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DYNAMIC STABILITY OF SPACE VEHICLES

Volume XIII - Aerodynamic Model Tests for Control Parameter Determination

by David R. Lukens

Prepared by
GENERAL DYNAMICS CORPORATION
San Diego, Calif.
for George C. Marshall Space Flight Center

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FOREWORD

This report is one of a series in the field of structural dynamics prepared under contract NAS 8-11486. The series of reports is intended to illustrate methods used to determine parameters required for the design and analysis of flight control systems of space vehicles. Below is a complete list of the reports of the series.

Volume I	Lateral Vibration Modes
Volume II	Determination of Longitudinal Vibration Modes
Volume III	Torsional Vibration Modes
Volume IV	Full Scale Testing for Flight Control Parameters
Volume V	Impedence Testing for Flight Control Parameters
Volume VI	Full Scale Dynamic Testing for Mode Determination
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Volume VIII	Atmospheric Disturbances that Affect Flight Control Analysis
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Volume XV	Shell Dynamics with Special Applications to Control Problems

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1/INTRODUCTION

Aerodynamic forces and moments encountered during flight are important effects which must be considered in the stability and control of launch vehicles. The determination of these forces and moments is necessary for stability and control analysis of launch vehicles. The use of aerodynamic models is a powerful tool for the solution of a wide range of problems associated with the flight of launch vehicles. This monograph will introduce the concepts, techniques and problems associated with small scale aerodynamic model testing. Emphasis will be on stability and control, pressure distributions and dynamic stability for vehicles of a wingless missile shape. The discussion will be aimed toward the collection of data required for making control system analysis of full scale vehicles.

Aerodynamic model tests are often instrumented for other parameters such as loading, heating or local pressures where venting or flame holding could be a problem. As aerodynamic forces will constitute the major disturbing force on the vehicle during boost phase of flight, their determination cannot be overlooked at any time during the program.

2/STATE OF THE ART

In the developmental phase, aerodynamic forces and moments are analytically calculated by using theory and literature searches. These calculations are checked by testing very early during this development phase.

Model testing has been and will continue to be extensively used to define the aerodynamic properties of a launch vehicle. These physical tests of scaled models are justified if they provide data with less expenditure of time and money than that required for full scale testing and if produced on a schedule such that the data is useful in prototype design and construction. Useful data can be divided into two categories. It can be used first, to refine an analysis using an existing theory or to confirm it, and second, to conduct exploratory tests where a theory does not exist.

3/CRITERIA

The derivation of and use of accurate aerodynamic forces and moments is important even for the large cylindrical non-winged classes of launch vehicles. It becomes even more important if aerodynamic control surfaces are used during part of the flight.

Early in the development phase analytical methods, combined with a literature search of previous test results, may be used to arrive at a first approximation to these parameters. However, test programs are also extensively used during the development phase to accurately derive the aerodynamic forces and moments prior to the building and flight testing of a launch vehicle. Model testing may, and usually will, comprise most of the testing done. Quite accurate data can be obtained by properly choosing the model test set up and test procedures.

4/RECOMMENDED PRACTICES

This section on recommended practices will discuss the items to be considered in planning, designing and conducting a model test for the determination of aerodynamic forces and moments.

Section 4 is divided into four subsections. The first will consider the design requirements and parameter variations to be considered for the model. The second will discuss the test setup, the general factors which influence the type of test to be performed and the type of tunnel to be used. The third subsection will discuss the items to be considered in performing the test itself. The final subsection will present recommendations for further effort in this field.

4.1 MODEL DESIGN REQUIREMENTS AND PARAMETERS

It is usually a good idea to prepare a quick pre-design of the model with the desired method of support and visit the tunnel facility selected for the test program prior to starting the detail design. If information is available the pre-design should position the model at the desired location within the tunnel.

It is a rare case when all of the design requirements can be specified at the beginning of the program. A schedule should be set-up on when they will be available in order for the design to proceed with a reasonable amount of efficiency. The designer should be aware of the cost budgeted for fabrication and make his design accordingly.

