Loosely Coupled CFD/CSD Analysis of Helicopter Rotor in Hover with Overset Mesh Technique

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ABSTRACT

This paper presents a combination of a computational structural dynamics (CSD) and high fidelity computational fluid dynamics (CFD) analysis which is based on overset structured grid. Regarding a helicopter rotor in hover, aerodynamic loads are computed from the three-dimensional Euler/Navier-Stokes solver in overlapped grids, and blade motions are estimated from the geometrically exact rotor beam analysis. While combining those two analyses, a loosely coupled method is used and the results are validated regarding a civil transport helicopter.

INTRODUCTION

In an analysis of rotary wing aeroelasticity, it is generally difficult to predict accurately the airloads acting on the rotor blades and the resulting blade motions. It is because the flexible rotating blades experience complicated aerodynamic forces and moments, that in turn result in large elastic deformations, while interacting with unsteady aerodynamics. Furthermore, being different from the fixed wing aeroelasticity, rotary wing aeroelasticity is affected by additional different phenomena, such as reversed flow, dynamic stall, vertical wakes, and the blade vortex interaction (BVI), etc. All of these phenomena also induce excessive vibration and noise, which generally bring fatigue problems in the helicopter components, restrict the operation envelope of the helicopter in urban areas, and make the pilot and passengers feel uncomfortable. To correctly understand and alleviate these problems, an accurate analytical framework for the interactions between structure and aerodynamics is essentially required.

Over the last decade, many researchers have conducted various CFD/CSD coupled analysis and attempted to validate the results for UH-60A[1], HART-I, and HART-II rotors[2]. Lim [3] performed assessment of rotor dynamics correlation for descending flight using those three data sets, and showed a significant improvement in predicting BVI airloads from the CFD/CSD coupled analysis. Because of the rapid numerical dissipation, however, it still requires more profound investigations to predict the rotor wakes accurately.

In the present paper, a three-dimensional Euler/Navier-Stokes CFD solver is developed utilizing overset mesh technique and geometrically exact CSD solver, which are validated independently before coupled analysis. Next, two analysis models are combined using a loose coupling method, which is a typical coupling technique for the steady-state problem, such as a hovering rotor.

NUMERICAL METHOD

CFD Formulation

In order to analyze a flow near the rotor blade precisely and include the viscous effect, the following conservation form of Navier-Stokes equations is considered.

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}+\frac{\partial \mathbf{G}}{\partial z}=\frac{\partial \mathbf{E}_v}{\partial x}+\frac{\partial \mathbf{F}_v}{\partial y}+\frac{\partial \mathbf{G}_v}{\partial z} \tag{1}$$

Here, Q is a conservative variable vector and E, F, G is inviscid flux vectors. And E_V, F_V, G_V is viscous flux vectors.

For computation of unsteady flows involving moving solids, time metric and connectivity information of the overset grids are required at every time step. This additional cost can be avoided for a hovering rotor if the equations are solved in the rotating frame. For the non-inertial reference frame, source terms have to be included in the righ-hand side of Eq. (1) to account for the centrifugal acceleration of the rotating blade.

$$S=\begin{bmatrix} 0 \\ -\rho\Omega\times U \\ 0 \end{bmatrix} \tag{2}$$

where Ω is the angular velocity vector of the rotor.

In the present paper, evaluation of the inviscid flux is based on RoeM scheme[4] which is an improved version of Roe’s FDS. TVD MUSCL approach is used to obtain the second- or third-order accuracy with van leer limiter. The Lower-Upper-Symmetric Gauss-Seidel (LU-SGS) scheme, suggested by Jameson and Yoon is used as an implicit time integration method. The simple algebraic turbulence model of Baldwin and Lomax is used to estimate the eddy viscosity.

Overset Mesh Technique and Grid Deformation Algorithm

In order to represent complex geometries and flow features, a single structured mesh system may not be sufficient. Overset structured grids have the advantage in that different grids can be generated independent of each other and can be placed in the region of interest without any distortion. Unlike the block structured grid, the grid interfaces need not be matched and this greatly simplifies a grid generation process. Such flexibility is invaluable in the problems, such as rotorcraft applications in which the blades are in a relative motion to each other.

The penalty to pay, however, is the additional computating cost which is required in identifying points of overlap between the meshes and interpolation of the solution in the overlap region. Moreover, due to the interpolation procedure, there is a possibility of a loss of the conservation property of the numerical scheme. However, these errors can be minimized by proper selection of mesh structure and overlap optimization procedure.

