METU Email: akayran@metu.edu.tr

Most of the multibody modeling and simulation tools for modeling helicopter rotors use beam models of the blade and the rigid rotor hub. Stress recovery in the blade and in the rotor hub are then performed by means of cross-sectional analysis tools or finite element analysis tools which use the load information obtained in the multibody simulation of the rotor. Multibody dynamic analysis codes DYMORE [Bauchau, 2007] and CAMRAD [Johnson, 1988] are used for the development of comprehensive models of rotors and rotorcraft. Park and Jung studied the rotor aeromechanics in descending flight by using the DYMORE code [Park J.-S. and Jung S. N. 2012]. Floros et al. used CAMDRAD and DYMORE in order to calculate loads and stability for a proposed unmanned tilt rotor aircraft [Floros 2006].

In the present study, multi body simulation program MSC ADAMS [MSC ADAMS Guide, 2010] is used to model the helicopter rotor and to perform multibody simulations using flexible models for the helicopter blade and the rotor hub. MSC ADAMS is widely used in the literature for flexible modelling of mechanisms and multibody systems and allows dynamic stress recovery by coupling it with the finite element analysis program MSC Nastran. The objective of this article is to set up a helicopter rotor system in MSC ADAMS with flexible blade and hub and to perform multibody simulations of the rotor with user defined simple load cases and aerodynamic load calculations. In this study, it is not intended to integrate detailed rotary wing aerodynamic solver to the established rotor system since this requires substantial amount of work and this is considered as future work of this study. The effects of design modifications on the stress history in the rotor hub and in the critical section of the blade are studied.

METHOD

Helicopter rotor is modelled in MSC Adams [MSC Adams Guide, 2010] program which is a flexible multibody modelling and simulation code. In this section, description of a helicopter rotor and its major parts are introduced briefly. ADAMS kinematic model and building of the flexible blade and the rotor hub is explained, and simplified aerodynamic blade loading and dynamic stress recovery is explained.

Rotor Parts

The rotor assembly is mainly made up of a rotor hub, dampers, rotor blades, pitch control levers, pitch links, and swash plate as demonstrated in Figure 1.

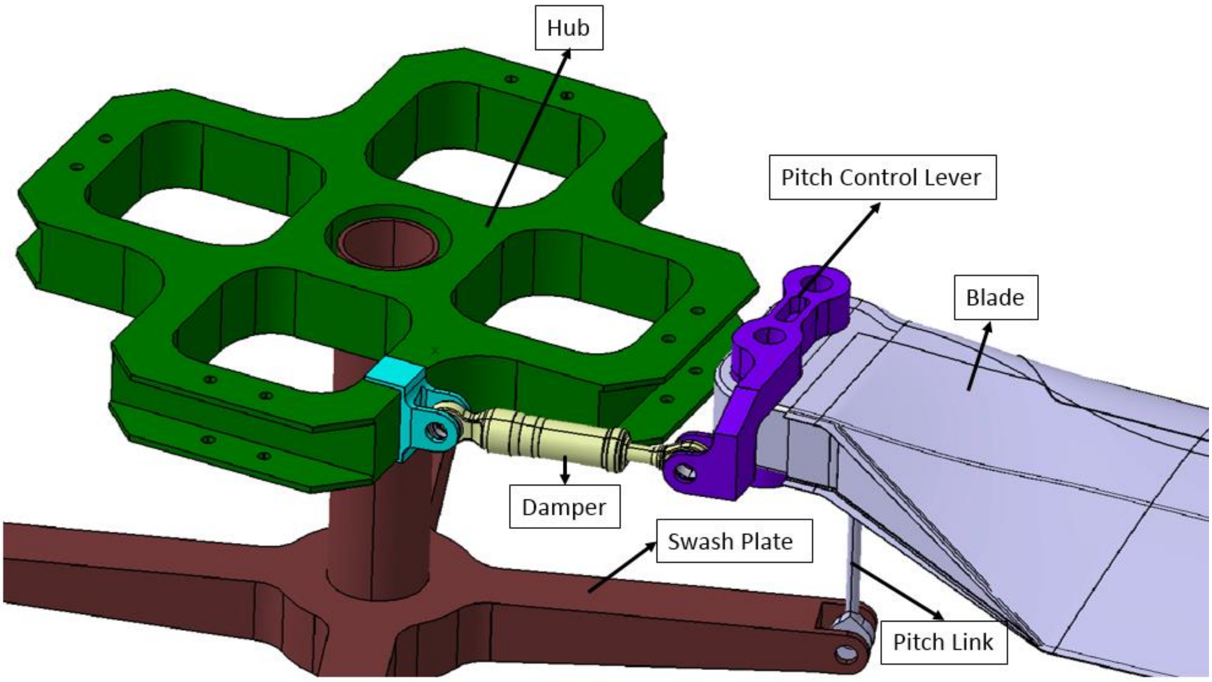

Figure 1 Rotor assembly

Hub

The hub is connected to the transmission mast for mechanical power transmission and provides connection for the rotor blades by a set of hinges.

Damper

Dampers are installed between the blades and the hub to damp out the lead and lag movement of the blades.

Blade

Rotor blades are fundamental parts of the helicopter rotor system and they are subjected to various distributed external loading. Therefore, rotor blades play an essential role for dynamic characteristics of the rotor system and loading conditions of the other rotor parts.

Pitch Link

Pitch link is used for transfer pitch change commands to the rotor blades. One end of the pitch link is connected to the blade via the pitch control lever and the other end is connected to the swash plate.

Pitch Control Lever

Pitch control lever is the connection interface for the pitch link, damper, the blades, and the hub. It transfers blade torsional loads to the flight control system and pitch change loads to the blades.

Swash Plate

The swash plate is used to transmit flight control input to the blades via pitch link. Swash plate is connected to the hub by using set of parts and joint in order to accomplish up and down motion while rotating with hub.

Kinematic Model

In the kinematic model of the rotor, hub is connected to the ground as a revolute joint because ground is used as the helicopter fuselage and other parts of the rotor are connected to the hub by series of joints since they are rotated with the hub. Specifically, blades are connected to the hub by a spherical joint via pitch control levers in order to represent the fully articulated rotor configuration. One end of the pitch link is connected to the blade via pitch control lever by a spherical joint, and the other end of the pitch link is connected to the swash plate via spherical joints. Swash plate is connected to the hub by prismatic joint and it is used for changing pitch links' positions to control the blade angles while rotating with hub. Damper consists of two parts and they are connected to each other via the prismatic joint. One end of the damper is connected to the hub and the other end is connected to the pitch control lever via the spherical joints. Kinematic model of the rotor and joints locations and types are presented in Figure 2 for one blade. Table 1 summarizes the joint numbers, joint types and the connected parts. For other blades and rotor parts, connection methodology is identical.

