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Measuring vibration-induced variations in pressures between the human body and a seat

Chi Liu*, Michael J. Griffin

Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Southampton, SO17 1BJ, England, UK

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ABSTRACT

When measuring total dynamic forces between the human body and seats during vibration, variations in force over the buttocks and the thighs have previously been ignored. In this study, sensors in a pressure mat were calibrated by applying static and dynamic pressures through foam and calculating transfer functions between the applied pressures and the outputs of the sensors. This provided static calibration of individual pressure sensors and dynamic calibration of groups of pressure sensors. Measurements of dynamic pressures were used to calculate the vertical forces over the ischial tuberosities, middle thighs, and front thighs and compare with similar measurements obtained by another method. Dynamic calibration of the pressure mat reduced errors in the total dynamic force to 10% at frequencies less than 5 Hz and less than 30% at frequencies between 5 and 15 Hz. Recommendations are offered for measuring dynamic pressures between the human body and seats in vibration environments.

Relevance to industry: Dynamic pressure distributions at seat interfaces influence sitting comfort during whole-body vibration. Understanding of the dynamic performance of pressure sensors and recommendations on calibrating and using pressure sensors in vibration environments can assist seat design and other situations where dynamic pressure measurements are of interest.

1. Introduction

In static conditions, sitting comfort is influenced by static pressures between the human body and the seat (Ebe and Griffin, 2001). In vibration conditions, dynamic forces over the seat surface contribute to the discomfort caused by whole-body vibration (Ebe and Griffin, 2000a; b; Zhou and Griffin, 2014). Although the distribution of dynamic pressures between the human body and a seat during whole-body vibration contribute to discomfort, there are doubts about the accuracy of measurements of dynamic pressures and the calibration of pressure sensors.

The total forces acting on the human body sitting on a seat have been measured to quantify the dynamic response of the seated human body while exposed to whole-body vibration (e.g., Fairley and Griffin, 1989). Although total forces reflect the overall properties of the body, such as the principal resonance and the effective stiffness and damping, the variation in dynamic response over the contact area of the buttocks (including the ischial tuberosities and the thighs) is ignored. If the distribution of dynamic pressures between the human body and a seat could be accurately measured during vibration they would be expected to show a large variation.

The dynamic pressures at the human-seat interface have been measured over both a rigid seat (e.g., Wu et al., 1998) and a compliant seat (Wu et al., 1999). Pressure measurements have also been used to derive the apparent mass of the body (i.e., the transfer function between the dynamic force over the seat and the acceleration of the seat) when sitting on a compliant seat (Hinz et al., 2006; Dewangan et al., 2013). Plantar pressures have been measured to derive the apparent mass of the human body standing in different postures while exposed to vertical vibration (Tarabini et al., 2013).

Flexible thin-film pressure sensors have been used in the above studies. There are currently two sensor types: capacitive sensors (as used by Wu et al., 1998, 1999; Hinz et al., 2006; Tarabini et al., 2013) and resistive sensors (as used by Dewangan et al., 2013). In capacitive sensors, the distance between the two parallel plates of a condenser (i.e., the sensor) changes with the applied pressure, resulting in a change in the capacitance. In a resistive sensor, the resistance of the sensor is affected by the load. Both types of sensor have been reported to have non-ideal performance for both static measures (Paikowsky and Hajduk, 1997; Arndt, 2003; Palmer et al., 2009; Saggin et al., 2013) and dynamic measures (Dewangan et al., 2013; Tarabini et al., 2013; Saggin et al., 2013).

When measuring static pressure with either type of sensor, the

* Corresponding author.
E-mail address: liuchi0511@gmail.com (C. Liu).

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pressure signals have been found to increase over time during a constant static load (Paikowsky and Hajduk, 1997; Arndt, 2003; Palmer et al., 2009; Saggin et al., 2013). The extent of the increase has varied between studies (Paikowsky and Hajduk, 1997; Arndt, 2003; Saggin et al., 2013) and has been reported to be independent of load but dependent on temperature (Saggin et al., 2013).

When measuring dynamic pressures with either type of sensor, the forces calculated from the contact area and the measured pressures have been found to be lower than the applied forces, with greater underestimation at higher frequencies (Dewangan et al., 2013; Tarabini et al., 2013; Saggin et al., 2013). The underestimation is suggested to arise from the viscoelastic behaviour of the material of the sensors (Tarabini et al., 2013; Saggin et al., 2013) and the low sampling rates of the system (Dewangan et al., 2013).

The static calibration of pressure sensors is performed by applying static pressures over the sensors for a period of time (e.g., Palmer et al., 2009). Since the pressure signals increase over time during a constant static load, the coefficient that relates the digital outputs of a sensor to the applied pressure is time-dependent. In measurements, the sensor is loaded for a period of time before recording and the coefficient that has been obtained for the same period of static loading during calibration is used to derive the pressures from the sensor outputs.

