TRANSONIC FREE-FLIGHT MODEL TESTING AT LARGE SCALE

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SUMMARY

The use of free-flight models for transonic testing at high Reynolds numbers is discussed. Several specific examples of experimental investigations are briefly reviewed to illustrate the scope of research that can be conducted by utilizing the advantages of free-flight models. These advantages are primarily the lack of interference or constraints imposed by test facilities and model support systems and the dynamic freedom possessed by free-flight models. High Reynolds numbers are obtained by using large models flown at relatively low altitudes. It is shown that models 10 meters or more in length will be required for research at Reynolds numbers sufficiently high to provide representative simulation of flow conditions for large modern aircraft. Several methods for launching models of this size are discussed. These methods include free drops from airplanes or balloons and ground launches with the use of internal or external rocket motors. All the launching methods discussed have been successfully demonstrated on flight vehicles of the size and weight required to attain the necessary test conditions.

NOTATION

a_n normal acceleration, multiples of G

a_t transverse acceleration, multiples of G

C_D drag coefficient

C_f skin-friction coefficient

C_L lift coefficient

C_{L_t} trim lift coefficient

C_m pitching-moment coefficient

C_n yawing-moment coefficient

C_p pressure coefficient

c speed of sound, m/sec

l characteristic length of model or aircraft, m

M Mach number

m mass, kg

R Reynolds number, based on total length

S area on which aerodynamic coefficients are based, m^2

s_f scale factor, $\frac{\text{model length}}{\text{airplane length}}$

V velocity, m/sec

α angle of attack, deg

β angle of sideslip, deg

ν coefficient of viscosity

ρ air density

$\phi_o(f)$ power-spectral-density function of normal acceleration

Subscripts

A airplane

M model

INTRODUCTION

Approximately two decades ago aircraft became capable of traversing the transonic speed region and penetrating into the supersonic. The well-known limitations of existing wind-tunnel testing at transonic speeds stimulated the development of schemes such as ventilated throats to alleviate the boundary-induced interference. Such tunnels became operational in the early 1950's and although interference effects near

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M = 1.0 were not entirely eliminated the limitations were tolerated because continuous operation of aircraft near M = 1.0 was not contemplated.

Before transonic tunnels became operational and during the early years of their use, a considerable amount of research and development took place at transonic speeds utilizing free-flight models, either rocket-launched from the ground(1,2) or dropped from aircraft.(3) These techniques provided aerodynamic data which were continuous through the transonic region with no tunnel wall or support system interference and bridged the gap between the capabilities of the existing wind tunnels and the needs of the aircraft designers. As the design and operation of transonic tunnels were refined, the use of free-flight model testing at transonic speeds declined in the U.S.A. in favor of higher speed free-flight research. At the present time the situation has again arisen where the flight characteristics of many aircraft exceed the capability of ground testing facilities and techniques to reproduce or satisfactorily simulate. This has resulted from two circumstances. One is the increasing cruise speeds of subsonic aircraft, with the probability that future designs will maintain continuous cruise speeds near M = 1.0. The other is the increasing size of aircraft which produces flight Reynolds numbers considerably above those which can be attained in present wind tunnels. To provide the required capability in ground test facilities will be very expensive and time consuming. Free-flight model testing offers a means of alleviating the problem by providing, at a relatively early time, large-scale interference-free data at selected conditions for correlation purposes and for assessing the value of simulation techniques. This paper reviews the background of past experiences in free-flight model testing and the current techniques available for such testing.

BACKGROUND

The need for increased testing capability has been well documented in published literature.(4,5,6) This includes not only the transonic region but other speed regimes as well, although fluid flow characteristics near M = 1.0 and the flow restrictions in a closed test facility near M = 1.0 make this region of particular interest and importance. A primary problem is that of scale effects on boundary-layer shock-wave interaction.(7,8) Not only is aircraft performance affected but a number of other characteristics such as loads and load distribution, stability, buffeting, and maneuverability are also affected and may be of paramount importance. References (4-8) present examples illustrating the effect of scale on flow characteristics over wings near M = 1.0. The failure of customary methods of simulating boundary-layer characteristics and shock position lead to obvious discrepancies between model and full-scale results.

Figure 1 illustrates the gap which exists between the maximum Reynolds numbers currently attainable in wind tunnels and those at which current and projected aircraft operate. All values of Reynolds numbers are based on overall length of the aircraft. The current and projected aircraft include the presently operating large subsonic aircraft and the supersonic transports. An order of magnitude difference exists between the capabilities of wind tunnels and the aircraft flight conditions.

As indicated in another paper at this conference by Igoe et al., it may not be necessary to attain the full-scale flight Reynolds numbers. An increase to some value above that currently available in wind tunnels may provide adequate aerodynamic simulation. The magnitude of the increase required has not been firmly established.

FREE-FLIGHT TECHNIQUE CHARACTERISTICS

Figure 2 lists some significant features of the free-flight model technique which make it attractive for aerodynamic testing. The scale of the tests is determined by the size of the models, and is limited primarily by the manpower and funds one is willing to devote to the design, construction, and testing of the model, and to the ground handling equipment available. Techniques exist for launching aircraft models of a significantly increased size over that currently permissible in transonic ground facilities. Further discussion of this subject is included later. As noted in the second item in Figure 2, free-flight models are free from interference effects caused by the test facility boundaries or any model support system.

