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Numerical Study of Rotor Blade Loads in High Speed Flight

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ABSTRACT

A loosely coupled analysis using a hybrid Navier-Stokes free-wake CFD methodology (GT-Hybrid) and a multi-body dynamics analysis code (DYMORE) has been applied to the 1974 rotor loads problem. Present results are compared with the original 1974 results as well as modern results from comprehensive codes, along with other CFD/CSD simulations. Considerable similarity in the results between present CFD/CSD coupled analysis and comprehensive analyses is seen. It is found that the present methodology along with other modern results shows improvements over the past methods.

1. INTRODUCTION

The prediction of loads developed on rotor blades remains a challenging problem due to the complex environment under which the helicopter rotor operates. Rotor blades experience a wide range of aeroelastic phenomena because they are thin, long and flexible. One of primary goals of rotorcraft aeromechanics research is to understand the fundamental aerodynamics and structural dynamics and their interactions which determine the helicopter rotor blade airloads and structural response. Earlier studies were focused on the development of mathematical models, solution methods, and computer codes to predict desired rotor characteristics for use by researchers and designers. With the advent of the high performance computers, computational tools have been extensively developed for improving the prediction of rotorcraft aeromechanics. (Ritu 2014)

In 1974, there was a cooperative effort, 1974 Rotor Loads Comparison, among Government, universities and industries. (Ormiston 1974) They tried to investigate the problem of blade loads prediction by comparing results from a variety of rotor codes applied to a specified common rotor and determining the relative agreement or disagreement among the results from the various codes. By using a well-defined problem as the basis for comparisons it was anticipated that the amount of agreement or lack thereof among the various codes would provide at least a qualitative measure of the collective state-of-the-art of loads prediction methods as a whole, even in the

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absence of direct comparisons with experimental data. Present authors performed a loosely coupled analysis using a hybrid Navier-Stokes free-wake CFD methodology (GT-Hybrid) and a multi-body dynamics analysis code (DYMORE) for the one of conditions from 1974 rotor loads problem. The basic objectives of this study are to compare present results with the 1974 results as well as modern results and to understand better the aerodynamic and aeroelastic characteristics as well as the modeling issues of the relatively generic 1974 rotor configuration.

2. NUMERICAL METHODOLOGY

A loosely coupled analysis is used in current calculations. The CFD solver (GT-Hybrid) and CSD solver (DYMORE) communicate in a loosely coupled manner. The delta-trim algorithm or loose coupling procedure pioneered by Tung, Caradonna and Johnson (1986) is used to obtain trim solution and convergence of the CFD/CSD coupled analyses.

2.1 GT-Hybrid (Rajmohan 2010)

GT-Hybrid is a three-dimensional unsteady viscous compressible flow solver. The flow is modeled by first principles using the Navier–Stokes Methodology. GT-Hybrid solves the three-dimensional unsteady Navier–Stokes equations in the transformed body-fitted coordinate system using a time-accurate, finite-volume scheme. A third order spatially accurate Roe scheme is used for computing the inviscid fluxes, and a second-order central differencing scheme is used for viscous terms. The Navier–Stokes equations are integrated in time by means of an approximate lower upper symmetric Gauss Seidel implicit time-marching scheme. The flow is assumed to be turbulent everywhere, and hence no transition model is currently used. The temporal change in computational cell volume is accounted for by explicitly satisfying the geometric conservation law. GT-Hybrid currently has the capability to use advanced turbulence models such as Spalart–Allmaras detached eddy simulation (SA–DES) and kinetic-eddy simulation to compute the eddy viscosity.

In the hybrid CFD methodology, the flowfield near the blade is resolved through the Navier–Stokes solution, whereas the influence of the other blades and of the trailing and shed vorticity in the far-field wake are accounted for by modeling them as a collection of piecewise linear bound and wake vortex elements, as shown in Fig. 1. The near wake is captured inherently in the Navier–Stokes analysis. The use of such a hybrid Navier–Stokes/vortex modeling method allows for an accurate and economical modeling of viscous features near the blades and an accurate “nondiffusive” modeling of the wake in the far field. The vortex model is based on a Lagrangian wake approach, where a collection of vortex elements are released from the rotor blade trailing edge and are convected downstream by a combination of the freestream velocity and the bound and wake vortex element self induced velocities. The strength of the vortex elements is based on the radial and temporal gradients of the bound circulation and the number of spanwise wake elements and wake time step increment chosen by the user. The influence of these vortices on the blade aerodynamics from the wake model is computed by appropriately specifying the vortex-induced velocities at the far-field boundary of the Navier– Stokes domain, neglecting the contribution of the elements within the CFD volume grid released from the blade. The multiple trailer wake model is based on Prandtl's lifting-line theory. For a three dimensional blade, the bound vorticity, located at the quarter-chord line of the blade is trailed into the wake from the blade tip and root. Vorticity is also shed from the blade mid-span regions because of radial changes in the bound circulation. Therefore, the single tip vortex is replaced by user-specified number of multiple vortex segments trailed from all of the blades. The trailers are equally distributed along the blade span. The strength of the vortex elements is based on radial gradient of bound circulation and number of wake trailers chosen by the user.