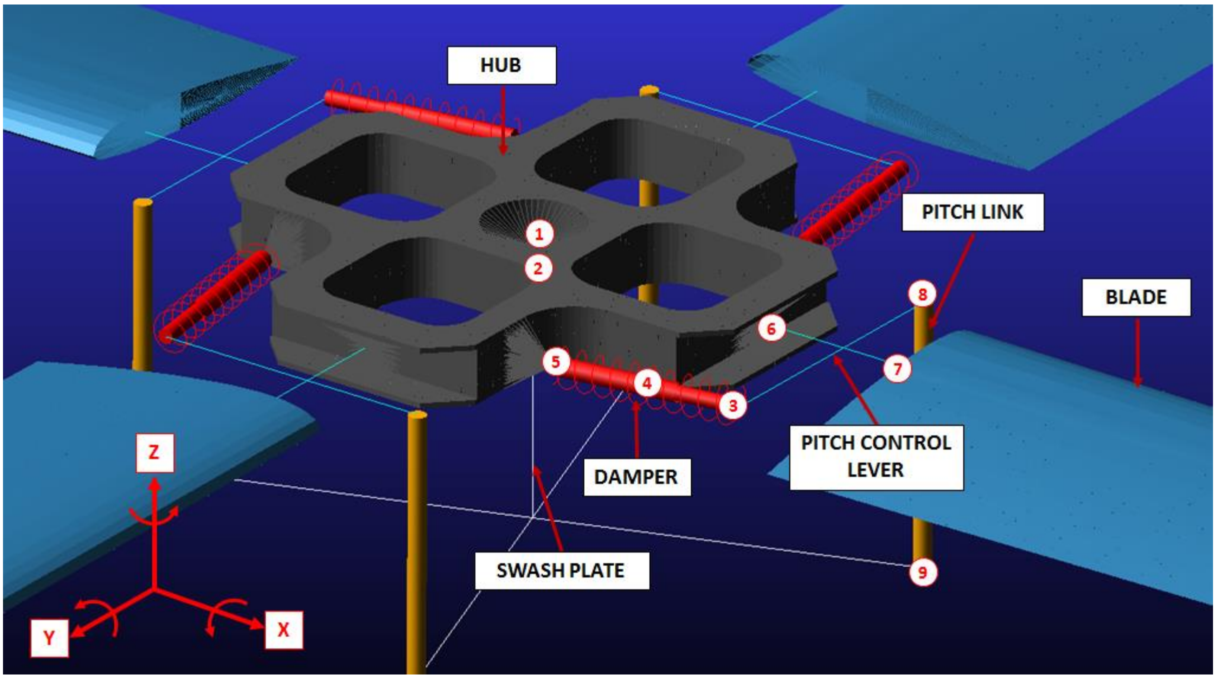

Figure 2 Kinematic model of the rotor

Table 1 Joint types in the kinematic model

Joint No	Joint Type	Parts Connected
1	Revolute	Hub - ground
2	Prismatic	Hub - Swash Plate
3	Spherical	Damper - Pitch Control Lever
4	Prismatic	Damper (Hub side) Damper (Pitch Control Lever side)
5	Spherical	Hub - Damper
6	Spherical	Pitch Control Lever - Hub
7	Fixed	Blade - Pitch Control Lever
8	Spherical	Pitch Control Lever - Pitch Link
9	Spherical	Swash Plate - Pitch Link

Implementation of Flexibility

In the rotor model, blade and hub are modeled as flexible parts by using MSC Patran and MSC Nastran [MSC Nastran Quick Reference Guide, 2014]. Computer aided design (CAD) files of the parts are imported to Patran for meshing and generation of the connection points. In order to connect the rotor parts to the flexible parts, attachment locations need to be specified as a node and these nodes are joined to the flexible parts by using multi point constraint (MPC) method. In the flexible hub model, nine connection points are created for the blades, dampers, and the ground connection. The sample blade model has 0.9m span length and 0.15m constant chord length with symmetrical airfoil. In the flexible blade model, nine connection points are created for load application and the hub connection. Following the preparation of the finite element models of the hub and the blade for analysis in Patran, modal analysis approach is used for modal stress recovery by using solution sequence 103 of Nastran. After performing the modal analysis in Nastran, model neutral file (mnf) generated by Nastran is exported to MSC Adams. Finite element models of the hub and the blade and their connection points are presented in Figure 3 and Figure 4, respectively.

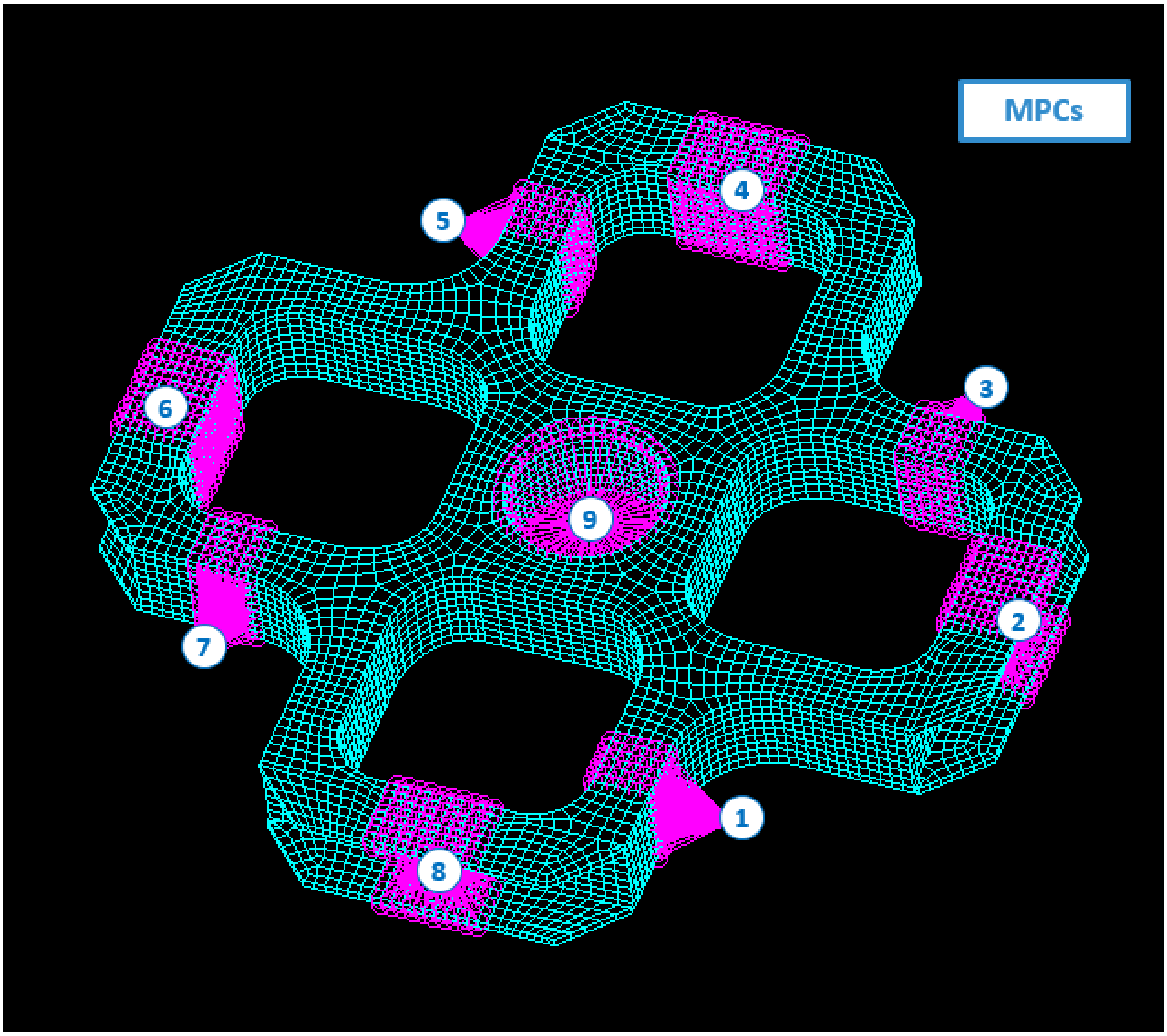

Figure 3 Rotor hub and connection points

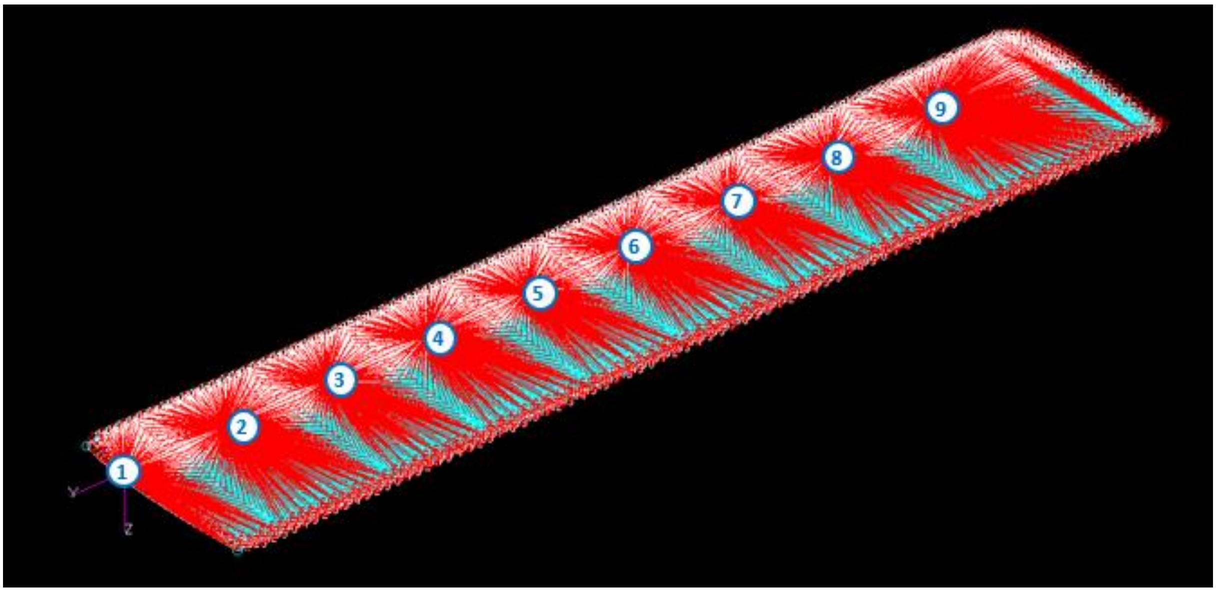

Figure 4 Finite element model of the rotor blade and load application points

Loading

Blade is subjected to two types loading; inertial and aerodynamic loading.

