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CONTACT PRESSURE MEASUREMENT ON A BIOMEDICAL PUMP BY FILM SENSORS

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Abstract. *In this work the problem to measure the contact pressure distribution between two elements of a bio-medical pump is considered. What is important to know are the spatial distribution of pressure and its evolution in time in order to better design pump components.*
A polymeric capacitive sensor matrix has been selected and a prototype sensing element has been tested in order to define metrological characteristics and dynamic properties.
A single sensing element has been used to perform preliminary measurement inside the pump in order to specify metrological characteristics of the matrix.

Key Words: *contact pressure distribution, bio-medical pump, polymeric capacitive sensor.*

1. Introduction

The biomedical pump analyzed has a ball screw which generates the alternative motion of a plate that pushes a rubber bag which contains the working fluid (Figure 1). If the distribution of pressure between the plate and the bag is not symmetrical the ball screw is not simply loaded axially, but also by a bending moment, that could cause mechanical problems. The knowledge of the pressure distribution, which causes the eccentricity of the force resultant, allows a better design of the screw and then a higher reliability and a longer working life of the system.
The pressure distribution at contact surface between plate and rubber bag is also changing in time in a periodic way (period between 0.5-1.0 s). The goal of this work is the development of a

matrix of pressure sensors (at least four sensors on a square cm) and relative data acquisition and processing system that allow to acquire this pressure distribution and its evolution in time.

2. Sensors for contact pressure measurements

For the purposes of this work it is important to develop a dynamic pressure distribution measurement device to be used when tests of the pump are in progress on already developed test benches that reproduce working conditions. Many sensors based on different physical principles have been proposed for the measurement of pressure at contact surface between two rigid or flexible bodies. Some contact pressure measurement systems have been used for measuring pressure distribution at interfaces between objects, with application to comfort analysis and improvement of vehicle seats (1), for various biomedical applications such as measurement of contact pressure between hand and handle of a tool in order to analyze vibration transmission to the hand (2, 3) or between foot and ground for plantar pressure analysis (4, 5). Many applications have been developed (6) also in other fields such as robot technology (tactile sensors), for contact force mapping of mechanical parts. The film sensors used for those applications are based on piezo-polymer, capacitive, conductive-ink or resistive polymers sensing elements. However, many metrological problems remain unresolved, due to non-linearity, reological behavior, mounting surface curvature and shape, dynamic characteristics, etc. Also frequency limitations can be due to the sensor itself or to the electronic processing and data acquisition system when a matrix of many sensing elements is necessary.

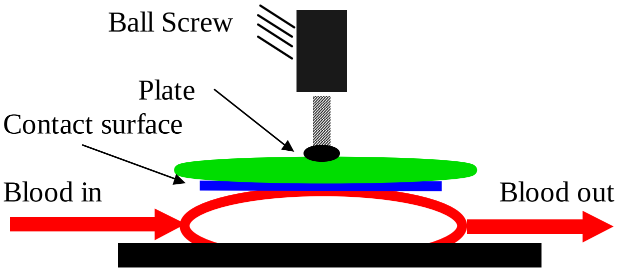

Figure 1: The measurand.

Piezo polymers have probably the best metrological characteristic but cannot measure very slow fluctuations or static pressure components. Sensors based on conductive ink or resistive polymers have shown from preliminary tests that metrological characteristics change with time and have large hysteresis.

In this work capacitive sensing elements have been selected on the basis of information available in literature and then tested. This choice has been made mainly because of their capability to measure both dynamic and static pressure with acceptable linearity and hysteresis. No useful mechanical model of the sensing element has been found in literature in order to understand the intrusivity and mechanical filtering effects due to the presence of the film between the two surfaces.

3. Static tests of the sensing element

Capacitive sensing elements are sandwiches composed basically of two metallization layers applied on the two faces of a flexible material. The capacity of the sensing element is a part of an electrical circuit that changes its parameters accordingly to changes of capacity due to global thickness change of this sandwich when compressed. Two relevant transfer functions can be identified: the first between the applied pressure and the thickness change (mechanical transfer function) and the second between thickness change (distance between condenser armatures) and output electrical parameter. Preliminarily this work analyses the mechanical transfer function.

