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Abstract

This paper discusses the development at the Arnold Engineering Development Center (AEDC) of a measurement technique to be used in continuous-flow wind tunnels to measure approximately 5- to 50-millisec-duration impulse loads on test articles. Accelerometers are used in conjunction with a cross-flexure balance to obtain force and moment measurements of impulse loads as short as approximately 5/1000-sec duration. A math model of the mechanism is developed and used to show the measurement concept is a valid scheme. Results from a laboratory demonstration of a two-component measurement system also indicate excellent agreement between impressed impulse loads and the measurements from the mechanism.

Nomenclature

c	Damping parameter, lb/ft/sec
FN, FORCE	Normal force, lb
k	Spring constant, lb/ft
m	Mass of test article, slugs
t	Time, sec
x	Axial location, in.
XCP	Axial location of applied force, in.
z	Vertical position of test article relative to equilibrium position, ft
θ, Theta	Angle of cross-flexure balance relative to equilibrium angle, rad
ζ	Damping factor

Introduction

The Arnold Engineering Development Center (AEDC) is developing a wind tunnel test technique to measure short-duration forces and moments. The measurement of short-duration loads from pulsating control jets of intercept missiles is important to programs such as Theater High Altitude Area Defense (THAAD), Navy Standard Missile (NSM), Atmospheric Intercept Technology (AIT), and Air Superiority Missile Technology (ASMT). The integration with respect to time of short-duration forces and moments is the impulse of the short duration load. Short jet bursts of approximately 5- to 50-millisec duration may not allow the flow to establish equilibrium, and transient jet interaction (JI) effects may occur. Autopilots of missiles have in the past been modeled from static force and moment wind tunnel data. As a result, autopilots and control systems are often designed with excess capability to handle the additional risk of modeling transient events with steady-state measurements. Measurements of transient events like short-duration jet pulses may result in more effective autopilots and control systems that cost less and are more efficient.

The approach selected for developing a mechanism to measure short-duration forces and moments in continuous-flow tunnels is based on the method developed for making force and moment measurements in short-duration (shock) tunnels. The method for making static force and moment measurements in short-duration wind tunnels is detailed in Ref. 1. The method involves marrying accelerometers with standard static force and moment strain-gage balances to produce an instru-

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ment that has both the frequency response of accelerometers and the operational efficiency of operational wind tunnel balances.

The theory presented here for a one-component measurement is generally expandable to many components of measurement. For a single-degree-of-freedom system, the following differential equation combines acceleration, damping, and spring terms and is used as the data reduction equation to calculate the impressed load:

$$m\ddot{z} + c\dot{z} + kz = FN(t) \qquad (1)$$

The short-duration normal force *FN(t)* is calculated by adding together the information from an accelerometer, rate transducer, and balance. The acceleration term is obtained from accelerometers, the damping term is obtained from either a rate transducer or the integration of the accelerometer measurements, and the spring term is obtained from the balance. The impulse is the integration of the short-duration force *FN(t)* with respect to time over the time of the pulse duration. Therefore, the impulse of a pulsed jet used to control intercept missiles is calculated from readings from accelerometers, rate transducers, and balances.

AEDC is beginning the development of a complete six-component mechanism to measure impulse loads with the demonstration of a two-component measurement capability. The two components selected for demonstration are pitching moment and normal force. Pitching moment is determined from pitching motion, and normal force is determined from plunging motion. The test mechanism employed to allow pitching motion of the test article was a cross-flexure balance mounted to a sting that bends to allow plunging motion.

A cross-flexure balance similar to the one displayed in Fig. 1 was chosen since the pivot point of the cross flexure can be known from static calibration in advance of the impulse experiment. A concept drawing of the test mechanism to validate the measurement technique in a laboratory environment is presented in Fig. 2. A cylindrical calibration body to simulate a test article is attached to the cross-flexure balance. The cross-flexure balance is mounted to the end of a sting that is mounted to the test unit bulkhead.

