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Embedded surface-pressure measurement with flexible piezoelectric thin-film sensors

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Abstract

Flexible thin-film piezoelectric polymer sensor arrays have been proposed in several scientific applications since the early 2000s. Across domains, research has proven that these sensor systems include considerable innovation potential by overriding existing application barriers and cost reduction. Nevertheless, this sensor technology has not yet been industrialized to a large scale industrial appliance or even mass production. Rather, there appears to be a large gap in experience and systematic knowledge compared to conventional piezoelectric sensors. In order to illuminate the sensor-properties of this technology (frequency shift, gain and linearity), the current work examines a generic design of a piezoelectric polymer film sensor array and a corresponding amplification circuitry as an integrated measurement system. In this course, we present the buildup of a test rig that allows to apply a sensor excitation over a wide pressure and frequency range. Using this facility, we perform studies with mono-frequent pressure signals as well as step excitation with high pressure rates, benchmarking the developed thin-film sensor array with a well-known, commercially available reference system. Moreover, we investigate the developed amplification as single component. We compare experimental response to a simulated sensor with numerical and analytical calculations. The results show that the developed measurement system (piezoelectric polymer film sensor array and amplifier) is highly competitive to state-of-the-art, technically mature measurement systems.

Key words: piezoelectric, dynamic sensor, polymer sensor, thin-film, sensor array

Introduction

Sensing surface pressure on the basis of functional materials, such as piezoelectric polymers, is a vital trend in the development of new sensor generations.

In this course, bionic approaches can be a significant opportunity. During evolution for instance, the principle of an elastic, flat and force sensitive skin has established itself as one predominant sensory system. A likewise ability to sense the local and temporal distribution of surface forces in a highly resolving manner can provide enormous potential for a multitude of technical and commercial applications. However, for most applications this challenge lacks technologies that provide affordable, robust and seamless integration.

A technology that targets to unleash such potential should comply with the requirement to sense the local and temporal distribution of surface forces

- in a local and temporal highly resolving manner
- on curved and elastic surfaces
- under high load/stress
- with minimum interference to the measurement object and its environment

In nature, these requirements are mostly addressed by the principle of piezoelectricity [13], [14]. However, piezoelectric torque converters based on ceramic and monocrystalline materials that are in industrial use do not comply with above requirements due to marginal elastic formability and tendency to fracture.

Moreover, existing technologies for local pressure resolution require space that is not available and would exceed the desired resolution itself. In addition, the modification of measuring objects is a major issue.

In the current work, we present a sensor approach with the following properties

- flat (a few tenth mm)
- flexible
- robust and break-proof
- high dynamics

- high local resolution (<1 mm)
- marginal interference with measurand
- fabricated with conventional printing technologies

Of particular importance is the extensive width of the dynamic range and frequency band covered by the presented technology. This includes a wide spectrum of technical applications. Fig. 1 compares the typical pressure and frequency bands for industrial applications with the range of the presented sensor system, based on piezoelectric polymers.

Various research illustrates the capabilities of these piezoelectric transducers for appliance in automotive (crash-sensors, tire contact force sensors) [4, 8, 9], fluid technics (turbomachinery, areodynamics, cavitation, turbulence) [5, 6, 7, 10], Structural Health Monitoring [1], mechanical contact force measurement [3] or Health Care [2].

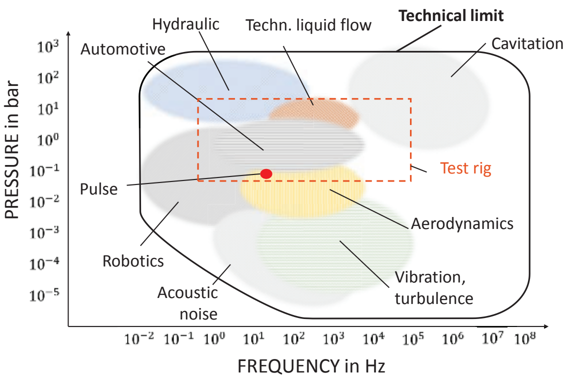

Fig. 1. Classification of typical pressure and frequency bands of industrial applications within the boundaries of polymeric piezo transducers. The depicted measurement range represents the current boundaries of our measurement systems, which can be altered by variation of functional material.

