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Research Article

Calibration Technique for Recovery of Short Duration Aerodynamic Force

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Force measurement is one of the key issues for design of high speed vehicle configurations. They are routinely tested in impulse facilities where the test duration is in the order of few milliseconds. Since, the experiments are performed in short test times, it is expected that the model never achieves the steady state. So, the measurement diagnostics must account this fact while inferring the forces from the measured parameters. One of the methods is the determination of *characteristics system response function* by including the dynamics of the system. The aim of this work is to develop a calibration experimental setup and measure axial force on generic aerodynamic body configurations during a short time (~0.6 ms). A generic aerodynamic model attached to a "stress bar" is suspended freely and an impulse load is applied at the tip of the model. An accelerometer fitted with the model records the signal corresponding to the motion of the model. Then, the system characteristics function (impulse response function) is obtained from input force history and output accelerometer signal and further used to predict any unknown forces of similar nature. The recovered forces are compared well with the applied ones with a reasonable accuracy of ±5%.

1. Introduction

There has been an increase in the demand for dynamic calibration of force measuring devices in many industrial applications, automobiles, and aircrafts [1–3]. With respect to high speed and hypersonic flow environment, the force measurement on aerodynamic models is challenging due to the need for fast response devices and dynamics involved in the integrated model-balance system [4]. Most of these measurements are performed in short duration impulse facilities where the typical time scale of measurement is in the order of few milliseconds or less. The traditional technique is to obtain velocity data from laser-Doppler interferometry from which acceleration data can be derived [5]. The other method is to obtain the acceleration history from the model directly and to subsequently determine the forces with the knowledge of mass. In this way, the cause of the motion can be predicted from model accelerations by determining the forces during steady-state measurements [6–8]. Each of these techniques has relative merits/demerits and is best suited when the size of model is small. But, when the size and weight of the model increase, it is almost impossible to obtain steady-state signal during short time-scale measurement. So, the system dynamics must be included in the measured signals for predicting the unknown forces. One of the methods is to use the concept of "stress-wave" which propagates within the model and its support system for any applied force. Ideally, the motion can be detected by measuring model vibrations using accelerometers [6–8] or strains induced in the model by the use of strain gauges/piezofilms [9, 10]. For known forces, the system characteristics in the form of impulse response function can be obtained [11, 12]. With the knowledge of response function, inverse method can be applied to predict unknown forces from the measured signals. Based on this technique, the time history of the unknown force can be determined by identifying the system characteristics function for a given model-balance configuration [13, 14]. This type of force measurement technique is known as "stress wave force balance (SWFB)" system. The principle of SWFB lies in accepting the fact that no steady state is achieved in test duration and that time histories of applied forces on the model can be obtained from the measured signals by using

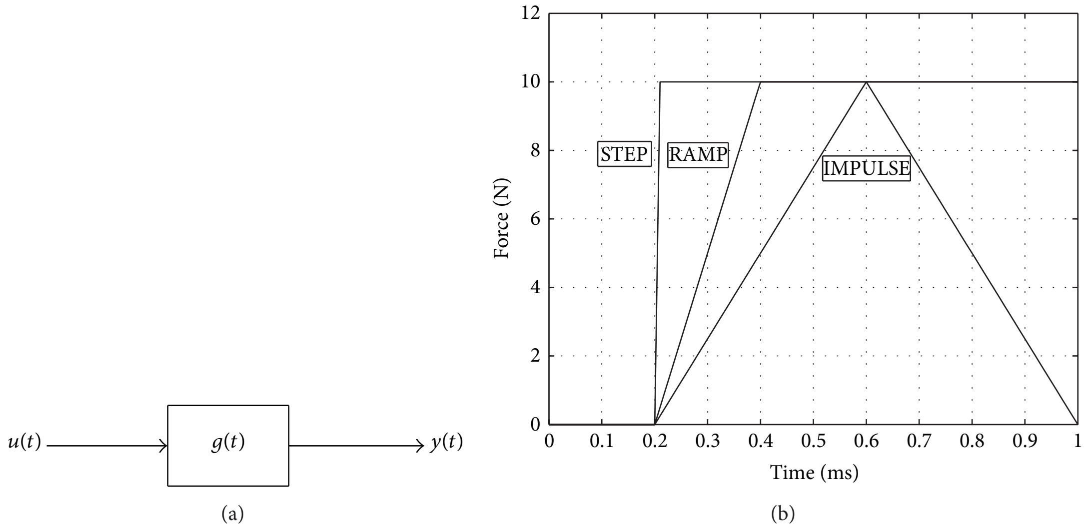

Figure 1: Schematic representation of SWFB: (a) linear input and output relation, (b) nature of short duration forces.

any high frequency sensors (accelerometers, strain gauges, etc.).