Inertia Load

The helicopter rotors are subjected to the series of motions in order to control direction of the helicopter in the flight. From these rotor motions, rotor parts are subjected to the significant inertia loads. These inertia loads of rotor mainly come from blade control inputs and rotation of the helicopter rotor.

In the ADAMS model, rotor is rotated at the hub center at a specified rotational velocity and blade control inputs are given via swash plate and pitch links as collective input and inertia loads are calculated by ADAMS automatically.

Aerodynamic Load

In order to calculate aerodynamic forces, the lifting line theory is used. Formulation of the lifting line theory is implemented into the ADAMS model for the calculation of aerodynamic forces without a need for external calculations. In the ADAMS model, aerodynamic loads depend on the local wind velocity relative to the blade and the blade angle of attack, at each load calculation point in the blade. Both relative wind velocity and angle of attack values are evaluated in ADAMS and used as input for aerodynamic loads calculations. Therefore, different flight scenarios can be analyzed easily in the generated ADAMS model. Simplified aerodynamic loads calculation methodology is described in Figure 5 and Figure 6. Aerodynamic loads vary with the relative wind velocity and the local effective angle of attack. For the rotating blade, relative wind velocity depends on the forward flight velocity and the rotational speed of the rotor. For the hover case, due to the zero forward velocity, relative wind velocity depends only on the rotational velocity of the hub. Therefore, for constant rotational velocity, aerodynamic loads are also constant for each blade at different azimuth locations. However, for the forward flight condition, as it can be seen in Figure 5, relative wind velocity varies depending on the azimuth angle of the blade due to the forward flight velocity component. As a result of this, aerodynamic loads on the blades vary with the azimuth angle that angle is measured in the ADAMS model from Joint 1 rotation and used as an input for calculation of relative wind velocity for each blade.

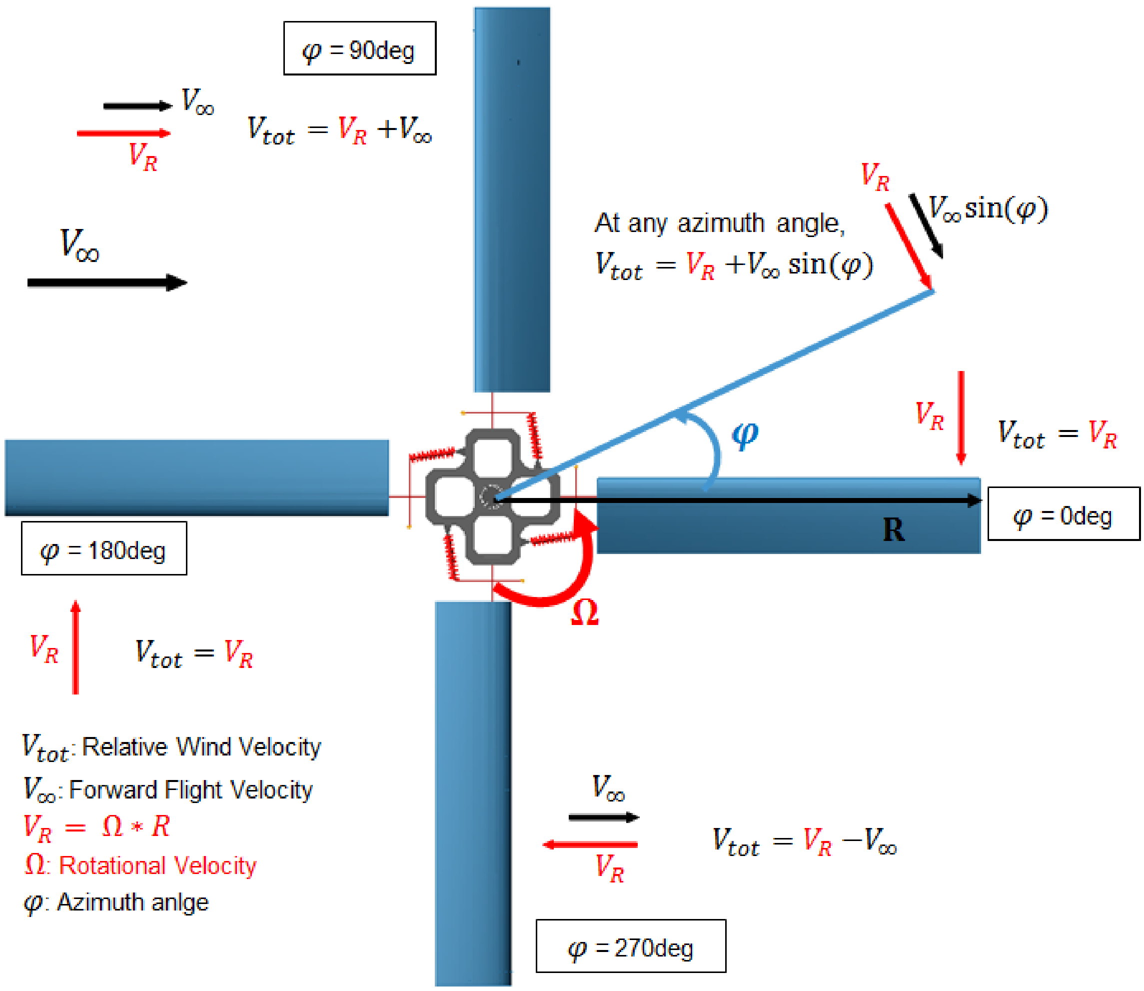

Figure 5 Relative wind velocity at different azimuth angles

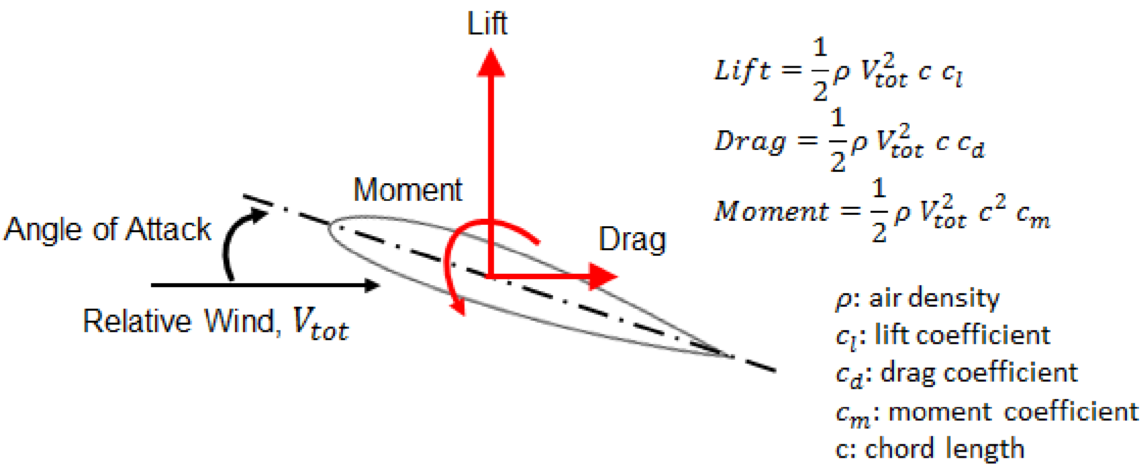

Figure 6 Formulation of aerodynamic loads

Stress recovery procedure

In order to recover stresses in flexible bodies, Adams/Durability plugin [MSC Adams/Durability Guide, 2011] is used. With Adams/Durability, stresses can be recovered inside ADAMS by using the Modal Stress Recovery method. For Adams/Durability to calculate stresses in the flexible body, modal neutral file (MNF) with modal stress matrix need to be generated in Nastran. Generated mnf file contains the body properties (center of mass, moments of inertia matrix, mass), the reduced stiffness and mass matrix, and the normal modes. For preparation of the mnf file, number of mode shapes is chosen as 26, which is default number in the Adams preparation tab in the Patran. After importing the mnf file into the Adams model as flexible part, Adams/Durability is able to store the flexible body stress data for the specified analysis. Then, from the Durability menu in Adams, stress history output can be exported for the desired node for further analyses.