Instrumentation on the test mechanism is needed to obtain information on the pitching and plunging motion. The rotation angle of the calibration body mounted on the cross-flexure balance is measured using strain gages attached to the flexures of the balance. Rotational acceleration of the calibration body is calculated from the differences of two vertical acceleration measurements from accelerometers mounted fore and aft of the cross-flexure balance pivot. The vertical location relative to the equilibrium position of the test article resulting from plunging motion is measured by the bending strain of the sting using strain gages mounted on the sting. Vertical acceleration of the test article is calculated by the average of the measurements of the vertical sensing accelerometers. A pitch rate transducer is mounted on the pivot axis at the end of the roll arm and used for rate information.

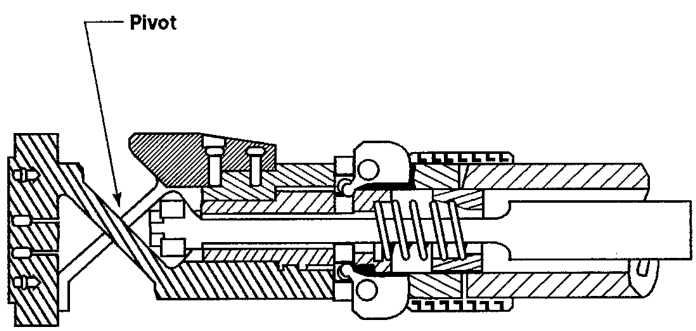

Figure 1. Cross flexure balance.

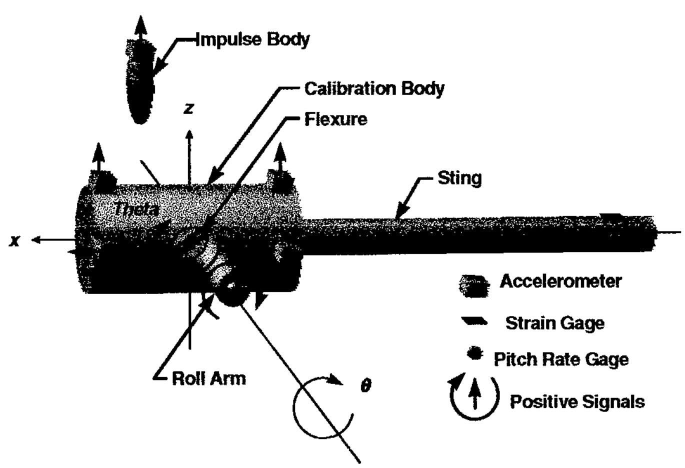

Figure 2. Laboratory experimental setup.

Math Model

The impulse measurement mechanism is modeled to facilitate understanding of the results of the laboratory experiment. The system equations of motion are solved using a computer program to model the experimental hardware dynamics. The program translates, compiles, and executes a FORTRAN code to solve the differential equations and provides output of the variables for the various test cases. Realistic mass, moment of inertia, spring stiffness, and impulse loads are used in the model. The equations of motion also include the aerodynamics of a representative configuration in a wind tunnel environment. The equations used to model the measurement capability also include electrical noise and filtering effects of the transducers.

A short-duration, externally impressed force and moment is included with the modeling equations. The response of the system to the impressed load is used to examine certain properties of the system. The 40-millisec external force and moment included in the simulation is presented in Figs. 3 and 4, respectively. The load increases linearly from zero for the first 10 millisec. The load is constant for the next 20 millisec and then decreases linearly to zero over the final 10 millisec. The representative response of the system to the load is presented in Fig. 5. Only the accelerometers respond during the first 10 millisec of the load. The accelerometers provide the primary information during the first 10 millisec of the representative impulse. The sting starts to respond by flexing after the first 10

