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Improved rotor aeromechanics predictions using a fluid structure interaction approach

Younghyun You, Deokhwan Na, Sung N. Jung *

Department of Aerospace Information Engineering, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 05029, Republic of Korea

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ABSTRACT

The measured HART (Higher harmonic control Aeroacoustic Rotor Test) I data in a descending flight condition is validated using various numerical approaches including CFD (Computational Fluid Dynamics)–CSD (Computational Structural Dynamics) coupled analyses with isolated rotor model and rotor-fuselage model. A CSD-alone approach is also conducted for reference purpose. A three-dimensional (3D) compressible RANS (Reynolds Averaged Navier Stokes) flow solver is employed for the CFD code. Good convergence behavior is found for both coupling analyses. It is observed that the rotor-fuselage model improves the correlation significantly as compared with the measured data. Specifically, the highly oscillating section normal forces signals marked in the advancing and retreating sides of the rotor are captured accurately. Detailed harmonic analysis and the gradient of the airloads signals are observed to prove the validity of the prediction model. The upwash induced due to a fuselage as well as the increased vorticity over the rotor flow fields are attributed to the enhanced correlation. The predicted blade elastic motions and structural moments also indicate improvements with the present rotor-fuselage model.

1. Introduction

In the perspective of rotorcraft aeromechanics disciplines, a low speed transition particularly in descending flight regimes is one of the critical conditions in generating abrupt impulsive rotor loadings leading to high vibration and noise [1]. Among other features, the blade-vortex interaction (BVI) phenomenon is of prime concern creating unsteady pressure fluctuations in the vicinity of the blade passage caused by the preceding blade motions and their trailed wakes. To understand the BVI flow characteristic more closely and suppress the noise and vibration actively, an international consortium is formed to carry out a wind tunnel test at the large low speed facility of the DNW (German–Dutch wind tunnel) in 1994 [2]. A 40% scaled BO-105 rotor model along with a fuselage is used for the test. A range of sophisticated measurement techniques are introduced to measure the noise level, blade surface pressure, tip vortices, blade motions, and structural moments with and without the application of HHC (Higher Harmonic Control) pitch control inputs.

The measured data set of HART I rotor exhibits a wider spectrum compared to the follow-on HART II experiments. For instance, HART I rotor is installed with 124 pressure transducers for chordwise airloads measurements at 3 different radial stations [3] whereas HART II allows only single radial station for chordwise airloads distributions with 51 pressure sensors [4]. In addition, 32 strain gages are used to measure blade structural moments (13 flap bending, 12 lag bending, and 7 torsion) for HART I rotor, as compared with 6 spanwise measurements (3 flap bending, 2 lag bending, 1 torsion moment) for the case of HART II [3,4]. These wide range of data sets need to be exploited to verify the prediction capability of an analysis system and to tailor analytical models for more reliable prediction methods. Despite the advantages, HART I rotor has been received less attention than the postdecessor program HART II rotor in terms of the volume of publications reported in the literature [5]. It is noted also that the structural properties of HART I blades are measured recently using the original set of blades tested in DNW [6]. This means, most of the earlier published works on HART I rotor (before 2013) are based on the estimated properties provided by the manufacturer of the blades. Taking these into consideration, there is an obvious gap in the literature to examine the quality of the measured HART I data.

The CFD–CSD coupling in rotorcraft applications is pioneered by Tung et al. [7] for predicting rotor aerodynamic loadings in high speed conditions to take advantage of the first principle-based flow representation by CFD approach in the aeromechanics analysis. This innovative concept, however, has not been successful almost for two decades because of the difficulty in meeting a convergence and immature in computer hardware and software

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* Corresponding author.
E-mail address: snjung@konkuk.ac.kr (S.N. Jung).

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technologies [8]. Once the proper coupling method is established, the classic two unsolved problems such as a phase shift in section lifts and an underprediction in the section pitching moments [9] have been demonstrated to be resolved in the case of UH-60A rotor [10,11]. Even with a significantly increased computational burden, a CFD–CSD coupled approach is conceived to be desired particularly for airloads and structural loads prediction of a helicopter rotor. So far, very limited work has been found for the validation of HART I data using CFD–CSD coupling except the work of Lim et al. [12] where improvements on section airloads are demonstrated over a CSD approach. However, no structural loads correlation is presented and the effect of the fuselage is neglected in Lim et al. Furthermore, the blade structural properties used are necessary to be updated.

Based on the aspects stated above, the present study is conducted to fill the gaps in the literature associated with HART I rotor. Major features of the present work are stated as: 1) improved correlations of the measured HART I rotor data are assessed using a loose CFD–CSD coupled approach; 2) the influence of a fuselage on HART I rotor is identified using both isolated rotor model and rotor-fuselage model; 3) the structural blade properties measured recently by Jung et al. [6] are implemented in the analysis; and 4) predictions on structural loads and blade elastic motions as well as the section airloads are validated against the measured data.

