Aeromechanics & Aeroacoustics Predictions of the Boeing-SMART Rotor Using Coupled-CFD/CSD Analyses

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MOTIVATION

This paper will highlight helicopter aeromechanics and aeroacoustics prediction capabilities developed by Georgia Institute of Technology, the Pennsylvania State University, and Northern Arizona University under the Helicopter Quieting Program (HQP) sponsored by the Tactical Technology Office of the Defense Advanced Research Projects Agency (DARPA). First initiated in 2004, the goal of the HQP was to develop high fidelity, state-of-the-art computational tools for designing advanced helicopter rotors with reduced acoustic perceptibility and enhanced performance. A critical step towards achieving this objective is the development of rotorcraft prediction codes capable of assessing a wide range of helicopter configurations and operations for future rotorcraft designs. This includes novel next-generation rotor systems that incorporate innovative passive and/or active elements to meet future challenging military performance and survivability goals.

Phase I of the HQP program focused on the development of prediction methodologies by coupling comprehensive structural dynamics (CSD) analyses to computational fluid dynamics (CFD) codes. For this phase of HQP, efforts were centered on validating these prediction methodologies for several conventional rotor. The use of coupled DYMORE/OVERFLOW/PSU-WOPWOP codes developed by the Georgia Institute of Technology and the Pennsylvania State University team demonstrated significant improvements in prediction accuracies and correlations [1] over classical stand-alone comprehensive methods in all aspects of aerodynamics, structural and acoustics responses of the rotor. Overall, these observed improvements were on par with previous and/or other concurrent CFD/CSD efforts [2, 3, 4].

In 2007, DARPA extended the HQP effort (Phase IB) to investigate the robustness of these CFD/CSD methodologies for unconventional rotor designs that utilize innovative on-blade active controls for dynamic tuning. An active flap rotor currently under-development at Boeing (i.e. the Boeing SMART rotor) was selected as the candidate for this code validation effort. Participants were asked to make blind predictions for a number of selective HQP-designated flight conditions prior to the full-scale rotor testing in the 40- by 80-Foot Wind-Tunnel of the National Full-Scale Aerodynamics Complex (NFAC) at NASA Ames Research Center in 2008. In addition, rotor performance, blade structural load and acoustics data were also acquired for an expanded test matrix, covering both baseline (no active flap excitations) and active flap test points, at other flight conditions [5, 6, 7].

This paper will report on the application of the DYNMORE/OVERFLOW/PSU-WOPWOP codes to predict the aeromechanics and aeroacoustics features of the Boeing-SMART rotor. In particular, additional CSD/CFD code refinements and modeling strategies, specifically developed for addressing the unconventional Boeing-SMART rotor design with active flap, will be reported. Results from these code refinements will also be demonstrated to show good correlations with experimental data.

EXPERIMENTAL SETUP

The SMART rotor test in the NFAC wind tunnel [5, 6, 7] was a joint effort by DARPA, NASA, Army, and Boeing, with participations from the University of California at Los Angeles, Massachusetts Institute of Technology, and the University of Maryland. A modified full-scale MD 902 Explorer rotor with on-blade piezoelectric-actuated trailing-edge flap was used to demonstrate the capabilities of active-flap technology in forward flight. The 5-bladed bearingless rotor has an HH-10 (12% thick) airfoil that transitions to the HH-06 (9.5% thick) airfoil beginning at r/R=0.74. The blade region from 0.93*R* to the tip has a parabolic leading-edge sweep (22° at the tip) with straight trailing edge and a 2:1 taper ratio. The 35% chord active flap, which spanned radially between 0.74*R* to 0.92*R*, with piezoelectric actuators embedded in the blade spar at 0.74*R*. The actuators are designed to drive the trailing-edge flap at frequencies from two-per-rev (2P) up to six-per-rev (6P) with as much as a 6° amplitude. The wind tunnel setup and microphone locations are shown in Figures 1 and 2.

