ADVANCES IN MODELING AND SIMULATION OF ROTORCRAFT NOISE AND ASSOCIATED IMPACTS ON SURVIVABILITY

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ABSTRACT

The acoustic signature of a rotorcraft is often the primary means of detection and identification by enemy forces in the modern battlespace. Additionally, this detection is often accomplished without the need for the sophisticated sensing equipment required for other signature components. While this vulnerability has existed for many generations of rotorcraft, the tools for predicting the acoustic signature and understanding its impact on mission survivability have lagged in development. This is partially due the need for development of multidisciplinary knowledge and capability to predict the aerodynamic performance, structural dynamic response, near-field acoustic character, far-field atmospheric propagation and human perception as well as the historical lack of required computational resources. The advent of cheaper and more ubiquitous computational resources at the all levels in the rotorcraft community alleviated the later issue and left the need for a significant investment to address the former.

Approximately four years ago, DARPA made this investment and identified teams of researchers guided by an advisory panel made up of industry and government experts aimed at developing the required assets. The DARPA funded Helicopter Quieting Program was initiated to focus on developing a suite of tools appropriate for use by the designer to predict the acoustic signature of rotorcraft. In the last year, the focus was expanded to leverage the signature prediction capabilities and develop tools appropriate for the mission planner and warfighter that enable visual analysis of the impact of signature change on survivability and operational effectiveness. The end product of this effort was three tool suites, verified using experimental data, capable of predicting the aerodynamic performance and acoustic signature of modern main rotors and the tools necessary to show the impact of signature changes on the mission effectiveness of the vehicle.

1 INTRODUCTION

The computational analysis a main rotor on a modern rotorcraft is a multi-disciplinary problem requiring combined expertise and resources from many technical areas as described in Figure 1. The fundamental principles and physics governing the production of aerodynamic loads, the dynamic structural response and noise for the main rotor of modern rotorcraft are well understood, as documented by Potsdam, et al., 2004. However, a comprehensive analysis capability employing state-of-the-art high fidelity computational analysis in each of the multiple disciplines had not previously been realized due to a combined lack of high-end computational resources and of investment from government or industry. The advent of cheaper and more ubiquitous computational resources at the all levels in the rotorcraft community alleviated the later issue and left the need for a significant investment to address the former. Approximately four years ago, DARPA made this investment and identified teams of researchers guided by an advisory panel made up of industry and government experts aimed at developing the required assets. The DARPA funded Helicopter Quieting Program was initiated to focus on developing a suite of tools appropriate for use by the designer to predict the acoustic signature of rotorcraft.

Due to the significant coupling of aerodynamic loads and structural response responsible for the production of main rotor noise, it was understood that the analysis would require integration of technical expertise and computational analysis from multiple technical disciplines. Additionally, to provide an analysis and prediction capability that would be credible to the rotorcraft government and industry communities, a level of oversight in the development of the tool sets was required. Moreover, development of the codes required verification against well known datasets for conventional rotorcraft analysis and against experimental data sets of a novel rotorcraft. The DARPA Helicopter Quieting Program was therefore structured to have three independent teams of researchers developing the tool suites under the review of an Advisory Panel made up of subject matter experts from the government and industry communities. The

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development was closely coupled with periodic progress reviews and program milestones were focused on direct and blind comparison with experimental data.

The three teams of researchers included the Georgia Institute of Technology and Penn State University, the University of Maryland and Stanford University and Teledyne Sciences Corporation (formerly Rockwell Sciences Corporation). Each of the teams proposed solution methodologies for signature prediction that leveraged various tools available to predict each segment of the solution shown in Figure 1. These tools included codes for Computational Fluid Dynamics, Computational Structural Dynamics and Computational Acoustic Analysis. While the underlying codes had previously existed in some form to address each component, the teams recognized the need for significant development in each tool for application to the rotorcraft problem and for integration of the tools into single architectures. The resulting effort developed and initially validated three tool suites against experimental data collected on conventional rotorcraft designs. Following this initial effort, a follow-on series of computations coupled closely to an experimental test of an advanced rotor design integrating active lift augmentation was used to validate the tools against novel rotorcraft designs. The results from each of these validation efforts will be presented to show the significant capabilities and improvements over the previous state-of-the-art.

