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# Unsteady axial force measurement by the strain gauge balance

A.R. Gorbushin [a,b,*], A.A. Bolshakova [b]

[a] Moscow Institute of Physics and Technology (MIPT), 9 Institutskiy per., Dolgoprudny, Moscow Region 141701, Russia
[b] Central Aerohydrodynamic Institute (TsAGI), 1 Zhukovsky Str., Zhukovsky, Moscow Reg. 140180, Russia

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ABSTRACT

A new method was developed to measure the unsteady force measurement by means of six-component strain gauge balance which finds use in technological processes, e.g. in wind tunnel experiments. A mathematical model in the form of damping spring was used as a core of the method. It was verified by results of experiments involving applying harmonic and step force. Applicability of the balance matrix defined in static conditions was validated by an experiment with harmonic steady-state oscillations of the balance. The developed methodology provides the measurement of arbitrary non-stationary load in inertial or non-inertial system using a strain gauge balance with relative deviation at the level of 0.3–3% in the whole balance' operating frequency range, including the natural frequency. A dynamic calibration method was developed for the axial force of a six-component strain gauge balance by applying a harmonic force to the ground part of the balance.



## 1. Introduction

Measuring dynamic loads is an important problem in various fields of science and technology. One of its application is measuring the mass of goods transported by trucks and trains [1]. Another application of this problem is the development of high-frequency sensors for industrial robotic manipulators [2] and measurement of dynamic forces acting on alpine skiers [3]. The most difficult task is to measure the aerodynamic force and the moment during wind tunnel testing. The flow pulsations existent in the wind tunnel affect the aircraft or automotive vehicle models and cause them to oscillate on the balance and the supporting device. The rapid increase in the flow velocity in short-duration and shock wind tunnels is another source of excitation of the model's oscillations. The resulting oscillations of the model cause non-stationary aerodynamic loads acting on the model. In addition, there are so-called inertial forces and moments associated with the oscillating masses of the model and the balance. These inertial loads account for systematic errors in determining the aerodynamic forces and moments in wind tunnel experiments. Measurement of unsteady aerodynamic forces and moments during wind tunnel testing is important for solving aerodynamic, flight dynamics and strength problems:

1) determination of the averaged forces and moments obtained in case of a fixed position of the model support system and under quasi-steady flow conditions (velocity, pressure, temperature, etc.) [4];
2) determination of non-stationary aerodynamic derivatives of aircraft models at their free or forced oscillations in the flow [5];
3) determination of forces and moments at continuously varying angle of attack or yaw angle [6];
4) measurement of aerodynamic loads of models with oscillating lifting surfaces [7];
5) measurement of the non-stationary aerodynamic loads during the separation phase of flight, for example, during opening the parachute in the wind tunnel, in simulating an aircraft maneuver or the trajectory of an object separating from a carrier.

Measurement of non-stationary aerodynamic derivatives [5], loads at continuously varying angle of attack [6], forces acting on a model with oscillating lifting surfaces [7] require a frequency range not exceeding 50 Hz, which is below natural frequencies of the balance. To measure the force and moment vectors, a six-component balance is used. Accelerometers [4,8,9], magnetic systems [10], piezo films [4,11–13] resistors (so-called strain gauges) [4,9,14,15], piezo-optical transducers [16] and fiber Bragg grating force sensors [2] are used as sensitive elements of the balance. Sometimes accelerometers are used together with the strain gauge balance to separate inertial forces [4,15]. The relative standard

* Corresponding author.
*E-mail addresses:* gorbushin.ar@mipt.ru, gorbushin@tsagi.ru (A.R. Gorbushin), anastasya.bolshakova@tsagi.ru (A.A. Bolshakova).

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uncertainty in measuring the averaged aerodynamic coefficients with an accelerometer-based force balance is ~ 4–5% [8,9], whereas in case of using stress-wave force balance with piezo films it equals ~ 3% [12]. Most widely used in wind tunnels are strain gauge balances because of their high accuracy. One-component dynamometers have a standard measurement uncertainty referred to dynamometer's half of range 0.01–0.02%, and that of six-component ones is 0.05–0.3%. Strain gauge balances consist of an elastic body, sensitive elements and strain gauges which transform the deformations of the sensitive elements into electrical signals. Due to the elasticity of the sensitive elements, the balance itself is a dynamic system. Elasticity of the balance complicates the problem being solved as dynamic loads are measured by a dynamic system. As a rule, strain gauge balances are calibrated, under static conditions. To measure the dynamic loads, additional dynamic calibration is required. Currently, three methods are used to apply a known non-stationary force in case of dynamic calibration of balances:

1) step load (the Heaviside function) is set by cutting the thread connecting the load and the balance [4,12,15,17];
2) impulse load (the Dirac $\delta$ function) is applied by special calibrated hammer [4,9,12,13,17];
3) harmonic force applied to the metric part of the balance [7,10].