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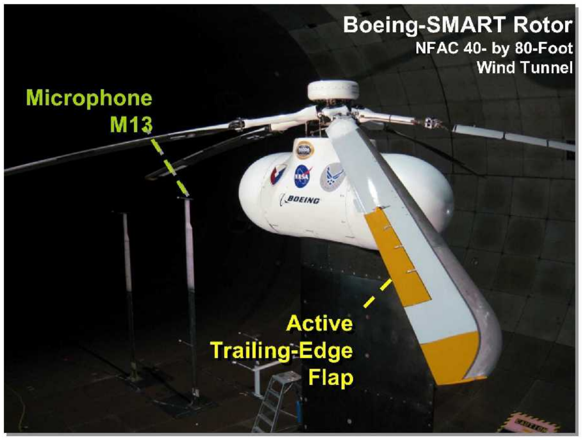

Figure 1. Boeing-SMART Rotor in the NFAC 40- by 80-Foot Wind Tunnel

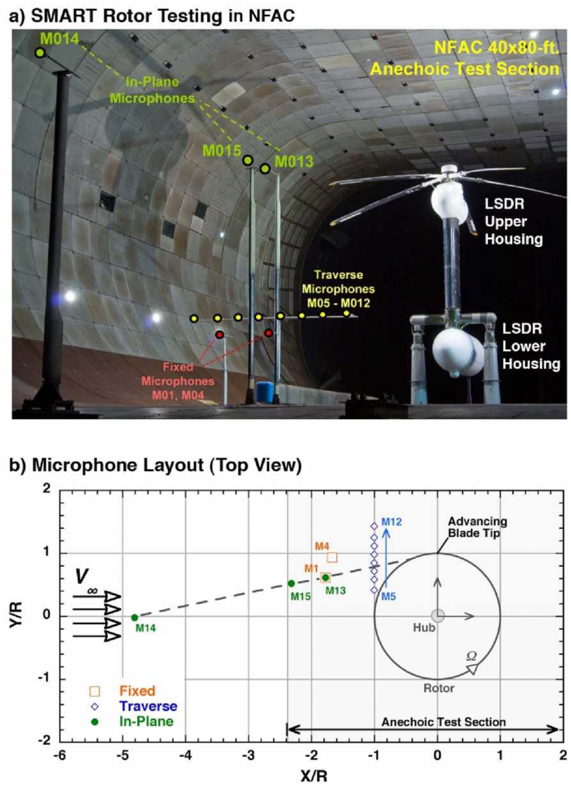

Figure 2. Microphone positions installed for Boeing-SMART Rotor

COMPUTATIONAL APPROACH

DYMORE Model

Dymore is a finite element based tool for the analysis of nonlinear flexible Multibody systems like rotor blades. The flex beam had five cubic beam elements and the blade used 27. The flap was modeled as 8 cubic beam elements connected with five connecting brackets to the main blade.

