Coupled URANS simulation for the MDART rotor in forward flight

By S. Hahn, S. Ananthan†, G. Iaccarino, J. D. Baeder‡ and P. Moin

1. Motivation and objectives

During Phase 1A (2004–2006) of the DARPA Helicopter Quieting Program, we have newly developed and validated a coupled-simulation technique for rotorcraft analysis, in which fully compressible and incompressible CFD solvers are combined for near-blade and wake/far-field regions, respectively (Hahn et al. 2005; Hahn et al. 2006). With this outcome, Phase 1B of the project has been recently launched. In Phase 1B, additional validations are planned to be continued by further applying our tools to more exotic configurations in practice. Another main focus of Phase 1B is on exercising various elements of our computational techniques systematically in the order of increasing sophistication and complication: For example, first tackle the problem using a standalone comprehensive code with a simply modeled wake, next proceed to the wake-coupling approach which only involves CFD on a single blade, and ultimately pursue the full-scale wake capturing which would require intensive computational costs but could provide more high-fidelity results (Sitaraman & Baeder 2006). This organized procedure will allow a clear identification of benefit and limitation in lower-order models.

With these techniques and procedures, we have chosen the MDART (McDonnell Douglas Advanced Rotor Technology) rotor as our first test case of Phase 1B. The MDART rotor is a pre-production version of the MD-900 Explorer, a five-bladed bearingless rotor. With demands for detailed test data to validate the performance of a bearingless rotor, a joint wind-tunnel test program was conducted by McDonnell Douglas and NASA Ames Research Center in 1994. The hardware details and measured data are documented in Jacklin et al. (1994), Nguyen et al. (1993), Nguyen & Lau (1994), Nguyen, Lauzon & Anand (1994), Nguyen et al. (1994), Straub & Charles (2001), and Shen (2003). In this program, the MDART rotor was extensively tested over a wide range of operating conditions, including the flight speed of up to 200kt (corresponding to the advance ratio of $\mu = 0.49$) and thrusts over 10,000lbs (amounting to the thrust coefficient of $C_T/\sigma = 0.13$). Since this wind-tunnel test was intended to obtain various quantities for state-of-the-art bearingless rotor systems, comprehensive measurements were conducted regarding diverse aspects of rotor design such as performance, loads, stability, acoustics, and response to open-loop higher-harmonic control (HHC) input. Therefore, it is a proper test case for the purpose of tool validation. Furthermore, our next goal is to explore the concept of smart rotor, such as investigated in Koratkar & Chopra (2002), using our computational tools. This issue will be addressed by analyzing the performance of MDART rotor blades equipped with trailing-edge flaps. Hence, it is important for further progress of our study to first obtain firmly established computational data on the baseline MDART rotor. In this paper, we describe the wake-capturing prediction for the baseline MDART rotor using our coupling technique.

† Postdoctoral research fellow, University of Maryland.
‡ Professor, University of Maryland.
S. Hahn et al.

2. Experimental condition and computational setup

The full-scale MDAR T rotor has five blades with the chord length and rotor radius of \( c = 0.254 \text{m} \) and \( R = 5.15 \text{m} \), respectively, leading to the aspect ratio of \( R/c = 20.3 \) (figure 1). Among the various conditions covered in the experiment, we have chosen a forward-flight condition, where the flight velocity and angular speed of the rotor are \( V_\infty = 63.4 \text{m/s} \) (\( M_\infty = 0.187 \)) and \( \Omega = 392 \text{rpm} \) (\( 41.05 \text{rad/s} \)), respectively, yielding the tip Mach number \( M_t = 0.62 \) and the advance ratio \( \mu = V_\infty/(\Omega R) = 0.3 \). In this case, the tip Reynolds number is \( Re_t = \Omega R c/\nu = 3.7 \times 10^6 \). On the other hand, the shaft angle is chosen to be \( \alpha_s = -9.1^\circ \). In the Cartesian coordinate system of our computation, the forward flight is embodied by introducing a freestream velocity \((0, V_\infty \cos \alpha_s, V_\infty \sin \alpha_s)\). The cylindrical coordinates, \( r = \sqrt{x^2 + y^2} \) and \( \psi = \tan^{-1}(-x/y) \), will be also used in this paper.