2.2 DYMORE (Bauchau 1998)

DYMORE is a computational structural dynamics (CSD) solver used in this study. It is a multibody finite-element code for arbitrary nonlinear elastic systems. The multibody models are constructed by connecting basic structural elements; the data for these elements are stored within an element library. Each of these elements has its own system of equations, which, when integrated, create larger and more complex equations. A schematic of the rotor multibody system in DYMORE is shown in Fig. 2. The structural elements include beams, rigid bodies, cables, springs, dampers, and various structural linkages. The code incorporates robust and efficient time integration algorithms for integrating the resulting large scale, nonlinear, differential, or algebraic equations. The rotor blades are modeled as elastic beams with geometrically exact composite beam finite-element formulation. DYMORE belongs to a class of solvers known as rotorcraft comprehensive codes. These solvers typically incorporate semi-empirical unsteady aerodynamic models for modeling unsteady aerodynamics, separated flow, and dynamic stall.

3. NUMERICAL RESULTS

3.1 1974 Rotor Loads Problem Specification (Ormiston 1974)

The rotor specified for the loads comparisons is a typical rotor with simple, well-defined characteristics. Table 1 shows details of the rotor configuration. The 50-ft diameter, three-bladed articulated rotor has rectangular, linearly twisted elastic blades with radially uniform geometric, mass, and elastic properties and zero chordwise offsets from the quarter chord. The offset hinges does not include kinematic coupling and the pitch control system was idealized to eliminate linkage kinematic effects. The coupled CFD/CSD simulation has been done for a relatively high advanced ratio (0.333) and advancing blade tip Mach number (0.895). Table 2 shows operating conditions.

3.2 Blade natural frequencies and trim solutions

Before the advent of modern methods, accurate solutions of the rotating beam problem were not trivial in 1974. This was evident from the 1974 results even for the very simple uniform blade configuration, as shown in Fig. 3. The different methods did not even use consistent fidelity modeling. The results show moderate variations among the results up to mode 6 (first torsion mode). Fig. 4 shows a conventional fan plot obtained from present DYMORE calculation. Results of DYMORE are also compared with results from another comprehensive code, called RCAS. It shows nearly complete agreement for the first five modes.

Figure 5 shows comparison of rotor trimmed forces and power from 1974 results and present simulations. The three rotor forces were all specified trim targets so that a successful trim solution with small tolerance settings should have met the target force. In 1974, like the blade frequencies, trim solutions were not trivial and approximate trim conditions were sometimes used. Nevertheless, the 1974 results varied a bit. The departures from the zero side force trim target are not significant in view of the expanded scale. Aside from the side force, the thrust and propulsive force of the present results closely match the trim targets. However, somewhat surprisingly, the variations in rotor shaft power are actually larger. The RCAS and Helios results are relatively close but UMARC and GT-Hybrid are significantly higher and this may be related to other aspects of the solutions.

3.3 Sectional Airloads

Figure 6 shows azimuthal variations of the blade normal force airloads at the 0.8R radial location. From 1974 results, significant variations are seen among simulations. Although these results did not include nonuniform inflow the differences as well as the higher frequency variations are attributed largely to dynamic stall modeling. The comparison of normal force airloads among GT-Hybrid and other results shows more consistent with each other than in 1974. In addition they do not show much evidence of retreating blade dynamic stall at 80%R.

3.4 Blade Structural Loads

Figure 7 and 8 shows azimuthal variations of blade flapwise and chordwise bending moments at 0.5R. Overall, the flapwise bending results are reasonably consistent. The present results may be a little more consistent among themselves than the 1974 results with perhaps the exception of the UMARC results. The present GT-Hybrid results are in quite close agreement with the results of HELIOS.