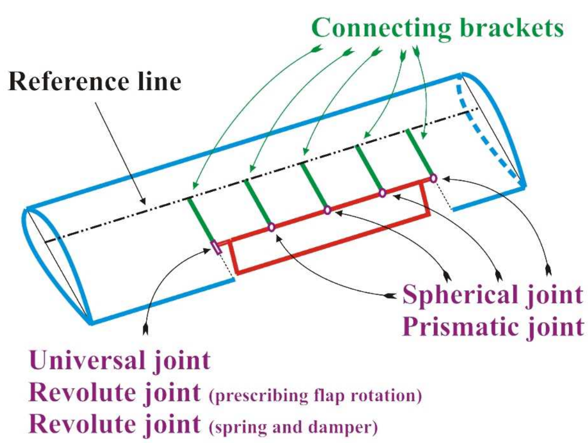

Figure 3. DYMORE model of the SMART Rotor Flap

OVERFLOW Model

OVERFLOW version 2.0y was modified at Georgia Tech during the first phase of the DARPA Helicopter Quieting Program. OVERFLOW is a compressible Navier-Stokes code that uses structured overset grids to resolve complex geometry. Chimera Grid Tools was used to create overset body fitted grids for the SMART Rotor. The edges and gaps of the flaps were modeled with tip caps to accurately resolve the flow in the gaps and tip loss effects at the edge of the flap as shown in Figure 5. In total, thirteen near body grids totally 1.7 million points were used to model each rotor blade. The entire domain consisted of approximately 20 Million grid points. Due to the very small gaps between the flap and the main blade, several high density xrays were used for hole cutting. This leads to a very large Xray file and domain connectivity consumed approximately 50% of the total computational time. For initial calculations, the Spalart-Allmaras turbulence model was used with 1/20° time steps.

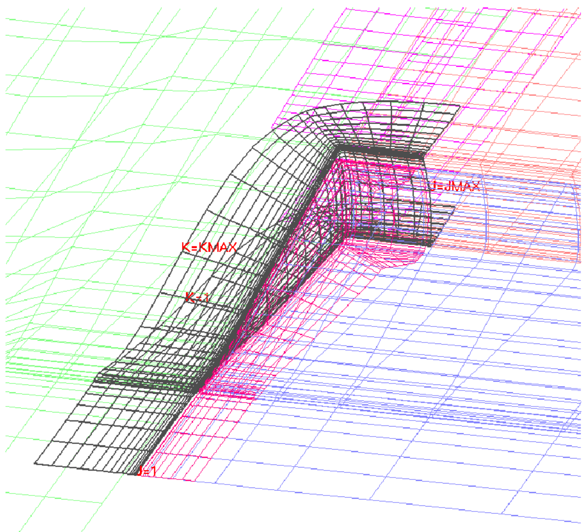

Figure 4. Computational surface grids near flap edge (every other point in each direction shown).

PSU-WOPWOP Model

PSU-WOPWOP is an implementation of Farassat's Formulation 1A of the Ffowcs Williams–Hawkings (FW-H) equation. PSU-WOPWOP is able to compute the acoustic pressure at any observer point or grid of observers from several different types of sound source definitions. The blade geometry and either surface pressure or section loading can be used in PSU-WOPWOP. PSU-WOPWOP is used to predict the noise from deformable on blade surfaces and/or off body permeable surfaces which surround the geometry to capture HSI noise.

PRELIMINARY RESULTS

During the DARPA Helicopter Quieting Program, five different cases were run and are summarized in Table 1. The MDART rotor has the same geometry and structural properties as the SMART rotor without active flaps.

Table 1. Cases run during DARPA HQP

Case	C_T/σ	α_{shaft}	μ	M_{adv}	Flap Schedule
MDART	0.08	-9.1°	0.3	0.805	n/a
SMART 1	0.08	-9.1°	0.3	0.805	δ=2°sin(5ψ+90°)
SMART 2	0.08	-9.1°	0.3	0.805	δ=2°sin(3ψ+60°)
SMART 3	0.07	-9.1°	0.38	0.805	δ=1°sin(5ψ+180°)
SMART 4	0.075	+1.5°	0.2	0.746	δ=2°sin(2ψ+240°) +1°sin(5y+330°)

Preliminary acoustic results are compared to the measured acoustic results in Figures 5 and 6. For the zero flap deflection case, permeable off body acoustic surfaces were used. For the SMART 2 case, on blade impermeable acoustic surfaces were used.