The concept of SWFB is well established in the literature where the propagation of stress waves is detected by measuring strain signals using semiconductor strain gauges [9, 10, 13, 14]. Based on the knowledge of measured strain signals and *system response function*, the unknown forces are predicted. This concept can also be extended when the vibrations induced in the model are measured by accelerometers. However, the *system response function* will change if the measurement diagnostics are different. So, the objective of the present investigation is to apply the concept of SWFB to determine the *system response function* of a dynamic system where the output signals are measured *using accelerometers*. An experimental setup has been developed for single-component force measurements on a system consisting of a model and stress bar. It is suspended freely and moves axially forward when the loads are applied. The load on the model is applied using an impulse hammer while the signals are recorded from the accelerometer fitted to the model. The *system response function* is obtained from the input force history and measured accelerometer signal. It is subsequently used to predict the unknown force from its corresponding accelerometer signal for the same model-balance configuration. In order to study the effect of mass and length of the integrated system, the stress bars of two different lengths are considered. The detailed discussions are given in the following sections.

2. Theoretical Background of Impulse Response Function

The forces on a model induce stress waves that propagate within the model and support structure. The motion of the stress waves can be detected by measuring signals of acceleration and strains. If the system is a linear dynamic system (i.e., the unknown forces that lead to linear strain/acceleration), then there exists a relationship between the output (acceleration/strain) and input (force) as shown in Figure 1(a). Mathematically, the relationship between input and output for a linear system can be expressed by (1). More details are available in [9]. Consider

$$y(t) = \int_0^t g(t-\tau)\cdot u(\tau)\,d\tau, \tag{1}$$

where $y(t)$ is the measured output signal at some point in the model-support structure due to the applied load $u(t)$ as shown in Figure 1(b). The function $g(t)$ relating the input and output is the characteristics of the structure, known as *system response function*. So, if the system characteristic in the form of impulse response is known, then deconvolution procedure can be applied to determine time history of applied load from the measured signal. When the signals are obtained for short duration forces (i.e., impulse), the system characteristics function is known as *impulse response function*.

Thus, it is possible to determine the response function of a linear dynamic system from the measured output response for a step load or impulse load.

3. Test Model and Pulse Calibration Experiment

A single-component stress wave force balance is comprised of a model attached to a long hollow stress bar. A generic aerodynamic blunt-cone model is fabricated from aluminum material with base diameter of 40 mm and apex-angle of 40°. Since sharp tip can affect the instruments while applying forces on the model, so it is made slightly blunt. In order to study the effect of weight and size of the integrated system on the measuring outputs, two different length (50 mm and 100 mm) stress bars are fabricated using brass. Both of the stress bars have the internal diameter of 19 mm and thickness of 1.5 mm. The aluminum model attached to stress bars is shown in Figure 2. The bar is supported by steel wires with

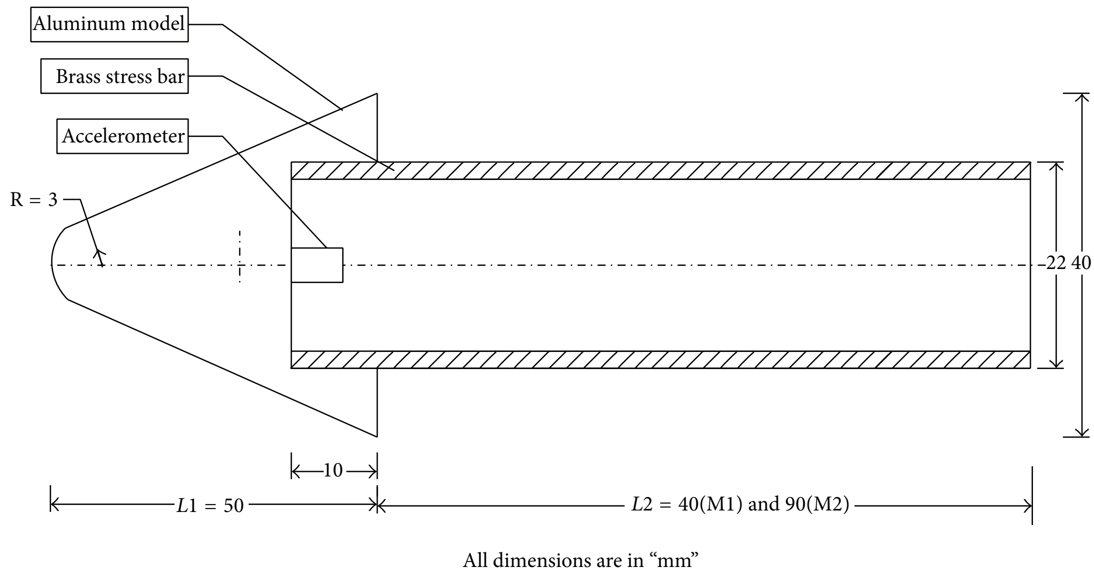

Figure 2: Design details of an aluminum model attached to a brass stress bar.