For chordwise bending moments, the 1974 results in Fig. 8 (left) show considerable variation among different codes. Aside from aerodynamic complexities, modeling lag dampers and flapwise and chordwise structural coupling of twisted rotating beams were partly unresolved issues at the time. This was noted for the 1974 blade rotating frequencies in Fig. 3. Interestingly, the comparison of present chordwise bending moments also show differences among the different codes.

4. CONCLUSIONS

A loosely coupled CFD/CSD analysis has been performed for the 1974 rotor loads problem. Despite the limitations of the present analyses and the lack of direct validation with experimental measurements, it seems evident that new methods are significantly improved over the 1974 methods. This is consistent with direct experimental validations obtained in recent years. While differences exist between current comprehensive analyses and coupled CFD/CSD analysis, there is considerable similarity in the results. However, the results to date are somewhat preliminary and more definitive conclusions could be obtained with refined simulations and additional simulations for other flight conditions.

Radius	20 ft
Chord	1.83 ft
Number of blades	3
Solidity	0.07
Twist, linear (from r=0 to R)	- 10 deg.
Airfoil	NACA0012
Root cutout	3.75 ft (0.15R)
Flap / lag hinge offsets	1.0 ft (0.04R)
Feathering axis, elastic axis, mass center, and tension axis locations	0.25c

Table. 1 Rotor Configuration

Tip speed	750 ft/sec
Shaft angle of attack	0 deg.
Rotor lift	16,500 lb
Rotor lift coefficient, C_L/σ	0.0897
Parasite drag area	25 ft^2
Side force	0 lb
Forward velocity	250 ft/sec
Advance ratio	0.333
Advancing tip Mach number	0.895

Table. 2 Operating Conditions

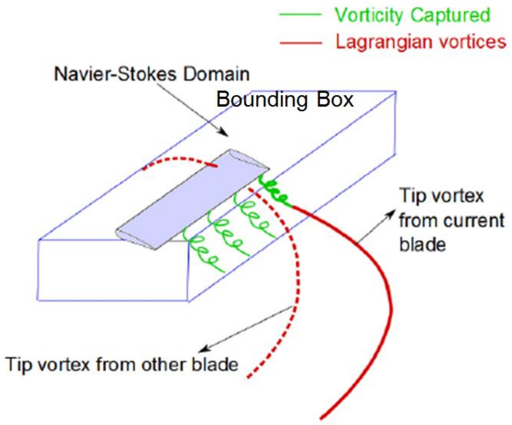

Fig. 1 Schematic of hybrid methodology

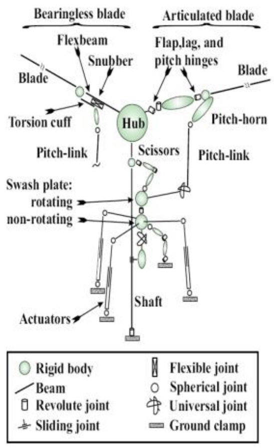

Fig. 2 Schematic of helicopter rotor model in DYMORE

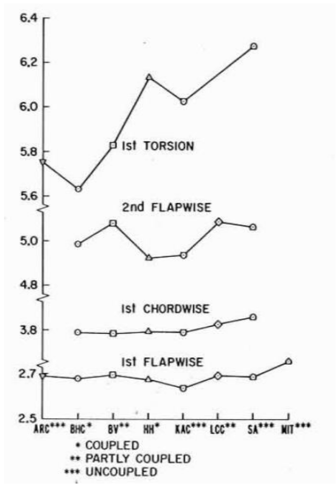

Fig. 3 Comparison of 1974 rotor blade rotating natural frequencies in vacuo (per rev.) at 100% nominal rotor speed, collective pitch = 0 deg