2. Analysis methodologies

A 3D compressible RANS flow solver KFLOW [13] is used for the CFD analysis. For timewise flow simulations, a second-order accurate, dual-time stepping scheme combined with a diagonalized alternating-directional implicit method is applied to compute the unsteady flow fields around a rotor. The inviscid fluxes are calculated using the fifth-order weighted essentially non-oscillatory (WENO) scheme, while the central differencing technique is applied to the viscous fluxes. The k–ω Wilkox–Durbin (WD+) scheme is adopted for the turbulence model. The characteristic boundary conditions using the Riemann invariant are applied to the far field boundary, whereas a no-slip condition is used at the solid wall surface. A moving overlapped Chimera grid system with the near body and the Cartesian off-body grid are employed. Either C-mesh topology grids or O-mesh based grids are formed respectively for the blade and the fuselage. Figs. 1a and 1b show the computational grid systems used for an isolated rotor model and a rotor-fuselage model, respectively, for the HART rotor. The blade grids extend 1.5 times of a chord length (c) in the normal direction, measured from the blade surface. The cell spacing for the first grid point from the wall boundary used is $1.0 \times 10 - 5c$. The off-body grids consist of an inner region which extends $4c$ upward, $3c$ below from the blade, and $1.5c$ away from the blade tip. The far field boundary is stretched up to $5R$ (blade radius), centered at the rotor hub. The cell spacing is $0.1c$ for the Cartesian off-body grids. The CFD computational grids consist of 6.4 M (million) cells for the blade grid, 29.1 M for the off-body grid, and another 2.5 M for the fuselage grid, leading to a total of about 35.0 M cells for the isolated rotor model and 37.5 M for the rotor-fuselage model, respectively.

A rotorcraft comprehensive code CAMRAD II [14] is used as the CSD analysis. CAMRAD II is characterized by multibody dynamics, nonlinear finite elements, and various level of rotorcraft aerodynamics. For the structural analysis, the blade motion is composed of the rigid body motion and the elastic deformation. The rigid body motion describes the motion of one end of a beam element, and the elastic motion is measured relative to the rigid motion. The beam elements are represented by 6 degrees of freedom (DOF) for the rigid motion and 9 DOF for the elastic motion (3 axial, 2 flap, 2 lag, and 2 torsion) that results in a 15 DOF for each beam finite element. The aerodynamic model is based on the ONERA-EDLIN unsteady airfoil theory combined with C81 airfoil table look-up. For the vortex wake representation, a free wake geometry is assumed and the formation of the tip vortices is modeled using a free rolled-up wake model. The rolled-up wake model is based on the feature that a tip vortex forms at the blade tip. In this study, the blade structure is modeled using 15 beam finite elements while the airfoil blade region is divided into 17 non-uniform aerodynamic panels with finer segments toward the blade tip, as shown in Fig. 1c. Specifically, the centers of each aerodynamic panel are aligned to coincide with the measured airloads stations to minimize the discretization error.

A loose coupling between CAMRAD II and KFLOW codes is used for the analysis [15]. The basic principle of the coupling is to exchange information between CSD-computed blade motions and CFD-computed airloads, per revolution base, to benefit the strength of the other code. The coupling iteration begins with CSD analysis using a built-in aerodynamic model. The resulting blade motions along with trim control angles are transferred to the CFD code to update the aerodynamic forces and moments. The difference in airloads between the two codes (i.e. delta airloads) is calculated and superposed to the CSD airloads for the updated blade motions and trim controls for the subsequent iteration stage. This process continues until the airloads and trim control angles indicate little or no noticeable difference compared to the previous iteration steps. It is remarked that the CFD results have a timewise interval of 0.2° ($\Delta\psi = 0.2°$) while CSD having 5° resolutions. Due to the varying resolutions in both results, appropriate data regression schemes are required to transfer data between CFD and CSD analyses. For blade motions, the interpolation in the radial direction is represented using a polynomial with the seventh order while the timewise domain is interpolated using a Fourier series containing up to the eleventh components, following the approaches given in Refs. [16] and [17]. The airloads in the spanwise direction are interpolated using a cubic spline fit whereas a random data selection at every 5° azimuth angle is applied for the timewise airloads data.

3. Results and discussion

The baseline case (BL; Dpt 140) of HART I rotor in low speed descent with an advance ratio $\mu = 0.15$ and a shaft tilt angle $\alpha_s = 4.5°$ aft (after the wind tunnel wall correction) is considered for the study. The target trim values specified are 3100 N, 11.2 Nm, and −20 Nm respectively for the thrust, hub roll, and pitching moments. The positive signs are defined respectively when the advancing side moves up and a pitch up is induced for the moments. A pitch bearing stiffness amounting 1,706 Nm/rad is adopted which has been chosen to match the measured non-rotating first torsion frequency and to represent the control system characteristic of HART I rotor. The detailed validation results are discussed in this section.

3.1. Trim convergence

Fig. 2 shows the convergent behavior of CFD–CSD coupled computations on Mach-scaled, section normal forces M^2C_n (Fig. 2a) and delta section normal forces ΔM^2C_n (Fig. 2b) obtained at 87% radial station ($r/R = 0.87$) with respect to the coupling iterations. The measured airloads data are presented for a comparison purpose. As can be seen, a clear convergence characteristic is reached with the advance of coupling steps considering that both section airloads results show no significant deviations after marching about six or seven coupling cycles. The section airloads at the initial stages of coupling present more flattened waveforms with