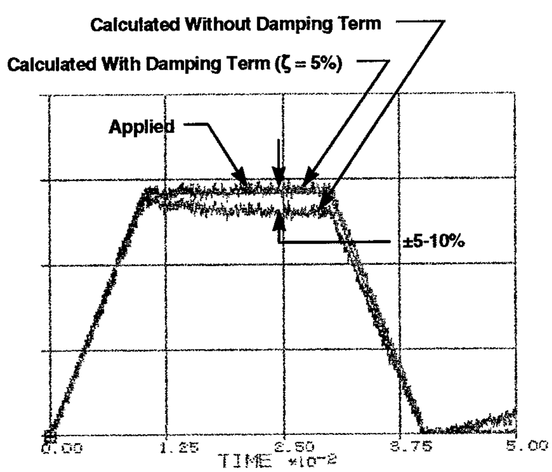

Figure 3. Short-duration applied force.

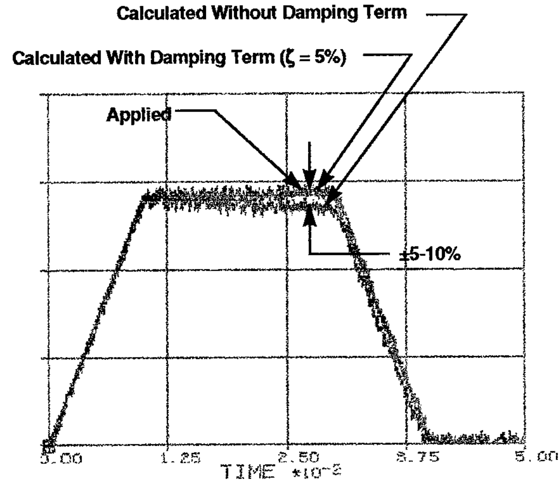

Figure 4. Short-duration applied moment.

millisec. The resistance to motion caused by the flexing sting causes the decrease in the measured acceleration during the next 20 millisec of a constant impressed load.

Estimation of the measurement capability of the chosen approach for two degrees of freedom is performed with the math model. Representative noise and representative signal lag due to the filtering effect of the transducers are also included in the math model. The electrical noise is assumed to be ± 3 counts RMS on all measurements and the accelerometers are modeled with a 700-Hz cutoff frequency filter. The capability of the proposed mechanism to measure short-duration forces and moments is presented in Figs. 3 and 4, respectively. The calculated forces and moments using the damping term in the reduction equation are excellent representations of the impulse loads and errors are generally less than ± 3 percent for the 40-millisec-long pulse. The measured impulses (i.e., the area under the load versus time data shown in Figs. 3 and 4) are less than ± 1 percent in error.

A method of validating the math model is to show that it exhibits the characteristics observed by other authors. It is shown by Cooksey in Ref. 2 that the bulk impulse can be measured by using just the balance signals. Cooksey's method is to integrate with time the output of the balance from the beginning of the short-duration pulse until the balance output dampens out to the original reading. The calculation of the integration of the bal-

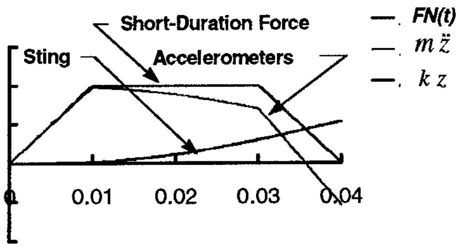

Figure 5. Contributions of accelerometers and sting to the short-duration force measurement.

ance and sting gage output is also incorporated into the math model. The results of the integration of the balance to estimate moment impulse for the case of no aerodynamic loads are presented in Fig. 6. The integration of the sting gage output converges to the impulse as Cooksey's method predicts when the aerodynamic coefficients in the code are set to zero. This condition represents the case where the experiment is demonstrated in a vacuum or with negligible aerodynamic loads, as in still air.