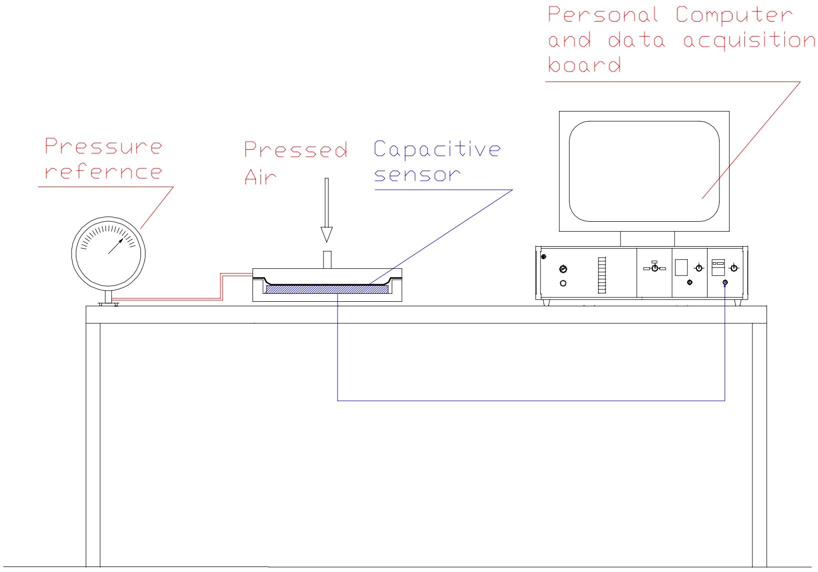

Figure 2: Test bench for static calibration.

Because of the complexity of the system, typically, once realised the sensor it needs to be calibrated. Therefore in this work single sensing elements have been statically calibrated using the test set-up of Figure 2.

The calibrator realized applies a reference pressure to the sensor by a thin rubber membrane. Between the membrane and the superior part of the calibrator there is air and its pressure can be changed. The air pressure is measured by a reference gauge. Figure 3 shows a typical result: the abscissa axis is the reference air pressure (q_i [bar]) applied to the capacitive sensor, and the ordinate axis is the pressure measured by sensor (q_o [bar]). The calibration curve was calculated using the least squares criterion. The points (q_i, q_o) followed a linear trend (the correlation coefficient R was 0.99) in a wide pressure range (0 ÷ 6.5 Bar), without reaching saturation. The uncertainty relative to the full-scale output was lower than 1.4%. The maximum value of hysteresis was 0.2 bar.

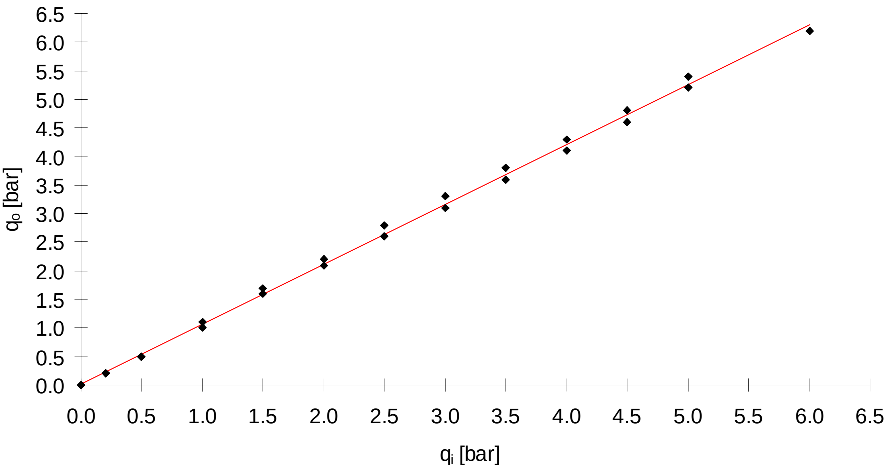

Figure 3: Typical results of static calibrations.

In order to have information to build a mechanical model that allows to estimate the filtering and intrusivity effects of the matrix, at this first stage of analysis, the sensing element can be approximated as spring-damper combination (a first order model). No useful information has been found in literature so that the load-deformation curve of a single sensing element has been detected during static loading. A typical result obtained is illustrated in Figure 4.