In Figure 7, the whole process of the multibody simulation of helicopter rotor system with flexible blade and the hub is summarized in a flow chart.

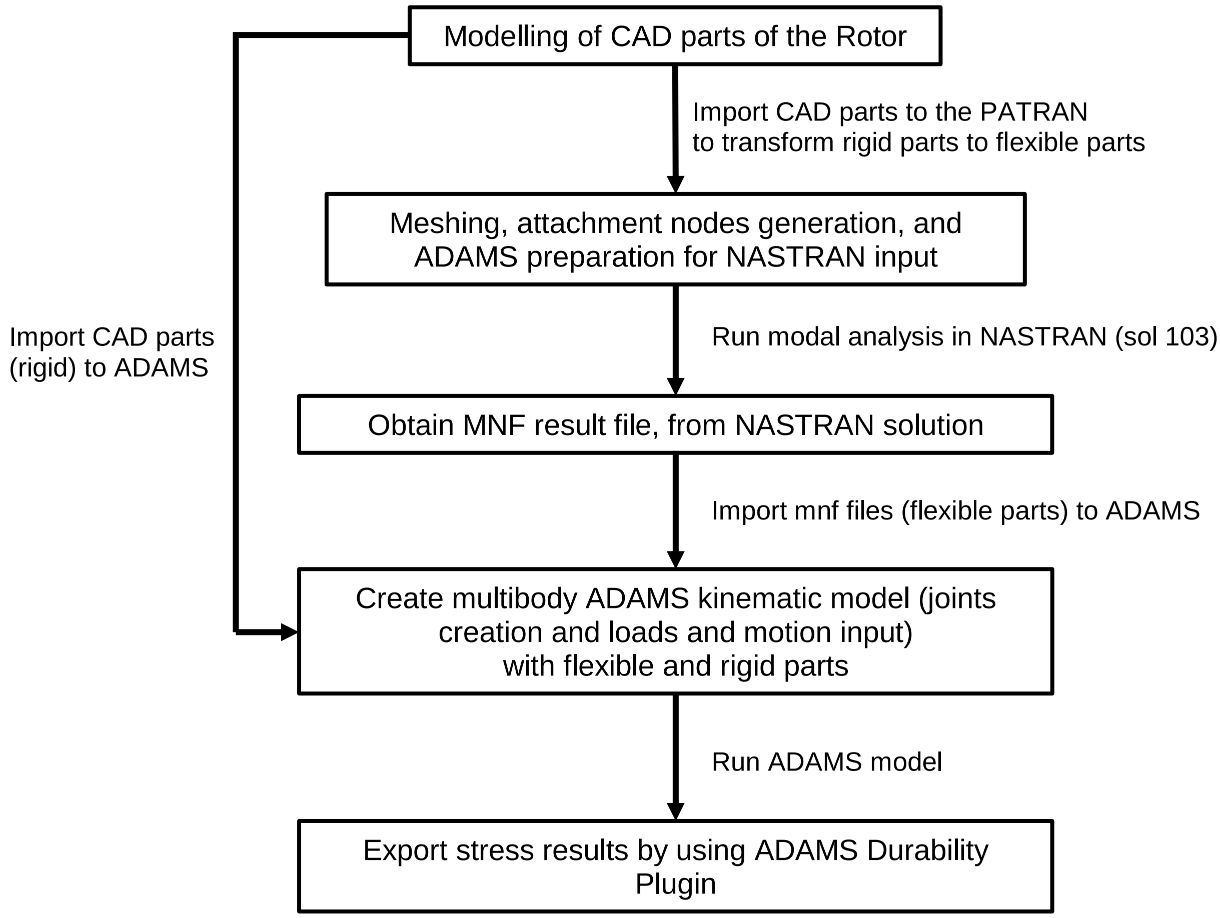

Figure 7 Flow chart of the multibody simulation process of the helicopter rotor

RESULTS

In this study, helicopter rotor is analyzed with different flight cases and design parameters. By considering results of different flight cases, helicopter rotor blade motions can be investigated for the verification of the ADAMS model. For example, in the hover case (no wind condition), static equilibrium is expected for blade angles however, for the forward flight case, blade undergoes flapping motion due to the lift asymmetry. Results and discussions for the sample flight cases and design parameters are given in this section. For each flight case and the selected design parameters, rotor is rotated at 4000deg/s constant rotational velocity and collective input is 10 mm in the negative z direction in order to give positive pitch angle to the blades, as shown in Figure 2. Rotation motion of the rotor is given to the hub at joint 1 and the collective input is given to swash plate as a displacement motion at joint 2, as shown Figure 2 and Table 1. The rotor is started to rotate from the stationary position (zero rotational velocity) and its rotational velocity is increased gradually to 4000deg/s in order to avoid excessive inertia loading. As it can be seen from Figure 8, rotational speed of rotor is increased gradually to 4000deg/s from time=0 to time=20 s, and between time=20 s and time=30 s, it is kept constant.

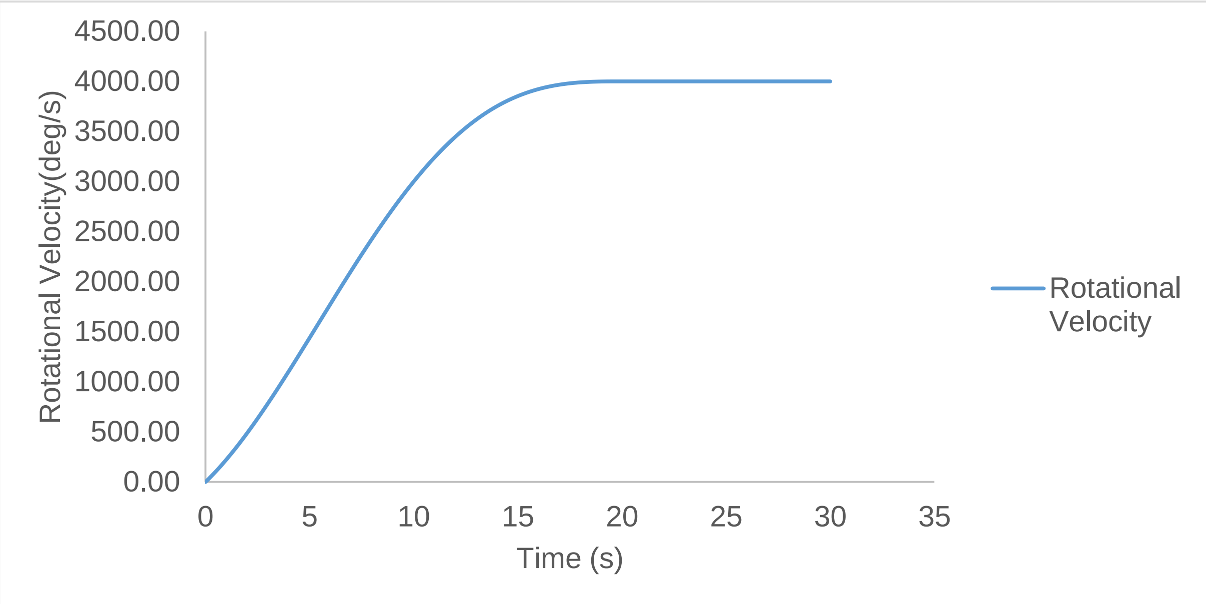

Figure 8 Rotational velocity of the rotor versus time

Analysis results of the flight cases

For both hover and forward flight conditions, collective input and rotational velocity are applied in the same way. Blade angles are measured from joint 6 in Adams, as shown in Figure 2. In Figure 2 rotation around the z-axis is the lagging motion, y-axis is flapping motion, and x-axis is pitching motion. In the Adams model, collective input is applied at the beginning of the analysis after that rotation is applied to the rotor for both flight conditions. Initial blade angles come from the collective input of the rotor and they change under the effect of the aerodynamic loads.