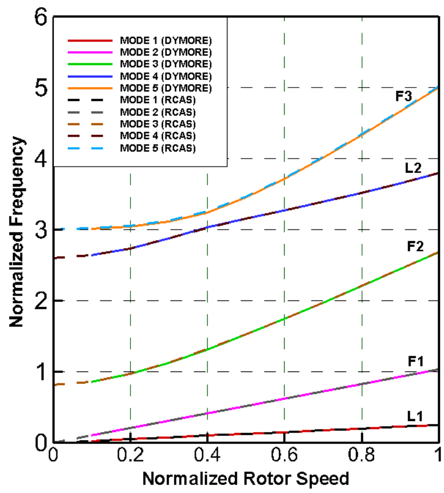

Fig. 4 Comparison of rotating blade natural frequencies (per rev) vs rotor speed

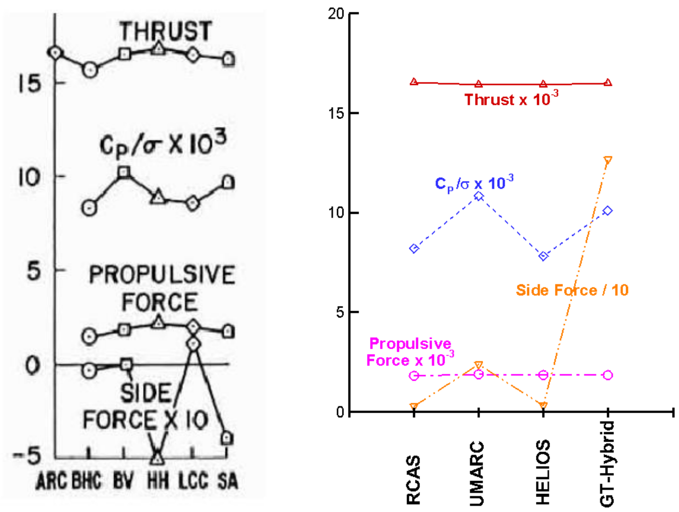

Fig. 5 Comparison of trim rotor forces and power results
(Left : 1974, Right : Present)

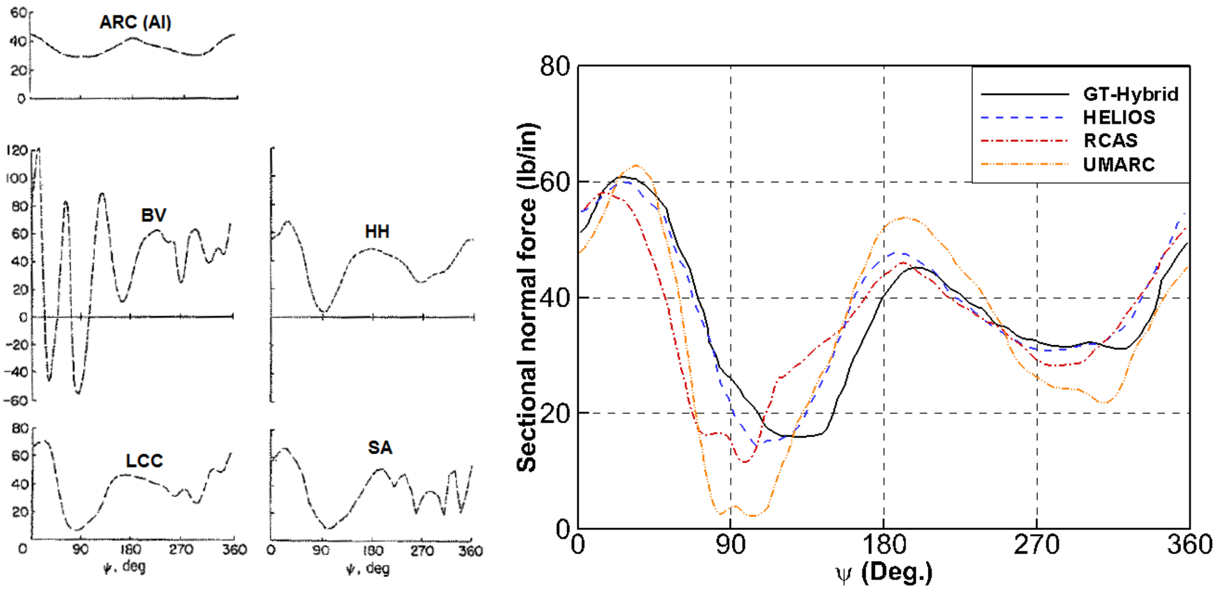

Fig. 6 Comparison of lift and normal force airloads (lb/in.) vs azimuth; r=0.8R
(Left : 1974, Right : Present)