From this result it is possible to see the non-linear behaviour of the capacitive sensing element, due to the polymeric material and structure between the two condenser plate. This result allows to estimate values of the stiffness. The stiffness changes with applied pressure, therefore a value around the working point must be used to estimate intrusivity and filtering effects due to mechanical characteristics of the sensor. The non linear behavior of the sensing element requires the characterization to be performed for the typical values of pressure and pressure fluctuation that is expected the sensor will measure; this because the transfer function and input-output relation of a non linear device changes with load.

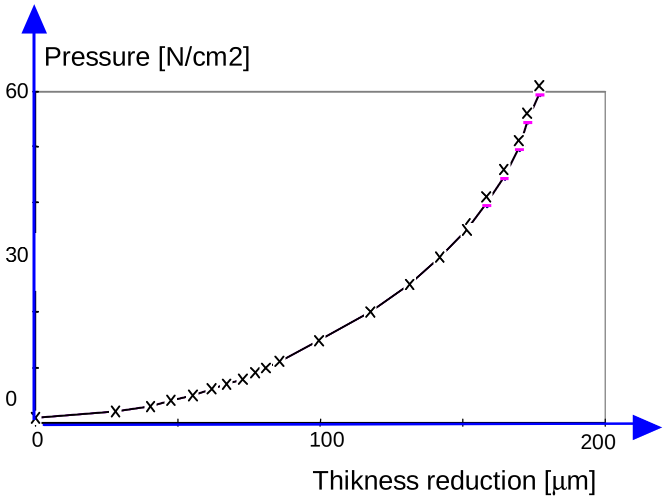

Figure 4: Typical pressure - sensor thikness reduction curve.

Therefore dynamic tests have been performed at the pressure level expected inside the pump, that, from preliminary measurement of forces with load cells has been estimated in the range 0 ÷ 30 N/cm^2.

4. Dynamic tests of the sensing element

All the tests have been performed using the configuration of Figure 5. The sensing element is compressed between two rigid surfaces and a proximity sensor has been used to measure displacements between them. Compression force, generated by the electrodynamic exciter, is measured by a load cell. Tests have been performed using sine excitation and typical signals obtained are illustrated in Figure 6. The area of the sensing element is 1 cm^2, then the force values correspond to pressure values in N / cm^2. For the measurement of the force that stressed the sensor, the inertia force of the plate fixed above the load cell is also calculated. Figure 7 shows the displacement versus the force. The deviations from the theoretical ellipse of the spring-damper model is tolerable and is due to the non linearity of the sensing element.

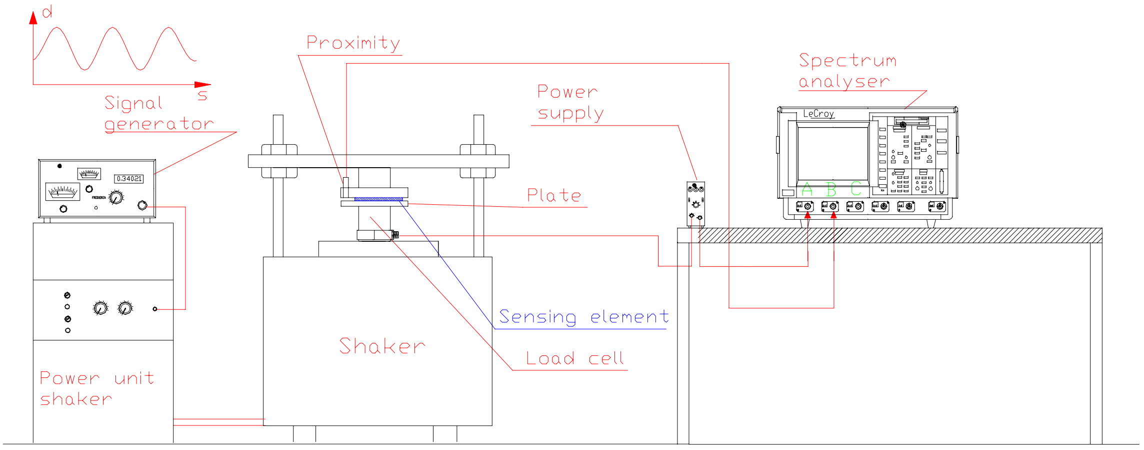

Figure 5: Test bench for dynamic characterization.