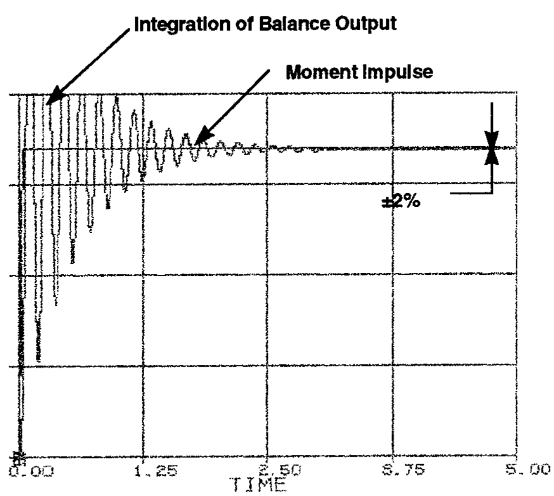

Figure 6. Impulse evaluation by Cooksey's method of vacuum condition test case.

The math model is a tool to be used to evaluate different assumptions of the measurement technique to guide the development. The technology to measure rotational and linear accelerations directly for the first term in Eq. (1) is mature and well understood, as presented in Ref. 3. Similarly, the strain gages used to measure plunging location relative to the equilibrium position and rotational attitudes of the test article for the third term in Eq. (1) are also well understood. However, the second term in Eq. (1) is the damping term which is proportional to velocity. Methods to obtain rate information are to either differentiate position information from the strain gages or to integrate acceleration information from the accelerometers. Either option is computationally cumbersome and requires the knowledge of the past to calculate the present state. Therefore, comparisons are made using the math model of two calculations of the short-duration force and moment measurements; one calculation includes the damping term (second term) in Eq. (1), and the other does not include the damping term. The two calculations for damping levels of zeta (ζ) of 5 percent are presented in Figs. 3 and 4 for force and moment, respectively. No significant errors between the two calculations are observed for the first 10 millisec. However, errors of approximately 5 to 10 percent during the second half of the 40-millisec pulse are shown in Figs. 3 and 4 for force and moment, respectively. Inclusion of the damping term is necessary for large values of damping (ζ of 5 percent), and may be neglected for small levels of damping (ζ of 0.5 percent). The necessary inclusion of the damping term complicates the data reduction. Evaluation of pitching and plunging damping from the test data after the test may need to be made before making final calculations of short-duration force or moment measurements to include the damping terms.

Laboratory Experiment

An experiment was performed in the Air Calibration Lab (ACL) using the proposed mechanism to validate the measurement scheme in a laboratory environment. The overview of the laboratory hardware used to demonstrate the measurement scheme is presented in Fig. 7. The laboratory demonstration is of a two-component measurement system. A cylindrical calibration body containing fore and aft accelerometers is mounted to a cross-flexure balance. The cross-flexure balance and accelerometers are used to measure rotational motion to calculate impulse moment similar to the math model presented above. The cross-flexure balance is mounted to a sting that contains fore and aft strain gages. Vertical motion, used to measure normal force, is determined from the combination of the sting gages and the average of the fore and aft calibration body accelerometers.

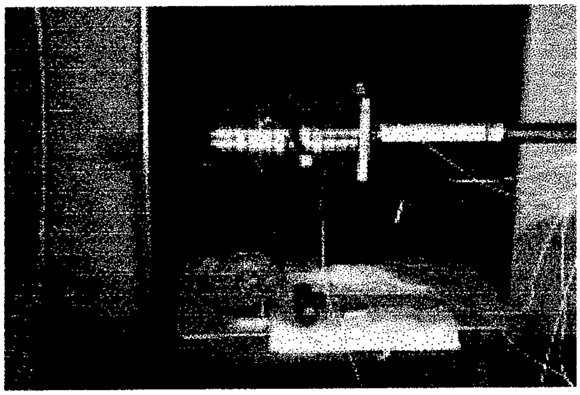

Figure 7: Overview of the laboratory setup.