In order to construct the updated grid system when the locations of grid points are changed by structural deformation, Delaunay graph technique is used, and it can keep the volume ratio of each mesh element. Grid system is re-constructed using the information of relative motion between the surface grid points and pre-defined reference points. A one-to-one mapping between Delaunay graph and the computational grid is conducted during the movement. Therefore, a new computational grid can be generated efficiently after the dynamic movement through the mapping while maintaining the primary qualities of the grid.

CSD Formulation

The present structural analysis is based on the mixed variational formulation by Hodges[5]. Shang implemented such formulation of a rotating beam in frequency domain, and Cheng and Kim further improved it to time domain. The formulation is derived from Hamilton’s principle which can be summarized as follows.

$$\int_{t_1}^{t_2}\int_0^l [\delta(K-U)+\overline{\delta W}]dx_1 dt=\overline{\delta A} \tag{3}$$

The internal force and moment vectors F_B and M_B, and linear and angular momentum vectors P_B and H_B are introduced as

$$F_B=\left(\frac{\partial U}{\partial\gamma}\right)^T,\quad M_B=\left(\frac{\partial U}{\partial\kappa}\right)^T,\ P_B=\left(\frac{\partial K}{\partial V_B}\right)^T,\quad H_B=\left(\frac{\partial K}{\partial\Omega_B}\right)^T \tag{4}$$

With the above equations, Eq. (3) can be written as following:

$$\int_{t_1}^{t_2}\int_0^l\left[\delta V_B{}^{*T}P_B+\delta\Omega_B{}^{*T}H_B-\delta\gamma_B{}^{*T}F_B-\delta\kappa_B{}^{*T}M_B\right]dx_1dt+\int_{t_1}^{t_2}\int_0^l\overline{\delta W}\,dx_1dt=\delta A \tag{5}$$

Expanding the variational terms in Eq. (5) with respect to u, ψ, F, M, P, and H, one can obtain the variational formulation based on exact intrinsic equations for dynamics of moving beams:

$$\int_{t_1}^{t_2}\delta\Pi_a dt=0 \tag{6}$$

The detailed expressions of Eq. (8) can be found in Ref. [6].

Discretizing Eq. (6) into N spatial finite elements, one can obtain following nonlinear governing equation:

$$F_S(X,\dot{X})-F_L=0 \tag{7}$$

where F_S is the structural operator, and F_L is the lift operator, and X is the unknown structural state variables. A time derivative of the unknown vector X is calculated by using 2nd order backward Euler method. Newton-Raphson method is used to solve the nonlinear governing equation (Eq. 7). Coupling with an aerodynamic model is implemented by the lift operator F_L.

NUMERICAL RESULTS

Flight test or experimental data for hovering rotor is quite limited for a CFD/CSD coupling analysis. Among a few of them, the UH-60A rotor in hover is adopted for comparison in present research.

Cp comparison and contour of surface pressure are given in Fig.1 and 2, respectively. Since the blade geometry of UH-60A is not completely opened to public, there is some uncertainty in the blade geometric discretization. In spite of those restrictions, the numerical results are in a good agreement with the experimental data at the most spanwise stations. Some discrepancy between the present analyses and experimental data is regarded to be originated from the different blade geometry.