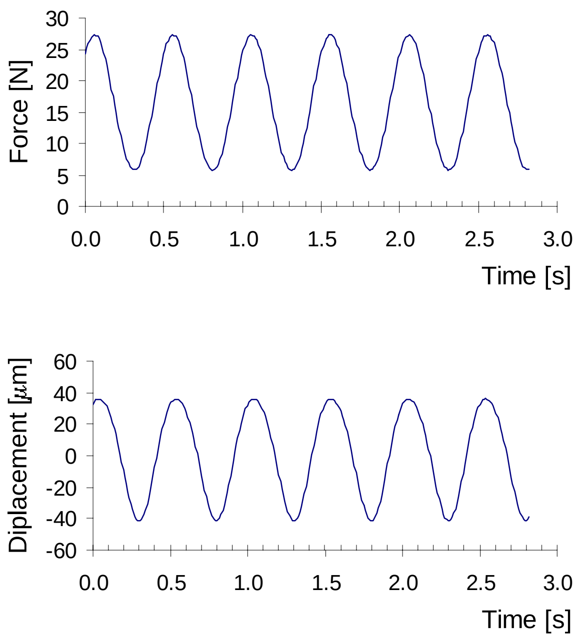

Figure 6: Time history force and displacement signal.

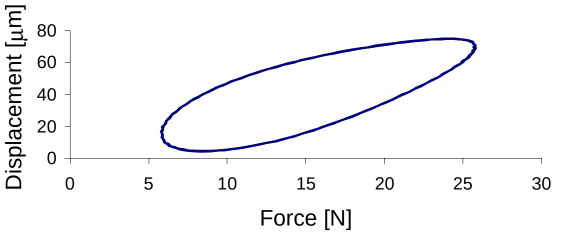

Figure 7: Buckling of the sensor vs 1 Hz sinusoidal force.

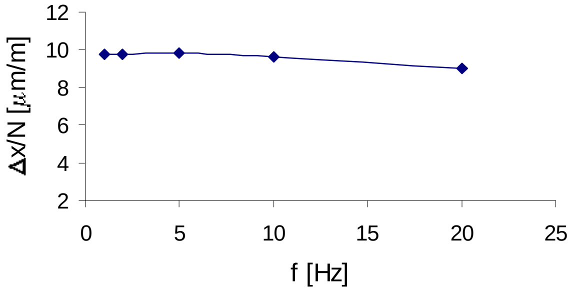

Figure 8: The ratio between displacement and force amplitude vs frequency.

Changing excitation frequency keeping fixed the level of force the ratio between displacement and force amplitude vs frequency is plotted in Figure 8. This results allow to establish that useful bandwidth is from 0 up to 10 Hz with tolerable mechanical transfer function decrease lower than 5%.

The model here assumed for the sensor is a spring-damper mechanical first order model. In this case we have $F = kx + cdx/dt$ as the total force due to spring and the damper measured by the load cell and if $x = A\cos(\omega t + \Phi_1)$ then $dx/dt = -A\omega \sin(\omega t + \Phi_1)$ then $F = kA\cos(\omega t + \Phi_1) - cA\omega \sin(\omega t + \Phi_1)$.

The amplitude of force fluctuation is then:

$$F_e = \sqrt{(kA)^2 + (cA\omega)^2}$$

From the measured values of A and F_e of signal of Figure 6 the knowledge of $\omega = 2\pi f$ and of k from the static tests it is possible to calculate c and then the time constant τ of the first order model: $\tau = ck$. Values obtained from the test at different frequencies are $c = 0.20$ Ns/μm and $\tau = 0.068$ s.

