Mechanical Systems and Signal Processing 62-63 (2015) 296–304

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Wave system fitting: A new method for force measurements in shock tunnels with long test duration

Changtong Luo*, Yunpeng Wang, Chun Wang, Zonglin Jiang

State Key Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 10 October 2014
Received in revised form
24 January 2015
Accepted 12 February 2015
Available online 3 April 2015

Keywords:
Aerodynamic force measurements
Strain gauge balance
Inertia compensation
Signal decomposition
Accelerometer-free
Shock tunnels

ABSTRACT

Force measurements in shock tunnels are difficult due to the existence of vibrations excited by a sudden aerodynamic loading. Accelerometer inertia compensation could reduce its negative effect to some extent, but has inherent problems. A new signal decomposition method, wave system fitting (WSF), is proposed to remove vibration waves of low frequency. The WSF is accelerometer-free. It decomposes the balance signal and can separate vibration waves without the influence on the DC component, and it does work no matter the cycle of the sample signal is complete or not. As a standard signal post-processing tool in JF-12, the application results show that it works reliably with high accuracy, and it can also explain puzzling signals encountered in JF-12. WSF method is especially useful and irreplaceable whenever only a few cycles of a periodic signal could be obtained, as is usual for shock tunnels.

1. Introduction

A new aircraft needs thousands of wind tunnel tests before it can really fly in the sky. For hypersonic vehicles, shock tunnels are the most promising ground-based-test facilities because they can provide a large range of stagnation enthalpy and flow velocities, and even duplicate hypersonic flight conditions. However, shock tunnels have a very short test duration (effective run-time), usually in milliseconds. This makes it very difficult to measure the aerodynamic forces. Classical strain gauge balance is used in our tests, though some other kind of balances such as accelerometer balance and stress-wave force balance system [12] might be feasible. In the beginning of the wind tunnel test, a sudden aerodynamic loading will excite the vibration of the model-balance-sting system, which can distort the balance signal sensed by strain gauges in force measurements. Special techniques must be applied to reduce the negative effect of the vibration to get the right result.

A practical and widely used solution is acceleration compensation [1,3,8,9,11,13,14]. That is, to embed some accelerometers into the balance in the hope that the vibration signal can be removed from the balance signal produced. But this method has inherent problems. First, the signal collected by the accelerometers depends on the global displacement of model-balance-sting system, but the strain gauges can only sense the local strains within the balance. In general, the global displacement and local strains might be inconsistent. In addition, the phase offset and partial compensation issues could also decrease the accuracy of force measurements.

---

* Corresponding author.
E-mail addresses: luo@imech.ac.cn (C. Luo), wangyp@imech.ac.cn (Y. Wang), wangchun@imech.ac.cn (C. Wang), zljiang@imech.ac.cn (Z. Jiang).

http://dx.doi.org/10.1016/j.ymssp.2015.02.024

In 2012, a super large shock tunnel, referred to as the Long-test-duration Hypervelocity Detonation-driven Shock Tunnel (JF-12) was developed [2]. JF-12 is capable of reproducing the pure air flow of flight conditions at Mach numbers from 5 to 9 and altitude of 25–50 km with at least 100 ms test duration. The long test duration brings much convenience for force measurements. The balance signal in JF-12 shows a periodic feature during the steady test phase. This enables us to develop a new method, wave system fitting (WSF), to analyze the aerodynamic force signals of strain gauge balance in shock tunnels with long test duration. The proposed method does not rely on any accelerometer, and derives aerodynamic forces directly from balance signals. The new method is accelerometer-free, so it does not have the problems caused by accelerometers to conventional strain gauge balances mentioned above.

2. Wave system fitting

2.1. Dynamics of structures

The test model used in this paper is a sharp cone of 10° half-angle and 1.5-m length, which is the largest sharp cone model so far in the world for force measurements in shock tunnels. We choose the sharp cone to test our force measurement method because it is a kind of standard test model which has been tested by several other hypersonic wind tunnels, and it has also an approximation solution with Newton's theory under laminar flow conditions. Thus, the results could be comparable.

The cone is connected with an inner strain gauge balance and a stiffness enhanced sting (Fig. 1). The connection detail of the three parts is shown in the lower left quarter of Fig. 1.

Structural analysis can help determine the vibration shapes and frequencies of the model-balance-sting system, and thus separate the signals of aerodynamic force and natural vibrations. For a simple structure such as a cantilever beam, it is not difficult to carry out its dynamic analysis. However, the structure of model-balance-sting systems used in wind tunnels for force measurements is usually quite complex, as shown in Fig. 1. Analytic solutions are not available any more. We have tried three different methods in this work to study the natural frequencies and mode shapes of vibration: finite element analysis (FEA), fast Fourier transform (fft) of knocking test signals and that of wind-tunnel test signals.

The balance signal of knocking and/or wind-tunnel tests involves many vibrations of high frequency. Usually, the amplitude of these high frequency vibrations is not so large. The total effect of a large number of these small vibrations behaves like white noise. The average of their displacement approaches zero, which means high frequency vibrations will not have much influence on the measurement accuracy. On the contrary, the balance signal also involves a few low frequency vibrations with large amplitude, which could affect the accuracy of measurement results if not properly handled. Therefore, we will focus only on low frequency vibrations in this paper. For the normal force of the sharp cone model, finite element analysis shows that the natural vibration frequencies of the model-balance-sting system are 24.8 Hz, 44.1 Hz, …, 147.9 Hz, …, 241.6 Hz, 250.6 Hz, …, etc. While the fft of knocking test signals gives 48.6 Hz, 146.0 Hz, 243.3 Hz, …, etc., and the fft of wind-tunnel test signals gives 49.9 Hz, 239.5 Hz for shot #20130422, and 49.9 Hz, 249.5 Hz for shot #20130427 (see Fig. 2).

By knocking test with a plastic hammer, we find that only a few of frequency of vibrations could be excited in a single knock. For example, the vibrations of frequency 146.0 Hz and/or 243.3 Hz might not be excited in some knocks. But all frequencies excited by knocking could be found in FEA frequencies approximately. A wind-tunnel test behaves like a single knocking. So only a few of knocking-test frequencies would be excited in one shot, as shown in Fig. 2. In summary, the inclusion relation of the three frequency set satisfies $\mathbb{F}_{\text{shot}} \subset \mathbb{F}_{\text{knock}} \subset \mathbb{F}_{\text{FEA}}$.

Fig. 1. The model-balance-sting system and its connection detail.