The dynamic freedom possessed by flight models permits the measurement of transient effects, such as the effect of pitch rate on maximum lift and buffeting, for example, and also permits determination of the rotary aerodynamic derivatives. Investigation of the effects of the inertial and aerodynamic cross-coupling is possible, as well as the motions of multiple bodies, such as the separation of crew escape capsules from aircraft or the separation of multiple components of configurations as proposed for advanced space transportation systems.

The last two items in Figure 2 list advantages of free-flight models relative to full-scale aircraft for investigation of special problems where structural or crew safety limitations may restrain test conditions. Since model design need not be structurally efficient, the model can be designed for loads that would be excessive for aircraft design or crew tolerance. Thus, problems involving unstable or potentially uncontrollable regions, severe buffeting, flutter, and so forth, can be investigated at large scale.

MODEL FLIGHT TESTING EXPERIENCE

Much experience in free-flight model testing was obtained and techniques were well developed in past years. A brief review of some of this experience provides a background for current needs. Summaries of free-flight model test and analysis techniques covering airplane performance and longitudinal and lateral stability and control parameters are contained in references (9,10). It was demonstrated therein that effects of airplane configuration changes, wing flexibility, wing location, and so forth, on the airplane flight characteristics can be determined, including nonlinear effects. Reference (11) contains a comprehensive summary of test information obtained utilizing a relatively simple and inexpensive flight technique for investigating the lateral control characteristics of wing-aileron arrangements. Several specific examples of free-flight investigations of aerodynamic phenomena at transonic speeds are briefly discussed in the following.

Flight experiments, reported in references (12,13) and summarized in Figure 3, investigated the skin friction, total drag, and base drag coefficients of a 3.66-meter low drag body of revolution at Mach numbers from 1.0 to about 3.5. The data near $M = 1.0$ were obtained at Reynolds numbers ($R = 60 \times 10^6$ based on total length) comparable to wind-tunnel capabilities at that time (about 17 years ago) and Reynolds numbers as high as 2.0×10^8 were obtained at the highest Mach numbers, which exceeds the capabilities of wind tunnels at the present time. The friction drag was derived from the measurements of a boundary-layer rake near the aft end of the body. The information on friction drag is summarized in Figure 3, showing a comparison of measured and theoretical values. The five different types of symbols represent five model flights. The use of larger models and additional measurement techniques such as the determination of boundary-layer transition from surface temperatures or by acoustic measurements could provide useful data in the high Reynolds number region of current interest at transonic speeds. The drag characteristics of complete airplane configurations have been extensively investigated at large scale also, on models such as that shown in Figure 4.(14) This 3.36-meter model produced Reynolds numbers about equal to the largest now available in transonic wind tunnels and considerably above those available at the time of the tests.

Figure 5 is an illustration of a Reynolds number effect disclosed in a rocket-model investigation of the lateral stability characteristics of a complete airplane,(15) using pulse rockets to provide yaw disturbances to the model. The flight results, at a Reynolds number more than three times that of the wind-tunnel test, showed linear directional stability contrasted with a nonlinear stability at the lower scale of the wind-tunnel tests. Similar results were obtained for the lateral force and rolling moment data. This effect was attributed to a vertical tail airfoil shape which was sensitive to boundary-layer characteristics in this Reynolds number region.

Figure 6 illustrates a severe roll-yaw-pitch coupled motion which was obtained on the same airplane configuration shown in Figure 5 when tested at a high angle of attack.(16) The results indicate that the model exhibited an unstable pitchup to angles of attack exceeding 25°, accompanied by a large amplitude pitching and rolling motion, producing large normal and lateral-force excursions. The basic nonlinear pitching-moment curve leading to this motion was also measured during the model flight and is shown in the upper right corner of Figure 6. A similar severe coupled motion was later encountered on a flight of the full-scale airplane.(17) The usefulness of the dynamic freedom of a free-flight model to uncover potentially dangerous flight conditions is obvious.

Another example of a dynamic problem amenable to free-flight model testing is illustrated in Figure 7. In this case the separation of a pilot escape capsule was investigated at low supersonic speeds. The Reynolds number for the tests corresponded to those for full-scale airplanes at altitudes of about 12 km.(18) Figure 7 shows the escape capsule model attached to a booster whose ratio of drag-to-weight simulated a full-scale airplane, and also an in-flight photograph of the capsule immediately after separation from the booster and with the simulated separation rockets still burning. Separation tests such as this could prove useful for multiple lifting-body configurations currently under study for advanced space transportation systems, particularly for abort conditions at low Mach numbers and high dynamic pressures, and for investigation of store or fuel tank release.

Figure 8 illustrates flight measurements of power effects on a configuration whose aft fuselage and tail surfaces were expected to be greatly affected by the exhaust from the jet engine.(19) The engine exhaust was simulated by a solid rocket motor modified to produce the required characteristics in the exhaust stream. Measurements of airplane trim changes (Fig. 8) were made as well as pressure measurements on the tail boom to define the power effects on pressures and to locate the impingement points of the jet exit and aft body shocks.

Free-flight models have been used to measure the loads on aircraft in continuous atmospheric turbulence at transonic and low supersonic speeds.(20) Figure 9 illustrates power spectra of accelerations measured on a sweptwing model and shows a large increase in accelerations near $M = 1.0$ at the model natural pitch frequency ($\simeq$ 10 cps), primarily attributable to a decrease in the airplane aerodynamic damping in this region. Small acceleration peaks at the first bending frequency of the wing ($\simeq$ 35 cps) are also evident. Gust alleviation schemes could be evaluated using free-flight models.

