A ground-test technique for simulating the aerodynamic forces that act on missile wings in flight has been investigated. This paper discusses the hardware required to demonstrate the interaction of the simulation forces with a cantilever plate analogous to a wing. Self-excited vibrations similar to those in flight flutter are produced in the plate for certain critical test conditions.

MISSILE-WING

Interactions of elastic, inertial, and aerodynamic forces are capable of producing in missile wings during flight a potentially dangerous flutter condition, or oscillation. The first two of these forces—elastic and inertial—are inherent in and associated with any wing motion. If, then, the third —aerodynamic—force can be applied to an actual wing by means of simulation, the stage is set for the three types of force to interact. This suggests immediately a possible technique for ground testing actual missile wings for the presence of flutter. Application of this technique and the development of pertinent test equipment are the subject of this paper.

An ideal flutter simulation program may be described as follows. For any chosen Mach number (speed) and altitude, the aerodynamic forces that are dependent upon wing motion are determined from theory. Air forces produced by electromechanical shakers are then applied to a test vehicle. If the selected theoretical air forces are valid and the shaker forces truly represent them, an oscillation of constant or increasing amplitude occurring during test implies that a similar oscillation will occur in flight. If a wing is dynamically stable, i.e., vibrations in the test are damped, it is inferred that stability will also be exhibited in flight.

The following discussion covers the work done to obtain a representation of the theoretical air forces. One task is to develop test forces that can simulate air forces acting on a metal plate in a state of both translational and pitching motion. A second task is to use these forces judiciously to simulate the distributed air forces acting upon a cantilever plate that bends and twists.

Selection of Simulation Forces

It is first necessary to choose a suitable aerodynamic theory that relates the air forces to the surface motions. Piston theory[1] is widely used for supersonic flutter analyses. In its simplest form, for a thin airfoil, this theory calls for a lift force varying with the angle of attack, a center-of-pressure at the midchord, and positive damping in both translation and rotation.

These forces may be used in the study of a very simple type of flutter that occurs in a long, rigid

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[1] H. Ashley and G. Zartarian, "Piston Theory—A New Aerodynamic Tool for the Aeroelastician," *J. Aeronaut. Sci.*, **23,** Dec. 1956, 1109–1118.

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FLUTTER SIMULATION

plate in which translational and pitching frequencies are established by springs supporting the ends of the plate. For such a system under conditions of supersonic flow, the air forces are uniform along the plate, thereby permitting representation in the form of a concentrated lift and moment acting at the midpoint. In a laboratory test to simulate the lift, a shaker is placed at the midchord; an electronic feedback loop is used to produce a shaker force proportional to the angle of plate rotation. The piston theory lift and center-of-pressure are thereby simulated.

Two additional important forces remain to be simulated, however: damping in translation, and damping in pitch. These are established by placing a mechanical damper a certain distance ahead of the midchord and an equally strong damper the same distance aft of the midchord; this distance should be set to produce the theoretical ratio between the translational and the pitch damping. The constants of the dampers are chosen to produce the values called for by the theory.

Since the wings of actual missiles are restrained by their roots, they will bend and twist, as shown in Fig. 1A, rather than merely translating and pitching as a unit. Accordingly, intrinsic aerodynamic forces are developed at each spanwise station. To

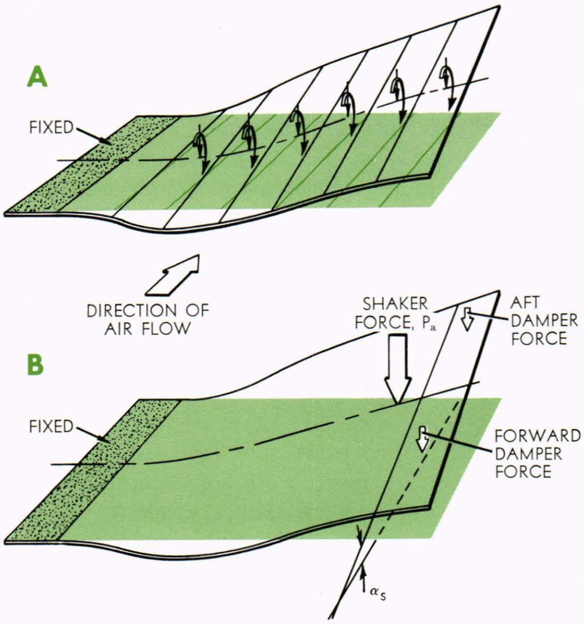

Fig. 1—(A) Distributed aerodynamic forces, and (B) concentrated simulation forces.