In Figure 9, Figure 10 and Figure 11 variation of the lag, flap, pitch angles of the blades are presented for the hover case. For the hover case, all of the four blades have the same pitch, flap, and lag angles respectively, and they reach to the equilibrium state between time=20 s and time=30 s. Because of zero forward velocity in the hover condition, relative wind velocity depends only on the rotational velocity of the rotor. As presented in Figure 8, since to the rotational velocity is kept constant after time=20 s, relative wind velocity is constant. As a result of this, all inertial and aerodynamic loads become constant after that time. For instance, lag angle stays at about -3° because of the constant drag force on the blade and the flap angle stays at +3° because of constant lift force on the blade.

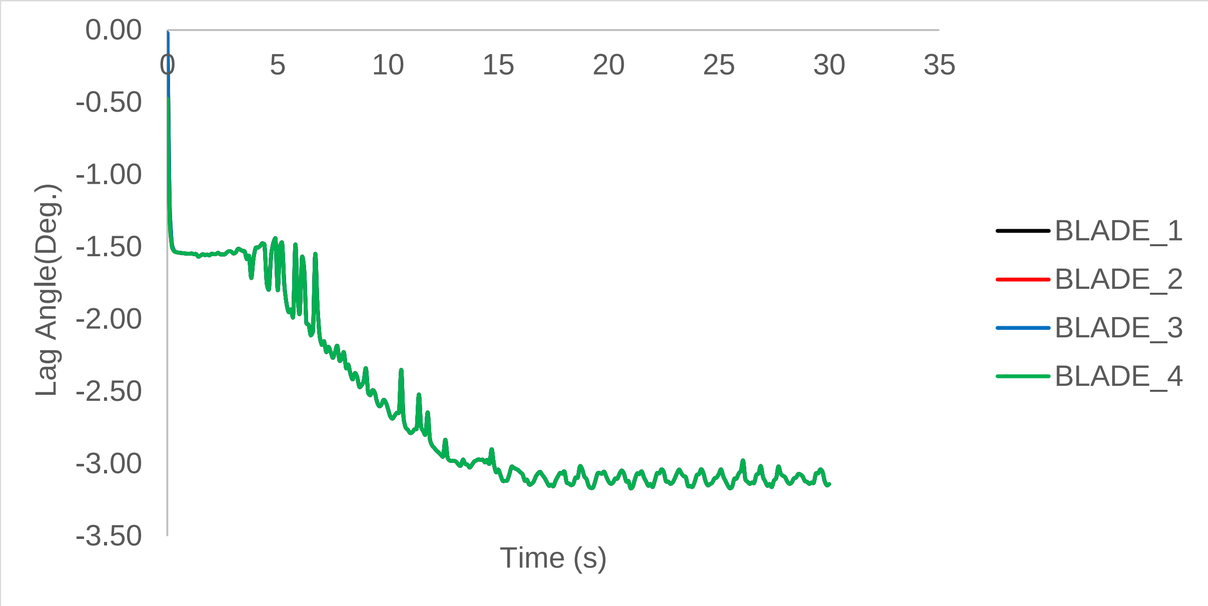

Figure 9 Variation of the lag angle with time for the hover condition

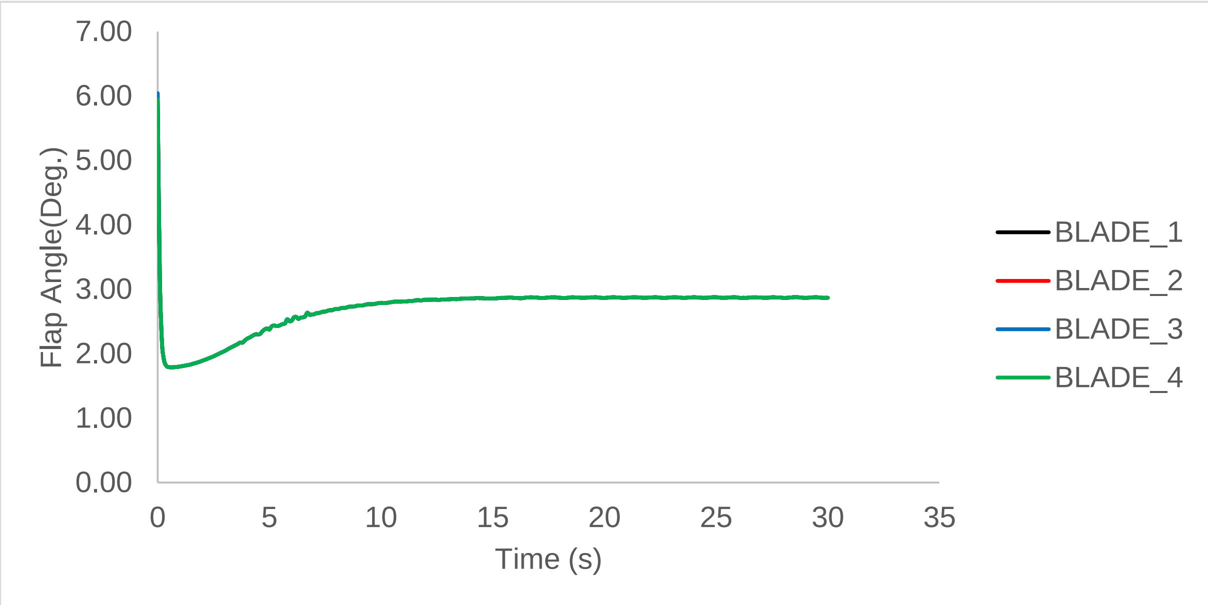

Figure 10 Variation of the flap angle with time for the hover condition

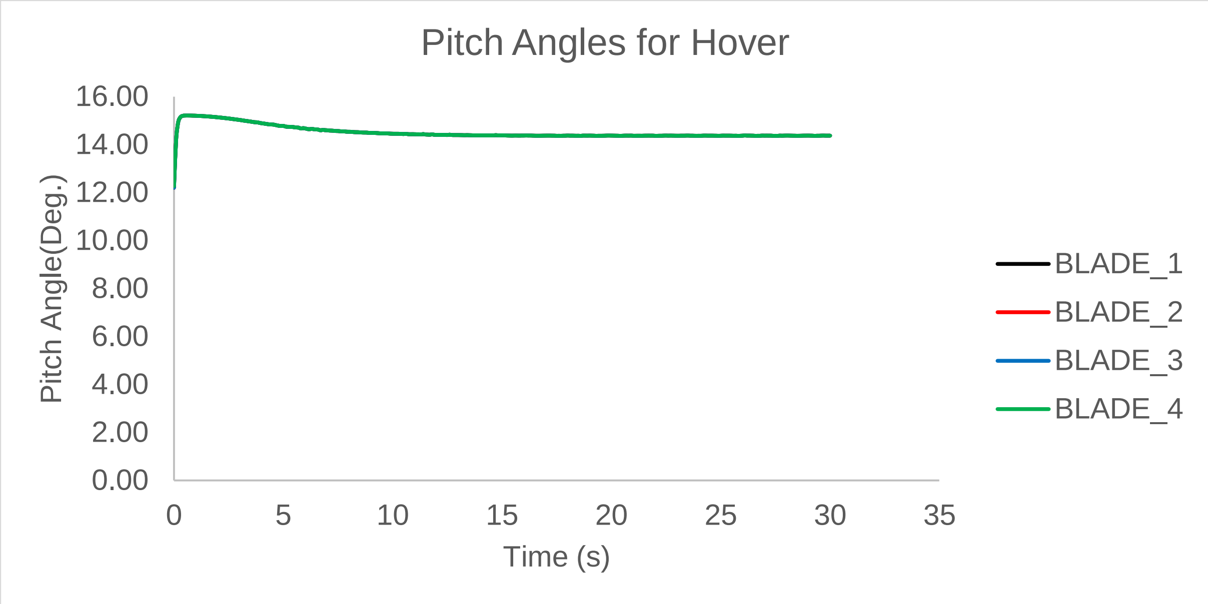

Figure 11 Variation of the pitch angle with time for the hover condition

In order to simulate the forward flight condition, forward velocity of the helicopter is taken as 50m/s in the calculation of the relative wind velocity in the ADAMS model for the calculation of aerodynamic loads. It is seen that as a result of the relative wind velocity variation with the blade azimuth angle, each blade has different lag, flap, and pitch angles at a time, and these angles change periodically as shown in Figure 12, Figure 13 and Figure 14.