The model design requirements should include most or all of the following:

1. Purpose of test including type of data to be collected and desired results.

2. Type of model and number required to do a particular task.

3. Selected tunnel or tunnels.

4. Tunnel operating conditions (max. temperature, dynamic pressure, Reynolds number and etc.).

5. Access to tunnel for model changes.

6. Model size, based on tunnel blockage, shock reflection clearance, tunnel support limits, balance availability, size and limits, location of model in steady flow, model internal capacity for mechanism, airflow and/or instrumentation.

7. Model supported in tunnel (how and from where ceiling, center line, wall and etc.).

8. Location and attitude of model (upside down, rotated 90°, etc.) for the required visual data (schlieren, shadowgraph, movies, or stills).

9. Maximum angle of attack, yaw and/or combination or pitch and yaw ranges. Specify what model reference is to be used for measuring these attitudes.

10. Specify leveling and alignment devices required to install the model in the tunnel.

11. Specify reference points or lines to be located on the model to insure efficient and speedy installation.

12. Specify model geometry both external and internal and tolerances.

13. Determine expected model loads and center of pressure.

14. Force and moment balance including physical size, load limits and moment diagram for positioning balance in the model.

15. Model weight requirements if any.

16. Model rigidity requirements.

17. Type of instrumentation and tunnel requirements for instrumentation.

18. All of the variables for each configuration to be tested.

19. Control surfaces.

20. Deflection of control surfaces and method to be used in setting and holding the required deflection angle.

21. Boundary layer trip devices.

22. Location of interface for model instrumentation leads with tunnel leads.

23. Model and instrumentation cooling requirements.

24. Reference points required for fabrication.

25. If some part of the model is to be remotely controlled, specify the accuracy required for positioning the part.

26. Inspection requirements after model has been completed.

27. Calibration requirements prior, during and after test.

28. Budgeted model costs and schedule.

29. Stress report requirements.

30. Safety requirements.

The engineer should review the design of the model prior to fabrication to insure that it is realistic from a standpoint of cost and the data required for his test program.

Most wind tunnels require a stress report be delivered prior to the tests. Since models and support structure must be designed and built quickly but accurately, it follows that the stress design of these must follow the same pattern. To save time, wherever possible, conservative assumptions should be made which will simplify the stress design. Load distributions should be simplified such that final results will be on the conservative side. This will save considerable time. Of course, if the conservative assumption fails to show a sufficient safety factor, then a more refined analysis must be made, or the model part in question could be statically loaded. The whole idea of the stress report is to show that the model is safe, and that it comes up to requirements of the tunnel staff concerned, when being tested at the maximum conditions of angle of attack, yaw, dynamic pressure, and temperature.

All wind tunnels have their own peculiar stress criteria. A typical one is where a safety factor of 3 on yield strength or 4 on ultimate strength is required, whichever is more conservative.

Some tunnels operate at sufficiently high temperatures that a thermal stress should be made on the model. Also the thermal stress can determine the amount of model deformation due to temperature. This is important because it can affect the aerodynamic test results. The model should be designed to keep this deformation or warp to a minimum. A typical problem is when a long slender model is being tested at an angle of attack in a hypersonic tunnel for several minutes it can warp to a "banana shape" unless the model is designed to keep this to a minimum.

It should be pointed out that thermal stress analysis accompanied by a thermal analysis that predicts the temperature distribution can be expensive and should be approached conservatively to avoid a lengthy, refined analysis. Not all tunnels have thermal stress requirements because they do not operate at high temperatures, or have a short test time or are not concerned because model failure will not damage their tunnel.

4.2 TEST SETUP

This section will cover the problems encountered in test planning and selection of test facility.

4.2.1 TEST PLANNING. Maintaining low cost is a problem that plagues any engineer planning and monitoring a test program. Therefore careful planning should go into requirements for the test program. The quality and quantity of data should be specified along with the acceptable manufacturing tolerances on the models and balances associated instrumentation. This should be done early in the program so everyone involved in the program can carry out his task accordingly.