In addition to the specific examples illustrated, free-flight models have been used to measure flutter, buffeting, inlet performance, and the effects of both external and internally retractable stores. The examples shown illustrate the wide variety of aerodynamic problems that are amenable to investigation by free-flight models.

MODEL FLIGHT TEST CONSIDERATIONS

Model Scale Required

Although several fluid flow parameters are involved when scale model tests are considered, the Mach number and Reynolds number are by far the most important for the transonic testing under consideration here. The basic objective of high Reynolds numbers is obtained in model flight testing by using model sizes larger than can be accommodated in wind tunnels and arranging for the test period to occur at altitudes lower than those at which the full-size aircraft will fly. The scale factor relation is shown in Figure 10 assuming that the model and aircraft Mach numbers and Reynolds numbers are to be matched. The scale factor (model length/aircraft length) is given by the equations on the lower left. On the right is a plot of model test altitude versus aircraft altitude being simulated as a function of scale factor.

Figure 10 shows, for example, that for an airplane cruising at 12 km, a 1/3-scale model would require a test altitude of 2.5 km, and a 1/4-scale model would require a test altitude of 0.75 km. Many modern transport aircraft are 200 or more feet in length, and these scales would require models 50 to 70 feet long. Fortunately, as discussed in the paper by Igoe et al., it may not be necessary to attain full-scale conditions. A rough approximation based on information in that paper indicates that Reynolds numbers about one-half of those needed for full-scale simulation for the largest aircraft might be sufficient. As indicated in Figure 11, models 10 meters in length would provide Reynolds numbers significantly larger than those available in current wind tunnels at transonic speeds and would approximate one-half the values of the largest aircraft. Also, of course, not all aircraft will be as large as the current and projected transport types and full-scale conditions can be attained for many airplanes with smaller size models. Thus, model lengths of about 10 meters would permit investigation of the major effects of Reynolds number for most aircraft types and this size range is used for discussion purposes in the following.

Test Techniques

Several launching techniques are available and have been demonstrated for test vehicles of the size considered above. These include air launching from aircraft, air launching from high-altitude balloons, and ground launching utilizing rocket propulsion.

Launching from aircraft is a reliable and proven test method. It has been repeatedly demonstrated in the testing of manned research aircraft at the NASA Flight Research Center. The air launching of unmanned drone aircraft of about the size of the models being considered herein has also been well developed and demonstrated. Further remarks on the use of drone aircraft for aerodynamic testing will be made later. Launching conditions are, of course, limited by the carrier aircraft altitude and speed capabilities. Figure 12 illustrates the Mach number and Reynolds number conditions that could be attained on 10 meter unpowered bodies in free fall from a typical launch altitude of 9.2 km and a Mach number of 0.6. Two different ballistic coefficients are shown. Reynolds numbers significantly higher than those available in ground facilities can be attained. In addition, the trajectories can be modified to produce other conditions by providing onboard rocket power.

Another air-launching technique which appears to have some advantages is the use of high-altitude balloons. The use of this technique for an investigation of the deployment of a large parachute at transonic speeds is described in reference (21). For aerodynamic testing of interest herein the test vehicle would be carried to altitudes of 18 to 30 km and dropped. Typical trajectories are shown in Figure 13 for 10 meter free-fall bodies of three ballistic coefficients chosen to provide Mach numbers at impact between 0.8 and 1.2. Reynolds numbers of about 2.3×10^8 are attained at $M = 1.0$ at impact for bodies 10 meters in length. Of particular interest is the fact that the freely falling bodies traverse a given Mach number range twice during the flights at widely varying Reynolds numbers. For example, the body with $m/C_DS = 4550$ attains $M = 1.0$ at 1.8×10^7 and 8×10^7 Reynolds numbers and for $m/C_DS = 15\,100$ Reynolds numbers of about 8×10^6 and 2×10^8 are obtained at $M = 1.0$. By varying the drop altitude, the ballistic coefficient of the test body, and by use of small amounts of onboard propulsion, considerable flexibility in the choice of test conditions is possible. Other than ground handling problems there is no fundamental reason why bodies longer than 10 meters could not be launched by balloon to attain even higher Reynolds numbers.

A considerable range of flight-proven balloon designs is available for the range of test vehicle weights required, and these are relatively inexpensive. The operational techniques of launching and controlling the balloons to provide the desired drop altitudes and geographical test locations are also well developed, but are, of course, subject to seasonal and meteorological conditions. Careful choice of these conditions will result in a high probability of successfully dropping the test vehicles in favorable locations with respect to ground-based recording and tracking equipment and within specified range safety zones.

Ground launching of flight vehicles by means of rocket boosters or internal rockets has also been well developed and demonstrated for the size and type of vehicles under discussion. Both drone aircraft and aerodynamic cruise missiles are in this category. Figure 14 illustrates two types of boost arrangements that have been used for launching of research models. The tandem booster arrangement offers the least aerodynamic and separation problems; but with large lifting surfaces and high dynamic pressure flight conditions, a severe aeroelastic divergence problem exists. This problem can be overcome with the parallel booster arrangement, but aerodynamic trim, interference, and separation problems require careful consideration.