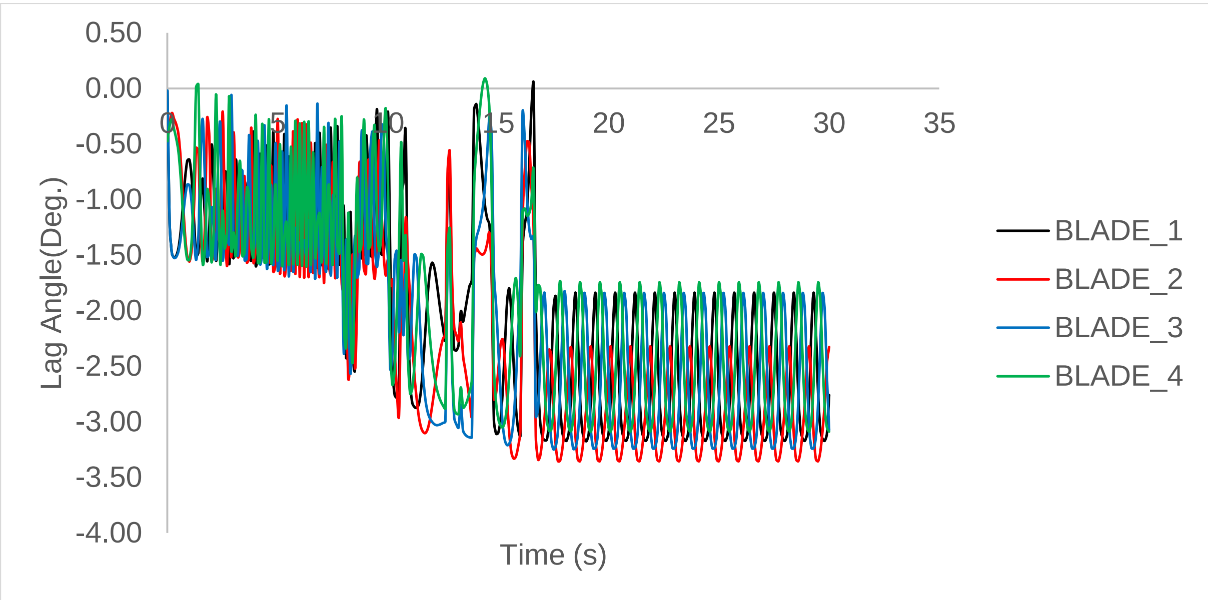

Figure 12 Variation of the lag angle with time for the forward flight condition

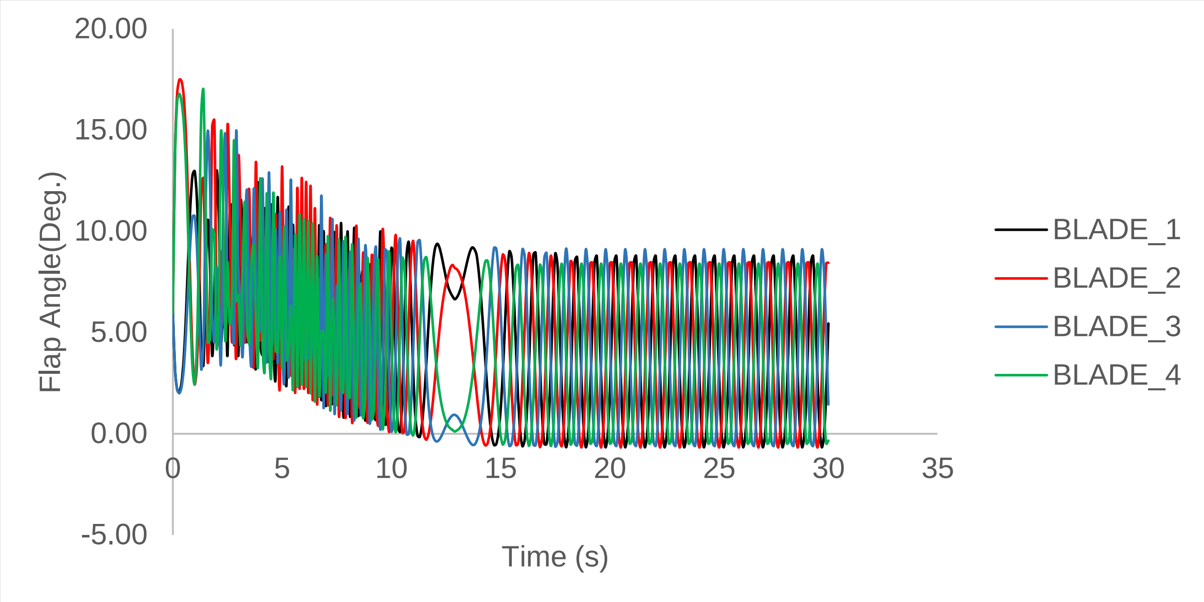

Figure 13 Variation of the flap angle with time for the forward flight condition

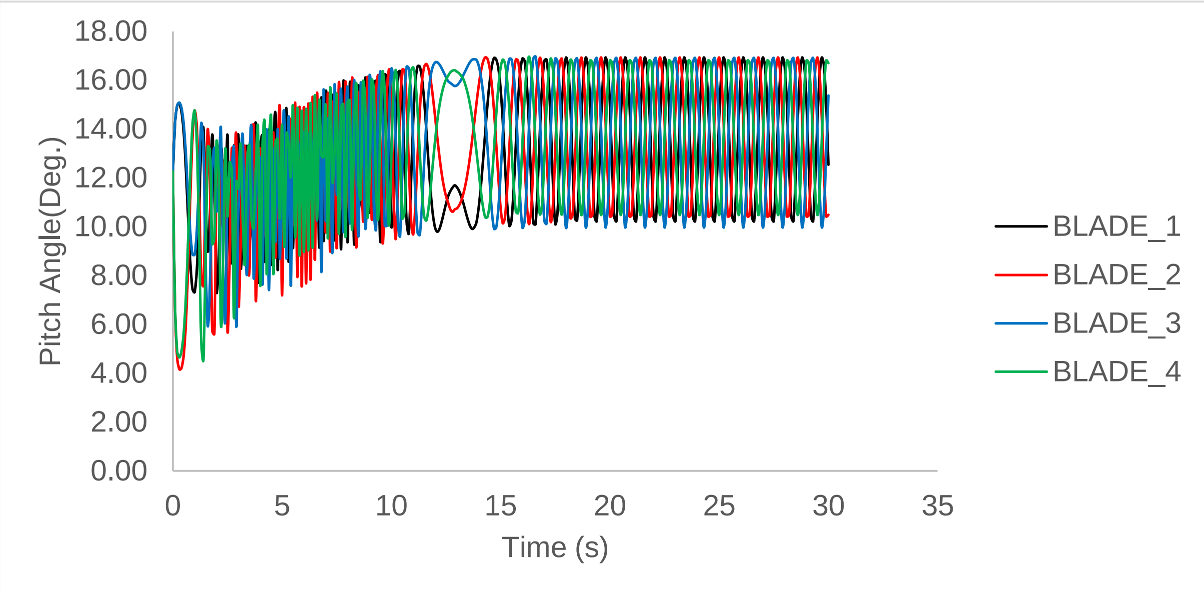

Figure 14 Variation of the pitch angle with time for the forward flight condition

For the hover and the forward flight cases, von Mises stress results are also investigated at the critical location in the rotor hub. For forward flight condition at time=27.7s, von Mises stress distribution and the critical location in the hub are given in Figure 15. Figure 16 demonstrates the variation of the von Mises stress at the critical location in the rotor hub respectively for the hover and the forward flight cases for time between 20s and 30s. Von Mises stress results are plotted for time between 20s and 30s in order to investigate how the different the flight cases affect critical stress state when the rotational velocity is constant after 20 seconds. It is seen that as a result of the forward flight condition, con Mises stress variation in the critical location of the hub increases significantly and periodic stress variation is observed. Such a variation of stress is the primary source fatigue failure in the long run. On the other hand, for the given example, von Mises stress variation and the peak stress for the hover condition is almost negligible compared to the forward flight condition.

