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Development of a new capacitive matrix for a steering wheel's pressure distribution measurement

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ABSTRACT

Pressure distribution measurements are becoming increasingly important in the automotive field for ergonomic optimization of components like seats or steering wheel. Nowadays, traditional sensors shows several drawbacks such as response variation in time, low sensitivity and high level of intrusiveness. Moreover the great difficulty of carrying out dynamical analysis in the area of interest highly limits their use. A new type of matrix, now available, promises to overcome such problems, and it has been widely tested in the automotive field. The matrix is based on a series of condensers which vary the capacity depending on the pressure applied on their surface. The high sensitivity and the chance of monitoring pressure distribution with frequency contents up to 200 Hz make this tool particularly suitable for evaluating steering wheel's goodness effectiveness in an on-road test.

Relevance to industry: The knowledge of the behavior of capacitive sensor matrix for pressure distribution at the operator's hand-car steering wheel interface may benefit automobile designers and manufacturers to evaluate steering wheel goodness and seat effectiveness perform through on-road tests and to evaluate the efficiency of the power steering mechanism.

1. Introduction

Many kinds of sensors, based on different physical principles, and measurement devices have been proposed for the evaluation of pressure distribution at contact between two rigid or flexible bodies (Tiwana et al., 2012). Many applications of these measurement systems have been carried out, for instance, to the operator's hand/tool handle system in order to analyse vibration transmission to the hand and human body (Gurram et al., 1993; Rossi and Tomasini, 1995; Marsili and Rossi, 1996a,b), to the operator's foot/ground system for plantar pressure analysis (Sanfilippo et al., 1992; Mair et al., 1988; CobbDr. and Claremont, 1995) and to vehicles seat comfort analysis and improvement (Wu et al., 1999; Shiratori and Ishida, 1992; Ng et al., 19 95). Moreover, many other applications have been developed in other fields such as robot technology (tactile sensors) (Iversen, 1993; Girão et al., 2013), for contact force mapping of mechanical parts (Bjoring et al., 2002; Welcome et al., 2004) and in biomedical engineering (Tiwana et al., 2012; Dong et al., 2005).

The film sensors used for these applications are based on piezo-polymer, capacitive, conductive-ink or resistive polymers sensing elements (Tiwana et al., 2012). At present, however, many metrological problems exists, mainly due to non-linearity, rheological behaviour, mounting surface curvature and shape, dynamic characteristics, etc. Moreover, frequency limitations are present due to the sensor itself, to electronic communication and to the data acquisition system, rather complex when a large sensing element matrix is required.

Piezo-polymers shows probably the best metrological characteristics but they are not suitable for slow pressure's fluctuations and static pressure components. Preliminary tests on sensors based on conductive ink and resistive polymers have shown unstable metrological characteristics over time and, in addition, remarkable hysteresis has been observed.

It is difficult to employ piezoelectric films for the measurement of the contact pressure because of their high sensitivity to interferences due to magnetic field and light (Marsili, 2000; Marsili and Rossi, 1996a,b).

An optical measurement technique permits to measure by a thermocamera both pressure and deformation of a body subject to pressure load (Marsili et al., 2009a). Particularly, in (Marsili et al., 2009b; Becchetti et al., 2010) it is shown how Thermoelastic Stress Analysis (TSA) and Digital Image Correlation (DIC) are both effective techniques, but it is difficult to realize an optical access to perform measurements on a steering wheel, that is a rotating mechanical component (Marsili et al., 2005).

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Here capacitive sensing elements have been chosen for the application described mainly because of their capability of measuring both dynamic and static pressure with an acceptable linearity and hysteresis (Fergenbaum et al., 2003). Polymeric-capacitive film sensors were found to be useful sensors in determining and monitoring the drivers' grip force while driving (Eksioglu and Kizilaslan, 2008). Here the attention is focused on the methods for the correct application of those sensors to measure pressure distribution at the operator's hand-car steering wheel interface.

The outline of this paper is as follows. First, the capacitive matrix to measure steering wheel's pressure distribution is described and both static and dynamic calibrations are analyzed. Then experimental measurements are discussed in different driving conditions. Results show that the capacitive matrix can be used both in on-road tests for evaluating steering wheel goodness and to evaluate the efficiency of the power steering mechanism.