Toward the end of the first phase of the program, an effort was started to analysis the impact of acoustic signature reductions on the survivability and operational effectiveness of the rotorcraft. This initial effort exposed the fact that the complete capability to analyze the impact and display it in a manner meaningful to the designer, mission planner and warfighter did not exist. Based upon this experience, DARPA expanded the focus of the program to address this deficiency. This new direction developed the necessary propagation modeling, environmental modeling and human perception modeling and culminated in a new tool called Advanced Propagation and Perception Analysis Routines (APPeAR). The tool is capable of taking a vehicle acoustic signature produced as the result of measurement or prediction, setting it in a realistic model of the tactical environment and displaying metrics of the resulting vehicle operational effectiveness.

2 VERIFICATION FOR CONVENTIONAL ROTORS

During performance of the first phase of the Helicopter Quieting Program, the three teams were tasked with making calculations of conventional rotorcraft including the UH-60 and several model scale tests for which the rotorcraft community had

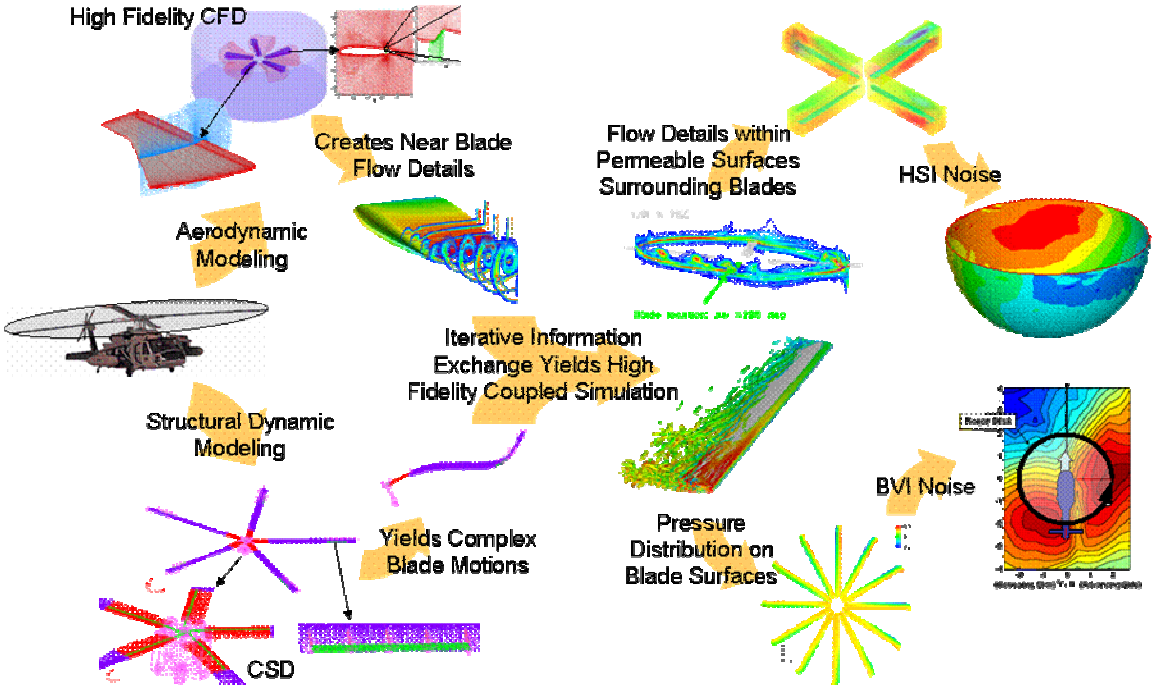

Figure 1 Graphical Description of the Multidiscipline Nature of Rotorcraft Noise Prediction.