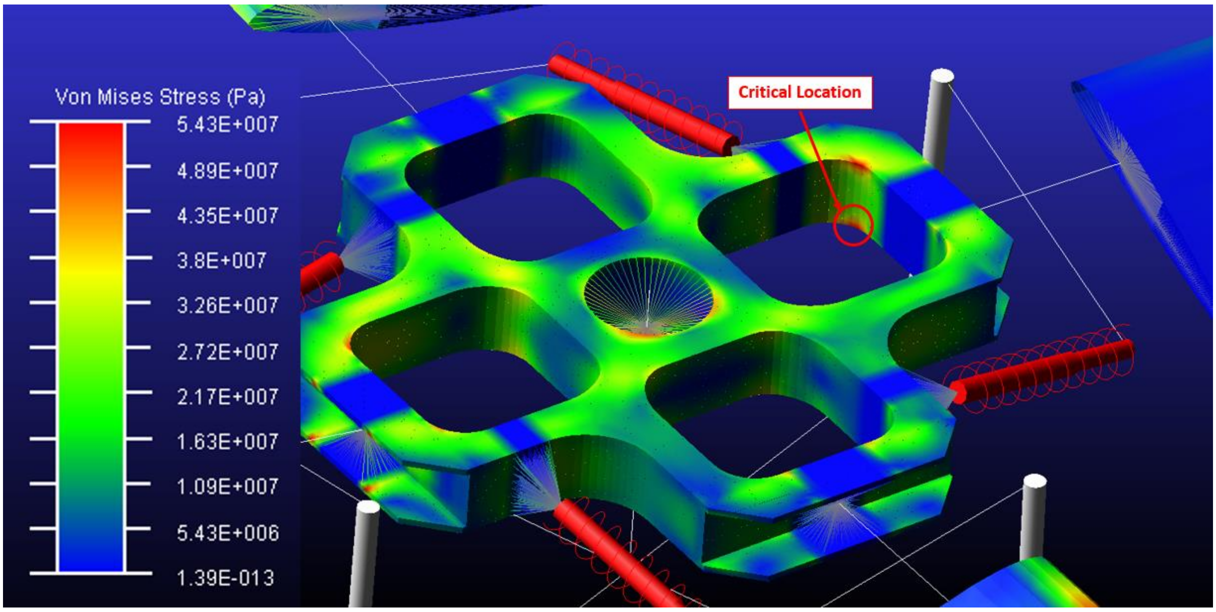

Figure 15 Von Mises stress result and the critical location in the hub at the time 27.7s for the forward flight condition

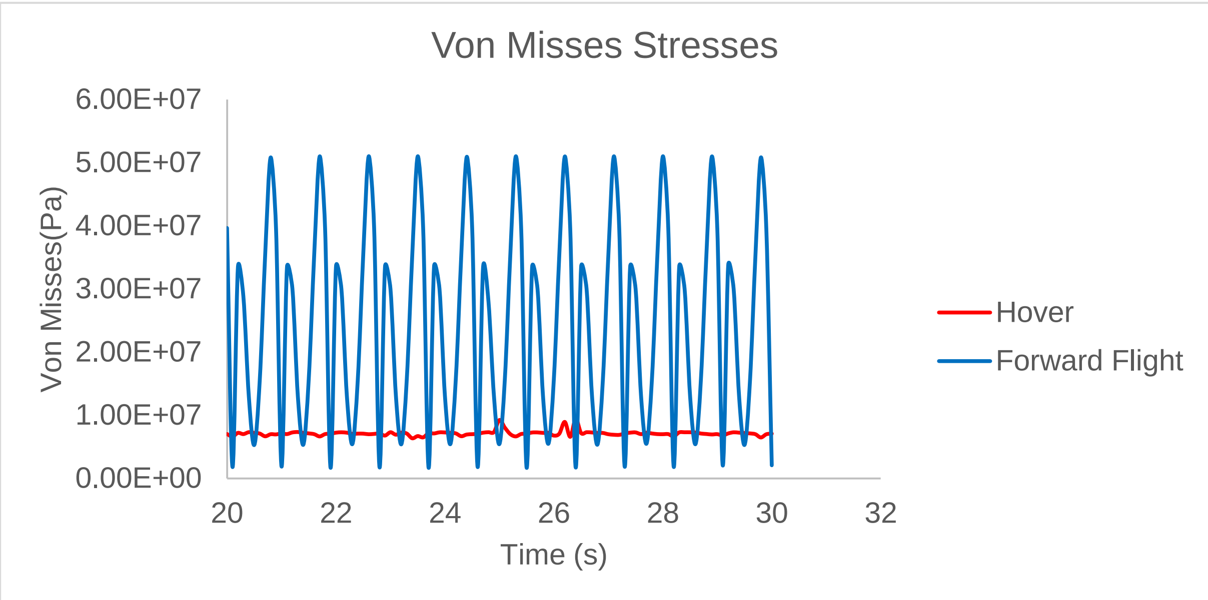

Figure 16 Von Mises stress variation in the critical location of the hub for the hover and the forward flight conditions

Effect of design parameter modifications

In this section, as an example of the effect of design modification, effect of different lag damper stiffness coefficient is investigated for the forward flight case. For this purpose, while damping coefficients are kept constant, dampers with 100 N/mm and 300 N/mm stiffness values are implemented in the rotor model established in MSC ADAMS. Dampers have significant effects on dynamic characteristic of a rotor by directly affecting the helicopter rotor blade lag angles. Figure 17 and Figure 19 show the lag angles and von Misses stress results for a blade with low and high damper stiffness coefficients, respectively. Stress results are taken from the damper-hub connection region as shown in Figure 18. It is seen that higher damper stiffness coefficient causes a decrease in the lag angle and the lower lag angle accounts for a more stable rotor, because change in the center of gravity location of the blade becomes smaller. In addition to this, due to the smaller lag angle, required space for blade motion becomes smaller. However, as shown in Figure 19, change in the lag damper stiffness coefficient does not have significant effect on the hub stresses because lag damper produces more or less the same force with lower damper stroke due to the higher stiffness.

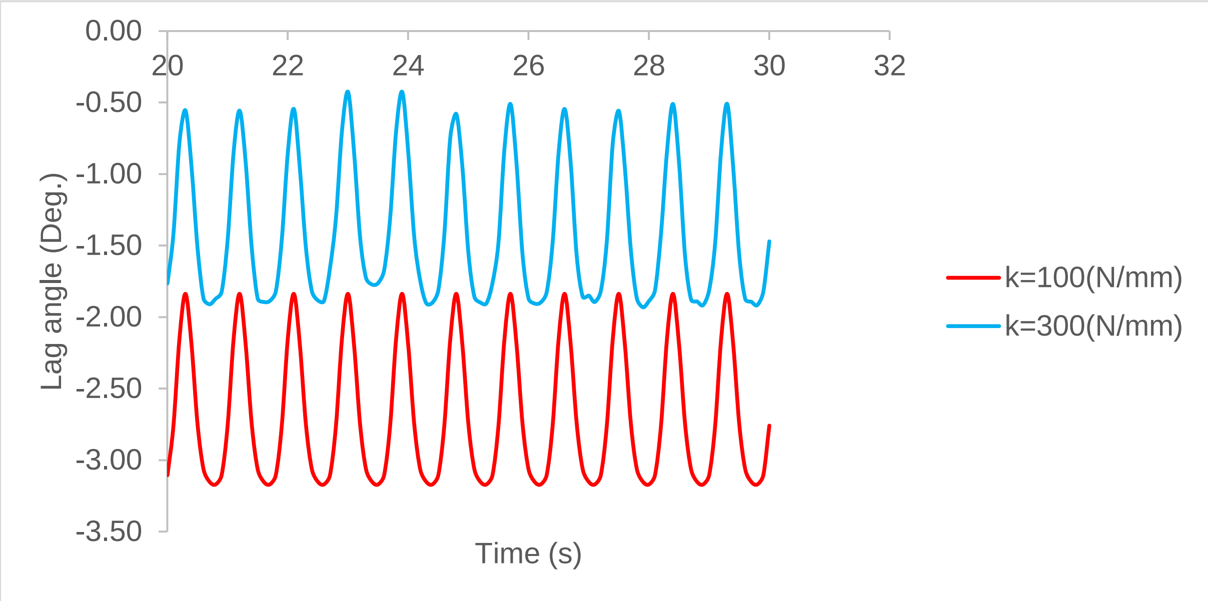

Figure 17 Blade lag angles for the100 N/mm and the 300 N/mm lag damper stiffness for the forward flight case