Figure 15 is a sketch of a model with an internal (or sustainer) rocket motor that attains the Reynolds numbers of interest at transonic speeds both during the ascent portion of the trajectory (Fig. 15) and during the reentry into the atmosphere. To utilize this reentry portion of the trajectory for research purposes, it may be necessary to include a control system in the vehicle to orient it to the correct attitude for reentry if the trajectory apogee is of such a height as to cause loss of aerodynamic stability. The test model sketched in Figure 15 was designed primarily for high Mach number testing and utilizes a standard Castor rocket motor, which is the same as the second-stage motor of the Scout launch vehicle. For transonic testing a motor with equivalent thrust but a shorter burning time would be preferable and a trajectory might be attainable which would eliminate the need for a control system and still permit two periods of transonic testing.

In general, the rocket-boosted ground-launched technique provides more versatility for research testing than the air-launched technique. Wide variation in trajectory parameters can be obtained by varying the launch angle and by varying the number and timing of the rocket stages. Test times are usually longer than for drop tests because of the more shallow trajectory angles. Multiple test periods in each flight can be provided by utilizing the reentry portion of the trajectory as well as the ascent, or by delayed firing of internal rockets. The test vehicle and propulsion system design and preflight testing effort is generally greater than for air-launched vehicles, however, because of more severe stability, loads, and aeroelastic problems. The choice of launch techniques requires a consideration of the test purposes and facilities available.

The launch and test techniques described above are characterized by short test times, and varying speed and altitude on the uncontrolled trajectories during the test period. For most test purposes this is satisfactory. The ability to control the flightpath would be of benefit for some purposes, and radio-controlled models have been used occasionally for special purposes, usually at low speeds. This technique has not been used extensively for research, however, because of expense, complexity, and questionable reliability.

A significant development which offers promise of providing a means of transonic research flight testing is the successful development of reliable drone aircraft capable of transonic and supersonic speeds.(22). These aircraft are of about the size considered desirable herein for high Reynolds number testing, are capable of sustained transonic and supersonic speeds, are capable of both air and ground launching, and are recoverable and reusable to minimize expense. The cost of these aircraft plus modifications for research purposes may not be unreasonable when the aircraft are procured as a part of a mass production effort for other purposes. Research flights at constant speed and altitude would be possible to permit more thorough investigation of the transonic region to determine loads and maneuverability, for example. Although the use of drone aircraft for transonic research testing has not yet been proven practical or economical, it is being considered by several groups in the United States and deserves further investigation.

Recovery

For some test purposes, simple expendable test vehicles have proven to be the most economical. The general increase in size, complexity, and cost of test vehicles to simulate the increased performance and size of aircraft have led to renewed interest in the recovery and reuse of research vehicles. Recovery techniques have been developed to a high level of reliability. Particularly attractive is the air-snatch technique described in reference (23). This procedure results in the minimum damage to the test vehicle and thus minimum refurbishment cost before reuse. Efficient aerodynamic decelerators are available to permit descent of a vehicle to land or water impact with little or no structural damage. In a recent series of tests to measure the characteristics of large-size parachutes at supersonic speeds, two test vehicles were repeatedly recovered and each was flown five times. The cost for the final flights of each was less than 20 percent of that for the first flights.

In many cases it is not necessary nor desirable to recover the complete test vehicle. Onboard camera pictures such as that shown previously of a separating escape capsule can be particularly valuable, and this can be accomplished by ejection and recovery of an instrumentation package or externally attached pod. Recovery of other instruments may also be desirable, not necessarily for reuse but for obtaining data which cannot be conveniently or economically recorded by remote transmission means. Tape-recorded data in lieu of telemetry is one example.

Dynamic Scaling

It is rarely necessary to require dynamic similitude for free-flight model testing at transonic speeds. For the determination of lift and drag characteristics, stability and control parameters (including aerodynamic nonlinearities such as illustrated in Figs. 5 and 6), and loads measurements dynamic similarity is not required. The motions, loads, and accelerations of the test models are reduced to nondimensional coefficients utilizing the known mass and inertia characteristics of the models, and these coefficients are, in turn, used to calculate the motions, loads, and accelerations of the full-scale airplane.

In cases where it is desirable to reproduce a particular motion such as for the escape capsule mentioned above, which can then be directly scaled to full-size airplane motion, dynamic scaling must be considered. The wing loading, relative densities, and reduced frequencies of the model and its components must be adjusted to desired values. Reference (25) discusses this subject further.

It is fortunate that it is rarely necessary to require dynamic similitude since this condition is difficult to attain on the models. Practical design, construction, and operational requirements usually result in models having wing loadings which are too low and radii of gyration that are too large for complete dynamic simulation. The practical result is that the angular motion amplitudes of the model are smaller relative to the translatory motion amplitudes than are those for full-scale, and that rotary aerodynamic derivatives derived from these motions have degraded accuracy. Since most aircraft now have artificial damping added to the control system, the degraded accuracy is generally not of major concern.

For measurements where aeroelasticity is of importance, attention must be given to the aeroelastic deflection of the model components. Some discussion of the effects of structural elasticity on stability determinations is given in reference (8). Even if no simulation of aeroelastic effects is to be attempted, it is desirable to measure the vibration modes and frequencies and static bending and torsional deflection of structural components in order to adequately estimate the effects of aeroelasticity, or to permit analysis of expected or unexpected vibrations due to buffeting or flutter.