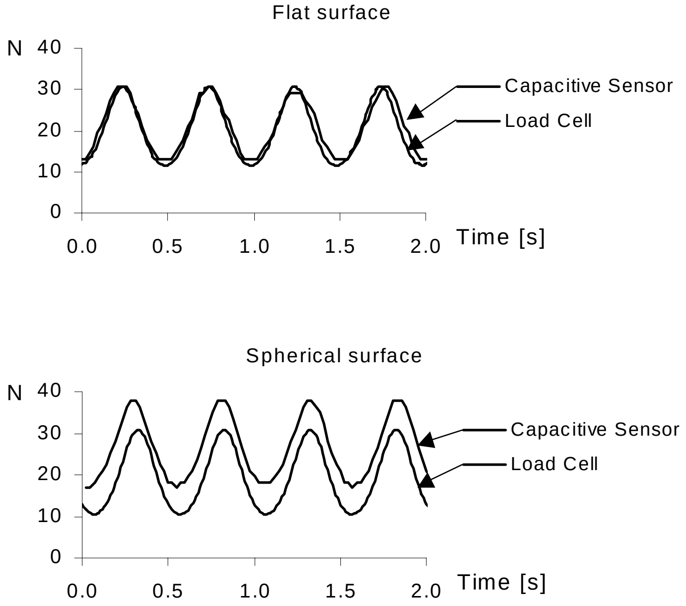

Figure 8: Time history load cell and capacitive sensor signal.

To analyze the effect of different shape of contact surfaces the test bench of figure 5 has been used whit the plate substituted by a spherical surface of 25 mm of diameter and the proximity support substituted by a foam layer. A comparison of the load cell signals and sensor output signal is illustrated in Figure 9. It is possible to conclude that an overestimation of about 30% occur when the sensing element is compressed and deformed to a spherical surface.

5. Definition of matrix metrological characteristics.

In order to define the metrological characteristics of the matrix the typical working conditions of the biomedical pump has been simulated using an electrodynamics exciter to move the plate (Figure 9) and single sensing elements have been positioned in different points between the plate and the rubber bag.

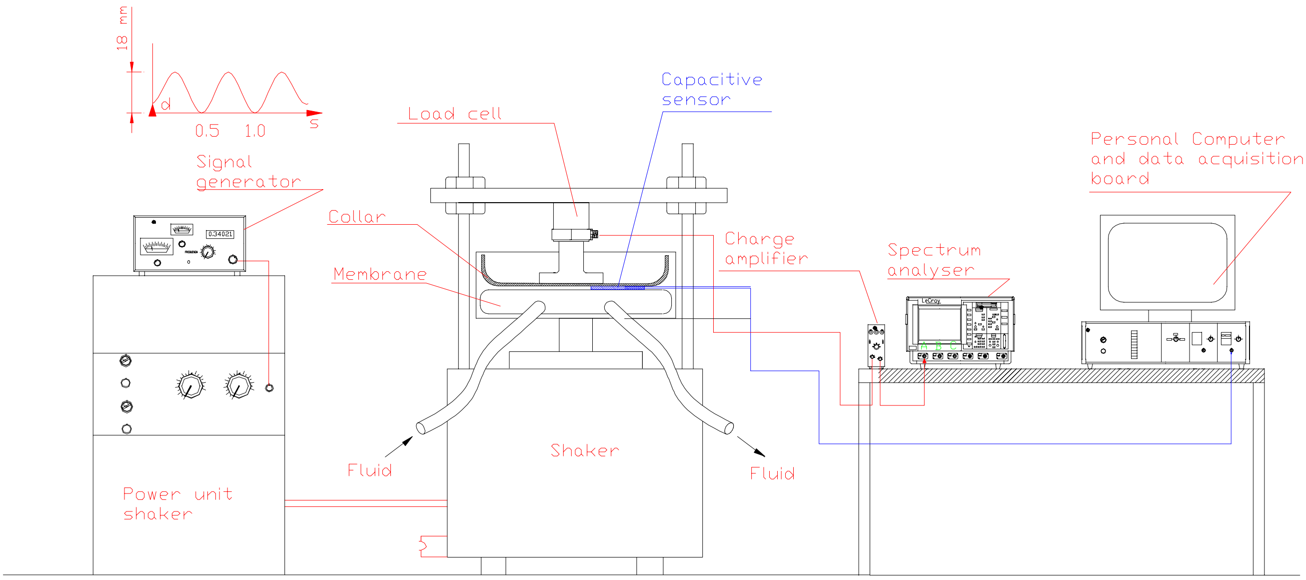

Figure 10: Test bench for dynamic calibration.

A load cell measures the reference force between the plate and the exciter. Assuming the plate and its connections as rigid bodies and with negligible inertia the force measured can be considered to be the pressure distribution resultant.