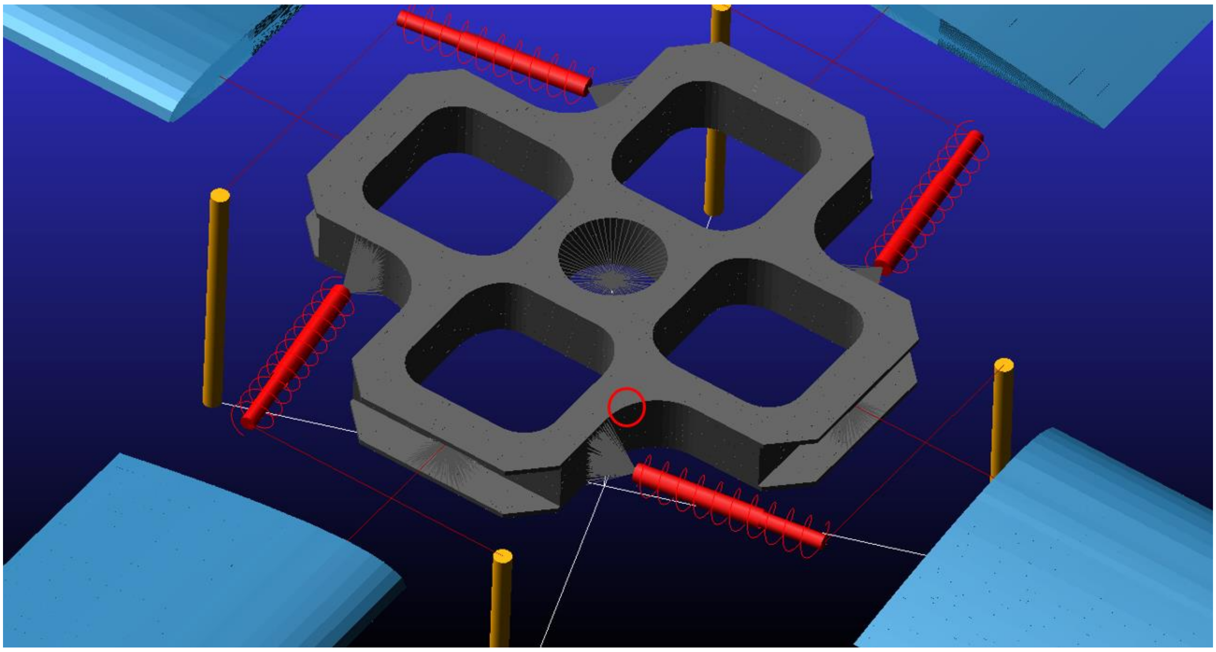

Figure 18 Damper-hub connection region in the hub

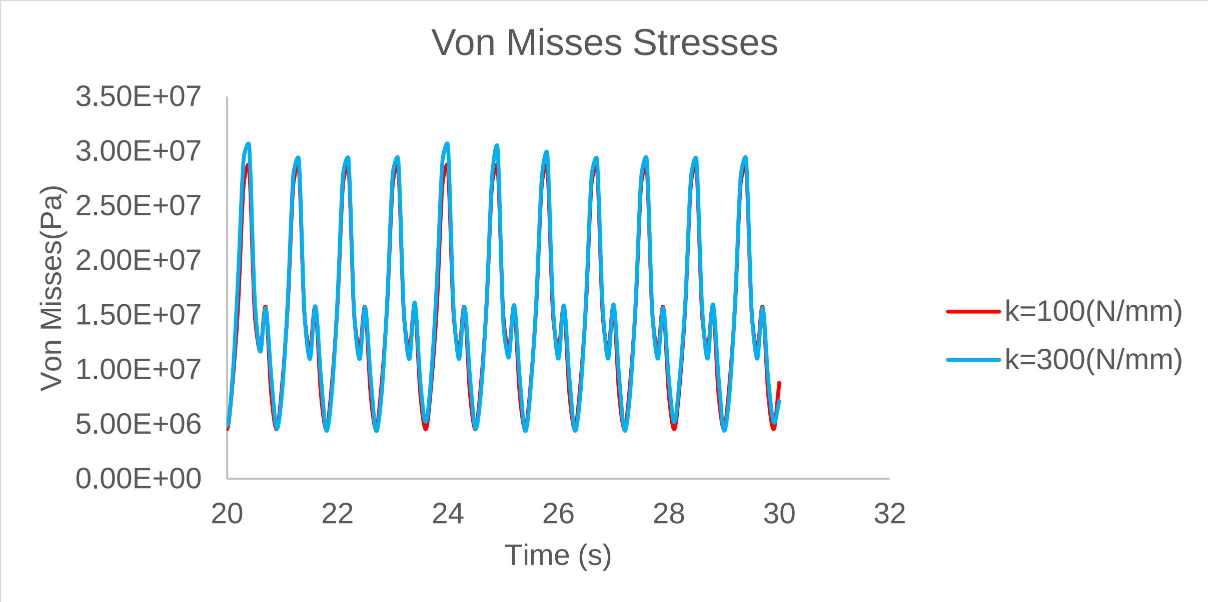

Figure 19 Von Mises stress variation of the damper-hub connection region in the hub for 100 N/mm and 300 N/mm damper stiffness for the forward flight case

CONCLUSION

In this study, demonstration of the setup of a flexible helicopter rotor system in MSC Adams is presented. For this purpose, helicopter rotor system is modelled with flexible hub and blade in MSC Adams program. Simple aerodynamic load calculation method for the hover and the forward flight conditions is embedded in MSC Adams without the use of any external aerodynamic load calculation tools. Multibody simulations of the rotor using flexible models for the helicopter blade and the rotor hub are then performed including the aerodynamic and and modal stress recovery is achieved by connecting MSC Adams with MSC Nastran. It should be noted that in most of the multibody modeling and simulation tools used for modeling helicopter rotor, beam models of the blade and rigid rotor hub are used. Stress recovery in the blade and in the rotor hub are then performed externally via cross-sectional analysis tools such as VABS or finite element tools. MSC Adams, integrated with MSC Nastran, allows flexible modeling of the helicopter rotor effectively.

Results presented for the hover and the forward flight condition show that for the hover condition at constant rotational speed of the rotor, lag, flap and pitch angles of the blades remain constant, as expected. For the forward flight condition, because of the change of the relative velocity with the azimuth angle, periodic variations of the lag, flap and the pitch angles are obtained in the simulations performed by MSC Adams. Periodic variation of the blade angles is the expected behavior in forward flight condition which shows that the established flexible rotor system is reliable. Evaluation of the stresses in the critical location of the rotor hub showed that for the forward flight condition, von Mises stress variation and the peak stress for the hover condition is almost negligible compared to the forward flight condition. It is also shown that the effect of stiffness of the lag damper on the von Mises stress in the hub-damper connection is not significant. Slight reduction in the peak stress is observed for less stiff damper.

This study comprises the first phase for the establishment of a flexible helicopter rotor blade in MSC Adams. Preliminary results obtained showed that the flexible rotor model established in MSC Adams provides the respective blade angles for the hover and the forward flight conditions reliably. Moreover, with the flexible rotor model, it is demonstrated that the stresses in the hub can be determined inside MSC Adams for the hover and the forward flight condition for further analyses. Design changes implemented during the course of the design process of the helicopter blade require the evaluation of the effect of the design change on the fatigue life of the rotor components. For this purpose, in the present study demonstration of the modification of the stiffness of the lag damper on the stresses at the hub-damper connection point has been made for the forward flight case. It is shown that time history of the stress can be collected corresponding to a design change for further evaluation of the impact of the design change on the fatigue life of the rotor hub.

For the future improvement of this study, geometric nonlinear response of the rotor blade can be taken into account, and aerodynamic load calculations can be improved. In addition to this, by using time varying stress results, evaluation of the effect of design modifications on the fatigue life of the rotor hub can be investigated via the fatigue damage equivalent load concept.

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