	Aircraft	Case	Scale	Test	Description
Far Field Data	UH-60	9505	Full	Flight	Low-Speed Level Flight
	UH-60	9121	Full	Flight	Mid-Speed Level Flight (no Dynamic Stall)
	UH-60	9310	Full	Flight	High-Speed Level Flight
	UH-60	9017	Full	Flight	Mid-Speed Level Flight with Dynamic Stall
	UH-60	8534	Full	Flight	High-Speed Level Flight *(conventional industry correlation data point)*
Near Field Data	UH-60	1310	~1/6	Tunnel	High-Speed Level Flight
	BO-105		~1/6	Tunnel	Baseline
	BO-105		~1/6	Tunnel	Minimum Vibration
	BO-105		~1/6	Tunnel	Minimum Noise

Speed Sweep

On Capturing Dynamic Stall

significant familiarity with the data. These included in-flight loading data obtained using an instrumented blade on a UH-60 helicopter. These measurements were a combination of blade surface pressures and blade acceleration levels during a variety of flight conditions. The tests and the experimental data are documented in NASA technical memoranda by Coleman and Bousman, 1996, Cross, et al., 1993, and Hamade and Kufeld, 1990, and Kufeld and Nguyen, 1989. The instrumentation, test conditions and experiments are detailed in these memoranda and are well beyond the scope of this paper. The reader is referred to these documents for specific details of the experimental data used in these comparisons.

From this large body of data a smaller subset was chosen for some specific operating conditions to perform verification comparisons between aerodynamic and structural dynamic calculations and measurements. Table 1 shows the test points and conditions selected for this effort. The cases include a variety of operating conditions intended to provide different levels of technical challenge to the teams. In addition to the UH-60 airload cases, a set of acoustic measurements made on a small scale model rotor in the DNW tunnel were selected as verification set for of the computational acoustic predictions. Again, the test points represented a range of operating conditions and microphones at several locations surrounding the rotor were used for comparison. Table 1 also shows the test points used for acoustic comparison.

For each case, extensive calculations for airloads and structural response were performed. These included planform normal force, chordwise force and moment about the quarter chord over the disk as a function of time. Additionally, calculations of unsteady pressure distributions over the blade surface for each blade location on the disk were made. These enabled direct comparison between the measured experimental quantities as well as comparison with derived quantities resulting from post test analysis of the data. During the course of the first phase of the program, the teams were tasked with multiple rounds of calculations against each of the cases outlined in Table 1. The complete reporting of the results is beyond the scope of this paper, however, Figures 2, 3 and 4 show a summary of results from the comparison between calculations and experiments. Figures 2 and 3 show comparisons of normal force distribution over the rotor disk. Figure 4 shows a specific trace of the blade forces for an extreme case where a double stall event has occurred during a blade rotation. This is a highly non-linear event and previous attempts to calculate this type of phenomenon with prior generations of analysis tools were unable to capture these types of events.

In Figure 2, the force measured normal to the blade plan form based upon integration of the measured and predicted blade surface pressures are shown. This case corresponds to a high speed level flight case without transonic effects. As such, it was considered a low challenge case and as seen in the figure, all of the teams were able to predict the case well. In Figure 3, similar results are shown for a more challenging case containing a double stall event. Here, each of the teams reproduces the experimental results to a varying degree. While subjective assessment of the tools performance can be made using the loading plotted over the rotor disk as in Figures 2 and 3, more objective evaluations of the tool performance can be done when the loads are plotted for a single radius as in Figure 4. In this figure, the details of the normal force, chordwise force and pitching moment can be inspected for specific details when compared against the experimental measurement. Here, the results of Teledyne Scientific Corporation are shown against

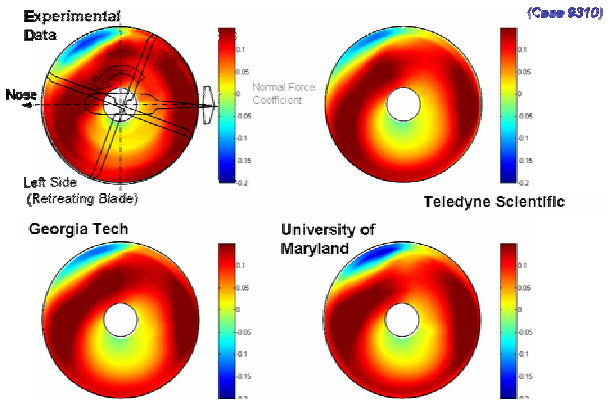

Figure 2: Comparison between Measured and Calculated values of Normal Force for UH-60 Case 9310 of High Speed Level Flight without Transonic Flow

