Sensors and Actuators A 247 (2016) 172–186

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

A novel multi-component strain-gauge external balance for wind tunnel tests: Simulation and experiment

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ARTICLE INFO

Article history:
Received 13 March 2016
Received in revised form 4 May 2016
Accepted 30 May 2016
Available online 1 June 2016

Keywords:
Multi-component external balance
Wind tunnel
Strain gauge

ABSTRACT

This paper presents a novel multi-component strain-gauge external balance to measure lift and drag forces as well as pitching moment in wind tunnel experiments. First, an innovative structure is proposed and its geometry is determined through a tedious trial and error scheme using finite element (FE) simulation. The sensor dimensions are thus chosen so as to acquire acceptable sensitivity and negligible interference error among the components considering maximum loading capacities. Appropriate locations of the strain gauges on the structure are determined via simulation. Then, sensitivities of the balance components are found using the FE analysis. Finally, the designed external balance is constructed and calibrated. It is found that the interference error among the balance components is less than 2.01%. Furthermore, the measured sensitivities of the sensor components are in a good agreement with the simulation results through which the design procedure is validated.

1. Introduction

Load cells are known as the most commonly used transducers employed in the wind tunnel balances to measure aerodynamic forces and moments affecting the model of a flying object. Nowadays, industrial load cells are manufactured in different forms and capacities. However, the majority of the load cells available in the market are single-component. On the other hand, single component load cells are not solely sufficient to measure multi-directional aerodynamic loads in the wind tunnel tests. As a solution to this latest problem, several single-component load cells may be installed within a mechanical framework so that each single-component load cell is responsive to a specific direction. Such transducers are usually called multi pieces external balances in the wind tunnel applications [1]. Although the mentioned technique is widely used in the wind tunnel experiments, the accuracy of such balances is significantly dependent on the accuracy of the machining process in constructing the mechanical framework of the balance system. Besides, the multi pieces external balances require more space in the wind tunnel. Another alternative for measurement of the multi-directional loads in the wind tunnel tests is known as the multi-component load cells. The multi-component load cells are usually referred to as one-piece external balances in the wind tunnel applications which are constructed from one single piece of material and are equipped with strain gauges [1]. Unfortunately, the multi-component load cells are rarely found in the market. It can be attributed to the fact that the users usually require different loading capacities in different directions. Consequently, the load cell manufacturers cannot commercially provide the multi-component load cells with very versatile combinations of loading capacities. Thus, such multi-component load cells are usually designed and manufactured based on the user requirements. The most challenging problem in designing such multi-component load cells is known as the interference error among the components. Hence, the designers attempt to reduce this error as best as possible. Different geometries and dimensions have been reported in the literature for such multi-component load cells each of which contains some advantages and drawbacks. Many researchers proposed various multi-component load cells for different applications i.e. wind tunnel, water channel, robotics etc.

Dubois [2] investigated the design, equipment, thermal effects compensation, and calibration of various multi-component strain-gauge balances used in large subsonic and supersonic wind tunnels. Molland [3] presented a five-component strain gauge load cell for wind tunnel tests. A shear-type aluminum sensing structure along with full bridge strain gauge circuitry was employed for each component. The bridge circuits including 120 Ω strain gauges were excited by a 7 V potential difference. The accuracy of the dynamometer was found to be ±1.2% of full scale (FS) for torque and

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http://dx.doi.org/10.1016/j.sna.2016.05.035

