Inertia-Compensated Balance for Wind-Tunnel Buffet Measurements

C. V. Stahle,* C. G. Stouffer,† and W. Silver‡
Martin-Marietta Corporation, Baltimore, Md.

A SIMPLIFIED experimental technique is presented for the measurement of the random buffet excitation of launch vehicle transverse bending modes using a rigid model. As a launch vehicle passes through the transonic region, it is subjected to large random pressure fluctuations because of boundary-layer separation and shock-wave interaction. These pressure fluctuations occur primarily over the forward portion of the vehicle and particularly at locations of abrupt change in shape. Because the effects of these fluctuating pressures cannot be predicted to the required degree of accuracy by analytical methods, they are investigated experimentally by wind-tunnel tests using scaled models.

There are two fundamentally different approaches to the wind-tunnel investigation of the transonic buffet excitation of launch vehicle bending modes. One approach is to use dynamically scaled models; the other is to measure separately the modal excitation due to fluctuating pressures and the motion dependent unsteady aerodynamic effects. This paper is concerned only with the first part of the latter approach, the measurement of the modal excitation due to random pressure fluctuations.

The excitation of the vehicle bending modes is defined by the integral of the instantaneous pressure fluctuations over the surface of the vehicle, weighing each area element by its associated modal deflection. The power spectral density and the cross spectral density of these integrated pressure fluctuations provide the desired measure of the modal excitation. The approach used in previous wind-tunnel tests has been to determine this modal excitation from measurements of the fluctuating pressures acting on the vehicle. Although pressure fluctuation measurements are necessary for the determination of local structural excitation, these measurements are not amenable to analysis of the over-all vehicle response. It becomes an impossible task to determine the modal excitation if only uncorrelated pressure measurements are made.

To provide more meaningful data than offered by the measurement of pressures alone, Cole and Coe developed a pressure integration technique for measurement of the integrated modal excitation.[1] Their technique utilized the signals from a large number of pressure transducers located over the forward portion of the model (Fig. 1). Because of the complexity and the necessary approximations made with this technique, a simplified technique for more accurately measuring the integrated excitation of the vehicle modes and the cross spectra of the excitation between modes was desired. Extending the work of the Cornell Aeronautical Laboratory, and in conjunction with the Aerospace Corporation, an inertia-compensated balance (ICB) technique has been developed by Martin which fulfills these requirements.

Principle of Operation of the ICB System

If a standard balance without inertia compensation were used to measure the moment at a point on the model, the balance would measure both the integrated moment of pressure fluctuations and the moment due to vibration of the model. The dynamic sensitivity of the balance would reflect the impedance of the model-sting dynamic system having peaks at model resonances and low points between resonances as shown in Fig. 2. If the model inertia effects were compensated, the calibration curve would be approximately a horizontal line with the input and output moments of the balance system being nearly equal. This type of compensation is accomplished by electronically combining an accelerometer signal with a balance signal to eliminate the inertia effects of model vibration on the measured moment.

The principle of operation of the ICB system can be explained by considering one accelerometer-bridge combination of the typical model arrangement shown in Fig. 1. The moment measured by the strain gage bridge of the balance

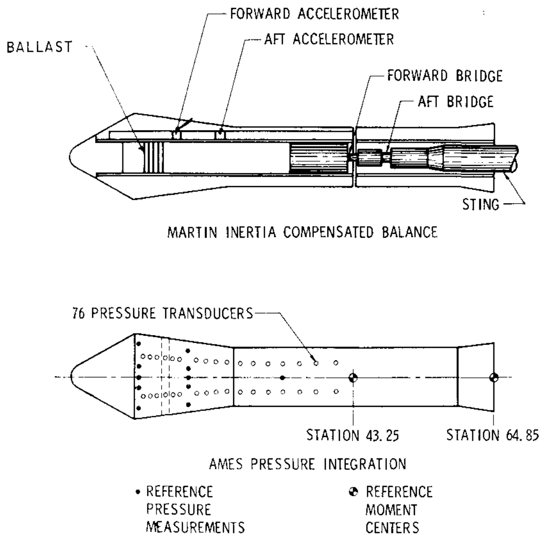

Fig. 1 Comparison of ICB instrumentation and pressure integration instrumentation.