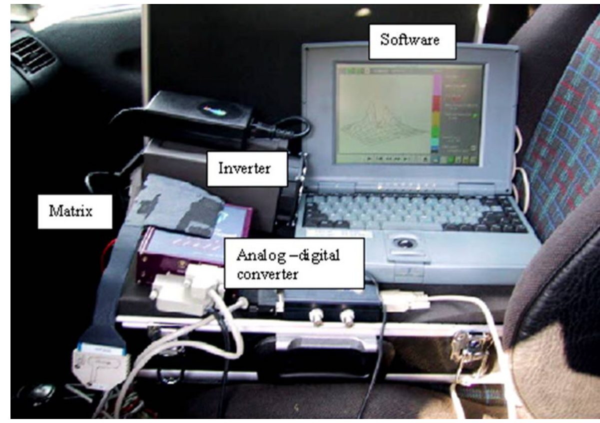

Fig. 1. Measurement instrumentation.

2. Polymeric capacitive sensor: static and dynamic characterization

In order to measure the contact force and grip's pressure distribution at the operator's hand-car steering wheel interface, capacitive sensor film matrix has been chosen.

Capacitive matrix and sensitive elements of this type have been widely tested and characterized referring to DOPTEST EU funded Project, under the Standard, Measurement & Testing Programme, just closed with the contribution of the authors (DOPTEST EU Project, 1997–2000). These transducers have been designed and realized by Novel Co. in order to measure the contact pressure distribution at the operator's hand–handle interface for hand held machines and tools at working conditions. They can provide information on actual input to the hand-arm system, concerning the dynamic contact pressure.

Polymeric capacitive sensors are made of a sandwich structure realised by deposition of two metal layers on two polymeric substrates. Each layer acts as the capacitor's single plate, whose dielectric is realised in silicon rubber. This material behaves as the spring and damper of a mechanical system compressed under the load applied to the sandwich (Ko and Wang, 1999).

An array of sensors can be realised so that a sensor matrix can be wrapped up to a cylindrical handle. Each capacitance value is read by a modulator-demodulator circuit, operating at the carrier frequency of 115 kHz. A pressure change causes a sensor compression and its capacitance variation. Basically, each sensor converts pressure into displacement of the capacitor plates, generating a capacitance change. A multiplexer circuit scans the sensing elements sequentially. This matrix therefore outputs pressure data, whose integral provides the mean grip force.

Static and dynamic responses of the sensor strongly depend on mechanical properties of the sandwich. Therefore parametric investigations have been performed on sets of single sensing elements with different characteristics.

A static calibration system has been realised (Deboli et al., 1999; Di Giulio et al., 2000). A reference manometer measures the value of pressure applied and the load is read by the capacitive sensor. Pressure values have been applied in the 0–6 bar range. This range highlights the sensor's both typical nonlinearities and hysteresis cycles. The nonlinearity is caused by the stiffness increase of the silicone rubber when pressure increases, therefore sensor sensitivity decreases.

Studying different silicone rubbers and sensor's sandwich designs, the sensing element's response has been optimised showing an hysteresis less than 10%, with residual nonlinearity. Deriving the calibration curve from these data, the sensor outputs, once converted in digital data, can be corrected and linearized. The demodulated analog signal is then sampled (8 bit) at 10 kHz sampling frequency.

In order to apply correctly polymeric sensors on handles, a relevant issue to be considered is related to their response when installed on curved surfaces.Therefore, dedicated spherical and cylindrical calibration devices have been designed with different curvature radius. The results of these tests have shown the measurements inaccuracy when the bending radius of the sensor's support surface has comparable dimension with that of the sensing element ($\approx$10 mm). In (Deboli et al., 1999) is shown that sensor calibration curves change significantly when curvature radius is less than or equal to the matrix element width.

In order to carry out sensor's dynamic characterisation, a dedicated test-bench has been realised (Becchetti et al., 2010). An electrodynamic shaker produces dynamic compression forces up to about 500 N. The force is applied by a flat rigid plate to the capacitive sensor compressed on a fixed flat plate. Particular attention has been paid to the structure stiffness and to the plates parallelism during compression.

Frequency Response Functions of all sensors, subjected to sine sweep excitation, have been measured within the 2 Hz–500 Hz frequency range. Test results show that sensor characteristics change with the polymers mechanics (dielectric material) and with the sandwich structure. Generally, it can be said that:

Fig. 2. Capacitive sensor matrix in the operator's hand position.