The robustness of the presented measurement system is being examined in [11] by applying a high frequent pressure excitation through cavitation (up to 100 MHz) in different hydraulic machineries. The marginal thickness of the sensor (< 100 µm) allows for having no interference with the fluid flow to be measured. The flat sensor design with its compact cable route require only marginal modification for integration within the hydraulic machinery.

For exploitation of the potential of polymeric piezo measurement systems outside of science and its transfer into a proven industrial measurement instrument, an extensive examination of its properties is necessary (frequency band, dynamic range, linearity, temperature range, stability, etc.).

The following questions arise:

- How can a measurement system based on piezoelectric (polymer) sensorarrays be calibrated?
- What bandwidth can be achieved?
- What technical apparature allows for applying maximum-pressure excitation with high frequency?
- What about linearity und hystheresis?

To date, piezoelectric sensors are being calibrated with monofrequent pressure excitation in comparison to a reference sensor. This is problematic as it presupposes a tight bandwidth of production tolerances probably affecting the tails of the frequency response spectrum.

Another method for calibration of piezoelectric pressure sensors is excitation through pressure step. Here, both sensor signals are being matched on the maximum amplitude. If the pressure can be sustained for a longer period, conclusions on the bandwidth of the sensor can be made (e.g. lower cut-off frequency).

Unfortunately, both approaches do not allow for any conclusions regarding the phase response of the system, which is essential for the determination of the sensor's bandwidth. Therefore, the current examination will apply multiplicity of monofrequent sinus excitations covering a wide frequency band. This examination will incorporate identical measurements on a commercially available reference sensor in order to compare the amplitude and phase response of the system. Finally, the step response of both systems is being compared.

A particular challenge in the quantification of a sensor's dynamic performance are the high technical requirements on the experiment set-up that will provide dynamic excitation as necessary. Major parameters are the maximum pressure, the location of the experiment machineries first resonance frequency as well as the choice of actuators. The design of such an experimental is another subject of this work.

Buildup of the sensor array and the measurement system

Subject to examination will be a generic one-dimensional pressure measurement array with 6 pixels arranged in one line. This can be regarded as a representative for any (even two-dimensional) arrangement of any number of pixels as described in [11]. The miniaturised amplification circuit is a multi-channel differential charge amplifier whose number of channels can, due to its modular construction, be scaled to any multiple of 6 or 8. The fully-integrated data-acquisition board comprises of an optional unit with 16 bit

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A/D conversion, digital signal processing and telemetry. The wohle system is a proprietary development by pd²m. The system can be configured to operate anywhere within the maximum pressure range between 100 Pa and 25 MPa.

For the current examination, the system has been configured for maximum pressure up to 20 bar and an amplification of 1 Volt per 16 bar. This configuration implies a calculative cut-off frequency between 0.3 Hz und 10^5 Hz, determined at 45° phase.

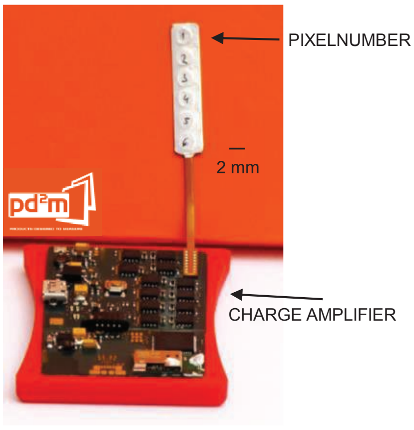

Fig. 2. 1D 6-Pixel thin film sensor array.

The transducer material is a piezoelectric polymer with a thickness about 28 µm, being contacted on a flexible medium. The diameter per sensor pixel is 4 mm. Pixels are arranged with a pitching of 1 mm. The compound is elastic and can be applied on heavily curved, respectively deformable surfaces. The thickness of the overall compound is only 0.3 mm. Further, the sensor compound is covered with a protective against aggressive chemical influences and undesirable electric radiation.

