View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Infoscience - École polytechnique fédérale de Lausanne

Optimisation of a Thick-Film 10...400 N Force Sensor

Thomas Maeder*, Grégory Affolter, Niklaus Johner, Giancarlo Corradini, & Peter Ryser

Laboratoire de Production Microtechnique (LPM), Ecole Polytechnique Fédérale de Lausanne (EPFL),
BM 3.142, EPFL Station 17, CH-1015 Lausanne, Switzerland ; http://lpm.epfl.ch
* Corresponding Author : tel. +41 21 693 58 23 ; fax +41 21 693 38 91

Version of record: Microelectronics Reliability 48 (6), 902-905, 2008.
http://hdl.handle.net/10.1016/j.microrel.2008.03.005

Abstract: The ring-on-ring bending principle allows the fabrication of simple, low-cost thick-film piezoresistive sensors for compressive forces in the 10 to 400 N range. However some imperfections are encountered in its basic embodiment, such as relatively high force-signal hysteresis and nonrepeatability (up to ca. 5%). These shortcoming were studied in this work, and major improvements achieved. Hysteresis was found to be mainly due to friction at the outer support ring, and considerably reduced by inserting a compliant silicone glue ring. The same glue ring was used to permanently bond the sensor to a rigid base, thereby giving well-defined and constant boundary conditions and also considerably improving the repeatability of the sensitivity. Overall, hysteresis and repeatability error were reduced down to a level of ca. 1%.

Key words: thick-film force sensors; low-cost; double ring geometry; hysteresis; repeatability

1. INTRODUCTION

The strain sensitivity of thick-film resistors are widely used in pressure and force sensor applications [1, 2], with mainly alumina or LTCC [3, 4] substrates. In force sensors, simple cantilever-type geometries are advantageous for the low force range, due to very economical batch fabrication on standard alumina substrates, or on others if higher sensitivity [4] or strength [5] is required. However, they are practically limited to moderate force ranges [6]. For higher forces (roughly up to 100 N), the bridge geometry was introduced [6], and later extended to double ring for even higher forces and better integration [7] (Fig. 1 left). In the latter case, which is the object of the present work, forces up to ca. 400 N may be attained in practice, and the issue of potentially damaged substrate edges due to processing is avoided, because the edges only face small stresses in the double ring configuration. Finally, placement of the sensitive resistors is not critical, as the zone inside the inner ring is nominally at constant stress [8].

Bridge / double ring sensors face one main problem, however: the boundary conditions of the sensing structure (bridge or membrane) are hyperstatic, because lateral gliding is not free, but subject to friction forces. Upon application of a force (Fig. 1 right), the sensing element bends, which creates small lateral movements on the supports. Upon increasing force (Fig. 2 left), the lateral friction forces on the two concentric rings create a bending moment opposite of the nominal, applied one, resulting in a lower output signal. The converse is true (Fig. 2 right) for decreasing force, which potentially gives rise to hysteresis. Due to the very small movements involved, the actual observed hysteresis values (Fig. 3, equation 1) of the basic sensors [[7]] varied quite widely over a series of samples, but sometimes exceeded 5% of the full scale response (denoted %FS hereafter), which is unacceptably high. Another weakness of the original design is the absence of a base, the only specification being that the lower support ring be placed on "a flat surface". Due to the unavoidable and changing local geometric imperfections, this potentially leads to an additional variability in the sensor response.

This work has therefore the three following aims:

1. Check that friction is the main source of the observed hysteresis.
2. Check that the absence of a fixed base leads to variability in response.
3. Find a workaround to reduce these problems, while conserving the simplicity and low cost of the original sensor design.

$$Hysteresis = \frac{signal\ with\ decreasing\ force - signal\ with\ increasing\ force}{full\ scale\ response} \qquad (1)$$

2. SENSORS, MODIFICATIONS AND MEASUREMENTS

The fabrication details of the "CentoNewton" sensors are described elsewhere [7]. Briefly, the thick-film circuit on top of the substrate consists of a piezoresistive Wheatstone bridge with 2 inner active and 2 outer inactive resistors, together with the adjustment and signal conditioning electronic circuit. The two support rings (Fig. 1 right, inner-top & outer-bottom diameter 4.6 and 10.0 mm respectively) are screen-printed thick-film dielectric. The bending substrate (96% alumina, Kyocera A-476) thickness used in this work is 0.76 mm (0.8 nominal), giving a full scale force of 100 N at a nominal stress of 100 MPa [7].