To this problem, we have applied the same compressible–incompressible coupling technique as was used in our earlier study (Hahn et al. 2005; Hahn et al. 2006). We use the multi-block, structured SUmb code (Van der Weide et al. 2006) and the unstructured CDP solver (Ham & Iaccarino 2004) for compressible and incompressible flow solvers, respectively. Figure 1 shows the computational domain and grid system for each solver. The near-blade regions are solved by fully compressible SUmb (figure 1a), where the domain extends approximately to \( 5c \) from each blade tip. On the other hand, the wake and far-field regions are solved by incompressible CDP (figure 1b), where the extent of cylindrical CDP domain is \( 0 < r/c < 40.6 \) and \( -20.3 < z/c < 14.2 \). After generating regular structured-type hexahedral meshes in the CDP domain, inner holes were cut around five blades (figure 1b) using the in-house software developed at University of Maryland, which forms overlap regions between SUmb and CDP domains (figure 1c). The SUmb mesh is based on the CO-type topology (figures 1d and e). The cross-sectional shapes of the MDART rotor blades are McDonnell Douglas HH-10 and HH-06 inboard and outboard, respectively (figures 1f and g). The blade tips have a parabolic leading-edge sweep of \( 22^\circ \) and 2:1 taper ratio (figure 1f). We have set up cylindrical meshes clustered near the blade tip (figure 1h) in the CDP domain, while the core region is filled with typical H-type meshes (figure 1i). We initially tried a CDP grid system with an inner cylindrical hole and applied a slip boundary condition there. It resulted in spurious flow structures near the inner cylindrical hole and was not successful. The \( \nu^2 – f \) turbulence model (Durbin 1995) is used for both flow solvers.

A uniform computational time step of \( \Delta t = 2\pi/720\Omega \) (i.e. 720 time steps per revolution) is used for both solvers in the present study. A free-stream boundary condition, \((u, v, w) = (0, V_\infty \cos \alpha_s, V_\infty \sin \alpha_s)\), is imposed on the side and top boundaries of the cylindrical CDP domain, while the convective outflow condition is used at its bottom surface. For the blade-hole interfaces in the CDP domain, all three velocity components and four turbulence variables \((k, \epsilon, \nu^2, \text{and } f)\) are transferred from SUmb solutions to be used as the interface condition. The same seven variables are also transferred from CDP solutions to the outer surfaces of SUmb domain, where density is assumed to be constant and pressure is extrapolated from the interior SUmb solutions. This interface treatment has shown a reasonably good performance in our earlier studies. The SUmb–CDP coupling is conducted in a tight manner: i.e. all data exchange between each solver is performed at every time step. All searches, interpolations, data transfers are exclusively handled by CHIMPS (Alonso et al. 2006).

In regard to the CFD–CSD coupling, we use UMARC (University of Maryland Rotorcraft Comprehensive Analysis Code) as a comprehensive CSD code. Contrary to the
SUmb–CDP coupling, this CFD–CSD coupling is conducted in a weak manner: i.e. airload data and blade deformations are exchanged once per rotor revolution. Prior to the present coupled simulation, we first solved the same problem by weakly coupling UMARC and OVERTURNS (the overset-mesh version of TURNS; Srinivasan & Baeder 1993), and provided the fully converged UMARC–OVERTURNS blade-deformation data as the initial guess for the present coupled simulation. In this case, the flow quickly reached the periodic state. The overall configuration and computational setup are similar to our earlier experience on the UH-60A rotor (Hahn et al. 2006).
3. Results and discussion

