Closed loop approach to structural health monitoring for critical rotorcraft components

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ABSTRACT

INTRODUCTION

Rotorcraft design is challenging with respect to fatigue considering the wide range of loads to which it is subjected. There has been a continuous requirement from the helicopter community in terms of increased flight safety, increased life of components and decreased maintenance and inspection frequency. Structural Health Monitoring (SHM) has definitely catered to this requirement by introducing Condition Based Maintenance, thereby reducing the cost and time involved in maintenance activities. However, there is still an existing need for health monitoring improvements that can provide feedback in order to change the loads appropriately. The aim of the present work is to develop estimation of component level dynamic loads, stresses and strains thereby providing an opportunity for monitoring component damage variables which can then be fed to the Load Alleviation Control scheme to adjust the loads and ensure extended life and flight safety.

LITERATURE REVIEW

In structural design, two techniques are commonly employed to predict the durability if components and systems: Safe-life approach and damage tolerant approach. Safe-life approach allows the structure to be designed such that it withstands a predetermined fatigue life in terms of flight hours. Once fatigue life is reached the component is replaced even if there is no visible damage to the part. On the other hand, damage tolerant approach focuses on damage growth. This may be achieved such that a crack may grow up to a certain length where it will then be stopped by a crack stopper or the component will have fractures which then offers multiple load paths by transferring the loads by some other component (Ref. 1). The rotorcraft industry employs fatigue analysis extensively owing to the wide range of applications, operating environments and long time durations for which helicopters are used. A 2012 survey of the past 30 years, carried out by Augusta Westland Limited (AWL) Materials Technology Laboratory, concluded that fatigue failures account for approximately 55% of all premature failures in helicopter components (Ref. 2). The causes of low cycle fatigue are largely due to aircraft maneuvers, gust loading and through takeoff and landing. Critical helicopter components, classified as Grade-A Vital components by regulatory authorities, are subjected to significant fatigue loading in which failure would result in a catastrophic event. A list of fatigue critical components (Ref. 3) on the AH-64A Apache shows that many of the Grade-A Vital components are located in the rotor system, creating challenges for real-time load monitoring of those components. Without real-time SHM available, the life span of critical components is often underestimated. Furthermore, components are frequently over designed to counteract high dynamic loads, adding unnecessary cost and weight to the vehicle. Additionally, routine maintenance checks which could be performed less frequently if a health monitoring system were implemented, usually drive up the operational costs. Although longevity of components could be improved by decreasing frequency of maintenance activities, the depreciation in safety and risk of component failure introduced is unacceptable.

SHM in general uses the dynamic response measurements obtained for various sensors over time. These responses are analyzed statistically to determine the current health state of the system. Current methods for structural health and usage monitoring and load alleviation control rely on distributed sensing and operational monitoring to infer usage and estimate fatigue in critical components. Such inference processes are affected by significant uncertainty given the sensors′ type and locations, since they are often removed from hot spot areas characterized by maximum stresses. For example, past work for limiting pitch link loads has used proxy models of the vibra-

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tory loading. A classic example is the Equivalent Retreating Indicated Tip Speed (ERITS) parameter, which has been correlated as a function of airspeed and normal load factor with vibratory pitch link loads from retreating blade stall onset, can be limited to indirectly constrain the pitch link loads (Ref. 4). Another method involves automating current Non-Destructive Inspection techniques. For example, the use of a fully automatic inspection system that makes use of laser shearography for helicopter rotor blades (Ref. 5). However, this involves off-line maintenance which further drives up the cost. Furthermore, use of smart composite materials or multi-functional materials has gained attention for SHM applications due to their capability in providing on-line data on crack evolution as an advancement in sensor technology (Ref. 6). Hence, most of the research and development in terms of SHM is focused on increasing accuracy and optimizing the location of sensors.

A recent Penn State study (Ref. 4) using curve fits of pitch link vibratory loads as a function of aircraft states, demonstrated the potential for limiting peak-to-peak pitch link loads by limiting roll rate in a high fidelity FLIGHTLAB simulation of a utility helicopter, thereby reducing incremental fatigue damage. This is taken up as a potential opportunity and is considered in the work presented in this paper.

METHODOLOGY

Overview

The Finite Element Method (FEM) is used for modeling problems involving dynamic loads, mainly because of its flexibility in representing arbitrary geometric features. We use the same method for the proposed work. A structural model was developed in ABAQUS for a preferred component followed by running the model for air loads obtained from FLIGHTLAB for different maneuvers. The process is automated in the sense of extracting aerodynamic loads transmitted on the chosen component and performs analysis using these loads to generate interested output variables such as stress or stain rates. As an attempt to reduce computational cost in future research, a comparison of quasi-static and dynamic case was undertaken for a particular load spectrum. This was done by first determining the natural frequencies of the component which was then compared to the frequency of the rotor. Further, once the structural analysis was done and interested parameters are obtained, their harmonics are extracted to make it suitable as a feedback to FLIGHTLAB in order to implement load alleviation control scheme appropriately as shown in Fig 1.