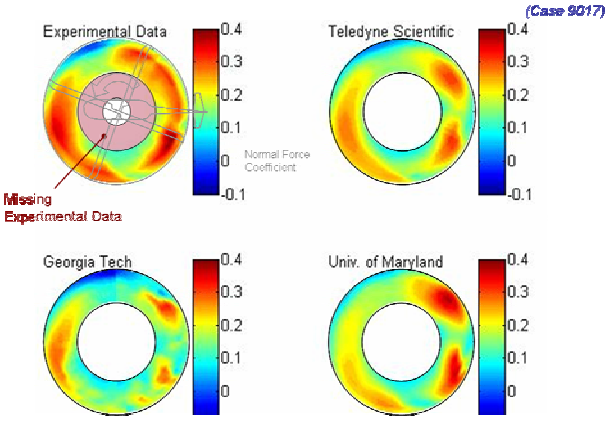

Figure 3 Comparisons of Measured and Calculated Normal Force for UH-60 Case 9017 Containing Double Stall Event on Blade Retreating Side

the experiment. The results capture the details of the double stall event very well.

As the teams achieved a level of confidence in the ability to predict the blade loading and response, predictions of the acoustic signature of the main rotor were attempted and compared to small scale measurements obtained for a variety of tests. Some of the most effective data for making these comparisons were obtained by Sikorski Aircraft, Inc. in a set of experiments made using a small model rotor in the DNW wind tunnel. The details of the test and results have been described by Lorber, 1991, and Liu and Marcolini, 1990. During the first phase of the program, acoustic calculations were made for several flight conditions corresponding to the locations of a set of microphones used in the experiment.

Figure 5 shows a comparison between measured and predicted rotor noise for a high speed case. The microphone location corresponds to directly in front of the vehicle in the plane of the rotor. Previous attempts to predict the noise have relied on solutions of unsteady pressure predicted or measured directly on the blade surface. When non-linear events relevant to the acoustic noise production of the blade occur off the surface of the blade, the calculations are unable to resolve the fine details of the acoustic signature. However, in this case where the high fidelity aerodynamic calculation was used to establish the unsteady pressure on a surface surrounding the blade, the calculations show significantly improve correlation with the measured data.

3 NOVEL ROTOR VERIFICATION

During a subsequent phase of the Helicopter Quieting Program, a computational and experimental verification was undertaken where a unique dataset was collected using an experimental rotor employing the use of and active trailing edge flap to modify the vibration and acoustic response of the rotor. The

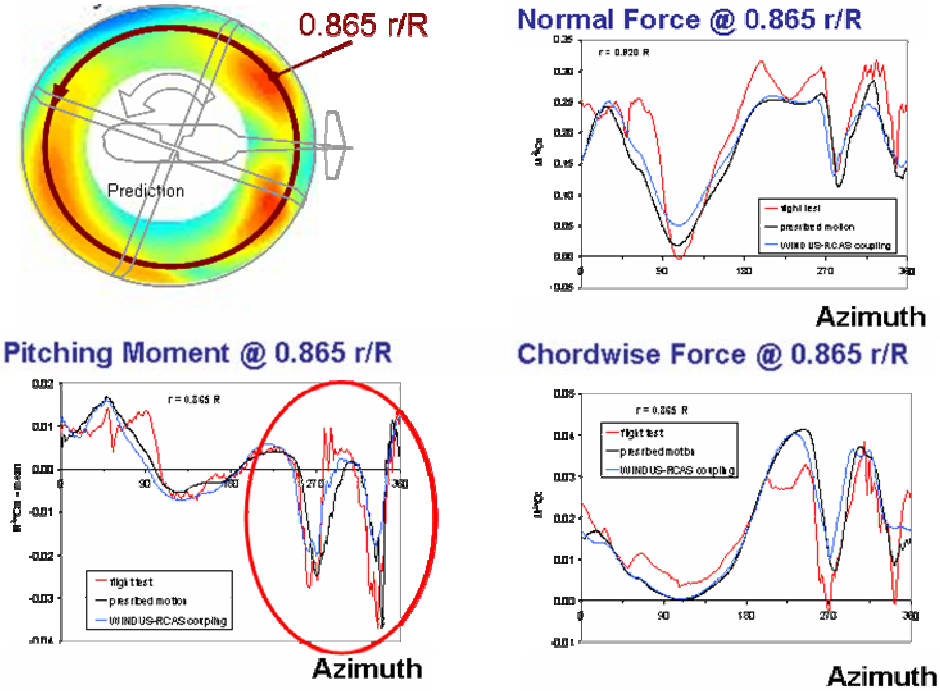

Figure 4 Detailed Comparisons of Measured and Calculated Normal Force, Chordwise Force and Pitching Moment at r/R = 0.865 for Case 9017 Containing Double Stall Event