As was described in Section 1, we first examined the performance of two rudimentary approaches for the MDART rotor case: A standalone comprehensive analysis using UMARC and a wake-coupling approach where CFD on a single blade is coupled with free-wake modeling. For the wake-coupling technique, we used UMARC, SUmb, and PWAM (Parallel Wake Analysis Module; Gopalan et al. 2006) for comprehensive, CFD, and free-wake-modeling solvers, respectively. Figures 2, 3, and 4 show comparisons of mean-removed flapwise, torsional, and chordwise bending moments, respectively, among standalone UMARC, wake-coupled, and experimental results. Figure 2 indicates that the wake-coupling approach indeed shows better agreement with the experiment than the standalone UMARC solution in flapwise bending-moment prediction. Especially noticeable is a positive bump around $\psi = 180^\circ$, shown at three inboard stations ($r/R = 0.21, 0.34,$ and $0.43$) in the standalone UMARC solution, and its elimination by the wake coupling. It results in better qualitative accordance with the experiment. Overall, the wake-coupled solution shows temporal behaviors much better correlated with the experiment, especially at two outboard stations ($r/R = 0.81$ and $0.89$). On the other hand, the advantage of wake coupling is not quantitatively prominent in torsional-moment predictions (figure 3). However, it is notable that the standalone UMARC and wake-coupled solutions show mutually out-of-phase behaviors in $150^\circ < \psi < 330^\circ$ (most distinct at the outboard location $r/R = 0.75$), and the phase information from the wake-coupling approach is in general closer to the experiment. Meanwhile, neither of the standalone UMARC and wake-coupled solutions shows a satisfactory prediction of the chordwise...
bending moment (figure 4). Most evident is the very good agreement between standalone UMARC solution and experiment at $r/R = 0.21$, which leaves room for further investigation. In general, the wake-coupled solution does not properly represent the high-frequency contents and shows much smoother behaviors than the experiment, while the standalone UMARC solution exhibits erroneous phase prediction. Therefore, a high-fidelity wake-capturing approach is believed to play an important role in the baseline MDART rotor prediction.

Figure 5 shows airload contours on the rotor disk obtained from the coupled SUmb–CDP simulation, where the mean airload is removed as was done in Sitarman & Baeder (2006) and Hahn et al. (2006). The overall trend is similar to what was observed in the UH-60A rotor for the high-speed forward-flight condition (C8534): i.e. negative normal force and pitching moment on the advancing side ($90^\circ < \psi < 180^\circ$) and strongly positive normal force near $\psi = 360^\circ$. The inboard normal-force distribution also shows a similar behavior to that in the UH-60A C8534 condition. Currently, no experimental data are available about normal/chordwise force components and pitching moment. Therefore, as an alternative to validate the present computation, we compared the results of coupled SUmb–CDP simulation with those from OVERTURNS computation. Figures 6, 7, and 8 show comparisons of normal and chordwise force components and pitching moment, respectively, between two different simulations. In general, the extent of agreement is very good in all three airload components. In particular, the accordance shown in the normal and chordwise force components is almost perfect at all radial locations, even though different turbulence models are used for each solver (Spalart–Allmaras and $v^2/f$ for OVERTURNS and SUmb–CDP coupling, respectively), which again confirms the
Figure 4. Time histories of the mean-removed chordwise bending moment at different radial locations. Legends are the same as in figure 2.

Figure 5. Mean-removed airload distribution on the rotor disk: Normal (left) and chordwise (middle) force components and pitching moment (right). Arrows denote the flight direction.

The suitability of our compressible–incompressible coupling technique for rotorcraft applications.

Figure 9 shows instantaneous vortical structures represented by iso-surfaces of $q_2 \equiv -\partial u_i / \partial x_j \times \partial u_j / \partial x_i$. Most of the typical flow features in high-speed forward flight are well captured in the present simulation. The most dominant flow feature is the long trail of tip vortices observed on the retreating side, whereas small-size vortices are also found to be shed near the rotor root. Thin vortex sheets formed along the entire blade span are also evident especially on the retreating side.
Figure 6. Time histories of the normal force component $C_n$: , SUmb–CDP coupling; , OVERTURNS.

Acknowledgments

This work is supported by the Defense Advanced Research Projects Agency (DARPA) of the United States Department of Defense.

REFERENCES


Figure 7. Time histories of the chordwise force component $C_c$: solid, SUmb–CDP coupling; dashed, OVERTURNS.


Coupled URANS simulation for the MDART rotor

Figure 8. Time histories of the pitching moment $C_m$: ––, SUmb–CDP coupling; \textcolor{red}{--}, OVERTURNS.

Figure 9. Iso-surfaces of $q_2$ at $\Omega t/2\pi = 4$. 


