Thick-film multi-DOF force / torque sensor for wrist rehabilitation

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Abstract

A complete six–degree-of-freedom (6-DOF) force / torque sensor has been designed and fabricated for wrist rehabilitation applications, with the focus laid on simple, straightforward manufacturing processes. This paper details the mechanical design, 3D-modeling, manufacture and characterisation of the sensor. Compared to previous work, this design has the advantage of simple, fully planar machining, and the load-sensing elements all lie on the same plane, making the device compatible with single-film deposition or a foil bonding process. The sensor was machined from steel, and the piezoresistive load-sensing bridges were deposited using thick-film technology. We used commercial thick-film materials in a first time. A new lead-free materials system compatible with low processing temperatures (<700°C) will shortly replace the commercial one and is expected to eventually also be adaptable to aluminium substrates.

Keywords: Force sensor; 6 DOF; thick-film; rehabilitation application; steel

1. Introduction

Recently, robotic devices allowing the patient to monitor his force / torque level in order to increase muscle strength and control of the impaired limb, and reduce abnormal muscle synergies [1,2] have been increasingly used in post-stroke rehabilitation exercises [3]. For the purpose of rehabilitation of wrist function, a force sensor measuring all six degrees of freedom (DOFs) is best to monitor the progress of such a complex joint – and also very useful for human-machine interaction. However, existing designs are quite complex, often requiring complicated machining steps and, even worse, gluing strain gauges in small recesses, resulting in expensive and complicated devices. We endeavoured to design a much simpler sensor, having a single planar sensing compatible with film deposition / foil bonding processes. Also, manufacture of this device is compatible with basic 3-axis milling.

Moreover this process allows rugged and relatively inexpensive devices, is well established in the sensor market and has previously been successfully used by the authors to fabricate a ligament-balancing force sensor for total knee arthroplasty (TKA) [4]. In this device, the thick-film sensing circuit has been deposited directly onto a steel structure, which is much more rugged than ceramic. This approach was also selected for the present sensor.

In this study, we present the mechanical concept of the 6-DOF force sensor, its fabrication and the characterisation of its response.
2. Mechanical design

2.1. Concepts

In order to detect the 3 forces and 3 torques exerted by the wrist (6 DOF), the sensor is structured with 3 modules placed in a triangular configuration, as depicted on Fig 1.

To concentrate deformations at precise locations, each module has some thinned sections that locally weaken the structure, which concentrates the elastic strains and thus allows piezoresistive sensing. These structures form three bridges (Fig. 2). The piezoresistive resistors are deposited onto these thinned zones, and linked electrically in reconfigurable Wheatstone bridges, which allows sequential extraction of two forces (tension/compression and vertical force, see Fig. 2). This reconfiguration is effected by swapping the positive and negative power supply of one half of each bridge by the means of analogue switches mounted in an H-bridge configuration. Overall, this gives 3x2 = 6 forces that, when combined appropriately, allow extraction of the 6 DOFs.

2.2. Dimensioning of the sensor

In addition to the thinned sensing sections, the design of the module has been optimised with additional laterally weakened zones at the end of the bridges acting as elastic hinges to decouple the shear loads and decrease their effects on the measurement. Due to the space needed by the thick-film conductors, the top side had to be somewhat widened, resulting in a T-shaped section or those “hinges”.

The dimensioning was based on the forces and torques exerted by the human wrist, which entailed some compromises in sensitivity of some axes, dictated by the simplicity of the device (Table 1). The thickness of the 3 bridges is 0.8mm for a width of 3.2mm and an effective length of 2.1 mm (3.1mm with a fillet of 0.5mm).
Table 1: Nominal and design forces (F) / torques (M). Nominal values are estimated for wrist function, and design ones are taken with 100 MPa calculated stress in the measuring structures.

| Axis | Nominal | Design |
|------|----------|--------|
| $F_z$ | 200 [N] | 200 [N] |
| $F_x, F_y$ | 100 [N] | 1'000 [N] |
| $M_z$ | 5 [N·m] | 20 [N·m] |
| $M_x, M_y$ | (not specified) | 3 [N·m] |

2.3. 3D- modelling

A finite-element modelling (FEM; example in Fig. 4) shows that the localisation of the strains is well defined and their magnitude corresponds well to the expected values. For applied $M_z$ torque, the strain tends to concentrate on the top of the T-section hinges, indicating that – although the levels are acceptable - the width of these zones should be reduced in future designs.

3. Manufacture and characterisation

3.1. Thick-film process

The screen-printed technology was used to apply the thick-film system (dielectric, conductor and piezoresistive resistor). As for the previous work in the field, this paper presents results for the sensor initially screen-printed with a commercial high-firing (peak: 10 minutes at 850°C) thick-film system. A first dielectric layer (ESL 4916) was applied to buffer the substrate-thick-film mismatch of the thermal coefficient of expansion. This was followed by a
second dielectric layer (ESL 4924) featuring better electrical insulation and chemical compatibility with the resistor. Finally, the conductor (ESL 9635B, AgPd) and the piezoresistive (Du 2041) compositions were deposited.

In a further step, the sensor will be fabricated using a new low-firing and lead-free (including resistors) recently developed [5] thick-film materials system using bismuth-based glasses. This new system features low-temperature processing (<650°C), which is very advantageous for piezoresistive sensing as this allows the use of high-strength martensitic stainless steels, lifting an important performance limitation of state-of-the-art thick-film sensors using steel substrates.

3.2. Characterisation

The setup for characterisation is depicted in Fig. 5 (a). Force cycles were applied to separately measure the 6 DOFs, and the signal drift has also been measured. Fig. 5 (b) depicts the results for Mz torque, with a relatively rapid unloading rate. We can observe a hysteresis which tends to disappear over time. Its origin, which can be due to drift in mounting stresses and/or anelastic effect within the steel structures, was not yet asserted precisely. The precision of the measurement for the forces Fx, Fy and Fz at nominal load is between 3 and 4 %, and that for the Mz torque is between 5 and 10%, due to the lower sensitivity of the sensor for this DOF.

![Fig. 5: (a) sensor in the setup; (b) Drift of the bridge 1](image)

4. Conclusion

A 6 DOF force / torque sensor for wrist rehabilitation has been successfully designed and fabricated using a steel substrate and a commercial high-firing thick-film system. A suitable mechanical design allowed measurement of the forces and torques with acceptable precision. Future work will use a lead-free low-firing thick-film materials system developed in our laboratory, which will allow a considerable improvement of performance through the use of high-strength martensitic steels. Moreover, further developments of this system are expected to allow also deposition on some aluminium alloys. Finally, the advent of an entirely lead-free system removes an important environmental concern about the future of this technology.

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