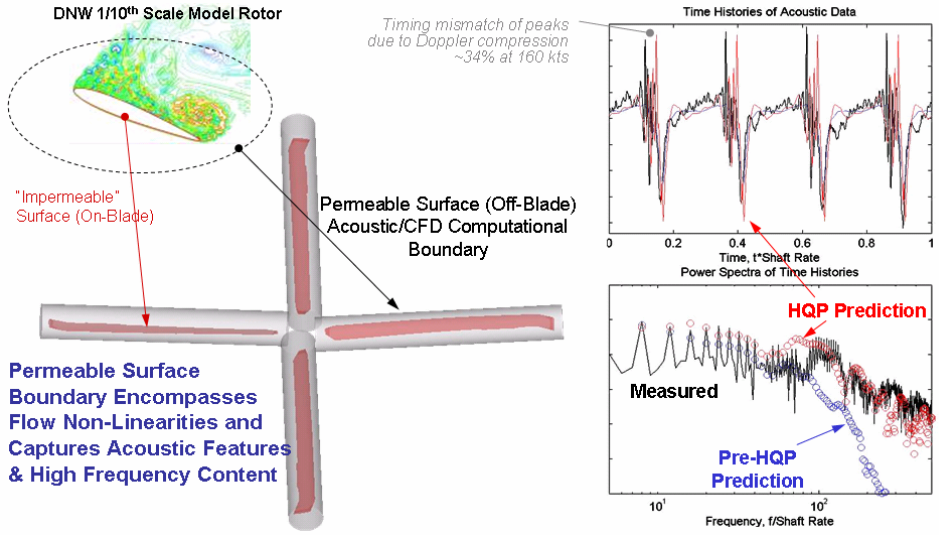

Figure 5 Comparisons between Measured and Predicted Noise Levels for a Small Scale Rotor in the DNW Wind Tunnel

oeing SMART rotor was used for this evaluation and is shown in the inset of Figure 6. The test was performed in the NASA Ames 40' by 80' wind tunnel. The SMART rotor installed in the wind tunnel is shown in the larger picture in Figure 6. During the test a set of strain gages were installed in one of the blades to measure structural response. Additionally, a number of microphones were installed in the tunnel as shown in Figure 6. The SMART rotor had a trailing edge flap that could be articulated by actuators to produce unsteady loads to modify the structural response of the rotor or offset unsteady loads on the blades to modify the acoustic radiation produced by the rotor.

During the testing four flap schedules were selected to produce impacts on the acoustic signature. The schedules were selected by exercising pre-HQP analysis tools to predict the aerodynamic and acoustic performance of the rotor. While preparations for the testing were underway, the rotor geometry, structural characteristics and the flap schedules were given to the performing teams to calculate the rotor performance. The calculations were completed by the performing teams prior to entry into the tunnel. After the hardware was installed and tested, significant differences in certain structural components were found between the test hardware