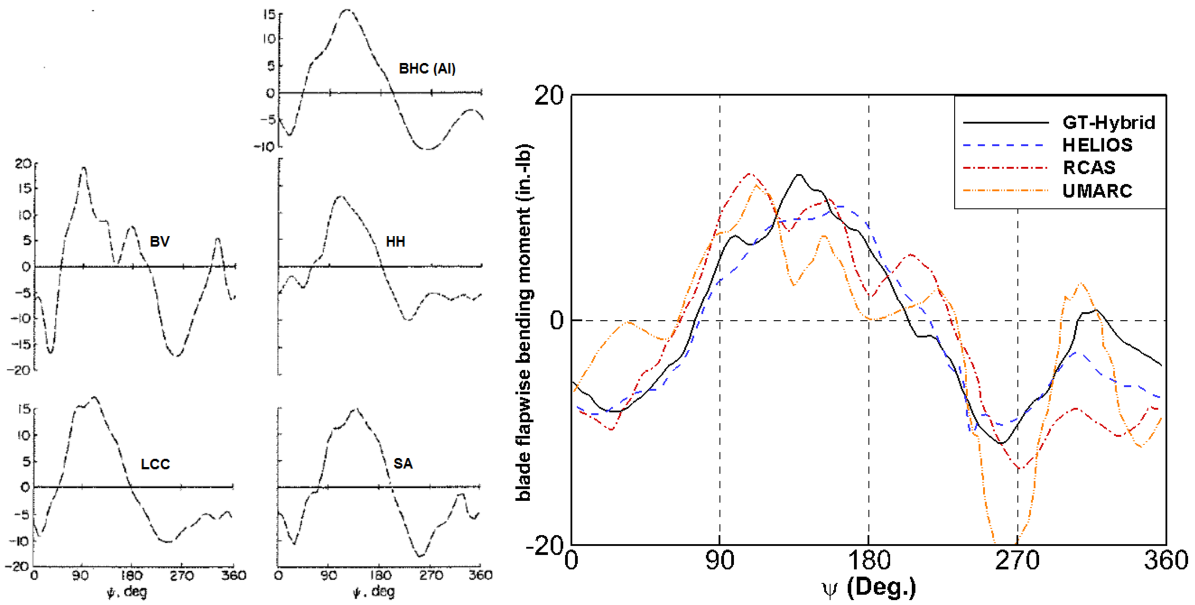

Fig. 7 Comparison of blade flapwise bending moment ($x10^{-3}$ in.-lb) vs azimuth; r=0.5R
(Left : 1974, Right : Present)

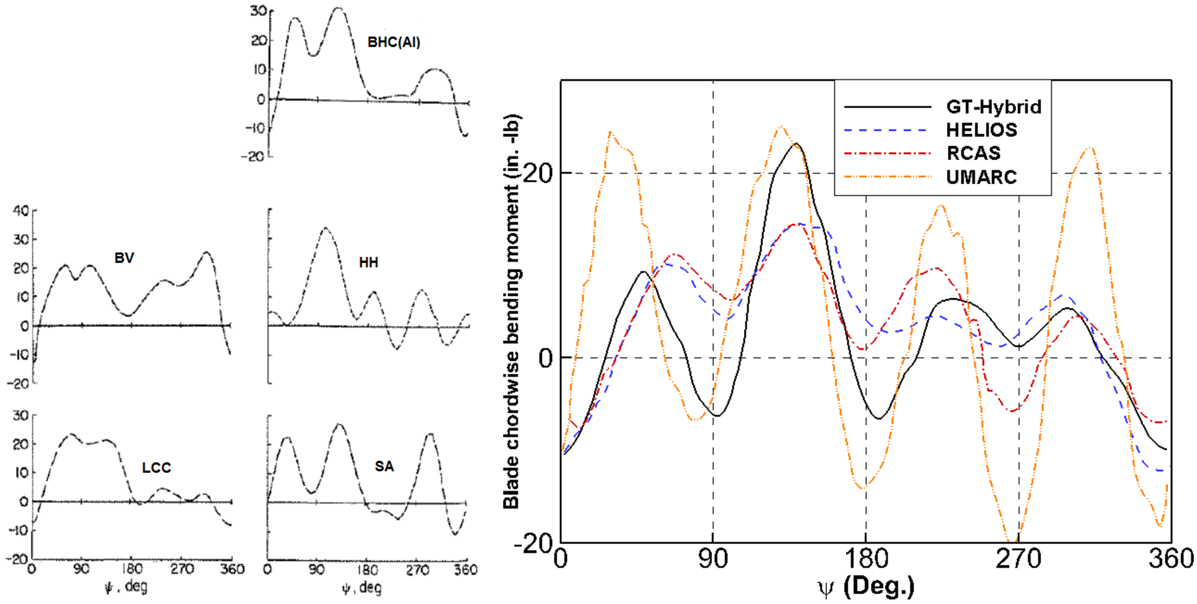

Fig. 8 Comparison of blade chordwise bending moment (x10^{-3} in.-lb) vs azimuth; r=0.5R (Left : 1974, Right : Present)

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