TRANSONIC TEST PROGRAM

The Langley Research Center of NASA has initiated a program whose ultimate objective is to obtain high Reynolds number data on transonic configurations. The first effort in this program consisted of four drop tests of a body of revolution having favorable transonic drag characteristics. These tests were made at the same Reynolds numbers as wind-tunnel tests in the Langley 8-foot transonic tunnel, in order to evaluate wind-tunnel boundary and sting interference effects before proceeding to larger scale tests. Figure 16 shows one of the models mounted on the launching aircraft. Further studies will be made to determine the course of future work in this program.

CONCLUDING REMARKS

The preceding discussion has indicated the types of transonic problems that can be investigated by the use of free-flight models and the range of operational choices that are available for conducting such tests. As pointed out previously, large-size models are required to obtain the desired high Reynolds numbers. Such models will be more costly than those that have been used in the past. This is paralleled by the greatly increased development costs of modern transport and military aircraft. Thus, model flight tests can still be economically justified where unknown or poorly known aerodynamic or dynamic effects can compromise the performance or safety of full-size aircraft. The exploratory aspect of flight testing for probing little-known phenomena or flight regimes, or for revealing unexpected phenomena and problems, has frequently proven to be the most valuable result of free-flight testing.

Instrumentation, data acquisition and analysis, and mechanical design and operation have been considered as outside the scope of this paper. These are worthy of extensive separate discussions. Finally, it should not be construed that the free-flight model test technique is offered as a substitute for new ground test facilities having increased capability. Model flights can provide verification of wind-tunnel and theoretical results, provide extrapolation of wind-tunnel results, furnish anchor-point data for correlation purposes, permit measurements impossible or very difficult to perform in wind tunnels, verify flow simulation techniques, and furnish a means of obtaining large-scale transonic data in the time period before larger wind tunnels became operational.

REFERENCES

1. Shortal, Joseph A.: Techniques of Model Testing in Free Flight. Paper presented at Fifth Meeting of the Wind Tunnel and Model Testing Panel, AGARD Fourth General Assembly (Scheveningen, The Netherlands), May 3-7, 1954. AG 15/P6, p. 56.

2. Hamilton, J. A.; and Hufton, P. A.: Free-Flight Techniques for High Speed Aerodynamic Research. J. Roy. Aeron. Soc., Vol. 60, No. 543, March 1956, p. 151.

3. Kurbjun, Max C.; and Thompson, Jim Rogers: Free-Flight Measurements of the Effects of Wing-Body Interference on the Transonic Drag Characteristics of Swept-Wing-Slender-Body Configurations. NACA RM L53C31, May 1953.

4. Heppe, Richard R.; O'Laughlin, B. D.; and Celniker, Leo: New Aeronautical Facilities - We Need Them Now. Astronaut. Aeron., vol. 6, no. 3, March 1968, p. 42.

5. Poisson-Quinton, Philippe: From Wind Tunnel to Flight, The Role of the Laboratory in Aerospace Design. Jour. of Aircraft, vol. 5, no. 3, May-June 1968.

6. Ring, L. E.; and Milillo, J. R.: Transonic Testing - A Review. Paper no. 70-580, presented at AIAA Fifth Aerodynamic Testing Conference (Tullahoma, Tenn.), May 18-20, 1970.

7. Loving, Donald L.: Wind-Tunnel-Flight Correlation of Shock-Induced Separated Flow. NASA TN D-3580, September 1966.

8. Jones, J. Lloyd: Problems of Flow Simulation in Wind Tunnels. Paper no. 69-660, presented at AIAA Fluid and Plasma Dynamics Conference (San Francisco, Calif.), June 16-18, 1969.

9. Gillis, Clarence L.; and Mitchell, Jesse L.: Determination of Longitudinal Stability and Control Characteristics From Free-Flight Model Tests With Results at Transonic Speeds for Three Airplane Configurations. NACA Report 1337, 1957.

10. Gillis, Clarence L.; Mitchell, Jesse L.; and D'Aiutolo, Charles T.: Determination of Lateral Stability Characteristics From Free-Flight Model Tests, With Experimental Results on the Effects of Wing Vertical Position and Dihedral at Transonic Speeds. NASA TR R-65, 1960.

11. Strass, H. Kurt; Stephens, Emily W.; Fields, E. M.; and Schult, Eugene D.: Collection and Summary of Flap-Type-Aileron Rolling Effectiveness Data at Zero Lift as Determined by Rocket-Powered Model Tests at Mach Numbers Between 0.6 and 1.6. NACA RM L55F14, September 1955.

12. Loposer, J. Dan; and Rumsey, Charles B.: Flight Measurements of Average Skin-Friction Coefficients on a Parabolic Body of Revolution (NACA RM-10) at Mach Numbers From 1.0 to 3.7. NACA RM L54G14, 1954.

13. Jackson, H. Herbert; Rumsey, Charles B.; and Chauvin, Leo T.: Flight Measurements of Drag and Base Pressure of a Fin-Stabilized Parabolic Body of Revolution (NACA RM-10) at Different Reynolds Numbers and at Mach Numbers From 0.9 to 3.3. NACA RM L50G24, 1950.

14. Chapman, Rowe, Jr.; and Wallskog, Harvey A.: Stability and Drag Characteristics at Mach Numbers From 0.8 to 1.5 of a Free-Flight Model Having 3-Percent-Thick, 60° Triangular Wing and Horizontal Tail Surfaces. NACA RM L54G23a, 1954.