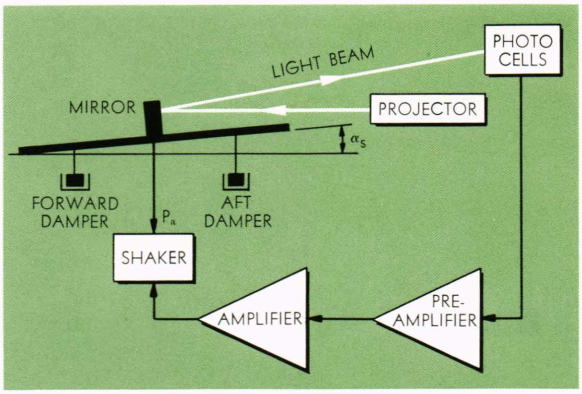

Fig. 2—Flutter simulation block diagram—one-channel.

simulate such a distribution, the most direct method would be to place sets of shakers and dampers along the span, each set reacting to the local translation and rotation of the plate. The end result would then be a test closely corresponding to a flight condition.

Before this method can be used, however, the basic shaker/damper set must be carefully evaluated. It is germane to consider, as part of the evaluation, the use of only one shaker/damper set to simulate the distributed air forces. The premise upon which these initial test forces are chosen is that they should correspond to the distributed air forces in their ability to do work on the plate.

Component Description

The shaker and two mechanical dampers, along with the other necessary feedback loop elements, are represented in Fig. 2, a damper being shown in more detail in Fig. 3. In order to create a shaker force in phase with the plate angle at some chosen spanwise station, the feedback loop of Fig. 2 is chosen. A 30-watt projector sends a light beam to a vertical mirror cemented to the plate, and the reflected beam is brought to a focus on a pair of photocells. Since the mirror is placed vertically on the plate, neither a vertical translation, a spanwise translation, nor a spanwise angular displacement of the mirror will produce an image shift on the photocells. The fore-and-aft movement and yawing rotation of the mirror are small because the plate is rigidly restrained from such motions. The only motion that will produce an image shift is a pitching angular displacement. The complete system, consisting of the plate plus the mirror, thus rejects all types of image shift except the one needed for the simulation.

The resulting small current that will be produced by the photocells is amplified by a special transistorized preamplifier. The preamplifier is followed by a power amplifier that drives the shaker voice coil.* The principal requirement for the power amplifier is that the shaker force be in phase with the input voltage and proportional to it, being independent of the shaker input impedance, which varies with both frequency and mechanical load on the shaker.

The overall capability of the system is 17,000 lb of shaker force per radian of plate deflection, from zero to 1000 cps. Such a performance number for the simulation lift coefficient is of significance because it is a measure of the maximum sea level Mach number condition that can be simulated by one shaker applied to an aerodynamic surface of a given area. To take one example, the simulation lift coefficient is equivalent to a value for a 100-in.^{2} surface in flight at Mach 4. Some appreciation of the actual applied force and angle magnitudes is gained from noting that the design of the shaker limits the force to 0.50 lb. Consequently, the angular movement necessary to produce such a force under the high-gain conditions is only 29 μrad.

Simulation of aerodynamic damping is provided by a mechanical damper mounted under and in contact with the cantilever plate (Fig. 3). The damper consists of a small vertical plate that is preloaded to follow the movement of a selected point on the cantilever plate. The vertical plate is held by a rubber band against ball bearings in tracks in one face of a firmly mounted 1.0-in. aluminum cube. The vertical, parallel tracks contain SAE 90 oil. The damping force generated by this oil in shear is 0.02 lb/in./sec of test-plate motion. With

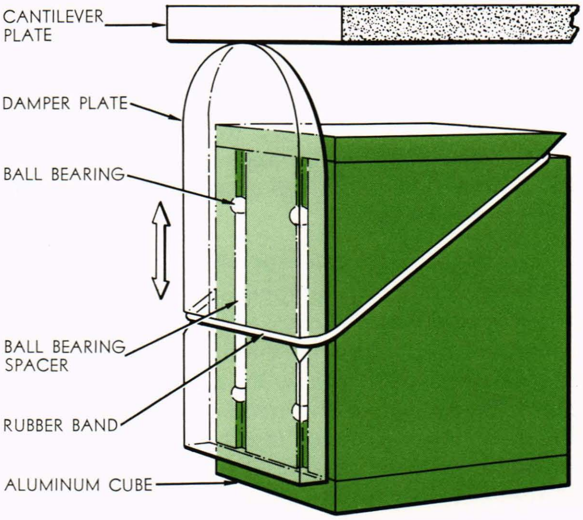

Fig. 3—General arrangement of the viscous damper.

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* Both the amplifier and associated preamplifier were designed by G. B. Bush, APL.