The system was excited by two impulse loads, one of approximately 5 millisec and another of approximately 50 millisec. The 5-millisec impulse load is impressed directly by an impulse hammer. The magnitude of the impressed load of the impulse hammer is well known, but the location of the impressed load is not known accurately. As presented in Fig. 3 and discussed above, the response to a 5-millisec impulse load is primarily from the accelerometers. The difference, as presented in Fig. 8, in the calculation of force from the response of the mechanism and the 5-millisec impulse load measured by the impulse hammer is ± 2 percent. Excellent agreement of ± 2 percent with the impulse hammer is obtained from the measurement system over the 5-millisec impulse.

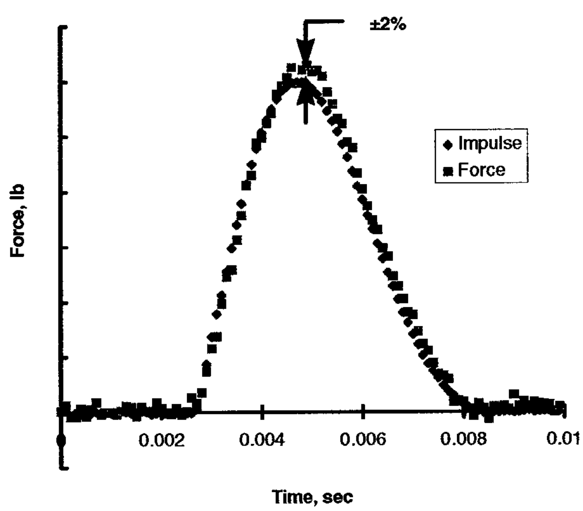

Figure 8. Comparison of impulse hammer and force measurements.

A 50-millisec impulse is impressed on the test mechanism using a heavy weight that is attached to the calibration body by a very thin wire. An accelerometer is attached to the heavy weight which is tied with some slack in the thin wire to the calibration body. The weight is dropped from a location directly beneath the calibration body. The slack in the wire is taken out as the weight drops, and the wire stretches and eventually snaps. The stretching process takes approximately 50 millisec and the acceleration is measured during the stretching process. The magnitude of the load is not well known; however, the location of the load is very well known. The results of the calculations from the response of the test mechanism to the 50-millisec impulse are presented in Fig. 9. The load location is correctly measured to ± 0.05. in. There is excellent agreement (± 0.05 in.) between the impressed 50-millisec impulse and the resulting calculations using data from the measurement system. Hence, the above-described concept of impulse measurement is valid and may be exploited for beneficial use.

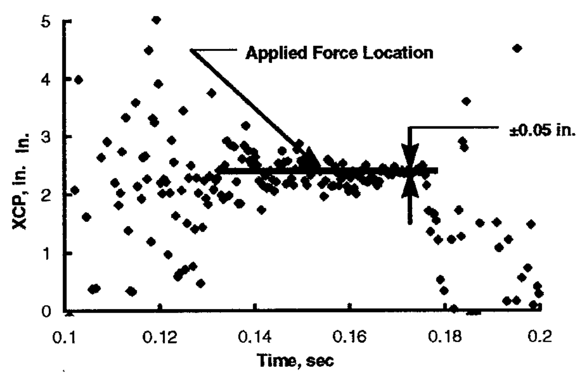

Figure 9. Impulse center-of-force location.

Summary

The paper shows the results of a laboratory experiment that was performed to demonstrate the impulse measurement technique to be used for experiments having motion with two significant degrees of freedom in the continuous-flow wind tunnels at AEDC. The responses of the hardware and transducers (cross-flexure balance and accelerometers) to short-duration loads indicate that the measurement capability is dominated by the accelerometers during the first 10 millisec. It is not necessary to include system damping in the data reduction for damping levels of ζ less than 0.5 percent. The force measurement capability is demonstrated to $\pm$ 2 percent. The center-of-force measurement capability is demonstrated to $\pm$ 0.05 in.

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