Experimental approach

The properties of thin-film polymers as piezoelectric transducers regarding thinness and stiffness promise a relatively wide parameter space regarding frequency and pressure range. Raising this potential however, relies on a performant (overall) measurement system.

The frequency response of the measurement system is being determined by the performance of sensor, wiring and amplification. The comparatively low piezoelectric constant of thin-film polymer transducers, presupposes relatively high requirements on the amplification circuitry. The design of an appropriate amplification is crucial for the exploitation of the potential of thin-film polymer transducers. In addition, the mechanical design of the sensor fundamentally determines response performance. Different layers (mounting, contacting, shielding, etc.) with varying stiffness properties are involved in the transducer buildup, effecting its response behavior and sensitivity against higher frequencies. In the following section firstly the electrical and subsequently the electromechanical transmission behavior of the proposed design is being investigated. In addition to the presentation of the experimental outcome, simulation results will be compared.

Review of the electrical system

For this examination, an experiment for the isolated review of the amplification circuitry has been set up. In this buildup the sensor is being replaced by a frequency generator with a serial connected capacity. This signal generator is being connected to the multi-channel amplification circuitry under review with a sinusoidal excitation. For acquisition and analysis of measurement data, the amplification output is being connected to a 12 bit Oscilloscope (350 MHz bandwidth, 2.5 GS/s). Both, the signal generator as well as the data acquisition on the other hand are being controlled via USB interface from a PC. In this course, the signal generator's excitation frequency and amplitude and the oscilloscope's sampling rate and measurement range are being jointly controlled.

Fig. 3 shows the resulting transmission and frequency response of the amplifier under review. The amplification circuitry is based on charge differential amplification. The total gain of the amplifier circuit is proportional to the feedback capacitor of the charge amplifier and the gain from the differential amplifier.

In order to consider the behavior over a wide range, the measurement has been performed for three different excitation amplitudes: 150 mV ≙ 90 %, 100 mV ≙ 60 % and 50 mv ≙ 30 %. The results show that the amplification gain is independent from the signal amplitude, i.e. the amplifier shows linear behavior.

Focusing on the phase response graph, the frequency bandwidth of the circuit can be determined by the ± 45° phase criterion. Doing so, the lower cut-off frequency can be identified at 0.5 Hz and the upper cut-off frequency at 58 kHz respectively. This frequency band is also being confirmed by the second criterion – the gain drop by -3 dB. The gain of 174 dB results from the definition of the transmission function: $Gain = U/Q_s$ with U output voltage from the amplifier and Q_s the electrical charge induced by the sensor.

Our analytical calculations modeling the circuit, wiring and sensor closely resemble the observed frequency response in the lower frequency range. The calculative upper cut-off frequency shows to be higher than observed. This is due to ideal assumptions regarding the amplifier.

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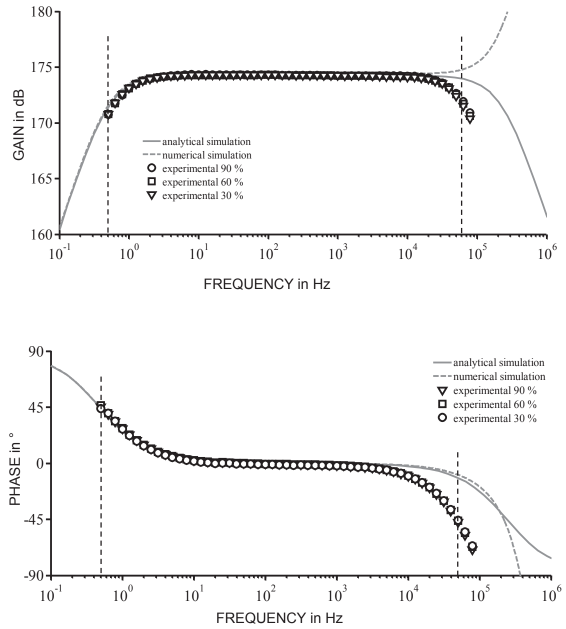

Fig. 3. Bode plot of the multi-channel amplifier under varying excitation amplitude.

