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VALIDATION OF THE PROCEDURES

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Approach

Assessing the fidelity of a complex system or analysis in a comprehensive manner is always an ambitious task. Validation of the same system, while providing objective proof of concept, increases the difficulty of the job by requiring all subsystems to be verified. Design methodology, especially for rotorcraft, needs a comprehensive validation procedure because of the interdisciplinary nature of the system. Both tool validation of the individual disciplines and proof-of-design for the entire system must be addressed. A primary goal of this activity is the comprehensive validation of all critical steps in the design integration process.

The ability to synthesize a design depends, to a large extent, on the correct prediction of critical phenomena. For a rotor system design which includes performance, dynamics and structural goals, the aeroelastic characteristics of the blade and stresses (for example) would be critical to know. Once the prediction fidelity of the rotor's phenomenological events is proven, parametric sensitivity of these design tools must be examined, since obtaining a global design will depend on quantifying the effects of controlled changes about some initial design.

Also of interest for rotor design validation is the evaluation of techniques for modifying a design. Techniques for changing performance, vibratory loads and material properties in a controlled way become invaluable design tools, but only if their consistency has been proven. Such techniques might include structural tailoring, modal alteration, and airfoil and planform variations.

Following the assessment of these design building blocks, their integration must be evaluated. For this to be an objective measure of rotor design performance, several conditions should be met. The rotor task and mission for the optimized rotor system should not be beyond the range of validity for which the phenomenological building blocks were assessed. Furthermore, the baseline rotor system should be one

which satisfies most of the design constraints and for which descriptive data are available.

The goal of the first phase of this project is to design and validate a rotor system which accomplishes a challenging mission and task. One candidate set of mission specifications is given in table 4.

The sequence of validation will focus on the verification of the integrated design system and both optimized and baseline rotor designs in model and full scale. In the process, the concurrent assessment of the critical phenomena analyses and modifying techniques will be made.

Sequence of Test Problems

As already mentioned, the analyses used herein for aerodynamics, dynamics, structures, and acoustics prediction are, respectively, CAMRAD (ref. 14), a finite element code or CAMRAD, Coupled Beam Analysis (ref. 10), and WOPWOP (ref. 28). Each of these analyses provide information which can be used to predict design performance and design sensitivity. Several tests are ongoing or planned to evaluate the input requirements for these modules as well as the accuracy of the individual modules. The investigations of these tools range from those which are basic to rotor design but are not highly sensitive to small perturbations in the design, to those techniques which, in fact, could drive primary design variables. Some examples follow.

Validating the basic rotor environment prediction tools.- The local rotor inflow drives the rotor's performance, loads and acoustic characteristics. Prediction of this primary phenomenon has been elusive (ref. 40). A comprehensive mapping of this important parameter has been accomplished at the Langley Research Center by a significant investment in materiel and personnel. Although the mean flow may not be highly sensitive to small rotor changes, there are indications that prime variables measurably affect both the mean and time dependent inflow velocity field. Global

codes which are design coupled need this information if basic design decisions are to be effected in an automated manner.

Another key rotor phenomenon which drives airloading and hence, acoustic design constraints, is blade vortex interaction (BVI). The WOPWOP code can predict this high frequency noise source as well as the low frequency loading and thickness noise harmonics. How well the BVI prediction can be made depends on the quality of the aerodynamic input. Proving the fidelity of this acoustic source prediction relies heavily on experiments designed to specifically probe this area of fluid mechanics (ref. 41).

Structural mechanics is a strong design driver and couples with other disciplines in all phases of the plan. Even as a separate discipline it can provide innovative structural concepts for rotors, but those predicted characteristics need to be proven if advantage is to be taken of them by, for example, aerodynamic design requirements. A series of experiments to explore the predictability and parametric sensitivity of composite couplings is underway (ref. 42). The ability to design and build a rotor blade structure which is efficiently strong for steady and oscillatory loads and which also provides useful couplings for rotor performance, dynamics and stability enhancement is the goal.

Rotor aerodynamic design usually includes multimission requirements. Even a point design must hover and transition to forward flight. The ability of aerodynamic codes to predict the performance sensitivity of geometric design variables is a controversial issue. A parametric study has been undertaken (ref. 43) to assess the rotor's performance variability with controlled geometric changes, while all other variables are held constant.

Higher order validation of the prediction tools. - The coupling of rotor aerodynamics, dynamics, and structures is, of course, the challenge which this design procedure faces. The phenomenological building blocks just mentioned must be

combined in a systematic manner, the success of which is traceable. Several multidisciplinary studies are ongoing to accomplish this.

An improved design for the UH-60 Growth BLACK HAWK rotor (ref. 22) achieved its performance goals but incurred generally higher blade loads. A brief attempt at passive dynamic tuning using a modal shaping technique resulted in both unchanged and improved designs, depending on the numerical model used to predict the best location for nonstructural mass. In order to more fully explore the coupled aerodynamic/dynamic design drivers, model blades with spanwise variable nonstructural mass inside an advanced blade have been prepared for tests in the Langley Transonic Dynamics Tunnel (TDT). These model blades (denoted GBH-T) will also be available to validate the dynamic optimization procedures described previously.