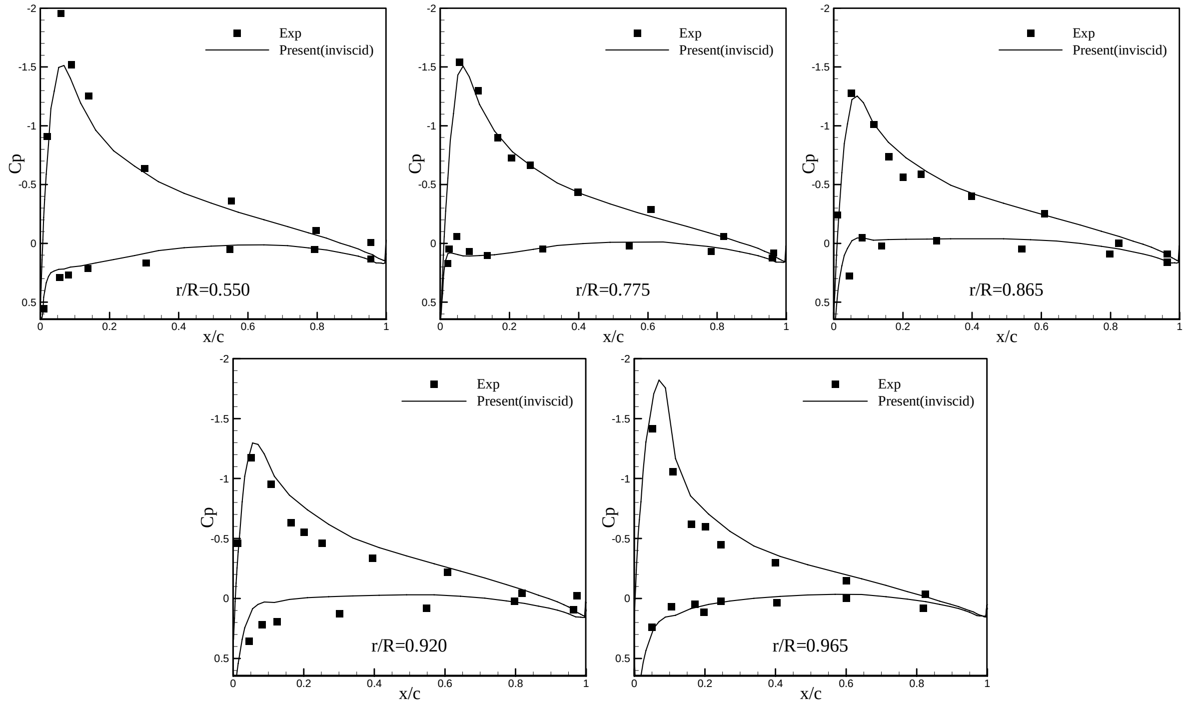

Figure 1. C_P comparison result with the experimental data for UH-60A rotor

Figure 3 shows the sectional C_T distribution of a UH-60A rotor in hover, which has been an intermediate validation target for the CFD/CSD analysis in the previous researches. As previously metioned, CFD/CSD coupling result agrees with the experimental data, but it still includes a discrepancy, especially near the blade tip. In the previous research, it is observed to be difficult to match accurately the numerical results to experimental data near the blade tip. Nevertheless, a further improvement is required for the present analysis and its updated results will be published in the future.

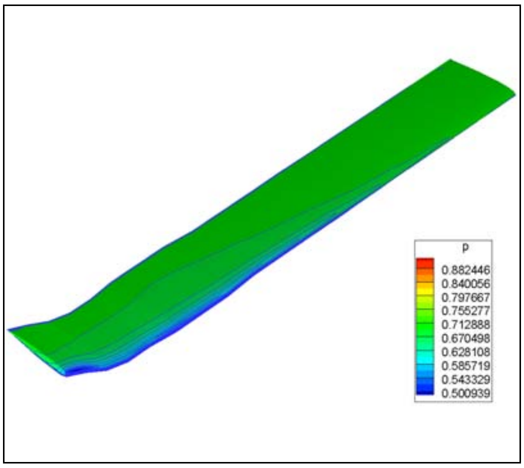

Figure 2. Surface pressure contour

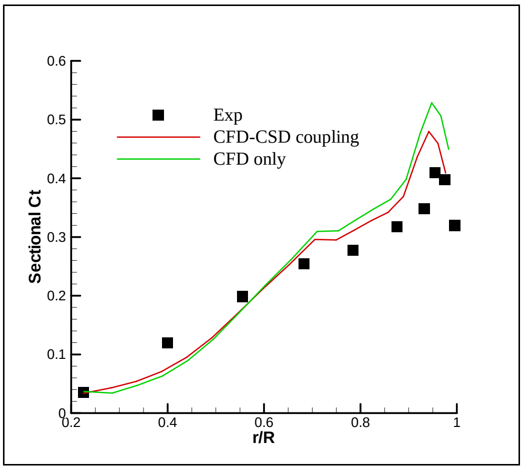

Figure 3. Sectional C_T distributions

CONCLUDING REMARKS

A loosely coupled CFD/CSD analysis is applied for a hovering rotor blade. A three-dimensional Euler/Navier-Stokes CFD solver and one-dimensional geometrically exact rotor beam CSD analyses are established and validated independently. For a UH-60A hovering flight test data, preliminary results are obtained by the present CFD/CSD coupled research. After further improvement, rotors in forward flight will be analyzed by present tools.

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