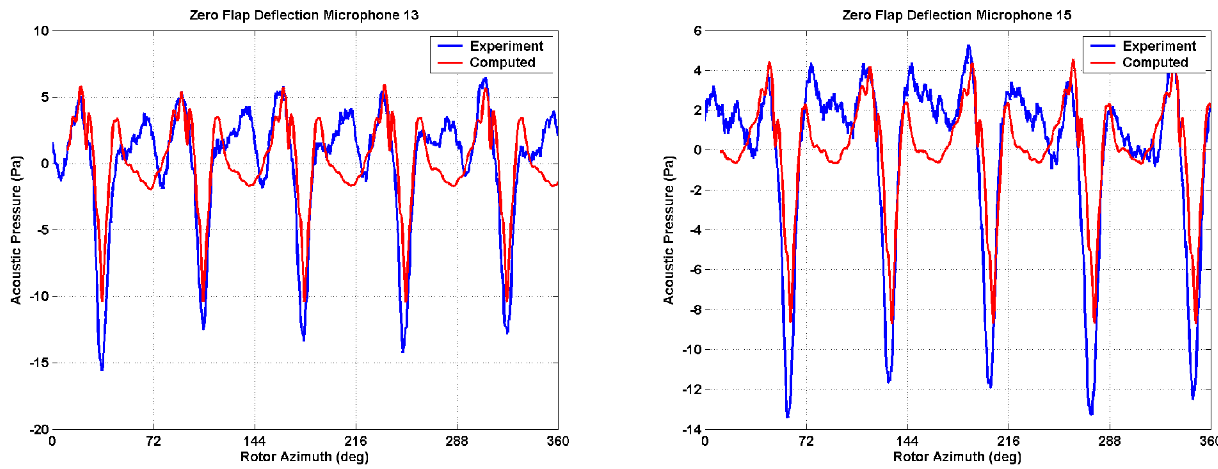

Figure 5. Preliminary Acoustic Results for Zero Flap Deflection (MDART case)

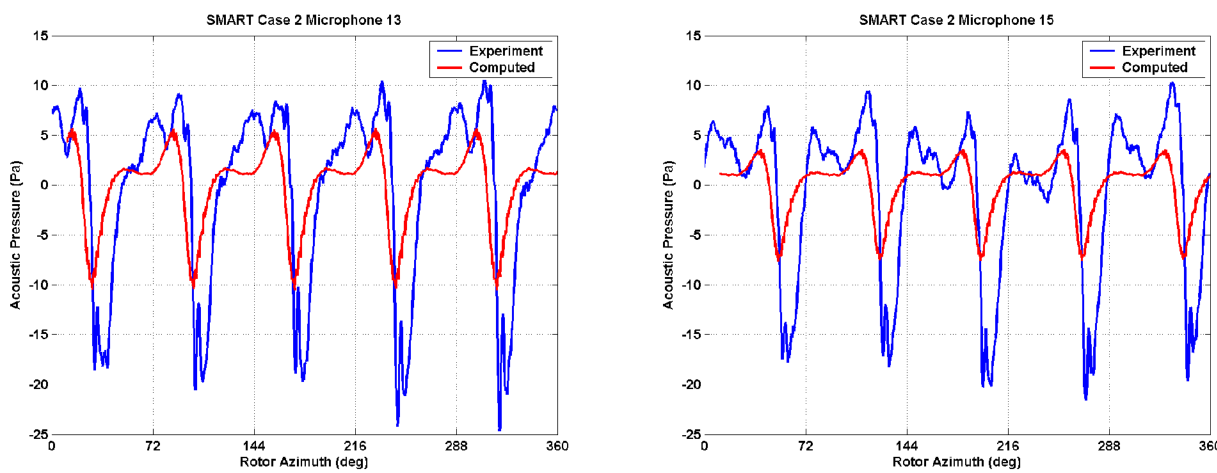

Figure 6. Preliminary Acoustic Results for SMART Rotor Case 2.

Additional Work to be presented in the full paper

- The effect of the flex beam stiffness will be examined. Preliminary indications are that the flex beam tested was roughly four times stiffer than originally expected. The stiffness of the beam is currently being tested. Cases will be rerun with the appropriate flex beam stiffness.
- The sensitivity of results to on blade and off blade acoustic surfaces and flap schedule will be documented.
- The acoustics on the high speed (155 knots) forward flight case with zero flap deflection will be computed and compared to experimental data.
- The effect of modeling the flap as a separate element in the CFD and CSD codes will be examined .

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