

A DESIGN OF EXPERIMENTS APPROACH FOR OPTIMIZATION OF NONLINEAR UNSTEADY AERODYNAMIC DYNAMIC TESTING

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Abstract

NASA Langley Research Center (LaRC) and Old Dominion University (ODU) Department of Aerospace Engineering are collaborating to develop a methodology for dynamic modeling of aircraft using wind tunnel measurements. Aircraft experience unsteady and nonlinear aerodynamics that are currently misunderstood and difficult to model mathematically. NASA LaRC has developed the hardware for a dynamic test rig for using the NASA Langley 12-foot Wind Tunnel (LaRC 12-FT WT). However, software development has been fraught with difficulty. Currently the software is being worked on by a NASA engineer. The software will be uploaded, bench tested, and implemented on the larger scale dynamic rig (DR) in the LaRC 12-FT WT. Concurrently ODU is working on a model simulation of the DR in order to determine possible sources of error in the rig. The second objective is to leverage the power of Design of Experiments (DOE) and Response Surface Methodology (RSM) to exercise, validate, and examine the sources of error on the DR. These methods will also allow for optimization of the rig to be conducted. The final objective is develop a general dynamic test modeling method for an aircraft using the DR and ultimately using a DOE/RSM approach to develop the necessary empirical models of aircraft unsteady aerodynamics.

I. Introduction

Due to the increased need for maneuverability of modern aircraft, the aircraft will experience unsteady and nonlinear aerodynamics that are currently misunderstood and difficult to model mathematically. For example, when aircraft maneuver rapidly the impact of *unsteady* flow phenomena becomes more pronounced, as demonstrated in Figure 1. Poor model response prediction occurs due to high angle-of-attack, rapid maneuvers, shock waves, separated flows, and vortical flows; as a few additional examples. One primary shortcoming of trying to accurately model the aerodynamics is the use of the conventional stability or aerodynamic derivative based model for the representation of aerodynamic loads in the aircraft equations of motion [1]. This conventional stability derivative approach is based on the work of Bryan in 1911, and estimates the loads on the basis of instantaneous motion parameters and a linear relationship between the motion and the loads [2]. However, for modern aircraft (military and commercial) with highly nonlinear aerodynamic characteristics undergoing agile maneuvers at high angle-of-attacks, the stability derivative model breaks down completely. Current experimental methods attempt to obtain dynamic stability derivatives using, most notably, forced oscillations methods. It is widely accepted that there is a need for improved and accurate

modeling of the nonlinear, unsteady, and time-dependent aerodynamic responses. These improvements are critical in order to maximize combat capability and to prevent accidental departure from controlled flight [1].

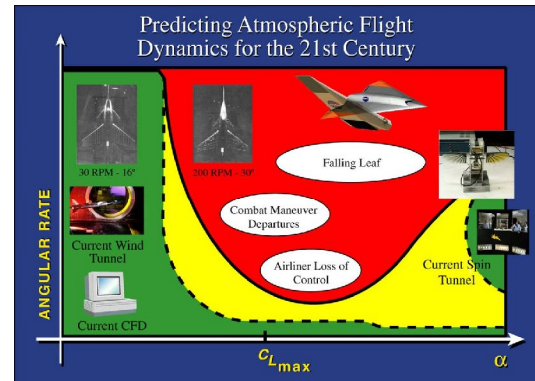


Figure 1: Demonstration of the range of unknown phenomena in flight; provided by Ref [3].

The discussion of the design of experiments approach for dynamic testing will begin with dynamic scaling. This discussion is needed for a good understanding of the forced oscillation technique discussion. Finally, a discussion on design of experiments and proposed optimization methods will be presented.

II. Dynamic Scaling

The concept of similitude is often used so that measurements made on one system (for

example, a model in the wind tunnel) can be used to describe the behavior of other similar systems (for example, full-scale flight). A summary of these similitude requirements is shown in Figure 2.