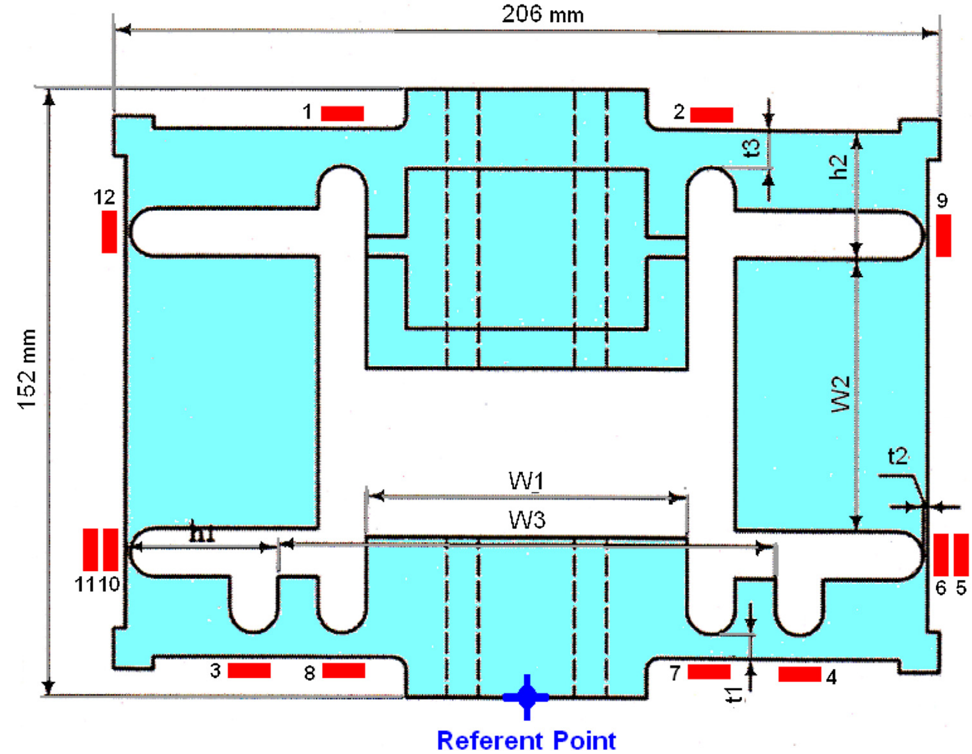

Fig. 1. Proposed sensing structure of the multi-component strain gauge external balance.

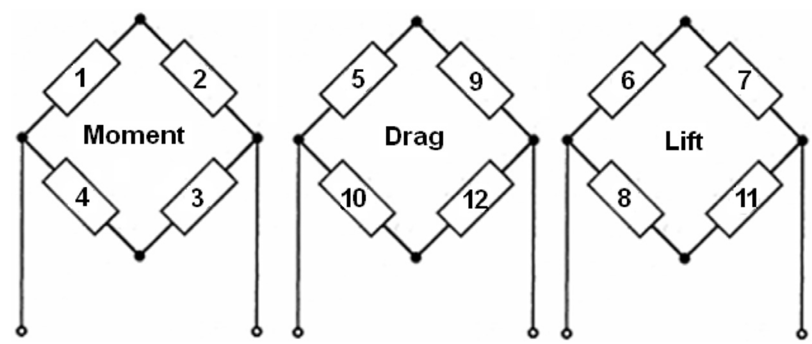

Fig. 2. Location of the strain gauges in the corresponding Wheatstone bridge circuit.

±0.4% FS for the remaining components. An acceptable repeatability characteristic, as well as relatively small interaction, was reported in this work. Almeida et al. [4] proposed a ring-type strain gauge-based sensing structure for wind-tunnel experiments. This balance was used to measure the lift and drag forces and the pitching moment. High-quality results with acceptable dynamic characteristics (up to 25 Hz) were reported. The first natural frequency of the structure was 250 Hz which was ten times the maximum used frequency in the calibration stage.

Tavakolpour-Saleh and Sadeghzadeh [5] designed and developed a three-component force/moment load cell for underwater hydrodynamic tests. Finite element method (FEM) was used to design the sensing structure and to determine the suitable locations of strain gages as well. Experimental evaluation of the proposed three-component load cell revealed an interference error less than 2.25%. A six-axis wrist force/moment sensor for robotic arms was designed by Kim [6] using FEM. An interference error less than 2.85% was reported from the experimental measurements. Sun et al. [7] designed and optimized a novel six-axis force/torque sensor for a space robot. They proposed a novel sensing structure with the through-hole beam. The presented sensor dimensions were optimized via response surface methodology (RSM). Finally, the experimental results revealed a good performance of the proposed multi-component force/torque sensor. Kang et al. [8] proposed an intentional stress concentration approach based on the application of binocular sensing structure to increase the sensitivity of a six-component load cell. The dimensions of the sensing structure were thus optimized using FE analysis. In addition, the influence of different structural dimensions on the strain distribution of critical points was investigated. Finally, the interference error was reported less than 2.5% FS. Kim et al. [9] designed and fabricated a column type multi-component force/moment transducer. The structural dimensions were first found analytically and later, verified by finite element analysis. A decoupling method based on addition and subtraction processes of signals of the strain gauges were proposed to reduce the interference error. As a result, the interference errors were found to be 7.3% FS for F_x component and 5% FS for the rest of components. Liu and Tzo [10] presented a novel six-component force sensor. They utilized four identical T-shaped bars as force sensing structure of the mentioned transducer. They applied FE