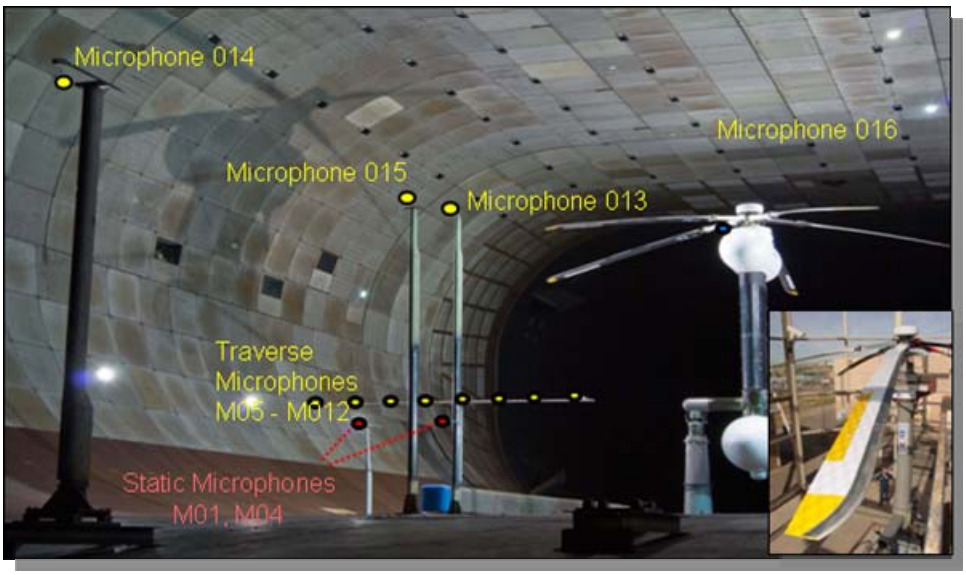

Figure 6 The Boeing SMART Rotor Installed in the NASA Ames 40' by 80' Wind Tunnel

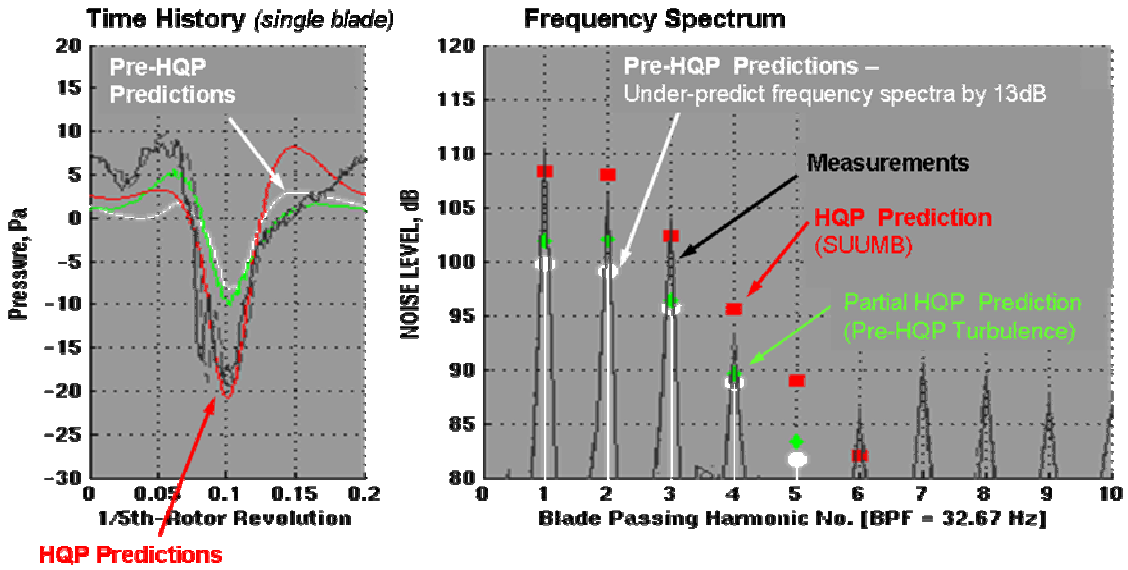

Figure 7 Comparison between Measured and Predicted Acoustic Levels for Pre-HQP and HQP toolsets

and the values given to the teams for prediction. Thus, the predictions of structural response were not able to be compared to the values measured with the strain gages during the experiment. However, the differences did not invalidate the acoustic comparisons.

Figure 7 shows a comparison between the experimentally measured acoustic signature, a prediction made using pre-HQP tools and the predictions made using the new tool suites. The comparison favorably shows how the pre-HQP tools under predicted the noise produced by the rotor while the application of the HQP tools enable much better prediction of the noise. Additionally, an intermediate computation was made using a partial HQP solution with a pre-HQP turbulence prediction methodology. The partial solution shows the correct trend toward the experimental data but the full application of the methodology clearly shows the best correlation with the experimental data. Here the pre-HQP tools actually redicted Table 2 shows a tabulation of the OASPL associated with the spectra from Figure 7. Here the correlation of the HQP tools with the experimental data is summed into a single number. Relative to the baseline case, the pre-HQP tools predicted a reduction in the OASPL. However, the experimental measurement and the HQP prediction showed significant increases in the radiated noise. The HQP tools predict the value to within 1 dB while the pre-HQP tools under predicted the experimental value by as much as 13 dB.