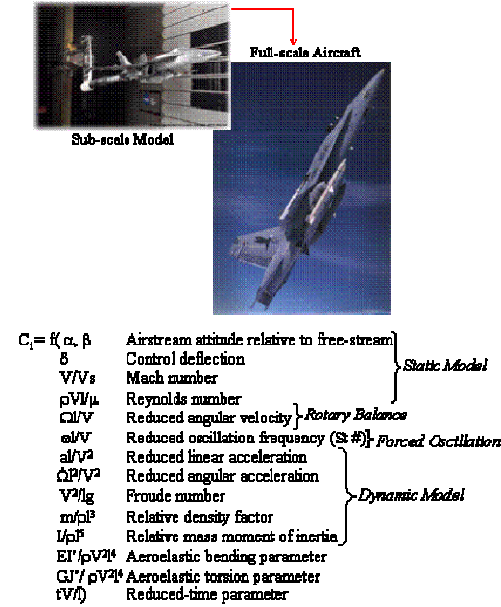


Figure 2: Similitude requirements; adapted from Ref [4].

As Figure 2 demonstrates, accurate predictions of full-scale characteristics require correlation of many, sometimes conflicting, similitude parameters [4]. It can be quite difficult in constructing models and tests that satisfy the similitude requirements for dynamic testing; this is especially true for forced oscillation testing. Therefore, many times trade-offs must be made

For example, Reference 4 demonstrated that for free-flying tests, it is impossible to properly scale inertia; at least scaling of the inertia ratios is important. This is required so that initial coupling between the motion axes is correctly represented. Even if matching inertia ratios could be obtained, the motion coupling due to rates will not be correctly represented. For illustration, examine the non-dimensional moment equations:

$$C_l = \frac{I_{xx}}{8 \rho S b^3} \hat{p} + \frac{(I_{zz} - I_{yy})}{8 \rho S b^2 \bar{c}} \hat{r} \hat{q}$$

$$C_m = \frac{I_{yy}}{8 \rho S \bar{c}^3} \hat{q} + \frac{(I_{xx} - I_{zz})}{8 \rho S b^2 \bar{c}} \hat{p} \hat{r}$$

$$C_n = \frac{I_{zz}}{8 \rho S b^3} \hat{r} + \frac{(I_{yy} - I_{xx})}{8 \rho S b^2 \bar{c}} \hat{p} \hat{q}$$

Thus it can be seen for a given rolling moment coefficient, an incorrect I_{xx} will result in incorrect roll rate acceleration. This example demonstrates the difficulty in dynamic testing.

Unfortunately, there are regions of the flight envelope that have significant aerodynamic nonlinearities in static and dynamic stability. One method to attempt measure accurately the nonlinear dynamics is to use a forced oscillation tests.

III. Forced Oscillations

Reference 4 defined forced oscillation tests involve models rigidly mounted on a support system which is then actuated to impart motion to the model while measuring forces and moments acting on the model. The motion shapes can take many forms, however, they are typically sinusoidal motions and/ or Schroeder sweeps.

The NASA Langley 12-FT Wind Tunnel will be used for this study as a concept development environment. The tunnel can typically operate ranging from 0.25 to 7 psf dynamic pressure. The tunnel has two captive dynamic test rigs available for use – the dynamic pitch rig and roll oscillation system. For this study the roll oscillation system (ROS) will be used.

The ROS is a computer controlled actuator mounted on a C-strut model support; as shown on Figure 3. The ROS allows a model to be sting-mounted through the rear of the model for conventional static and dynamic roll tests. In addition, the model can be sting mounted from the top or bottom of the model for dynamic yaw tests. Also, in addition to programmable motion shapes, the ROS system allows independent angle-of-attack and sideslip angle combinations [4]. The ROS motion capabilities are $\pm 170^\circ$ in roll with a maximum rate and acceleration of $190^\circ/s$ and $12,750^\circ/s^2$, respectively [4].

One critical limitation of using the ROS is that it can *mask* the dynamic measurements of an aircraft. For example, during dynamic measurements the frequencies one is attempting to measure ranges from 0.1 to 10 Hz. Frequency measurements are needed for obtaining the dynamic stability derivatives, as they are function of frequency. The rig itself may produce enough noise to mask the actual

measurement. Therefore, the first objective of this study is to leverage the power of design of experiments to discriminate between the actual sources of error caused by the rig and the actual measurement from the model.



Figure 3: Roll Oscillation System.