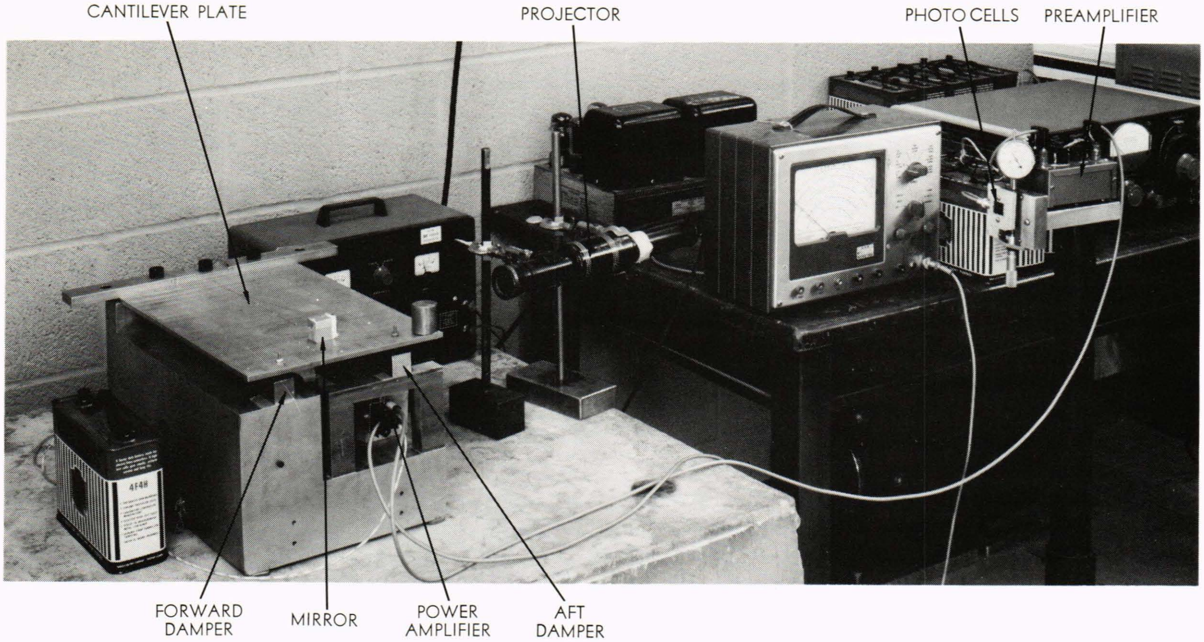

Fig. 4—Simulation test assembly.

several such dampers and the shaker, forces are then available to simulate the aerodynamic forces on the plate.

A Simulator System Evaluation

Tests on each of the components are valuable to show how well they meet the requirements of consistency, zero phase lag, low mechanical and electrical noise, and shaker-damper-support resonances well outside the expected ranges of flutter frequencies. It is difficult to decide, however, whether deficiencies found by these tests are serious. All the components must be tested ultimately in a closed loop to demonstrate whether small or hidden deficiencies will prevent successful performance. From such tests, tolerances on the requirements for component performance are derived.

To meet the need for closed-loop testing, a simple structure has been chosen to serve as a stand-in for the role to be played eventually by an actual missile wing. Such a test article should fulfill certain requirements. It must be simple enough that its major elastic and inertial characteristics can be readily computed, so that it is possible to check the experimental results by comparing them with theoretical calculations. The stiffness of the test structure should be sufficient to provide resistance to flutter until sea-level Mach numbers of the order of 2 or 3 are reached. Its natural frequencies should lie in the range from 10 to 200 cps, where most significant flutter problems have been found to occur. It should exhibit a tendency toward a torsion-bending flutter that has occurred in some missile wing problems in the past.

To meet these requirements, a 15.5 × 10 × 0.25-in. clamped cantilever aluminum plate was chosen. Its natural frequencies in bending and in torsion are 29.4 and 93 cps respectively, when a 0.35-lb mass is cemented to the tip trailing edge. The mass is so placed as to provide a mass unbalance leading to a torsion-bending flutter of the kind that commonly plagues missile development programs. The root of the cantilever plate is clamped firmly to a heavy aluminum block that is also the shaker base (Fig. 4).