The dynamic calibration of pressure sensors involves measuring transfer functions between the outputs of the pressure sensors and the applied dynamic loads, so the transfer functions can be used to correct the sensor outputs measured in experiments (e.g., Tarabini et al., 2013; Saggin et al., 2013; Dewangan et al., 2013). Dewangan et al. (2013) measured dynamic forces at the interface between a seated human body and a rigid seat using a force plate and also estimated the forces from pressures measured by a pressure mat. Both forces were used to calculate the vertical apparent mass of the seated human body and the ratio between the two apparent masses in the frequency domain was used to correct the apparent mass obtained using the pressure mat. In other studies, forces have been applied to individual sensing units of a pressure mat and transfer functions between the applied forces and the measured forces used to correct pressures measured when using the pressure mat (Tarabini et al., 2013; Saggin et al., 2013).

The dynamic calibration method used by Dewangan et al. (2013) is based on the total forces, and thus the obtained relationship between the sensor outputs and the applied loads is an average over all sensing units. If there is variation in sensitivity between sensing units, the relationship would depend on the distribution of the load over the pressure mat and not applicable for all loading conditions, so the relationship differed between subjects and depended on vibration magnitude (Dewangan et al., 2013). Although dynamic calibration of each sensing unit seems optimal, as reported by Saggin et al. (2013), this is difficult and time consuming for pressure mats containing thousands of sensing units. It would be more practical to undertake dynamic calibration by applying evenly distributed loads over groups of sensing units, but it is unknown whether this will reduce errors in either the total forces or the forces indicated by individual sensors.

Analogue signals from hundreds or thousands of sensing units on a pressure mat are scanned in sequence and then digitised. This introduces sampling delays between sensing units which increase with increasing number of sensors. There are consequent errors in measurements of dynamic pressure that depend on the scan rate and the frequency of the applied vibration.

The objective of this study was to define a method of quantifying the static and dynamic performance of a resistive pressure sensor. This involved investigating the causes of errors and defining a calibration method with controlled dynamic forces. Errors when using a calibrated system to measure dynamic pressures at the human-seat interface during whole-body vertical vibration were then investigated. It was hypothesised that the calibration method would reduce errors when using a pressure mat to measure the total dynamic forces between the human body and a seat during vertical vibration.

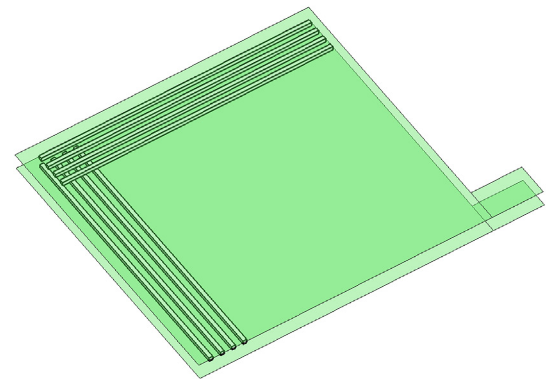

Fig. 1. Schematic of structure of the resistive pressure sensor.

2. Materials and methods

2.1. Pressure mapping system

The study investigated a resistive pressure mapping system consisting of a pressure mat and a data acquisition system. The pressure mat had a sensing matrix located between two polymeric films (Fig. 1). The sensing matrix consisted of two layers of conductive strips, with one layer distributed in rows at equal intervals and the other in columns at equal intervals. The conductive strips were covered by a layer of semi-conductive material with a rough surface. With pressure applied to the polymeric film, the upper conductor is forced into contact with the lower conductor at the intersections, forming a sensing unit and causing deformation of the rough surfaces. Such deformation increases the contact area and reduces the resistance of the sensing unit. The pressure sensor had 2016 sensing units (42 rows and 48 columns) with a total sensing area of 0.2081 m^2 (width: 487.68 mm; depth: 426.72 mm).

The acquisition system measured the resistance at each sensing unit in sequence. During acquisition, a selected column was excited by a non-zero voltage, with all the 42 sensing units on the excited column brought to the same voltage, while other columns were grounded. A multiplexor then connected each row of the mat in sequence to read the voltage that depended on the resistance of each sensing unit. After reading all the sensing units on the selected column, the reading of rows in the next column was commenced after a delay of about 20 μs. The maximum sampling rate was 100 frames per second, where one frame contained pressure readings from all 2016 sensing units.

Each sensor could measure up to 207 kPa (30 psi; 2 bar). There were 30 pressure ranges with the digital output automatically scaled to the selected pressure range. The digital output of a single sensing unit was an integer number between 0 and 255, so the resolution was the pressure range divided by 256. The pressure range used for the measurements in Section 2.2 was determined so that it would include the maximum pressure over the contact area required for the measurements in Section 2.3.

2.2. Static and dynamic calibration

2.2.1. Equipment

An indenter rig was used to apply controlled loads over the sensor (Fig. 2). The indenter rig had a steel frame mounted over an electrodynamic shaker (Ling V860). A flat horizontal metal plate was secured to the indenter head which was driven by a motor to provide vertical compression forces. An RDP MCL DC load cell measured the static force and a Kistler 9347B load cell measured the dynamic force above the indenter head.