15. Mitchell, Jesse L.; and Peck, Robert F.: Investigation of the Lateral Stability Characteristics of the Douglas X-3 Configuration at Mach Numbers From 0.6 to 1.1 by Means of a Rocket-Propelled Model. NACA RM L54L20, 1955.

16. Peck, Robert F.; and Mitchell, Jesse L.: An Investigation of the Longitudinal Characteristics of the X-3 Configuration With Wing and Horizontal Tail Surfaces of Aspect Ratio 3.0 by Means of Rocket-Propelled Models. Results at High Lift Coefficients. NACA RM L51G10, 1951.

17. NACA High-Speed Flight Station: Flight Experience With Two High-Speed Airplanes Having Violent Lateral-Longitudinal Coupling in Aileron Rolls. NACA RM H55A13, 1955.

18. Hollinger, James A.: Separation Tests of Rocket-Propelled Models of a Pilot-Escape Capsule. NASA TN D-2901, 1965.

19. Jackson, Bruce G.: Free-Flight Transonic Model Investigation of Jet Effects on a Fighter-Type Configuration Employing a Tail Boom and Three Horizontal-Tail Positions. NACA RM L57J31, 1957.

20. Vitale, A. James; Press, H.; and Shufflebarger, C. C.: An Investigation of the Use of Rocket-Powered Models for Gust-Load Studies With an Application to a Tailless Swept-Wing Model at Transonic Speeds. NACA TN 3161, 1954.

21. Darnell, Wayne L.; Henning, Allen B.; and Lundstrom, Reginald R.: Flight Test of a 15-Foot-Diameter (4.6-Meter) 120° Conical Spacecraft Simulating Parachute Deployment in a Mars Atmosphere. NASA TN D-4266, 1967.

22. Miller, Barry: USAF Widens Unmanned Aircraft Effort. Aviation Week and Space Technology, Vol. 93, No. 19, November 9, 1970, p. 46.

23. Highly, Frank M., Jr.; and Long, Robert T.: Recovery, Sea and Air. Paper presented at the AIAA Sounding Rocket Vehicle Technology Specialist Conference (Williamsburg, Va.), February 27-March 1, 1967.

24. Murphy, Glenn: Similitude in Engineering. The Ronald Press Co., New York, 1950.

25. Neihouse, Anshal I.; and Pepoon, Phillip W.: Dynamic Similitude Between a Model and a Full-Scale Body for Model Investigation at Full-Scale Mach Number. NACA TN 2062, 1950.

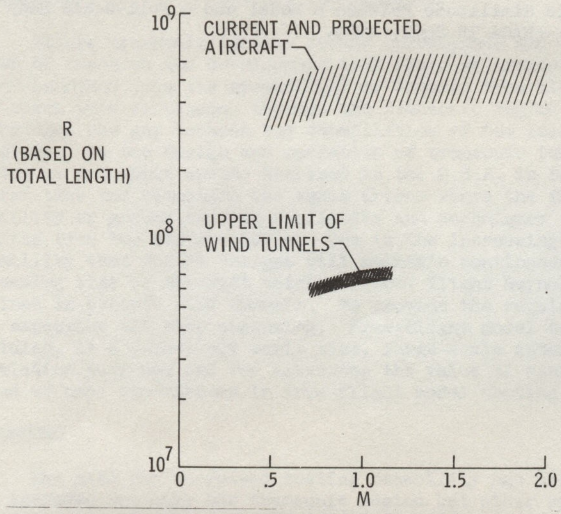

Figure 1.- Flight and wind-tunnel Reynolds number.

LARGE SCALE
FREEDOM FROM WIND TUNNEL BOUNDARY AND SUPPORT INTERFERENCE
DYNAMIC FREEDOM, INCLUDING CROSS-COUPLING AND MULTIPLE-BODY EFFECTS
RELAXED LOAD AND STRUCTURAL LIMITATIONS
NO CREW SAFETY LIMITATIONS

Figure 2.- Desirable features of free-flight model testing.

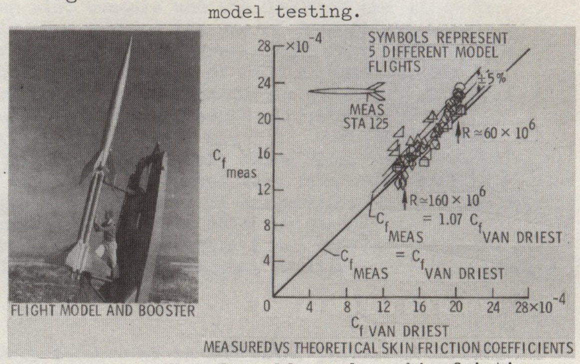

Figure 3.- High Reynolds number skin-friction measurements.

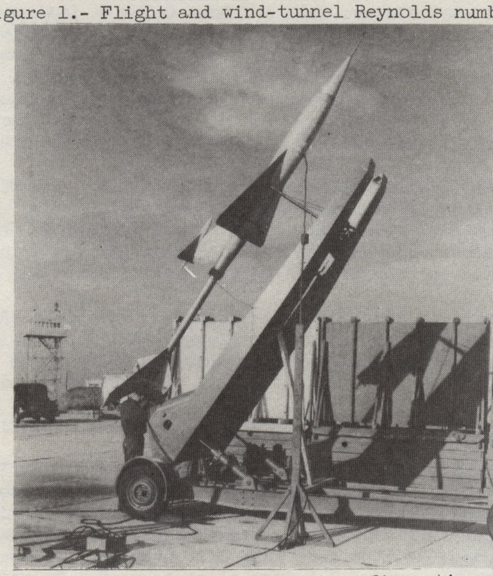

Figure 4.- Delta wing airplane configuration for large-scale flight tests.

