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Prediction of Helicopter Maneuver Loads Using a Fluid–Structure Analysis

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A fluid–structure analysis framework that couples computational fluid dynamics and computational structural dynamics is constructed to study the aeromechanics of a helicopter rotor system under maneuvering-flight conditions. The computational fluid dynamics approach consists of the solution of unsteady Reynolds-averaged Navier–Stokes equations for the near field of the rotor coupled with the dynamics of trailed vortex wake that is computed using a free-vortex method. The computational structural dynamics approach uses a multibody finite element method to model the rotor hub and blades. The analysis framework is used to study the utility tactical transport aerial system pull-up maneuver of the UH-60A helicopter. Results shown illustrate the correlation of predicted performance, aerodynamic and structural dynamic loading, with measured flight-test data. The normal load factor and the peak-to-peak structural and aerodynamic loading show good correlation with flight-test data, indicating that the analysis framework is suitable for preliminary design purposes. Important phenomena such as advancing-blade transonic effects and retreating blade flow separation are predicted satisfactorily. However, deficiencies are noted in the accurate prediction of stall onset, reattachment, and shock-induced separation.

I. Introduction

HELICOPTER rotor systems operate in highly unsteady flow conditions that are characterized by transonic flows, dynamic stall events, and returning-wake interactions. In addition, there is a large extent of aeroelastic coupling, due to the slender construction of the blades. All of these factors contribute to make the prediction of aerodynamic and structural dynamic loading on helicopter rotors a very challenging problem, even in steady forward flight. Maneuvering rotorcraft further augments this challenge because of additional aerodynamic and structural effects due to the hub motion and associated wake transients.

The simulation tools for rotorcraft analysis (termed comprehensive aeroelastic analyses) have historically been using lifting-line-based aerodynamic models (with suitable enhancements that use table lookup, unsteady flow, and stall models). However, such models are known to have inaccurate prediction capabilities [1]. There are two main reasons for the inaccuracies in the lifting-line models. The first is the inability to resolve unsteady transonic effects, and the second is the inability to accurately resolve the returning-wake effects [2]. The advent of the computational fluid dynamics (CFD) and computational structural dynamics (CSD) coupled approach replaces the lifting-line aerodynamic model with a higher-fidelity computational fluid dynamic model that solves the Reynolds-averaged Navier–Stokes (RANS) equations. This methodology has led to considerable improvements in the airload prediction, as demonstrated by various research efforts [2–6]. The primary reason for the improvement can be attributed to accurate prediction of aerodynamic loading, especially the pitching moments caused by unsteady transonic flows and improved representation of returning-wake effects [3].

An important aspect of CFD-based aerodynamic load prediction methodologies is the resolution of the wake structures. There are two well-established methodologies that are in use at the moment for wake predictions. They are 1) wake coupling [7] and 2) wake capturing [3,4,8]. In the wake-coupling methodology, the geometry of the vortex wake, circulation strength, and core growth rate are computed externally by solving the vorticity transport equation. The wake positions so obtained are embedded into the RANS-based CFD analysis using the field-velocity approach [9]. The wake-capturing methodology, in contrast, models the entire rotor system and attempts to capture the wake structure as part of the solution. The advantages of the wake-coupling methodology are computational efficiency and ease of modeling. However, it suffers from the empiricism that is used to model the physical diffusion of vorticity. The wake-capturing methodology has the advantage of being a first-principle-based modeling technique without any empiricism. However, it does suffer from high computational cost and numerical diffusion in predicting the wake structure. An evaluation of the wake-coupling and wake-capturing methodologies for prediction of steady-flight conditions can be found in [10]. Several flight conditions that address flow phenomena such as transonics, stall, and blade–vortex interactions were studied in this work. It was observed that the wake-coupling approach produced results of comparable quality as the wake-capturing approach for all of the flight conditions that were studied.

The main focus of most recent research efforts was on predicting rotor airloads in steady-flight conditions. The periodic nature of the flowfield and structural response facilitates the use of the so-called loose-coupling approach for interfacing the CFD and CSD analysis modules. In the loose-coupling approach, the analysis modules exchange relevant data only every rotor revolution. The inherent decoupling within a revolution provides a fast and robust way for establishing aircraft trim and a fully periodic structural response. In contrast, simulating an unsteady helicopter maneuver necessitates the exchange of forces and motions at every time step between the fluid and structure methodologies.

Recently, Bhagwat et al. [11] and Bhagwat and Ormiston [12] performed the seminal studies on computing airloads and blade loads for the UH-60A pull-up maneuver using a CFD/CSD analysis that coupled OVERFLOW-2 (wake-capturing CFD) and RCAS (CSD and comprehensive analysis) [4]. Remarkable improvements were demonstrated in the prediction of aerodynamic and structural dynamic loads compared with conventional comprehensive analysis. This study triggered a lot of interest in the application of CFD/CSD

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