The transmission behavior of the amplifiers in use can be modeled better by a numerical calculation. Fig. 3 also shows the numerical calculation of the circuitry's transmission function, which exactly resembles the experimental observation. A deviation from the ideal parameters can be observed near the upper cut-off frequency. Instead of an analytically predicted decrease, the gain increases in the observation. This behavior is based on the particular behavior of the utilized operation amplifier, which derives from the theoretical ideal.

The higher cut off frequency reveals higher in the calculation than in the experiment. This behavior is rooted in the input circuitry of the measurement. The setup with the signal generator and input condensator requires a capacity of 33 nF in the input condensator to deliver a stable signal. The requirement for such high value significantly reduces the upper cut-off frequency of the amplification. These circumstances are elaborately described in [11]. When the amplifier is directly connected to a piezoelectric sensor, the upper cut-off frequency should draw near the numerical expectation. A review of the transmission behavior with a real sensor connected follows in the next section.

Review of the electromechanical system of actuator, sensor and amplifier

In order to examine the electromechanical properties of the measurement system, a test rig, capable of high load and likewise high frequency excitation, is necessary. This particularly concerns the actuator properties (frequency range for high forces, stiffness and maximum power density).

With respect to the maximum power of the actuator, the demand for higher frequencies requires minimum mass for all moving parts of the buildup. Piezo stack type actuators are particularly suited for this purpose, delivering homogeneous excitation even with higher dynamics. Their marginal motion ranges however, increase stiffness requirements on the experiment buildup.

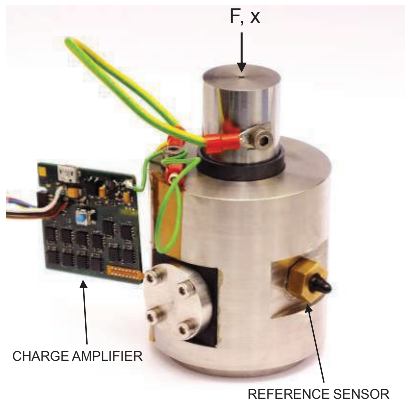

Fig. 4. Test rig with thin-film sensor array, multi-channel differential amplifier and reference senor.

Fig. 4 shows the hydrostatic test rig (pressure chamber) that has been built up for the current examination. This is being mounted into a test bench that has initially been developed by [12] for the thermal and mechanical evaluation of stack type piezo actuators.

The test bench consists of a stack type piezo actuator P-025.080P® with a force-regulated amplification unit of type E-481. Both components are manufactured by Physik Instrumente GmbH®. In the test rig, the actuator is capable of a motion range up to 0.12 mm and frequency up to 500 Hz.

In order to apply a uniform pressure on all pixels of the sensor-array and the reference sensor, all of those are being placed into a fluid volume within the hydrostatic test rig (Fig. 5). Both, actuator and test rig are being clamped together with a load cell within the test bench. As the actuator excites the piston of the hydrostatic test rig, the static pressure of the fluid is being modified.

In order to measure phase and amplitude of the excitation signal, the motion range of the piston is being measured by a position-sensor. The motion range of the piston is in proportional relation to the pressure induced. The positioning has been set, so that the influence of the test rig's structural resonance behavior on the measured motion range can be neglected. The load signal within the load cell is not being used for the current purpose for two reasons. On the one hand, the vibration behavior of the test bench derogates the phasing between actuator force and pressure within the pressure chamber. On the other hand, the friction in the sealing would lead to an error in the relation between actuator force and pressure.

The sensor-array is being inserted sidewise through a seal into the pressure chamber, so that all 6 Pixels are in the same distance to the piston and surrounded by fluid. As a reference, we use the piezoelectric sensor M105C12® and the amplifier 482C05® both from PCB Piezotronics®. The reference system is being configured for a pressure range up to 68.9 bar (1.000 Psi) and calibrated for 1.267 MPa per Volt. According to the system's data sheet, the lower cut-off frequency is <0.1 Hz. The amplifier's upper cut-off frequency is declared 10 kHz at -3 dB. The reference sensor is flush mounted to the chamber wall (by screw). Its' center axis is 4 mm above the thin-film sensor array.