If the program is a research type program or requires the use of a new testing technique with which the tunnel personnel have little or no experience, then two test periods should be scheduled in the tunnel, at a minimum of 6 to 8 weeks apart. This is difficult to do because of costs, scheduling and justification to within program and budget constraints. It should be pointed out that in order for such a test program to be a complete success, a minimum of two test periods are necessary. This allows exploratory development of the technique and time to understand the capabilities and limitations of unusual test techniques before running a complete program.

If the program is a hardware development program, usually several models are required, each designed for a different purpose and therefore tested in different wind tunnels. Also in a hardware development program it is desirable to test one or more models in more than one tunnel, and to correlate the results.

The number and type of test runs should be outlined early in the program and this outline should specify the type of data to be collected during each particular run, including visual data. As the program proceeds the total planning of the test should be compiled in a pre-test report. It should be prepared while the model is being designed and fabricated. It should be completed and delivered to the wind tunnel prior to the start of the test at an agreed upon time (typically six weeks prior to the test). This report should contain at least the following items:

1. Test Objectives
2. Model Description
3. Instrumentation Requirements
4. Calibration Requirements
5. Photo Requirements (Schlieren, Shadowgraphs Stills and Movies)
6. Balance Requirements
7. Test Runs and Test Conditions
8. Data Presentation
9. Data Reduction Procedure
10. Model Drawings and Sketches
11. Predictions

If boundary layer trips are to be used to fix transition, additional runs should be allowed to insure that the desired results have been obtained prior to making the remaining test runs.

Predictions should be made prior to the test at each of the selected Mach numbers, Reynolds number and model attitude. The predictions should be modified to account for Reynolds number differences and configuration modifications necessary to incorporate the support. These predicted characteristics can be used in the design of the models and to select balances which are compatible with the loads expected in the wind tunnel. Also they can be used during the tunnel test to assist in monitoring the data while the test is in progress.

The overall technical approach should be based on a balanced program consisting of an experimental investigation combined with analytic-empirical analyses. The program should be so planned that predictions made prior to the test and the tunnel results, when correlated, will confirm the analyses or provide data for improving the prediction methods.

4.2.2 SELECTING TEST FACILITY. Once a model need is determined a test facility must be selected. Selecting the proper wind tunnel is an important item that affects the quality and quantity of data as well as cost of the program. Different wind tunnels have different operating conditions, instrumentation, balances, data readout, and methods of supporting a model. An effort should be made to use existing balances and support hardware. Also it is important to use existing instrumentation techniques whenever possible.

Some items to consider in selecting a wind tunnel are as follows:

1. Mach Number Range
2. Reynolds Number Range
3. Angle of Attack Range
4. Yaw or Pitch and Yaw Capability
5. Temperature Range
6. Laminar and/or Turbulent Flow (Can Boundary Layer Trips be used)
7. Existing Supports
8. Existing Balances
9. Model Size
10. Dynamic Pressure Range
11. Continuous or Intermittent Tunnel

12. Data Readout Capability (on line and for special instrumentation)

13. Data Accuracy

14. Visual Airflow Capability

15. Tunnel Speciality (does its personnel have experience in your type of test)

16. More Than One Model Required to get the Desired Data

17. Time to Make Model Changes

18. Time to Make a Test Run

Personnel at the wind tunnel should be contacted prior to making a definite decision on which facility to use. The above items should be discussed with them including the availability of the wind tunnel. Many experimental programs have been compromised because of the tight tunnel schedule and the priority of the particular program. This is even more true if the program is a research program rather than a hardware development program.

4.3 TEST PROGRAMS

This section will discuss the various types of testing which one will encounter in aerodynamic model tests for control parameters.

The two general types of data obtainable, force and pressure, are discussed in the first two sections. The third section covers the commonly used procedures for control effectiveness testing. This section is applicable to launch vehicle using moveable control surfaces. The final section discusses the various methods available for dynamic stability testing, both captive and free flight.

4.3.1 FORCE TESTING. The purpose of force testing is to make a series of measurements in a wind tunnel which define the overall loads on a scale model having one particular configuration. Usually a test program consists of testing several configurations at different attitudes and tunnel operating conditions. The tests are planned so the effects of these variables can be determined. The results are reduced to coefficient form, before applying them to the full scale vehicle. In any force test there can be many variables, and care must be taken to select the variations so the results will furnish sufficient data for making the analysis.