a rigid structure that allows the integrated system (i.e., model and stress bar) to move freely. During the pulse calibration experiment, an impulsive load is applied at the nose-tip of the model using an impact hammer (Model: 086C01; PCB, USA). The vibrations of the system due to the short-duration impulse are detected by an accelerometer (Model: 352C67; PCB, USA) fitted along the axis of the model (Figure 2). Both impact hammer and accelerometer are powered by a signal conditioner (Model 442B104; PCB, USA) which also has a provision to amplify the input and output signals. A digital storage oscilloscope (Model: DLM2022; Yokogawa, Japan) is used to record the signals from impact hammer and accelerometer for further postprocessing.

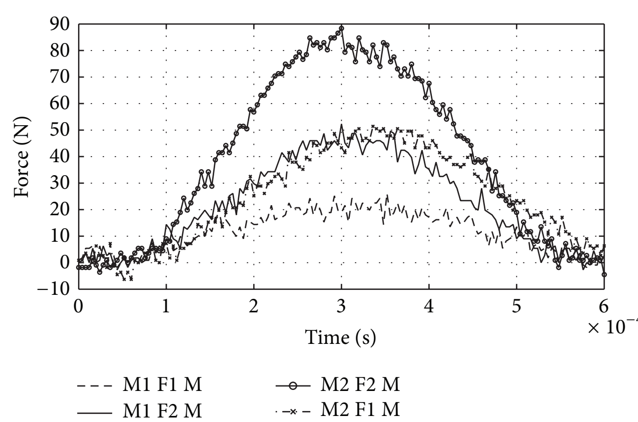

Figure 3: Force histories from the impact hammer measured at the nose-tip of the model.

4. Results and Discussions

The pulse calibration tests are performed on both models. It is desired that the model must move freely in axial direction when the impulse loads are applied. However, there are practical difficulties to ensure the exact axial movement of the model and also to achieve a "true impulse" during pulse calibration test. The impulse forces measured are applied manually on the model using an impact hammer. While applying the load with impact hammer, sometimes the force may not be exactly applied on the tip of the model. If the line of action of the force is not axial, it can lead to improper or incorrect signal. Those types of trials are rejected based on the nature of force signal and nature of the response obtained in the oscilloscope. After a number of trials, the signals from impact hammer are obtained with reasonable accuracy. The raw force histories obtained from the experiments conducted on two models using impact hammer resemble the nature of impulse loading (Figure 3). The corresponding raw signals recorded from the accelerometer also show the same trend (Figure 4). Low pass filter with a cutoff frequency of 30 kHz is used for removing noise (Figure 5). Cutoff frequency is fixed as 30 kHz since the maximum operating frequency of the accelerometer and the impact hammer is 20 kHz. The performance of the integrated system (model and stress bar) is evaluated experimentally through impulse response technique. In this case, the recovered force is compared with the input force applied by impact hammer.

4.1. Recovery of Force History from Experiments. It has been discussed earlier that unknown force history for a given model-balance system can be obtained with the knowledge of *impulse response function* of the system and measured signals from the accelerometers. During the experiments, the force histories and the corresponding accelerometer signals are obtained for both models, as shown in Figures 3 and 4, respectively. The notations used in these figures are given in Table 1. It is well understood that the stress waves induced by the impulse load have to travel a path of 50 mm axial

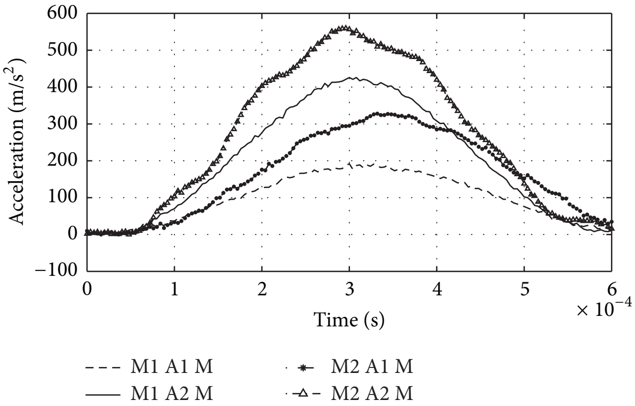

FIGURE 4: Acceleration history obtained from the accelerometer.