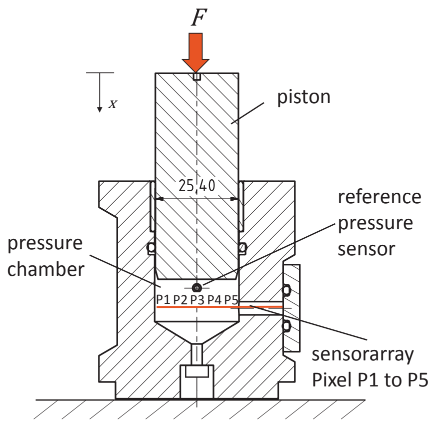

Fig. 4. Hydraulic test rig.

The pressure-position characteristic of the system can be designed by calculation of a cylindric cushion filled with fluid and compressible walls. In this course, the pressure delta dp is a result of the volume change dV over the effective compressibility κ_{eff}, with the chamber volume V

$$\mathrm{d}p/\mathrm{d}V = \kappa_{eff}/V.$$

The effective compressibility of the system is the sum of the fluid's compressibility κ_{fl} and the compressibility of the cylinder κ_z

$$\kappa_{eff} = \kappa_{fluid} + \kappa_z.$$

The stiffness of the cylinder can be approximated by barlow's formula, with the cylinder-bottom and the piston neglected

$$\kappa_z = \delta/Ed.$$

δ is the wall thickness, E the elastic modulus and d the diameter of the pressure chamber. Regarding the compressibility of the fluid, the de-aeration plays an essential role. Even marginal gas inclusion can induce a heavy increase of compressibility and accordingly to a reduction of maximum pressure. A liquid/gas composite's bulk modulus K_{fluid} is given by

$$K_{fluid} = \frac{K_l(V_l + V_g)}{V_l + \frac{K_l}{K_g}V_g}.$$

The indices l and g relate to liquid and gas respectively.

Conjoint with the pressure-position characteristic of the utilized piezo actuator, the geometry of the pressure chamber is being defined as diameter d = 25.4 mm and length L = 15 mm with distilled water as liquid for the parameter range under review (> 30 bar and > 500 Hz). The diameter of the chamber is sufficient for applying a uniform pressure on pixels P1 to P5 simultaneously. For the particular sensor design, pixel P6 is located in the insertion hole and cannot be included in the evaluation.

In the current design of the pressure chamber the finite speed of pressure waves (sonic speed) and the position difference leads to a delay of < 5 µs between sensor array and reference sensor. The resulting phase shift is < 1°.

Results of the electromechanical review

For determination of the phase response and the transmission behavior, the actuator applies a sinusodial excitation, which is being varied over a frequency band from 0.1 to 500 Hz. The pretension is 2 kN corresponding to a static hydraulic pressure of 3.9 MPa. The sampling rate for evaluation is 20 kHz per channel and the characteristics are being determined as an arithmetic mean value.

Fig. 6. compares the phase response for both the thin-film sensor-array and the reference sensor. It also compares the gain plot. The transmission function $Gain = p/x$ is defined as the amplitude relation between piston position x and the transient pressure p within the fluid.

The gain in Fig. 6 indicates the stiffness achieved within the experimental test bench. Further, the measurement confirms the location of the lower cut-off frequency (0.5 Hz) from both, the analytical and numerical calculations. Unfortunately, at 500 Hz we reach the maximum performance of the utilized actuator within the setup. Higher frequency ranges could therefore not be reviewed. The linearity of the gain in relation to the excitation frequency is < 1 % for all sensor-pixels.