Most wind tunnels have provisions for force and moment testing. This can consist of external and/or internal balances both having the capability of measuring these 6-component data, normal force, side force, axial force, pitching moment, yawing moment and rolling moment. Usually an external balance will determine the 6-component force and moment data about the wind axes and the internal balance about the body axes. Regardless of which axes the data is recorded about it can be transferred later to the other axes.

Most tunnels have different internal strain gage balances with different physical sizes and different load capacities, which are available to the user. Some tunnels only have 3-component balances. The scale of the model is determined most often by the availability of a balance. Sometimes a particular test requires that a new balance be made and calibrated specifically for a model. In general a balance must be selected, before a force program can proceed beyond the planning stage. Some things to consider when selecting a force balance are as follows:

1. Maximum expected load of each component and its center of pressure.
2. A moment diagram should be available with the model so the balance can be located within the model.
3. Model attitude limitations.
4. Physical size of balance.
5. Does balance have to be water cooled? Is it temperature-compensated?
6. Does a good balance calibration exist? Does it include interactions?
7. Is a spare balance available?
8. Is a dummy balance available for checking model assembly? Are there ring and plug gages available to shop for fabricating parts to be mated to balance?
9. Details of how balance is attached to the model and sting.

The model support has an effect on the forces and moments and a test program sometimes requires additional runs to be made to determine the magnitude of these effects. The balance cavity pressure is most always measured when an internal balance is used and its effect subtracted out of the drag data. Also the base pressure is sometimes measured and its effect subtracted out of the drag data.

4.3.2 PRESSURE TESTS. The reason for pressure tests is that the results can provide fundamental data for evaluating the local loads, boundary layer, center of pressure, critical Mach number, and overall forces and moments on a particular configuration. Pressure measurements can also be made to determine skin friction although some tunnels prefer skin-friction gage. Wake measurements can also be made using a rake containing multiple total-head tubes.

It is generally advisable to conduct pressure distribution tests as well as force and moment tests on a particular configuration. You can determine the lift, pitching moment and form drag from pressure data measured normal to the surface of the body in several locations. It is still desirable to measure the forces and moments from a balance, primarily because of the difficulty of getting sufficiently complete pressure distribution data. Wind tunnels are set up to reduce the balance data to coefficient form much quicker than pressure data and, usually, the balance data can be provided immediately after a test run and evaluated prior to the next run.

Sufficient number of pressure taps should be located flush and normal to the surface of a body to define the pressure field, including the base area. The spacing of the taps should be in a manner such that they are located closer together in the areas of interest or where large changes in the pressure level are expected to occur.

The pressure taps are usually connected with small tubing to a pressure measuring device, i.e. transducer or manometer. There are tests where scanivalves with the capability of sampling several taps while only using one transducer are desirable. The wind tunnel personnel should be contacted to determine the maximum number of pressure taps that can be accommodated during one test run and which of the measuring devices are available for your test. There are some tests where the test conducter is required to furnish his own measuring devices and read-out. If this is a requirement it can substantially increase the cost of the program.

It is desirable to take shadowgraphs or Schlierens simultaneously with the pressure measurements when testing at the higher speeds. These photographs can be used to quickly determine the location of the shock patterns and point of boundary layer transition.

The static pressure data recorded from the tests are usually reduced to a pressure coefficient (C_p) in the following manner:

$$C_p = \frac{p_m - p}{q}$$

where

p_m = measured pressure on model (psia)

p = tunnel free stream static pressure (psia)

q = tunnel free stream dynamic pressure (psi)

Plots can then be made of C_p vs. chordwise or axial location of the orifices. Integration of the pressure coefficient over the surface area resolved to a vertical direction gives normal force coefficient. The center of pressure is determined by dividing the moment of the area of the normal force per unit length about the leading edge by the integrated normal force coefficient.