The boundary conditions at the dielectric rings are detailed in Fig. 4. The applied force is transmitted through the force disk, which is glued onto the sensor substrate inner dielectric ring with soft silicone adhesive (Dow Corning Q5-8401), making sure that a thin ≈20 µm layer of glue separates the dielectric from the force disk (that the parts are not in direct contact). Silicone adhesive was chosen because its compliant elastomeric properties are stable over a very wide temperature range, from ca. -40°C to 200°C [9].

For the outer ring, three variants were fabricated (several sensors per variant) and tested. All sensors were first fabricated as variant A, then modified either into variant B or variant C.

- **Variant A** (basic sensor) [7]. The bottom dielectric ring simply rests on a nominally flat steel or ceramic base. The friction at this contact is thought to be the major cause of the hysteresis shown in Fig. 3, and different surface imperfections of the base at different spots are thought to give rise to variability of response.
- **Variant B**. To check the friction-hysteresis hypothesis, variant B was introduced, where the bottom outer dielectric ring was replaced by 6 steel balls in a hexagonal arrangement, glued onto the sensor substrate in the same manner as the force disk (see above). This creates a quite compliant link, where dynamic friction at the contact points should be replaced by (small) rolling / tilting of the balls.
- **Variant C**. Here, the sensor substrate / outer dielectric ring is soft glued to a thick ceramic base in the same way as the force disk, creating a 2nd relatively compliant link, but probably not as compliant as variant B. Moreover, the position of the sensor on the base is now fixed, which should give much better repeatability.

The sensors were tested as in the previous study [7], using a Promess instrumented press fitted with a precision load cell. Testing consisted of applying several cycles of a ramp of increasing, then decreasing force. The force increase / decrease rate was ca. ±3 N/s, but tended to fall off sharply towards the maximal load due to the peculiarities of the press control, so the samples were loaded up to 1.5 x nominal load (e.g. 150 N) in an effort to alleviate this problem. The hysterisis, e.g. difference of output signal between increasing and decreasing force, was normalised to full scale response, defined as the change of signal between zero and nominal load (100 N). Each sensor was initially tested as variant A, and then again in modified form (variant B or C). For variant A, one sensor was also tested at different positions on the base.

3. RESULTS

The effect of modifying the basic variant A into either B or C is shown in Fig. 5 for 2 sensors each. Clearly, replacing the simple friction contact on the outer dielectric ring by a joint that can deform locally and absorb the slight lateral displacement without dry friction brings a very large improvement in hysteresis. Also, variant C, which is compatible with low-cost batch production, gave (almost) as good results as the very compliant variant B, and therefore constitutes an acceptable solution to the hysteresis problem. Note that while the inner and outer ring joints are the same for this variant (dielectric + soft silicone glue), the effect of the outer ring joint residual stiffness on the signal is larger than that of the inner ring, because lateral displacement and substrate tilting due to substrate flexure is much larger at the outer ring. This is compounded by the larger perimeter of this joint.

Variant C turned out to have two additional advantages: by attaching the flexible sensor substrate permanently to the base, 1) handling and attaching the sensor becomes more convenient, and 2) the fixed sensor position also improves the reproducibility of the sensor response amplitude.

The importance of this last point is illustrated in Fig. 6 (zoomed). One sensor (variant A) is first cycled 4 times at a fixed position on a thick ceramic substrate (plain curves): reproducibility is very good, as the observed standard deviation of the slope is < 0.1%. Then, the same sensor is cycled again 5 times, but moved randomly on the base before each test (discontinuous curves): variability of response is much higher, ca. 2%.

4. CONCLUSIONS

The output signal hysteresis of a simple force sensor for the ca. 10...400 N range with ring-on-ring loading were determined to be mainly due to dry friction between the outer thick-film dielectric support ring on the bending sensor substrate and the base. Also, local imperfections of surface topology of standard thick-film ceramic substrates lead to the response being dependent on where the sensor is placed on the base. By the simple step of gluing the outer ring to the thick ceramic base, using a thin layer of compliant adhesive whose deformation replaces dry friction, hysteresis was largely eliminated. Additionally, this step fixes the position of the sensor on the base, thereby improving reproducibility and usability.

5. ACKNOWLEDGEMENTS

The authors are indebted to Mr. Igor Saglini, Matthias Garcin, and Claude Amendola for help in fabricating the sensors.