Table 2 Measured and Predicted OASPL Levels for SMART Rotor Test

All Values dB Re 20 μPa OASPL = Overall Sound Pressure Level	Pre-HQP Tools	HQP Tools	Measurement
MDART Conventional Rotor	105.8	105.2	107.3
SMART Rotor Case 2 Cruise @ 123kts	103.5	111.9	112.5
SMART Rotor Case 4 Steady Descent @83kts	94.5	107.5	108.5

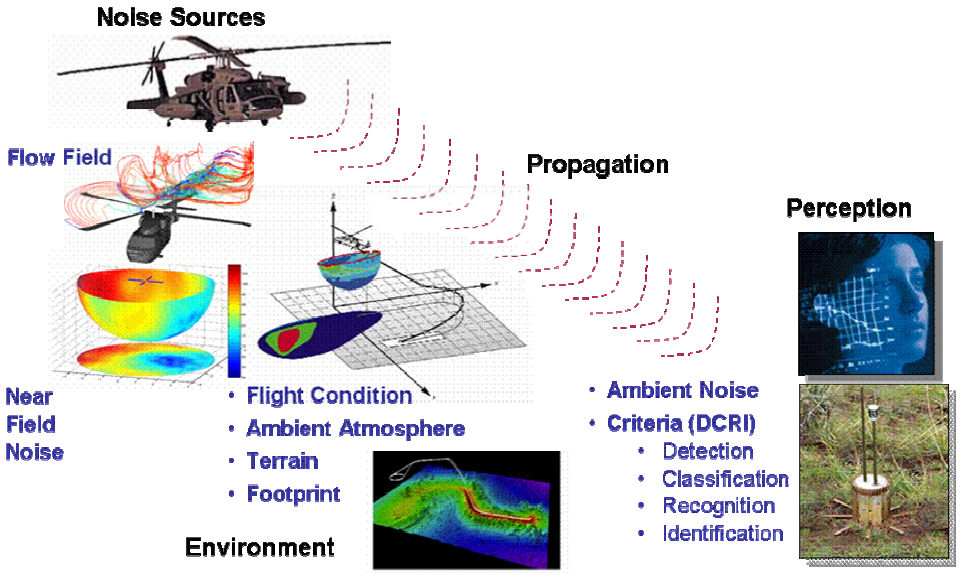

Figure 8 Graphical Description of Modeling of APPeAR Architecture.

4 APPeAR TOOL SET

As part of the HQP program, a set of analysis tools was brought together into a single architecture to assess the impact of changes in the acoustic signature of the main rotor on rotorcraft mission effectiveness and survivability. By starting with a measure or prediction of the acoustic signature, the tools assessed the impact of propagation through a real atmosphere over varying terrain on the noise, the impact of ambient sound levels, and the sensitivity of a human observer to the resulting noise. In the first phase of the program, an initial effort was attempted to answer what impact changes in the acoustic signature would have on mission effectiveness. This initial effort exposed the fact that the complete capability to analyze the impact and display it in a manner meaningful to the designer, mission planner and warfighter did not exist.

Based upon this experience, DARPA expanded the focus of the program to address this deficiency. This new direction developed the necessary propagation modeling, environmental modeling and human perception modeling and culminated in a new tool called Advanced Propagation and Perception Analysis Routines (APPeAR) as described in Figure

