Analysis of the dynamic transmission behaviour of piezoelectric film sensors

Andre Zander[1] and Rolf Kumme[2]

[1]Volkswagen AG, Wolfsburg, Germany
[2]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Abstract
The goal of this analysis was to obtain knowledge about the dynamic transmission behaviour of piezoelectric film sensors based on Polyvinylidenefluoride (PVDF). Therefore a cross-validation to the well-known behaviour of strain gauges based on constantan foils was conducted. The test equipment was composed of a shaker and a test piece with affixed sensors. The test piece was stressed through the connection to a load mass. The film sensors based on PVDF were mounted to the test piece in such a way that the load direction was parallel to the longitudinal axis of the PVDF-material. In this way it was guaranteed that the highest piezo strain constant d_{31} was mainly used. The output signals of the sensors were measured and the frequency response of the piezo film sensors in relation to the strain gauges were calculated. The results indicated that for frequencies above approx. 250 Hz the piezo film sensor frequency response modulus was a constant value with respect to the strain gauges and that for this frequency range there is the possibility to determine a specific transmission value of the used piezo film sensors similar to the “k-factor” of strain gauges. Furthermore, the high pass filter characteristic of the chosen charge amplifier could be identified.

Background

The background of this analysis was the search for an alternative to the currently used automotive side crash recognition systems.
The evaluated strain sensors have to measure the deformation of the vehicle especially of the door cross member, caused by the mechanical stress during a side collision to indicate this collision. The door cross member is a reinforcement of the vehicle door structure that is specially used for the passive safety of the passengers in side collisions.
These members are designed in such a way that plastic deformations only occur during side collisions where the deployment of passive restraint systems is necessary.

Design of the piezo film sensor

The sensor design was realized in cooperation with Mirow Systemtechnik GmbH Berlin [1]. The essential components are the sensor element and the charge amplifier which was laid out as “real charge amplifier” (Figure 1).

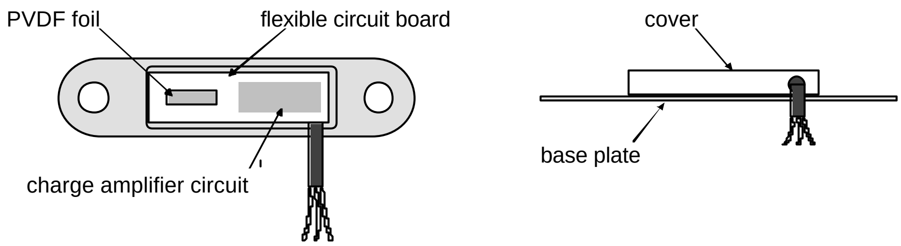


Figure 1 Design of the piezo film sensor

Piezoelectric active PVDF foils from MSI were used for the sensor element [2]. The charge amplifier and the PVDF foil are integrated on a flexible circuit board and electrically interconnected through conductor paths out of copper or conducting glue, respectively.

The connection between the PVDF foil and the flexible circuit board is guaranteed through epoxy resin adhesive. In the same way, the rigid connection between the circuit board and the base plate out of steel is ensured. A cover made of epoxy resin is used to protect the sensor. The high pass filter characteristic of the charge amplifier is laid out in such a way that for this application there is an appropriate lower boundary frequency f_u of 16 Hz [3].

Test equipment

The following requirements existed for the test equipment to achieve simple test conditions and to guarantee the reproducibility of the measurement results:

- unidirectional mechanical load of the test piece within an adjustable frequency range
- high output levels of the piezo film sensors (signal-to-noise ratio) at non-destructive load (elastical deformation)

In order to fulfil these requirements, test equipment was built in which a shaker stresses a cylindrical test piece through a load mass mounted on top of the test piece (Figure 2). In principle, this test piece with piezo film sensors and strain gauges is a force transducer with different strain sensors, which are compared in the experiment. The dynamic force was applied in the frequency range from 20 Hz up to 1 kHz.