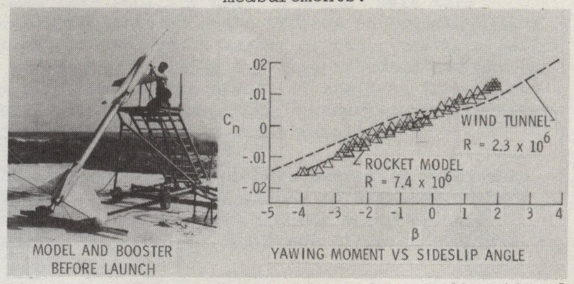

Figure 5.- Effect of Reynolds number on directional stability.

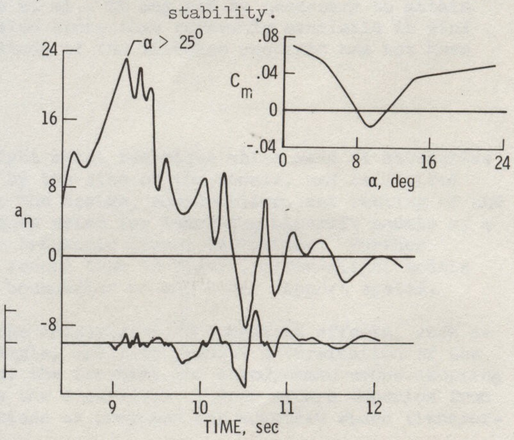

Figure 6.- Large amplitude coupled motion.

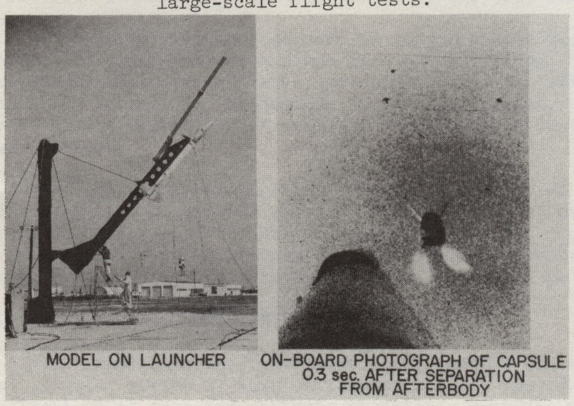

Figure 7.- Pilot escape capsule separation test.

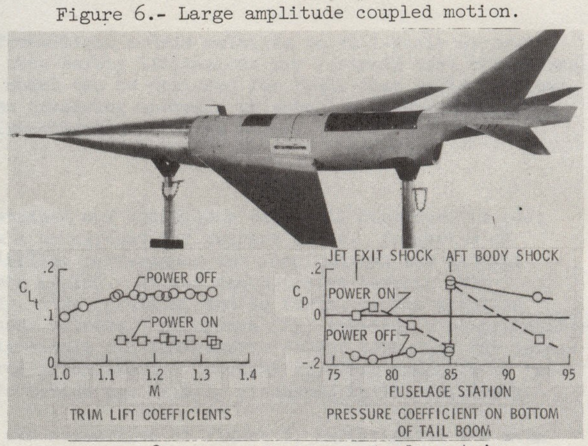

Figure 8.- Jet effects on airplane trim.

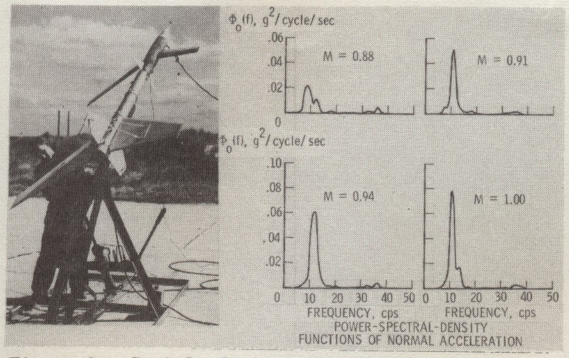

Figure 9.- Gust loads investigation in continuous atmospheric trubulence.

$$R = \frac{\rho V l}{\nu} \qquad M = \frac{V}{c}$$

FOR

$$R_M = R_A$$

AND

$$M_M = M_A$$

$$s_f = \frac{l_M}{l_A} = \frac{\left(\frac{\rho c}{\nu}\right)_A}{\left(\frac{\rho c}{\nu}\right)_M}$$

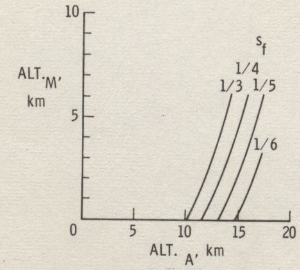

Figure 10.- Reynolds number scaling.