6. REFERENCES

[1] Morten B, Prudenziati M. Piezoresistive thick-film sensors. In: Prudenziati M, editor. Handbook of Sensors and Actuators vol. 1: Thick film sensors, Elsevier, 1994, p. 189-208.

[2] Belavič D, Hrovat M, Dziedzic A, Golonka LJ, Kita J, Holc J, et al. An investigation of thick-film materials for sensors and actuators. Proc. XXIX IMAPS Poland Chapter Conf., Koszalin, Poland, 2005, p. 357-360.

[3] Partsch U, Arndt D, Georgi H. A new concept for LTCC-based pressure sensors. Proceedings, 3rd International Conference on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT), Denver, USA, 2007, THA23.

[4] Birol H, Maeder T, Nadzeyka I, Boers M, Ryser P. Fabrication of a millinewton force sensor using low temperature co-fired ceramic (LTCC) technology. Sensors and Actuators A 2007;134:334-8.

[5] Maeder T, Jacq C, Corradini G., Ryser P. Effect of thick-film materials on the mechanical integrity of high-strength ceramic substrates, Proc. 15th European Microelectronics and Packaging Conference (EMPC), Brugge, Belgium, 2005, p. 377-81.

[6] Maeder T, Fahrny V, Stauss S, Corradini G, Ryser P. Design and characterisation of low-cost thick-film piezoresistive force sensors for the 100 mN to 100 N range, Proc. XXIX IMAPS Poland Chapter Conf., Koszalin, Poland, 2005, p. 429-34.

[7] Maeder T, Saglini I, Corradini G, Ryser P. Low-cost thick-film force sensors for the 100 N force range. Proc. XXX IMAPS Poland Chapter Conf., Kraków, Poland, 2006, 193-6.

[8] Vitman FF, Bartenev GM, Pukh VP, Tsepkov LP, "A method for measuring the strength of sheet glass", Glass and Ceramics 19 (8), 412-414, 1963.

[9] "Information about Dow Corning® brand adhesive/sealants", Dow Corning, www.dowcorning.com, 2008.

7. FIGURES

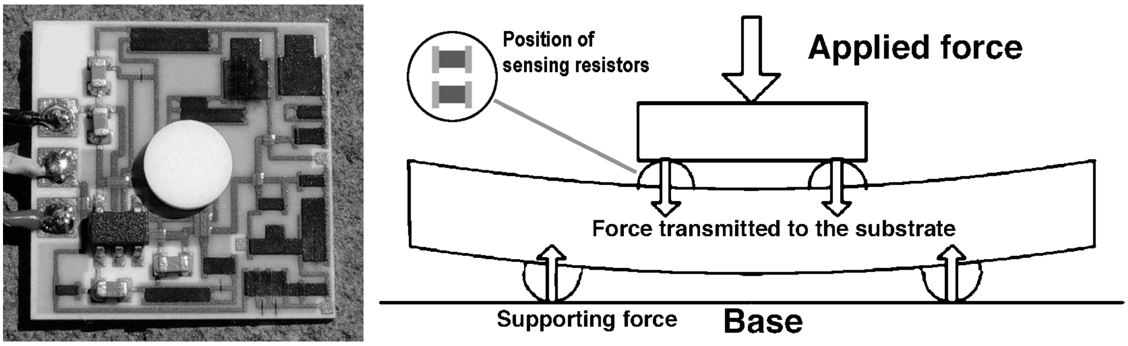

Fig. 1. "CentoNewton" double-ring force sensor [7] and ideal mechanical model. The inner and outer ring diameters are 4.6 and 10.0 mm, and the substrate is a 15.24 mm square. The position of the sensing resistors in the inner ring is shown in the inset.

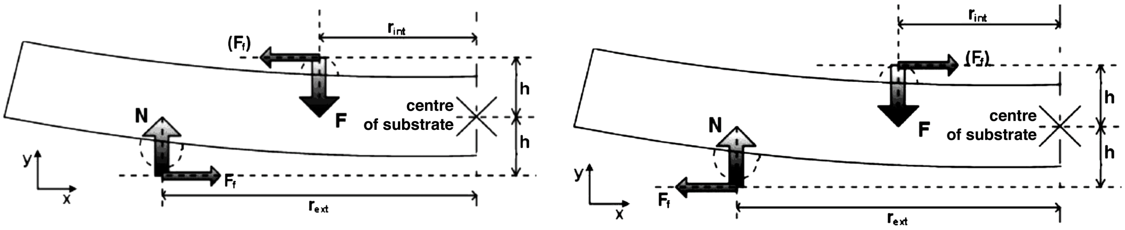

Fig. 2. Friction forces on the bending element with increasing (left) and decreasing (right) applied force.