IV. Design of Experiments

A typical question is *what is design of experiments?* To begin, experiments are used to study the performance of processes (shown on Figure 4) or systems. It is typically no longer cost effective for experiments to be performed in a trial-and-error manner; changing one factor at a time. A far more effective method is to apply a computer-enhanced, systematic statistical-based approach to experimentation, one that considers all factors simultaneously. That approach is called design of experiments (DOE).

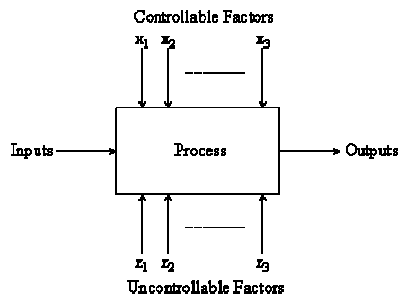


Figure 4: General model of a process or system.

Experimental design is a critically important tool in the engineering world for improving the product process. For example, some applications of experimental design in process development and engineering design include:

1. Improved process yields
2. Reduced variability
3. Reduced development time
4. Reduced overall costs
5. Evaluation and comparison of basic design configurations
6. Selection of design parameters so that the product will work well under a wide variety of field conditions; robustness
7. Formulation of new products

The way to perform DOE is problem dependent. However, a common approach is to define an interesting standard reference experiment and then perform new, representative experiments around it (refer to Figure 5). These new experiments are laid out in a symmetrical fashion around the standard reference experiment. Hence, the standard reference experiment is usually called the center-point.

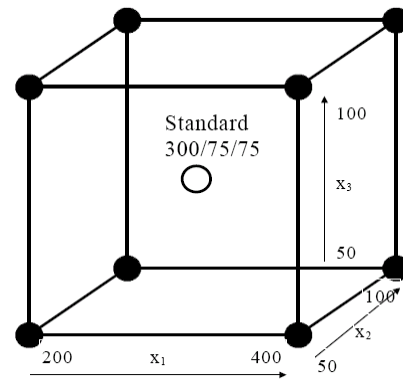


Figure 5: Example of a symmetrical distribution of experimental points around a center-point experiment.

V. Roll Rig Simulation

Since improved software for the ROS is currently being developed by a NASA contracted engineer, this study will perform an initial DOE on a simulation of the roll rig. The model of the roll rig is illustrated on Figure 6. Figure 6 is a simplified simulation model of the ROS.

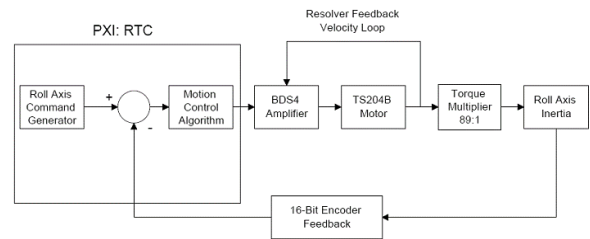


Figure 6: Simplified roll oscillation system model.

Referring to Figure 6, the roll oscillation system is modeled in Matlab® Simulink. Although this is a simplified overview of the model, there are quite very subtleties that are hidden in Figure 6. For instance, the amplifier and motor; called the plant, have nonlinear behavior. The nonlinearity makes it quite difficult to model in Simulink. To avoid this, current work is being conducted to create a transfer function of the plant. Once the simulation code is complete, system response will first be compared to previously obtained ROS experimental data. If found to be representative a designed experiment will be conducted to analyze the possible sources of error on the actual rig.

VI. Future Work

There is quite a lot of future work to be performed in this overall study after using DOE to determine the possible sources of error on the simulator. The actual ROS from the model is listed as follows:

1. Perform a DOE and analyze the actual rig.
2. Compare and validate the results between the model and actual rig.
3. Characterize and optimize data acquisition techniques for the roll oscillation system.
4. Develop a general test method to obtain the most robust empirical models for nonlinear unsteady aerodynamics.

VII. Conclusions

In conclusion, this paper provided an introduction to design of experiments for optimization of the nonlinear unsteady aerodynamic dynamic testing. The issues in performing dynamic testing were discussed. Also, the method of forced oscillations used for dynamic testing was discussed. Overall, the paper provided ideas and concepts to use design of experiments for the ROS.

VIII. Acknowledgements

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VIII. Literature Cited

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