will be the sum of the aerodynamic moment and the moment due to model inertia effects. This can be written as follows:

$$M_T(X_b, t) = M_A(X_b, t) + M_I(X_b, t) \quad (1)$$

where the effects of damping are neglected because the damping is generally small and would affect the bridge moment only in narrow frequency bands near the model resonances. Considering a flexible model, the inertia moment at the bridge location X_b can be written in terms of the model modes and the acceleration at a point on the model X_a as

$$M_I(X_b, t) = \sum_i \frac{M_i'(X_b)}{\omega_i^2} \ddot{\xi}_i = \sum_i \left[\frac{M_i'(X_b)}{\omega_i^2 \phi_i(X_a)}\right] \ddot{w}_i(X_a, t) \quad (2)$$

where $\ddot{w}_i(X_a,t)$ is the model acceleration at X_a. If, by proper selection of an accelerometer location, the term in parentheses can be made constant for all modes, Eq. (2) can be written as

$$M_I(X_b, t) = k \sum_i \ddot{w}_i (X_a, t) = K \ddot{w}_T (X_a, t) \quad (3)$$

where

$$K = \frac{M_1'(X_b)}{\omega_1^2 \phi_1(X_a)} = \frac{M_2'(X_b)}{\omega_2^2 \phi_2(X_a)} = \frac{M_3'(X_b)}{\omega_3^2 \phi(X_a)} = \cdots \quad (4)$$

That is, the inertia moment at the balance bridge will be proportional to the total acceleration at a point on the model. Then, from Eq. (1), the aerodynamic moment can be obtained by subtracting the inertia moment that is proportional to the model acceleration at X_a:

$$M_A(X_b, t) = M_T(X_b, t) - K \ddot{w}_T (X_a, t) \quad (5)$$

Hence, by subtracting the acceleration measured by a properly

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* Group Engineer, Vehicle Engineering Department. Member AIAA.
† Senior Engineer, Aerospace Mechanics Department. Associate Member AIAA.
‡ Engineer, Vehicle Engineering Department.

located accelerometer and multiplied by an appropriate "gain constant" K from the moment measured by the balance, the moment of aerodynamic pressure fluctuations is obtained.

It can be seen from Eq. (4) that a unique accelerometer location is required to compensate for two modes of the model. In order to provide compensation of three modes, the modal moment at the balance location must be a variable. During the design of the model, analytical mode shapes can be used to evaluate the modal moment at the bridge location $M_i' \cdot (X_b)$. The accelerometer and bridge locations at which the ratio of modal moment to modal acceleration are equal for the first and second modes and for the first and third modes are determined for the model-balance configuration being considered using relations similar to that of Eq. (4). The design is varied until the first three modes are compensated at the balance locations.

If the portion of the model forward of the balance bridge location is effectively rigid, the accelerometer will be located at the center-of-percussion of the model about the bridge location and the inertia effects of all modes will be compensated. By proper model design, this can be accomplished for the forward balance bridge location for the frequency range of interest. However, the flexibility introduced by the forward balance flexure is sufficient to invalidate this center-of-percussion relation for the aft bridge. Although guided by the design analysis for compensation of the first three model modes, final adjustments of the accelerometer locations and the mass of the model are made at the wind tunnel to achieve optimum inertia compensation.

Verification of the ICB System

Typical results obtained by sinusoidally exciting the model through the frequency range of interest are shown in Fig. 2 and indicate that the sensitivity of the system is constant well above the first three resonant modes of the model and sting support system. A maximum deviation of 10% is indicated throughout the frequency range of 10 to 140 cps, the range of interest for this particular model. In contrast to the ICB system, the inability of an uncompensated balance to measure the sinusoidal input moment is also shown in Fig. 2. A final verification of the adequacy of the ICB system to compensate for inertia effects was accomplished by applying a random excitation force to the model forward of the balance through a calibrated force transducer. The results indicated the capability of the ICB system to measure the power spectral density of the applied random moment within approximately ±1 db.