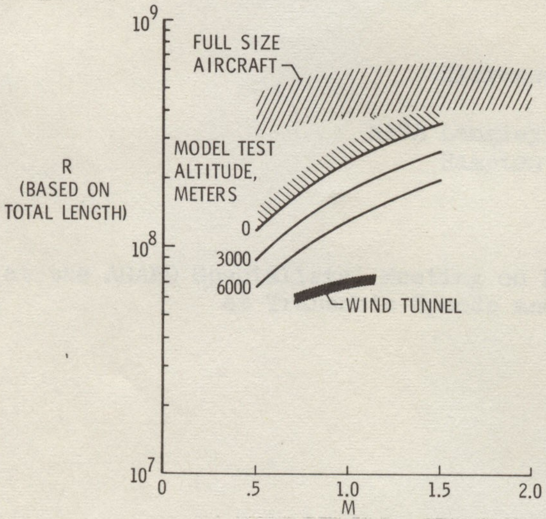

Figure 11.- Reynolds numbers for 10-meter model.

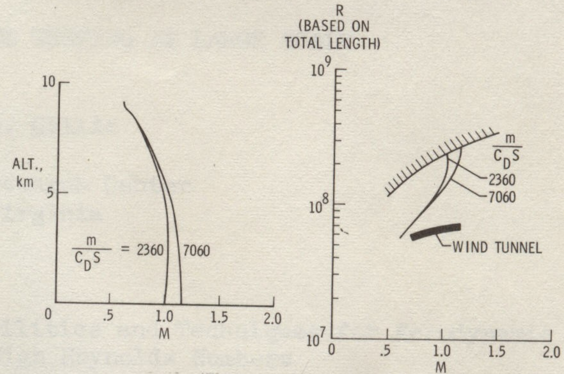

Figure 12.- Trajectories for 10-meter body dropped from airplane.

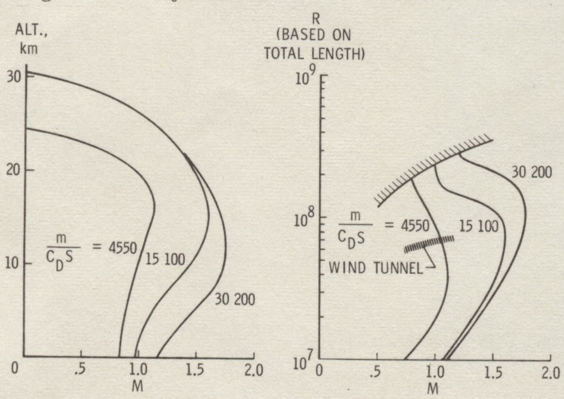

Figure 13.- Trajectories for 10-meter body dropped from balloon.

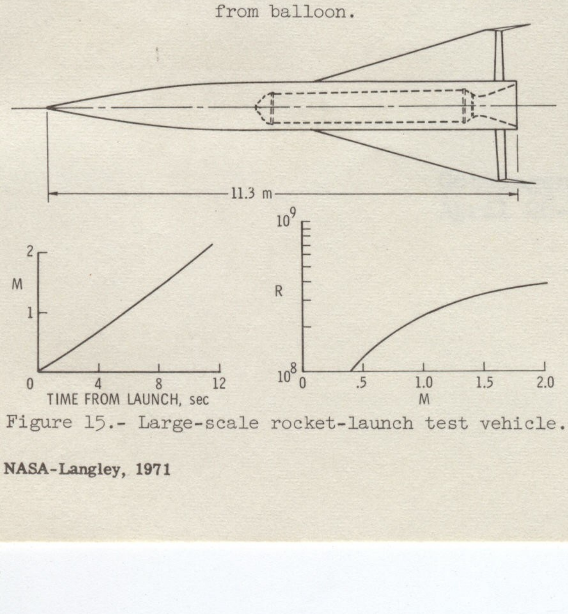

Figure 15.- Large-scale rocket-launch test vehicle.

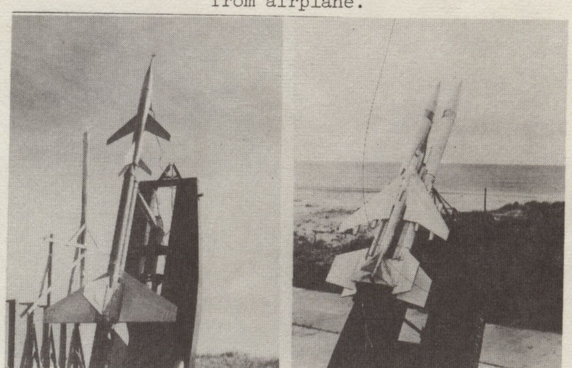
Figure 14.- Tandem and parallel booster configurations.

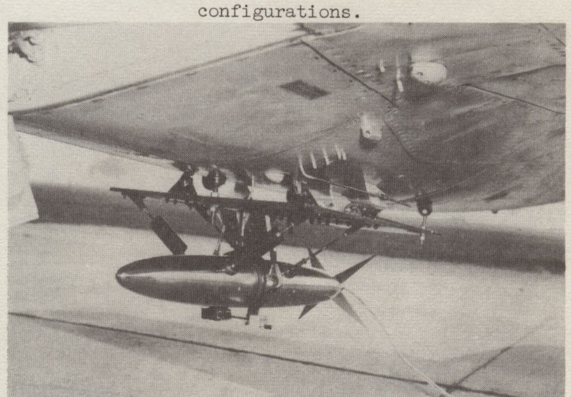
Figure 16.- Transonic drop body for wind-tunnel correlation.

NASA-Langley, 1971