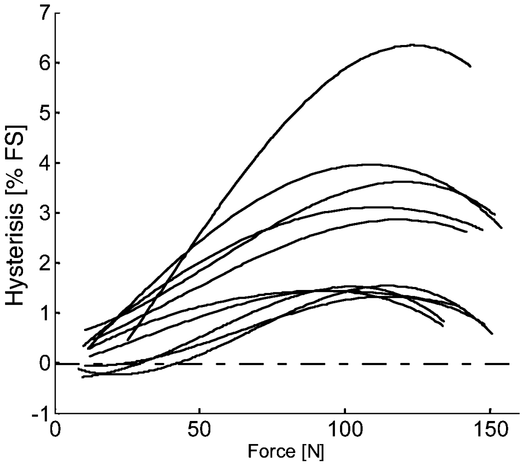

Fig. 3. Hysteresis (eq. 1) vs. applied force for a series of original sensors [7], where the outer ring simply rests (substrate thickness 0.76 mm, single loading-unloading cycle for each sensor).

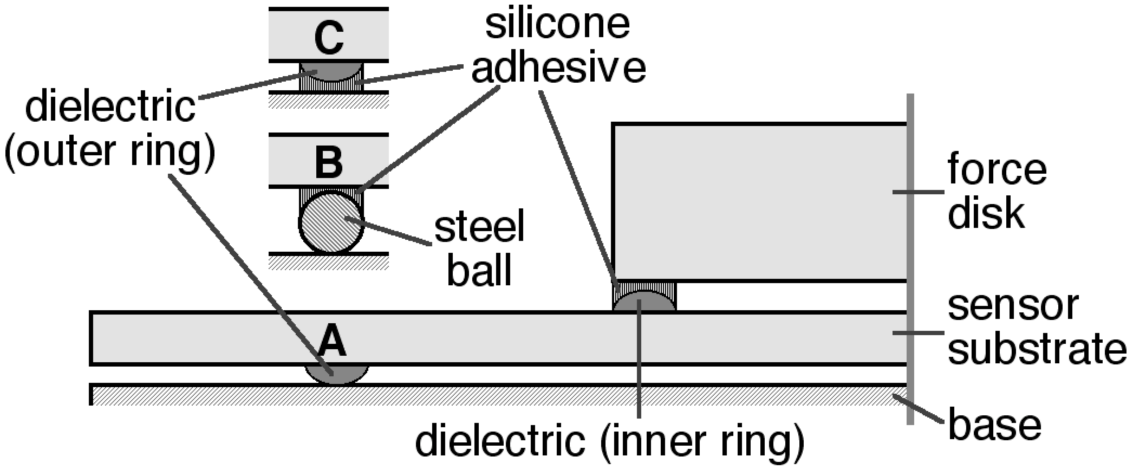

Fig. 4. Boundary conditions for inner & outer ring (inner ring same for all variants). A) basic variant, dielectric resting on base [7]; B) ring of steel balls glued with soft silicone; C) dielectric glued to base with soft silicone.