Large changes in rotor rpm have historically been avoided in the operation of modern helicopters. As previously mentioned, the effect of rotational speed on most design disciplines is large. In order to use that variable in a design, the coupling effects between disciplines must be well known. The Aerodynamically and Dynamically Advanced Multi-Speed (ADAM) Rotor project (ref. 44) is currently exploring both the performance and dynamic opportunities and challenges of large rotor rpm variations.

Blade-to-blade variability, well known for its effect on vibration, also influences performance and acoustics (ref. 45). The use of this alteration of rotor state is unpredictable by most of today's global codes since they either assume perfect blade track, or the parameter sensitivities which create a maverick blade are not well-known. In order to address the latter problem, a series of representative aerodynamic blades with parametric internal changes are soon to be tested at Langley for out-of-track response to single blade inertial, elastic, controls and aerodynamic perturbations. Once the response of a blade to these changes becomes predictable, another "degree-of-freedom" will be possible for the designer and, ultimately, for an optimization procedure.

Validation of an overall rotor design.- In addition to testing the fidelity of the individual prediction tools, the final design of the rotor system must be verified in terms of satisfaction of design constraints and minimization of the objective function. First, experimentally verifying the satisfaction of the design constraints can be achieved in several ways. One way is a scale model test of both baseline and optimized rotors in an environment which simulates the imposed mission while affording a minimum of test "excuses." The model rotor should be at least 1/5 geometric scale and fully Mach scaled, with dynamic similarity. The wind tunnel and model fixed system should be chosen to provide a measure of constraint matching for acoustics and stand frequency avoidance. Following this with a full-scale test of the same configurations would enhance the design's credibility.

Second, assuring minimization of the objective function, is more difficult. Not only does the advanced rotor need to perform better than the baseline in the areas of aerodynamics, vibration, and acoustics, but a determination of minima must be made. This will, in all likelihood, involve perturbation of the advanced rotor's state and characteristics in the neighborhood of the predicted optimum design. Such a process is laborious and hardware intensive. It is envisioned that the parametric variations on this advanced model rotor will be guided by the validation of the predictive tools. Again, a full-scale test of the rotor design, with results compared to the baseline, would be ideal. Considering the minimization of objective functions, the full-scale article should have some variability also, and this will be guided by the model test results.

SCHEDULE AND MILESTONES

The near term schedule and milestones for the integrated optimization procedure are shown in Figure 12. This schedule goes through the completion of phase 1 including the design, fabrication, and testing of the rotor test article which will be used to validate the overall phase 1 procedure. The schedule also includes the

completion of the phase 2 development and a significant portion of phase 3. All of the items in the milestones have been mentioned in the paper to some extent.

There is a certain amount of overlap among the phases. For example, the formulations of the phase 2 and phase 3 optimization problems take place during phase 1. The development of acoustic sensitivity analysis and airframe dynamic sensitivity analysis which are needed for phases 2 and 3 respectively are to be initiated during phase 1. This overlapping is essential in the case of the sensitivity analyses since they are long lead-time developments and represent ground-breaking research.

It is again emphasized that validation is a continuing and crucial feature of the work as evidenced by a validation line in the schedule. Although the validation line is contained within the phase 1 portion of the figure, it is understood that validation of the procedures is a continuing activity beginning with the initial optimization development step of each phase, through the analytical/test comparisons for the test article which will certify the overall procedure.

CONCLUDING REMARKS

This paper has described a joint activity involving NASA and Army researchers at the NASA Langley Research Center to develop optimization procedures aimed at improving the rotor blade design process by integrating appropriate disciplines and accounting for all of the important interactions among the disciplines. The disciplines involved include rotor aerodynamics, rotor dynamics, rotor structures, airframe dynamics, and acoustics. The work is focused on combining the five key disciplines listed above in an optimization procedure capable of designing a rotor system to satisfy multidisciplinary design requirements.

Fundamental to the plan is a three-phased approach. In phase 1, the disciplines of blade dynamics, blade aerodynamics, and blade structure will be closely coupled, while acoustics and airframe dynamics will be decoupled and be accounted for as effective constraints on the design for the first three disciplines. In phase 2,

acoustics is to be integrated with the first three disciplines. Finally, in phase 3, airframe dynamics will be fully integrated with the other four disciplines. This paper dealt with details of the phase 1 approach. The paper included: details of the optimization formulation, design variables, constraints, and objective function, as well as details of discipline interactions, analysis methods, and methods for validating the procedure. Three sections of the paper deal with the individual disciplines of rotor aerodynamics, rotor dynamics, and rotor structures. In each section, the appropriate design constraints, design variables, and analytical details for computing appropriate responses are described. Two sections of the paper describe how the acoustics and airframe dynamics behaviors are incorporated as constraints into the design procedure. For example, acoustics imposes a local Mach number constraint on the blade velocity and angle of attack; and airframe dynamics imposes constraints on the rotor blade natural frequencies to avoid ground resonance through coalescence of blade and airframe frequencies. The plan for validating the components of the design process was described and the strategy for overall validation of the design methodology was defined. These validations are viewed as critical to the success of the activity and are viewed as the primary products of the work. Finally, some representative results from work performed to date are shown in the appendix. These include aerodynamic optimization results for performance, dynamic optimization results for frequency placement, optimal placement of tuning mass for reduction of blade shear forces, and blade structural optimization for weight minimization subject to strength constraints.