Comparison with Pressure Integration Measurements

Having proven the capability of the ICB system to compensate for model inertia effects, wind-tunnel tests were conducted to obtain buffet excitation measurements comparable to those obtained previously by NASA Ames using the pressure integration technique. For this comparison, the NASA Model 8 hammer-head configuration was selected because of the large buffet excitation measured by Ames. The model was of the same scale and was tested in the same wind-tunnel facility, the Ames 14-ft transonic tunnel, as was the model used for the pressure integration measurements. The model configurations are shown in Fig. 1, which compares the two measurement systems.

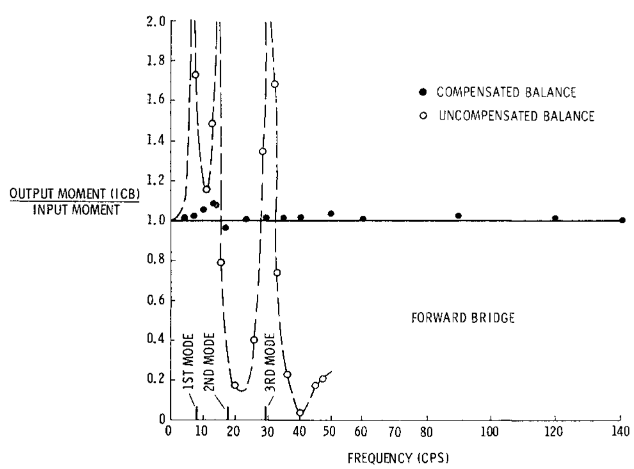

Fig. 2 Dynamic sensitivity of compensated and uncompensated balance.

The power spectral density of the aerodynamic moment about the forward reference point, Station 43.25, is shown in Fig. 3 for Mach 0.90. Comparison of the ICB data and the pressure integration data indicates negligible differences in the low frequency range (10 to 80 cps) and a maximum difference of 2 db at 110 cps. This is considered to be well within the expected accuracies of the data considering the necessary approximations included in the pressure integration technique and could possibly be due to differences in the pressure fluctuations as indicated by the comparison of surface pressure measurements that were also made. The power spectral density of the pressure fluctuations at this measurement location also differed by approximately 2 db at 110 cps. Good repeatibility of the ICB data is evident in Fig. 3, which includes data points obtained from two test runs. Similar comparisons were also made at Mach 0.95 with comparable results.

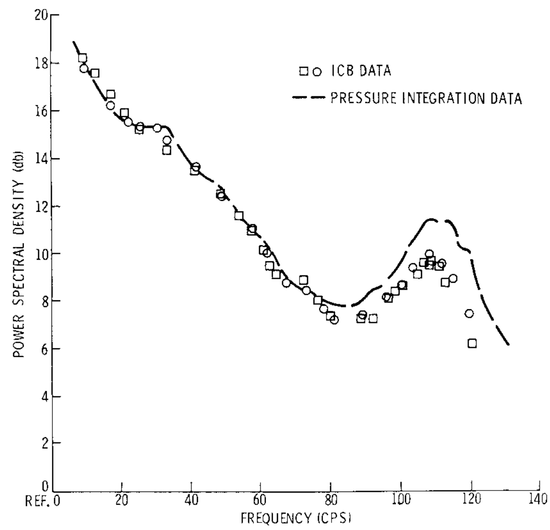

Fig. 3 Comparison of aerodynamic moment power spectral density.

On the basis of this investigation, it was evident that the inertia-compensated balance technique provides a considerable reduction in the complexity of the instrumentation even for a simple body of revolution. The comparison of the buffet excitation as measured by the two techniques provides increased confidence in the ICB system and verifies the capability of the pressure integration technique to measure the integrated buffet excitation over the frequency range investigated. For more complicated shapes, such as a glider configuration, the ICB provides the only practical approach. In addition, more meaningful data is obtained with the ICB, since the simultaneous measurement of the moment at two points is obtained enabling the modal excitations to be completely determined.

Reference

[1] Cole, H. A., Jr. and Coe, C. F., "Dynamic response of hammerhead launch vehicles to transonic buffeting," NASA TND-1982 (October 1963).