The most common method for determining the average aerodynamic loads for model oscillations in a wind tunnel is the use of different filters [4,18] for filtering inertial forces and moments. Another method for solving the problem of determining quasi-static aerodynamic loads in shock wind tunnels is based on the step-shaped form of aerodynamic load at the start of the wind tunnel. The model and the strain gauge balance are considered as a linear dynamical system – "black box" concept. The second-order non-homogeneous equation of motion can be solved by means of the Laplace transform. The relation between the applied load and the strain gauge balance signal is represented as a convolution integral [4,9,13,17,19]. The impulse response function is determined by applying a known dynamic load – the Heaviside step function and (or) its derivative – the Dirac $\delta$ function. The disadvantage of this method is the absence of the physical model of the model-balance system, which restricts the application of this method. It may be used only in shock wind tunnels. In [7], a method is proposed to define a correction factor to compensate for the inertial force during measuring the periodic force by means of a one-component strain gauge balance. The applicability of the method is limited to the measurement of sinusoidal force. The review carried out reveals that existing methods to measure non-stationary aerodynamic forces are applicable only for a limited number of cases – shock wind tunnels, free [5] and forced sinusoidal oscillations [7]. All these methods do not apply adequate physical model of the model-balance system. They provide a relative standard uncertainty in measuring the quasi-stationary forces at a level of 3–5% and dynamic force at a level of 10%.

In this paper, we use a physical model in the form of a damping spring [4] for the axial force of the six-component strain gauge balance. Application of an adequate physical model allows solving a wide range of problems related to the high-accuracy measurement of arbitrary dynamic loads with strain gauge balances in a wide range of frequencies with a relative deviation at the level of 0.3–3%. Masses of the oscillating model and balance, as well as the stiffness and damping coefficients of the balance are used in this model. Section 2 describes the facilities and methods to determine these constants. The mathematical model based on the physical model of the strain gauge balance is developed in Section 3. Section 4 deals with verification of the mathematical model using experimental data obtained at experimental facilities described in Section 2. In Section 5, method for measuring unsteady force is developed. Discussions and conclusions are drawn in Sections 6 and 7 respectively.

## 2. Experimental facilities

### 2.1. Ground vibration testing of the strain gauge balance

The scheme and detailed description of ground vibration testing (GVT) of the internal six-component strain gauge balance 6F-540 was given in [20]. Fig. 1 illustrates the GVT rig. Balance 1 was attached vertically to the vibration unit 2 by its ground end. Vibration unit 2 sets harmonic steady-state oscillations within the frequency range 10–1000 Hz with a nominal force of 10 N in vertical direction. The direction of the axial force was parallel to that of the force applied by the vibration unit. The axial force range of the balance was ±100 N and the standard measurement uncertainty (standard deviation) of its calibration equaled 0.32 N. Load 3 was mounted on the live end of the balance to decrease the natural frequency of the whole system to 752 Hz whereas that of the balance exceeded 1 kHz. The total mass of load, balance, and balance adapter was 1.48 kg. Signals of the balance were acquired by the NI PXIe-4330 measuring unit.

Piezoelectric accelerometers 4 and 5 (PCB 333B32 Piezotronics, range ±50 g) were attached to the load 3 and the vibrator 2 to measure acceleration of live and ground parts of the balance in the direction of its axial force. The standard measurement uncertainties of accelerometers equaled 5 m/s$^2$.

Accelerometer signals were converted to the required level by the amplifier and acquired by the ADC NI PXI-6255 module. The measuring channels were sampled synchronously with the frequency $f_{s1}$ = 25 kHz.

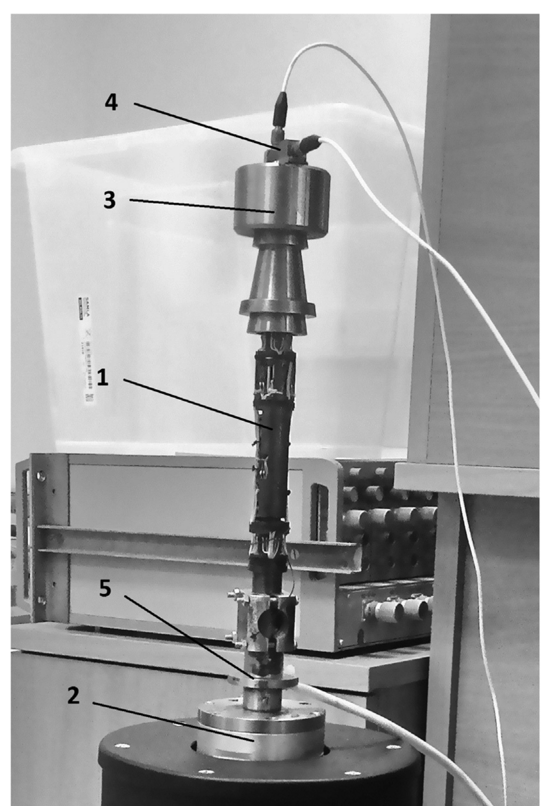


**Fig. 1.** Photo of the GVT rig for strain gauge balance.