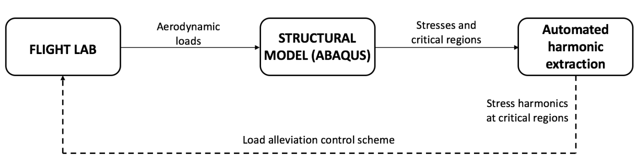

Fig. 1. Schematic of overall methodology

Component

Considering the recent Penn State study on pitch links as mentioned before, the preferred component was chosen to be the pitch link. Both collective pitch (changing the pitch of all blades simultaneously to generate thrust) and cyclic pitch (influences the blades angular position within its circle of rotation; direction in which the rotor disc is rotated) are achieved utilizing a swash plate system. This system as shown in Fig 2 is comprised of two rotating discs and transforms control inputs to blade angles. The control input is connected to the lower disc and rotor blades to the upper disc through the pitch links and pitch horns. Thereby, it is not difficult to realize that the pitch link operates in a dynamic environment of loads, thereby making it a critical component for investigation. Also, previous research shows high oscillatory nature of loads to which the pitch link is subjected, thereby making it an interesting component for the described study (Ref. 7).

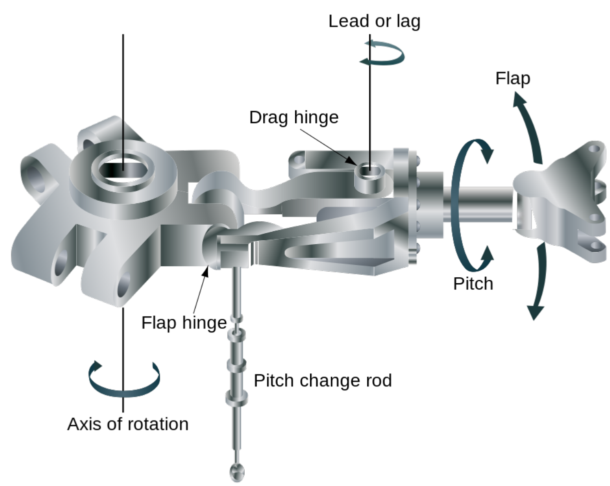

Fig. 2. Parts of fully articulated main rotor head of helicopter and the associated motions of the blades

FEA Set-Up

A representative model of the pitch link, utilizing 7075-T6 Aluminium, was developed in order to carry out the Finite Element Analysis. The pitch link is connected to the pitch horn via a pin joint where the center point of the hole surface is connected to the internal surface on either end as shown in Fig 3 to accurately capture the boundary conditions. Two types of loads are applied on the pitch link:

- Aerodynamic loads which are obtained from FLIGHTLAB developed by controls group involved in this this research.
- Body force which is obtained based on analytical calculations using the frequency of rotor and model's mass

properties. These calculations will be detailed in final paper submission.

Aerodynamic loads are applied to the center point of pin hole, hence getting distributed over the internal surface of the hole. Body forces on the other hand are applied over the entire volume of the pitch link. As an attempt to reduce computational cost in future research, a comparison of quasi-static and dynamic analyses was undertaken for a particular load spectrum. In the quasi-static set up, loads at each time step over the entire load spectrum were extracted and fed to the FEA model to run a static analysis. On the other hand, the dynamic counterpart included a steady state time marching dynamic analysis in order to include inertia effects associated.

The process is automated by implementation of a Python script in the ABAQUS model. The quasi-static block of the script allows the program to piece together many individual simulations in order to obtain a complete time history of the resulting stresses occurring on chosen elements of the pitch link or other selected critical components. The script begins by reading a text file of aerodynamic data and then enters a for loop with the aerodynamic vector in order to set the load value being applied to the model. If the aerodynamic value is greater than or equal to zero, the load is applied to the top portion of the pitch link (placing it into tension) where the boundary condition is constraining only this top half. Conversely, if the aerodynamic value is less than zero, the bottom connection point of the pitch link is constrained by the boundary conditions and the load is applied to the bottom surface, placing a compressive load on the pitch link.

SAMPLE RESULTS

The developed structural model was used to run a cyclic longitudinal doublet load obtained from FLIGHTLAB as shown in Fig 4. A quasi-static and dynamic case were run in order to check the possibility of implementing a quasi-static analysis. The stresses shown are for an element (four integration points) in the center of the model in order to accurately compare the two cases instead of capturing stress concentrations that can result in inaccurate inferences. As can be seen in Fig 5, both the results (dynamic and static) follow the trends of the applied load, however differ in magnitude. This difference is attributed to the inertial effects that come into play in the dynamic case and are absent in the quasi-static case. Further, different maneuvers shall be tested in order to check the sensitivity of results based on the type and the way in which a maneuver is executed.