4.3.3 CONTROL EFFECTIVENESS AND HINGE MOMENTS. The aerodynamic control hinge moments are important if the control characteristics of a vehicle are to be analyzed. In addition to the hinge moments, information on the forces generated by the control surface deflection on the complete vehicle is also required. The two methods most commonly used to measure the hinge moments are pressure plotting or a balance attached to the control surface. An internal balance is most often used depending upon the tunnel. If an internal balance is used it is usually of a small strain gage type, either a torque tube or beam and is considered part of the model. They are designed so the control surface can be released and deflected and then relocked at the desired test angles while data is being recorded. Small ball bearings or flextures are used for supporting and aligning the hinge line of the surfaces accurately. In order for the strain gage balance to function properly the surface must be free to float about the hinge line and be restrained only by the balance.

It is most important to know the angle settings accurately because slopes of hinge moment curves are determined over a small range of surface deflections. Static tares are made prior to the test in order to correct the static angle setting to the true angle after the airloads are applied to the surface. The static tares also indicate how well the mechanical friction due to the small ball bearings used to support the control surfaces has been reduced. If it has not been completely eliminated then the friction shows up as hysteresis. Sometimes the surfaces are supported by flexures in order to simplify the problem of reducing the friction during calibration. Preliminary calibrations should be made prior to delivering the model to the tunnel to be sure the hinge moment balance is functioning as designed. Final calibrations should be made at the tunnel with the tunnel data readout system. The final hinge moment data will only be as good as the calibrations.

In selecting the wind tunnel to be used for hinge moment tests and the corresponding model size it should be noted that effects of Reynolds number and boundary layer transition should be given primary consideration.

Some typical hinged surfaces for which it is desirable to know the hinge moments are as follows: All moveable control surfaces (fins, canards), body flaps, and exposed swivel mounted rocket motors. If a winged configuration is being studied then hinge moments on elevons and hinged flaps can also be determined.

After the hinge moments have been measured they can be reduced to a nondimensional coefficient with the following equation:

$$C_h = \frac{H}{q\ S\ \bar{c}}$$

where C_h = Hinge moment coefficient

H = Hinge moment (in-lb)

q = Dynamic pressure (psi)

S = Area aft of hinge line (in^2)

$\bar{c}$ = Mean aero chord aft of the hinge line (in)

The variation of plots can be made showing hinge moment coefficient with angle of attack α or with surface deflection (δ). The slopes of these curves ($\partial C_h/\partial \alpha$) and ($\partial C_h/\partial \delta$) can be summarized against Mach Number.

4.3.4 DYNAMIC STABILITY TESTING WITH MODELS. Dynamic stability testing can furnish information on the effects of Reynolds number, Mach Number, changes in center of gravity and geometry on the damping characteristics of a particular vehicle. Also, ablation simulation with phase lag is another type of test useful in studing re-entry problems. Testing with small scale models in the past has been difficult to perform but within the last few years techniques have been developed which make this type of testing less expensive and the data more meaningful. At least two techniques are available, (1) Free Flight and (2) Captive Technique. Free flight techniques include model flight (unsupported) in the air flow of the test section of a wind tunnel and free flight in a ballistic range. Captive model techniques include forced oscillation and free oscillation balances.

Current facilities do not have the capability of duplicating all of the flight conditions. Therefore the tests are planned to simulate the significant parameters as related to a particular vehicle. These methods are continaully being improved and when a test is being considered a study of the current test hardware, simulation techniques, methods of reducing the data and the scaling parameters should be carefully evaluated. Also, each facility has developed its own testing techniques and methods for reducing the data, therefore, a facility should be selected and then the model designed and fabricated to be compatible with it.

It is usually desirable to study the dynamic stability of a vehicle by using both captive and free flight techniques. The captive technique requires a support and sometimes it is difficult to evaluate its effect on the model. The free flight technique can furnish data for estimating this effect.

4.3.4.1 Captive Tests. Captive dynamic stability tests in a wind tunnel usually require the model to be restrained except for one degree of freedom. This one degree of freedom can be about the pitch or roll axis. Two types of captive techniques are used:

(1) Forced oscillation and,

(2) Free oscillation.

Both of these techniques require a support to restrain the model and to provide a pivot point for the oscillations.

Multiple shadowgraphs or Schlierens should be taken during the tests, particularly when there is concern that the aerodynamic characteristics may vary non-linearly with angle of attack because of flow separation.