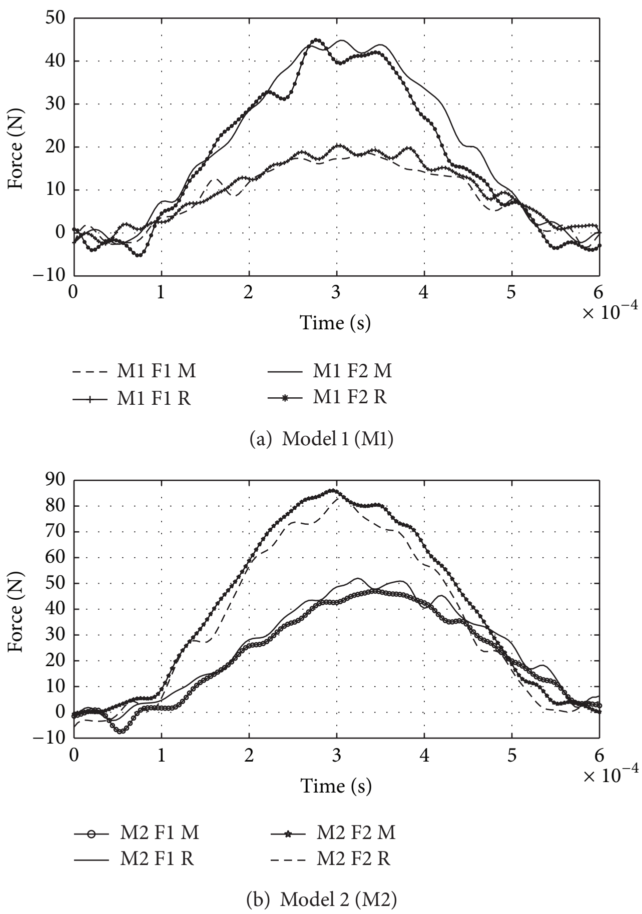

FIGURE 5: Comparison of measured and recovered forces using deconvolution technique.

distance within the aluminum model, and they are detected by the accelerometer. These waves travel at acoustic speeds (c) which is a function of material properties (density and Young's modulus). Referring to Table 2, it is possible to calculate the acoustic speeds for the stress wave propagation in the aluminum and brass material. Thus, the time taken by the first waves to reach the accelerometer location is about 10 μs. Referring again to Figures 3 and 4, there are two force histories and corresponding accelerometer signals for a given model. For each of the cases, the *impulse response function* is obtained from the input and output history using Fast Fourier Transform technique. It is then subsequently used to recover the other force from its corresponding output signal from accelerometer using deconvolution technique. The recovered forces compare very well with the measured force histories with reasonable accuracy of ±5%, which is based on the average error in the complete time domain of the signal for both models (Figure 5). When the stress bar length is further increased (thereby increasing its weight), the accelerometer signals get dominated by low frequency signals. In that case, the natural frequency of vibration has to be decided by the support mechanism (stress bar). When the size of the stress bar is kept as small (thereby, weight is reduced), the natural frequency of the system becomes more as detected by measuring signals from accelerometer. Hence, a small and light stress bar is a better option of support mechanism when the vibrations are detected by accelerometer [15]. However, the concept of impulse response technique can be still applied for recovery of force history for larger size of the stress bar. But, the propagation of stress waves within the support structure will have to be captured as output signals by some other methods (such as semiconductor strain gauges and piezofilms). Previous literatures do highlight a minimum stress bar length of about 400 mm for detecting stress waves using semiconductor strain gauges [7, 13, 14].

TABLE 1: Notations used in the figures.

M1 and M2	Model 1 and Model 2 (Figure 2)
F1 and F2	Force histories 1 and 2 (Figure 3)
A1 and A2	Acceleration histories 1 and 2 (Figure 4)
M	Measured
R	Recovered

For example, M1 F2 R: recovered force history (2) for model "M1."

5. Conclusion

Impulse response technique is used to recover short duration axial force histories from signals measured using accelerometers. It is found to be a promising method when system dynamics are more important and no steady-state measurement is possible. The system consists of a blunt-cone aluminum model attached to two different lengths of stress bars. Pulse calibration test is carried out by applying short duration impulses at the tip of the model. The vibrations of the configuration (model and stress bar) are captured by using an accelerometer. Impulse response technique is used to obtain the system response function, which is used subsequently to predict the unknown force histories. When predicted force histories are compared with measured signals, they are found to be accurate within ±5%. The low-frequency dominance is observed when the length is increased. So, a lighter weight stress bar keeps the natural frequency of the system high and suitable for short duration measurement using accelerometers.

Table 2: Material properties and stress wave speed.

Material	Young's modulus, E (N/m^2)	Density, ρ (kg/m^3)	Stress wave speed (m/s) $c = \sqrt{E/\rho}$
Aluminum	70×10^9	2700	5092
Brass	105×10^9	8600	3495

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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