CURRENT STATUS OF WORK

Structural models have been developed for quasi-static and dynamic cases for a cyclic longitudinal doublet load (a representative maneuver) with appropriate boundary conditions that will be detailed in the final paper. Stresses are obtained as interested parameters and compared for both the cases. Further refinement of the model is currently being discussed to draw inferences. Once the model is finalized, harmonics shall be extracted for the interested output variable (stress in this case) in the frequency domain so as to serve as an input back (serve as feedback) to FLIGHTLAB for appropriate load alleviation. Further, an approach to extend this to include damage will be presented in the final paper.

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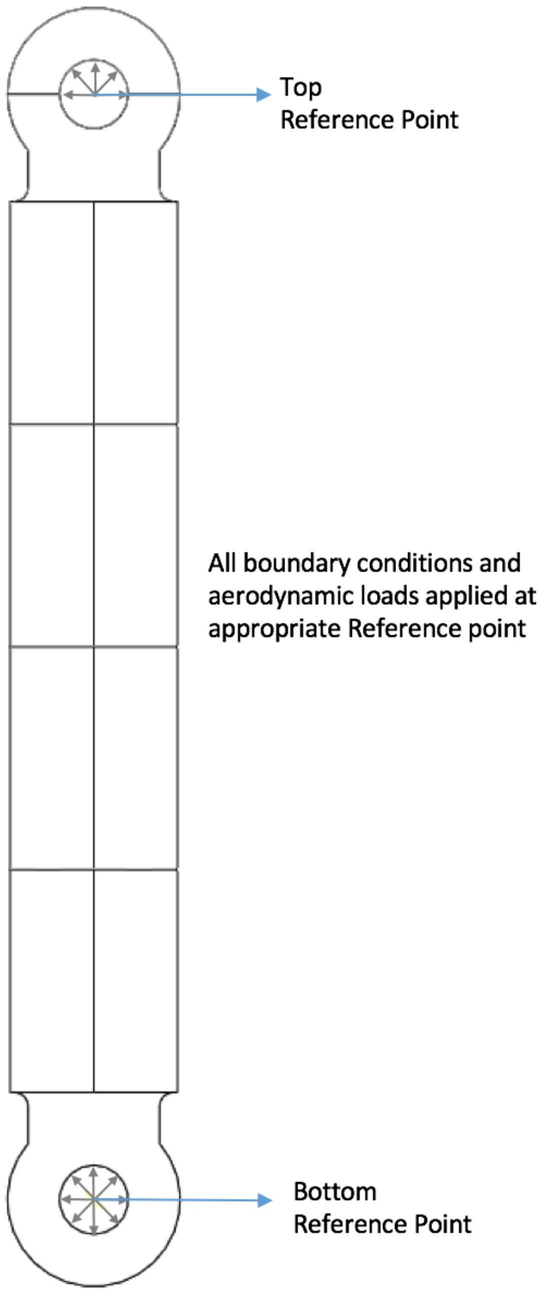

Fig. 3. Pitch link model with rigid body tie

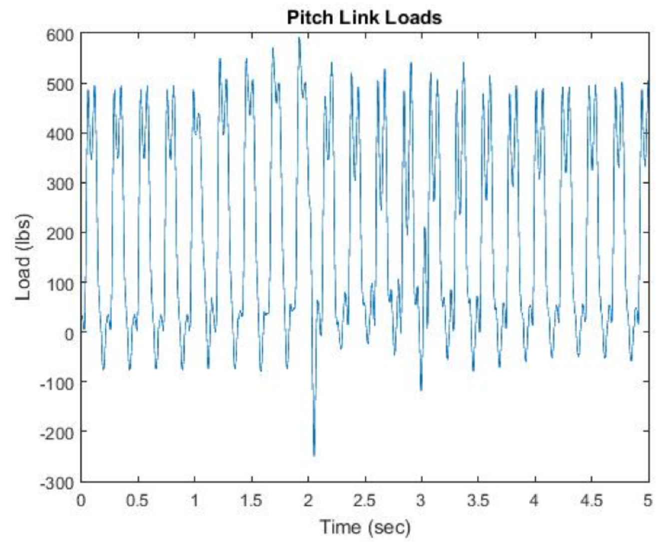

Fig. 4. Representative aerodynamic load

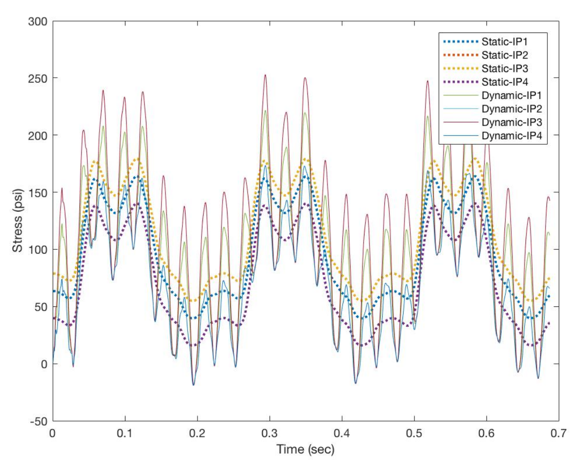

Fig. 5. Quasi-static and Dynamic results for representative aerodynamic load