A set of appropriate test conditions, for example Mach 2 at sea level, is chosen for simulation, and the theoretical air forces for these parameters are then calculated. Since most of the work done by these forces will be done in the zone where the natural modal amplitudes are greatest, it is desirable to locate the shaker force somewhere in this zone. In the torsion-bending type of flutter, the region from midspan to the tip is the site of the greatest work input. A spanwise location 12 in. from the root is chosen for the shaker driving point, a midchord location being selected because, as noted earlier, this is the center-of-pressure called for by simple aerodynamic theory. Electrical connections are made for the feedback loop as shown in Fig. 2. The gain in the preamplifier is adjusted so that when the plate twists through an angle α_s (Fig. 1B), a downward shaker force P_a is produced. The shaker force then simulates the Mach 2 air forces in terms of its ability to do work on the plate for all combinations of bending and twisting in the two fundamental plate vibration shapes.

The damping in bending and torsion remains to be simulated. One criterion for the damper forces is that they should equal the air forces in their capacity to absorb energy from the plate for any plate velocities in the fundamental bending and twisting types of motion. Here it should be noted that while limitations of the present damper design precluded a full simulation of the damping provided by the aerodynamic forces, a conservative simulation was attained. Minor modifications in the present design will ultimately permit full simulation. The present dampers do not absorb as much energy as do the actual air forces in bending or in twisting. Furthermore, the ratio of test bending damping to the test torsional damping exceeds the ratio provided by the flight air forces. Both of these deviations are conservative, according to calculations that have been made for this problem. Thus, the test results should indicate flutter as occurring sooner than in an actual wind tunnel test. The test apparatus is currently being revised to eliminate this defect, and it is expected that future tests will provide a much better simulation.

Test Results

With the correct lifting force simulation and the conservative damping simulation, closed-loop testing is ready to proceed. The feedback loop is closed, and the plate is seen to be stable; that is, when it is tapped, the vibration damps out rapidly. From this test it is concluded that the plate would be stable for sea-level flight at Mach 2.

When a second set of conditions is chosen for study, for example Mach 2.55 at sea level, the same sequence of force adjustment and placement is followed. It is now found that the plate will oscillate continuously at a frequency of 76 cps, and, by inference, that such an oscillation or flutter would occur at Mach 2.55 at sea level. In order to verify that the components of the system have functioned properly and that no gross defects have appeared due to unknown causes, a theoretical flutter analysis has been performed. The theoretical flutter Mach number of 2.20 and its associated flutter frequency of 74 cps compare fairly well with the measured values.

Using the same plate, it is possible to change the flutter characteristics by changing the mass unbalance. An increase in the mass unbalance may be effected by increasing the weight at the tip trailing edge from 0.35 to 0.50 lb, to study the trend both experimentally and theoretically. When this test is performed, the simulation air forces for a Mach number of 1.65 at sea level produce a sustained oscillation at a frequency of 73 cps. A theoretical study of the plate in this inertial state yields a flutter Mach number of 1.60 at a frequency of 70 cps. Again, a reasonable comparison is shown between theory and experiment, thus verifying proper functioning of the test forces.

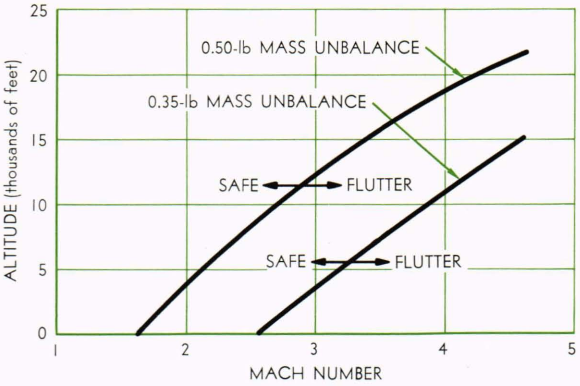

Fig. 5—Flutter boundaries for tip masses of 0.50 lb and 0.35 lb.

From the test data acquired so far, a few comments may be made regarding the variations of flutter Mach number with altitude. The variations are readily seen by aid of the concept that to produce an instability or flutter, the air forces at altitude should do the same work as the air forces at sea level. At a given Mach number, as the altitude is increased, the air density, dynamic pressure, and lift per degree are all reduced. Thus, the capacity of the airstream to do work on the plate is reduced and eventually becomes less than necessary for instability. The lift can now be increased by increasing the Mach number until the critical conditions are reached once again and flutter recurs. Such a trend is depicted in Fig. 5 for both cases of mass unbalance examined in the tests.

Conclusions

The preceding example of flutter simulation has shown that the components of the test equipment function properly on a test article possessing several attributes of significance in wing flutter problems. Further studies are needed on other arrangements to show proper closed-loop functioning for a wider range of frequency and inertia parameters. Refinements for closer control of damping levels, and an increase of the shaker forces to allow larger amplitudes before limiting, are desirable. Use of a number of channels of these components should make it possible to perform flutter simulation on actual missile wings. A rapid evaluation of flutter characteristics on missile components would serve as a check on other flutter calculations.