Tests have been performed at frequency of 2 Hz, using an electrical sine signal to drive the exciter, that generates an alternative motion of up to 18 mm and a maximum force of 500 N. During the tests the device is pumping water that goes on an external circuit with the possibility to change the hydraulic load until the desired value of force on the plate is obtained. Typical results are illustrated in Figure 11. It is possible to see that even if the driving signal is a sine signal the force and the pressure fluctuations are not due to the not linear characteristics of the sensor. Power spectrum contains not only a single significative peak but also higher order harmonics. From the frequency analysis, reported in Figure 8, only the band up to 10 Hz is measured with tolerable attenuation (lower than 5%).

The data acquisition and processing system developed to perform those measurements is capable to perform 500 pressure acquisitions per second on the sensing element.

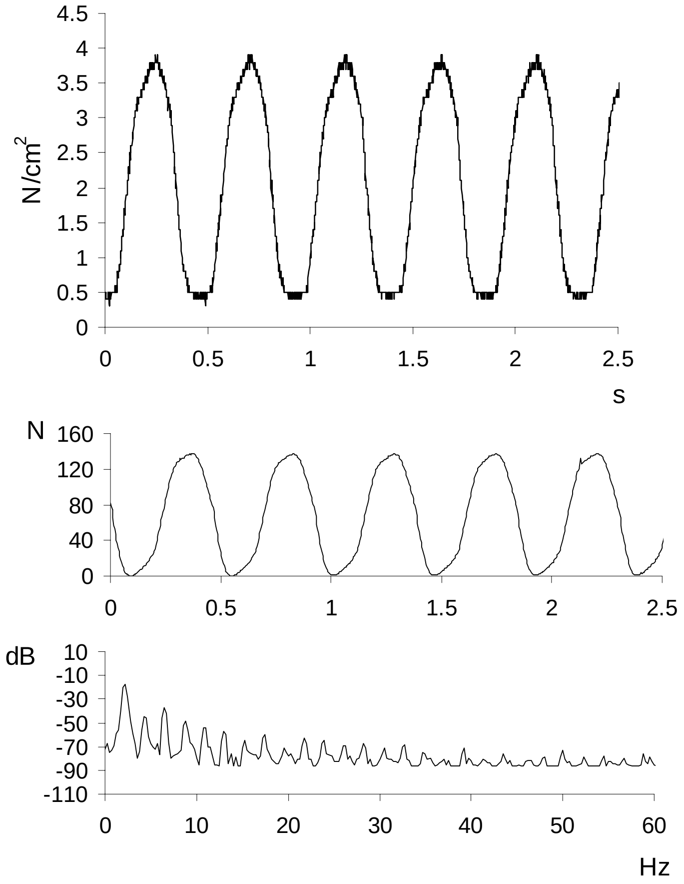

Figure 10: Typical pressure (with sensing element) and force (with load cell) fluctuation obtained and force spectrum.

Using a matrix of 16x16 (256 sensors), that meets the needs about spatial resolution, it is possible to obtain about 2 (500/256) complete pressure images per second. More information about pressure evolution in time can be obviously obtained measuring not on all the sensor cells of the matrix but only on that significantly loaded.

The most important parameter that can be computed from this results are relative to dynamic uncertainty tolerated when the matrix is used.

Resolution and dynamic range depend also on the behaviour of the data acquisition and processing system.

From those results it was possible to optimize both parameters in order to obtain for the matrix a measurement range of 30 N/cm^2 (that is the minimum to cover all the pressure fluctuations detected) which gives a resolution (being fixed at 8 bits the resolution of the analog to digital converter) of 0.1 N/cm^2. Hysteresis is in the order of 0.2 N/cm^2.

6. Conclusions

A technique for the measurement of the contact pressure distribution on a bio-medical pump has been proposed.

The technique is based on the use of a capacitive sensor’s matrix for the measurement of pressure changes both in space and in time.

The design specification (in terms of its metrological characteristics) for the matrix and for the relative data acquisition and processing system have been obtained from tests of single sensing elements performed on special purpose test benches on which relevant working conditions of the pump have been reproduced.

The effect of contact surface curvature has been analyzed comparing the sensor output when it works on spherical or flat surfaces. A first dynamic spring-damper model has been proposed to define its mechanical dynamic response.

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