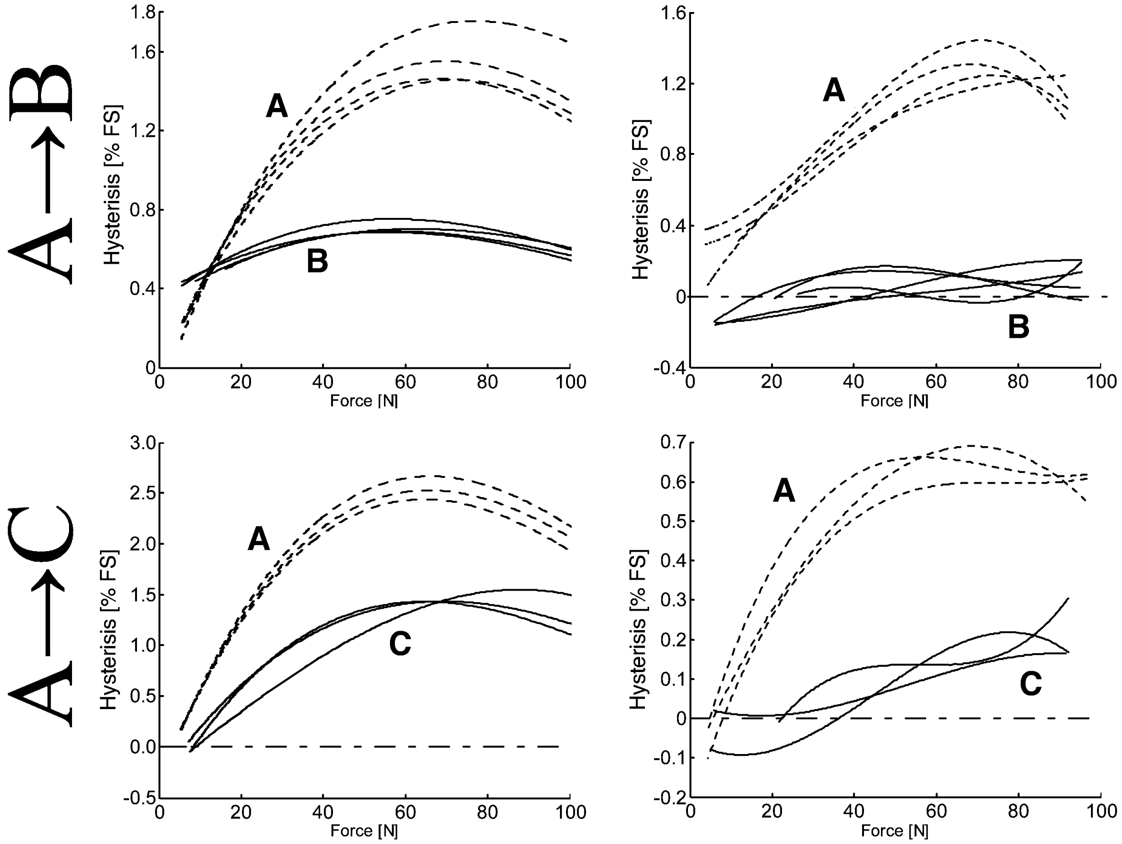

Fig. 5. Hysteresis (eq. 1) vs. force of 4 sensors, first measured in variant A (dashed lines, several cycles), then modified either into variant B (2 sensors, top) or variant C (2 sensors, bottom) and measured again (plain lines, several cycles).

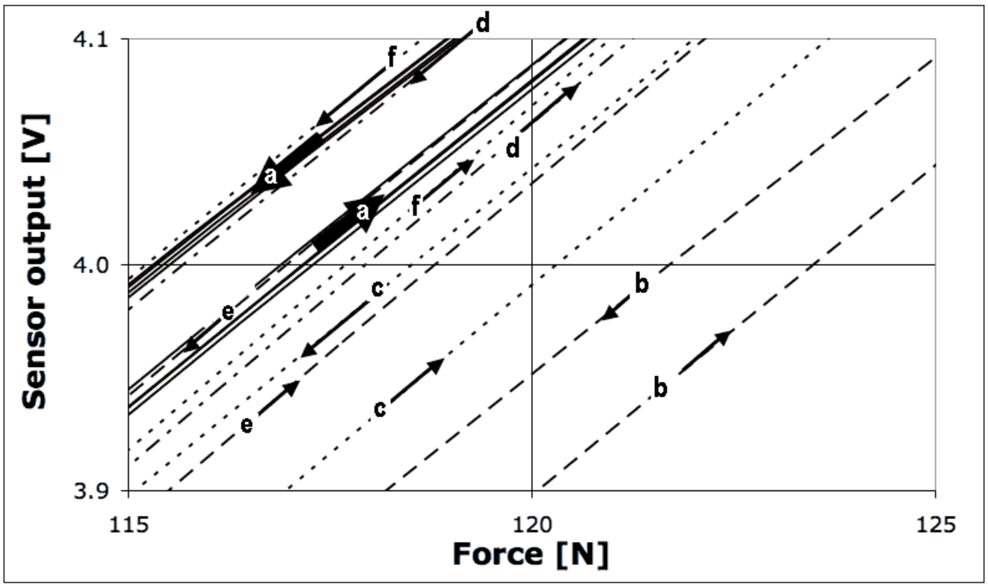

Fig. 6. Sensor output vs. applied force (zoomed) for one sensor (variant A), tested on ceramic base first 4 times without changing position (plain lines, thick arrows, a), then 5 times, randomly changing position on base before testing (dashed/dotted lines, thin arrows, b-f).