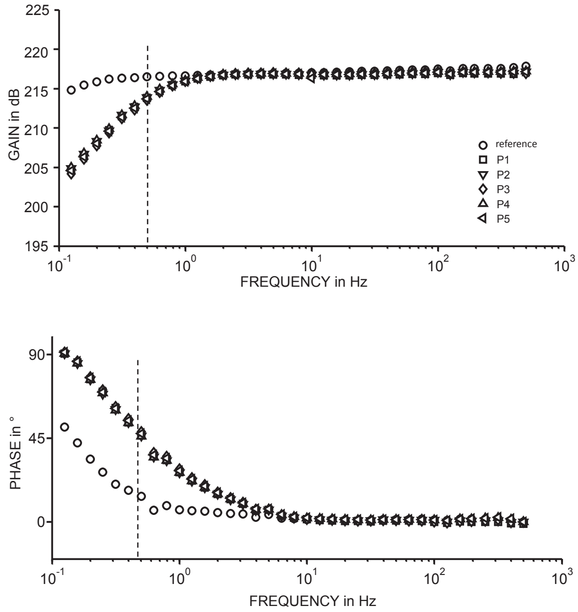

Fig. 6. Comparison of the bode plot of the thin-film piezo sensor-array and reference piezo sensor.

Fig. 7 shows the relation of gain to the amplitude of excitation for a uniform frequency. Here, the linearity-error of all pixels is below 1.5 %.

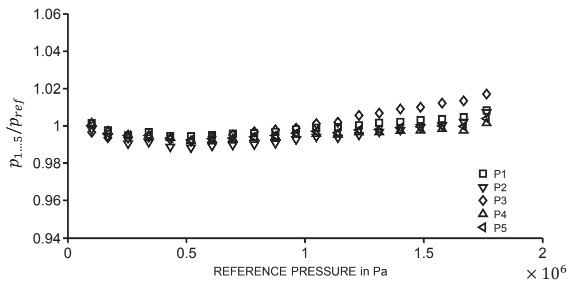

Fig. 7. Comparison of linearity error regarding excitation amplitude (thin-film sensor vs. reference sensor).

Finally. the step response of both measurement systems is being reviewed. For this purpose, the actuator excites a step from 1 kN to 2 kN (compare Fig. 8). The position-sensor shows that the actuator system takes 3 ms for this operation, corresponding to a pressure alteration rate of about 600 MPa/s. Due to the performance restrictions of the utilized measurement board, only one pixel of the sensor-array is being acquired (replicated with all pixels). Both sensors reflect the amplitude of the step likewise. However, as expected, the lower cut-off frequency of the reference sensor, comes at the cost of a higher time constant.

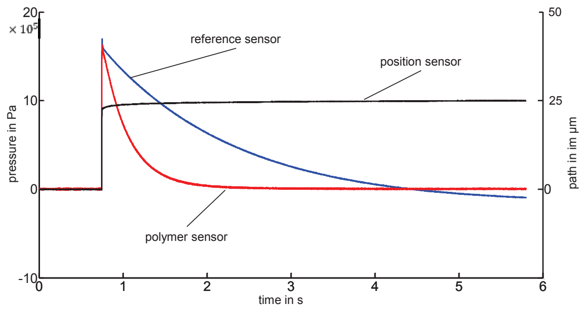

Fig. 8. Step response.

Conclusion and outlook

Thin-film polymeric piezo sensor-arrays turns out to be well-suited for the build-up of sensors that allow for an extremely high resolution of local pressure distribution. Due to their performance, plainness and flexible geometry, they can be used as a cost-efficient enabler for a wide spectrum of demanding applications.

Moreover, comparison of this sensor technology to state-of-the-art measurement systems on a functional level, reveals a highly competitive performance regarding transmission behavior, phase and frequency response. On basis of the presented development with regard to materials, processing and amplification circuitry, the polymeric thin-film sensor shows to be as mature for series production and appliance. The commercialization of miniaturised, calibrated thin-film polymer-based measurement systems opens novel application opportunities. The spectrum of pressure/force metrology is being significantly widened regarding local resolution, flexibility against geometric restrictions and usability without loss in measurement quality.

One important aspect not being regarded in the presented work is the temperature dependency of the measurement system. This will be highlighted further in our continuing work.

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