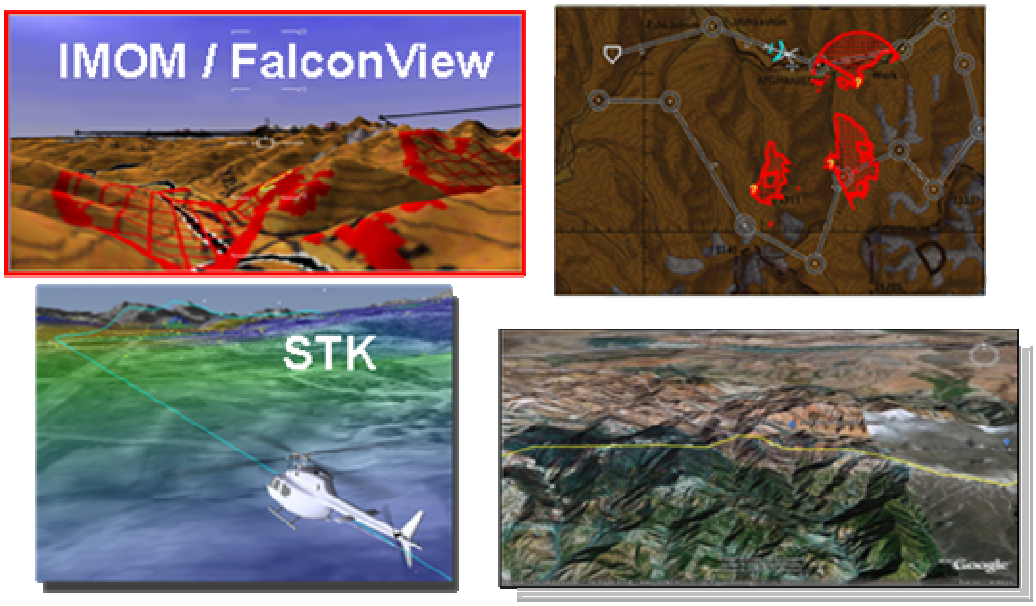

Figure 9 Example Displays Environments for Results from APPeAR Analysis

8. The tool is capable of taking a vehicle acoustic signature produced as the result of measurement or prediction, setting it in a realistic model of the tactical environment and displaying metrics of the resulting vehicle operation effectiveness.

The tools have been modularly combined into a single architecture that take inputs from a variety of modeling tools and combine the results to create output files appropriate for integration into a variety of visualization tools. Figure 9 shows example displays from a variety of visualization environments that the APPeAR architecture has been incorporated. The APPeAR toolset is currently being exercised by the community to explore utility and effectiveness.

CONCLUSIONS

DARPA's Helicopter Quieting Program has accelerated the development of analysis tools vital to the community's understanding of acoustic noise production in rotorcraft and the subsequent impact of signature changes on the operational effectiveness and survivability. The results of this program will change the way the acoustic signature of the vehicle is considered during the design process as well as allow the rotorcraft user the ability to realistically plan and evaluate a proposed mission profile. While significant progress has been made future investment is required to address the remaining signature issues associated with transient flight conditions and maneuvers.

REFERENCES

Potsdam, M., Yeo, H. and Johnson, W., 2004, "Rotor Airloads Prediction Using Loose Aerodynamic/Structural Coupling," *Proceedings of the American Helicopter Society 60th Annual Forum*, Baltimore, MD, June 7-10.

Coleman, C. P. and Bousman, W. G., 1996, "Aerodynamic Limits of the UH-60A Rotor," *NASA Technical Memorandum 110396/USATCOM Technical Report 96-A-011*.

Cross, J., Brilla, J., Kufeld, R. and Balough, D., 1993, "The Modern Rotor Aerodynamic Limits Survey: A Report and Data Survey," *NASA Technical Memorandum 4446*.

Hamade, K. S. and Kufeld, R. M., 1990, "Modal Analysis of UH-60A Rotor Blades," *NASA Technical Memorandum 4239*.

Kufeld, R. M. and Nguyen, D., 1989, "Full-Scale UH-60A Rotor Blade Nonrotating Modal Analysis Shake Test," *NASA Technical Memorandum 101005*.

Lorber, P.F., 1991, "Aerodynamic Results of a Pressure-Instrumented Model Rotor Test at the DNW," Journal of the American Helicopter Society, Vol. 36, pp. 66-76.

Liu, S. R. and Marcolini, M. A., 1990, "The Acoustic Results of a United Technologies Scale Model Helicopter Rotor Tested at DNW," *Proceedings of the AIAA 13th Aeroacoustic Conference*, AIAA 90-AHS Invited Paper, Tallahassee, FL.

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