4.3.4.1.1 Forced Oscillation. The forced oscillation technique has the model mounted on a sting supported balance which limits the angular displacement to small angles of attack. The balance is generally a cross-beam flexure instrumented with strain gages or a bearing with a restoring moment beam. The models are excited by a shaker through a push rod mechanism which oscillates the model at constant amplitude. The difficulty (depending on the vehicle shape) in this type of test is trying to mount the model on the balance with the desired angular freedom while at the same time sizing the internal structure for the required moments of inertia. Also, care must be taken in the design of the instrumentation and collection of the data from the standpoint that the dynamic air loads can be measured accurately while the model is in motion. It is desirable to plan two test periods for this type of testing--the first to verify the adequacy of the forced oscillation balance and model combination so that a more extended test period at a later time can be planned with confidence. A typical set-up for forced oscillation dynamic testing is described in Reference 5.

The oscillation data from a dynamic pitch test can be processed to obtain the stability derivatives ($C_{m_q} + C_{m_{\dot{\alpha}}}$) and the static stability derivative in pitch (C_{m_α}).

4.3.4.1.2 Free Oscillation. The free oscillation technique has the model mounted from a traverse rod that passes through the c.g. of the model, and has a ball or air bearing that allows the model to pivot about this axis. During a test the model is held at an angle of attack and when released the history of the resultant damped oscillations are recorded, either by high speed movies or with electronic pick-ups:

The data can then be reduced to obtain the stability derivatives (C_{m_q} + $C_{m_{\dot{\alpha}}}$) using the equation from Reference 6.

$$C_{m_q} + C_{m_{\dot{\alpha}}} = -\left(\frac{4\ V\ I}{q_\infty\ Sd^2}\right) \frac{\ln (\theta_1/\theta_2)}{(t_1 - t_2)}$$

where:

V = free stream velocity, ft./sec.

I = moment q inertia of model, slug - ft.^{2}

q_∞ = free stream dynamic pressure, lb./ft^2

S = reference area, ft.^{2}

d = base diameter, ft.

θ = amplitude of model oscillations, deg.

t = time, sec.

The static stability derivative (C_{m_α}) can be obtained from:

$$C_{m_\alpha} = - \frac{4\pi^2 I f^2}{q_\infty S d}$$

where:

f = frequency of model oscillation, cycles/sec.

Roll damping tests can be performed by rotating the model to the desired spin rate with a motor and then disengage the drive mechanism. The spin rate and time are recorded and reduced to the roll derivative (C_{ℓ_p}).

4.3.4.2 Free Flight Testing. Free-flying a scale model of a vehicle to study its dynamic stability characteristics is currently being done in wind tunnels and ballistic ranges.

The data from these techniques is recorded by movies or stills of Schlierens or shadowgraphs from which the model orientation, position and velocity can be determined and from which the pitching motion and damping parameters can be computed.

Free flight tests in a wind tunnel can provide useful dynamic stability data. This technique has two advantages over the other techniques mentioned in this section:

(1) There are no support interference effects and

(2) The g loads are considerably lower than those experienced with a ballistic range model.

Each wind tunnel has developed its own method of launching the models. Some of the methods currently being used or developed are:

(1) Wire launch model is held at the required attitude and the wire is cut to release it. (Reference 7).

(2) Launch gun accelerating model upstream a short distance thus increasing the view time. (Reference 7).

(3) Side launch, model is injected into the airstream from one of the walls.

Ballistic ranges are used to obtain stability data by gun launching a scale model down an instrumented range. The instrumentation consists of several stations located downstream of the gun to record the model attitude with Schlieren or shadowgraphs.

In addition to collecting the data on photographs some ballistic ranges have developed a technique for telemetering data from the model while in flight.

4.4 RECOMMENDATIONS

It is recommended that future development efforts include studies to list the important parameters required for an aerodynamic analysis on a particular type vehicle. This list would identify which parameters can be adequately determined by prediction techniques and those which have to be determined by experimental methods. Also it should note the cases for which it is desirable to use both methods during the program. In addition, the expected accuracy of the experimental vs. analytical technique should be recorded and compared with actual results when they become available.

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