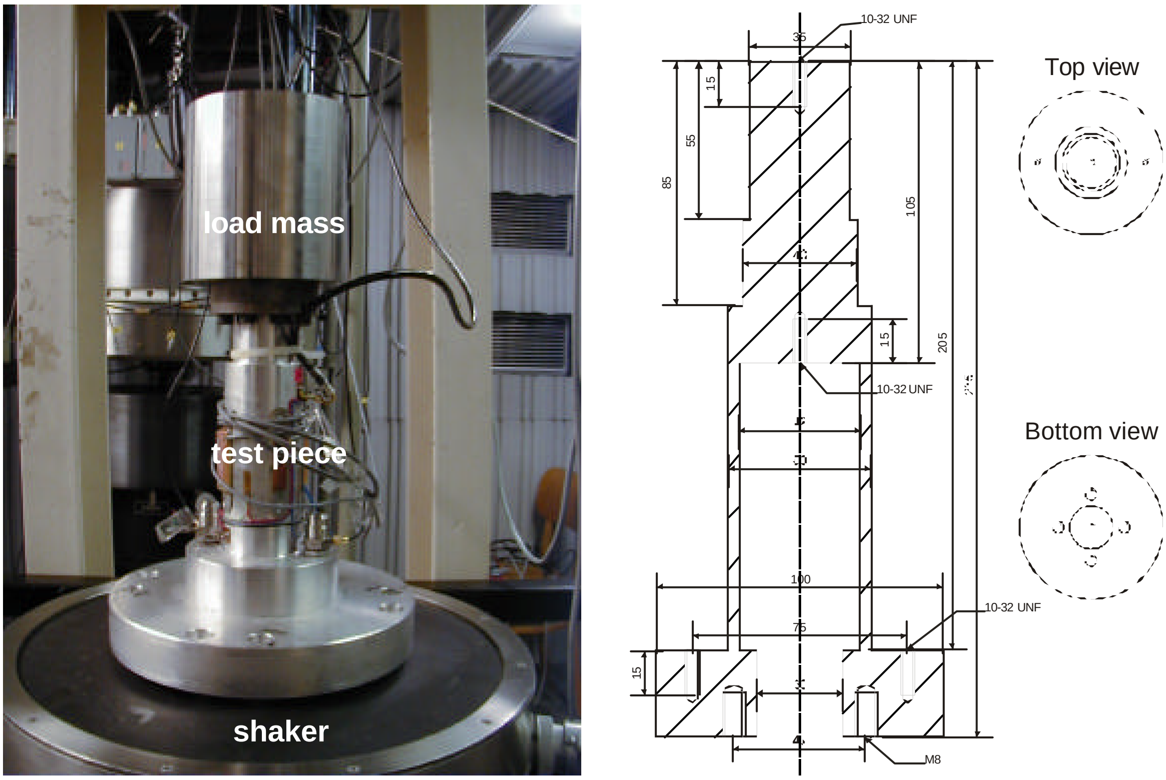


Figure 2 Test equipment and test piece

Due to the extremely different cross-sensitivity of the used sensor materials, the mechanical load had to be applied as rotationally symmetric as possible (parallel to cylinder symmetry axis).

In order to achieve a high signal-to-noise ratio of the film sensors, it had to reach a high dynamical deformation of the cylindrical test piece at elastic range. Besides the shaker, there were special requirements on the geometry and the material properties of the test piece.

Aluminium was chosen as material of the test piece. Aluminium provided a low modulus of elasticity but at the same time the appropriate stability of the test piece (E_{Al} = 71 GPa vs.

E_{Steel} = 210 GPa). With 4 mm the wall thickness of the cylinder was as low as possible. It had to be considered that the cross movement increases with the reduction of wall thickness.
The film sensors were mounted to the test piece in such a manner that the load direction was parallel to the longitudinal axis of the PVDF material. It was thus guaranteed that mainly the highest piezo strain constant d_{31} was used (d_{31} = 23 pC/N).
The electrical measurement of the test piece was composed of four piezo film sensors and a resistor bridge consisting of four strain gauges (Figure 3). To determine the influence of the film sensor cover made of epoxy resin, sensors were used with and without this cover and arranged opposite to the test piece. Due to anisotropy of the piezoelectric effect, the undesirable cross effects could be neutralised through averaging of the opposite film sensor pairs. The film sensors were glued to the test piece with epoxy resin adhesive.

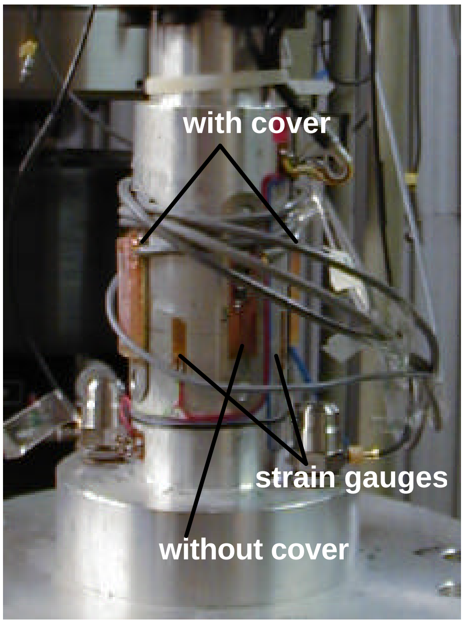
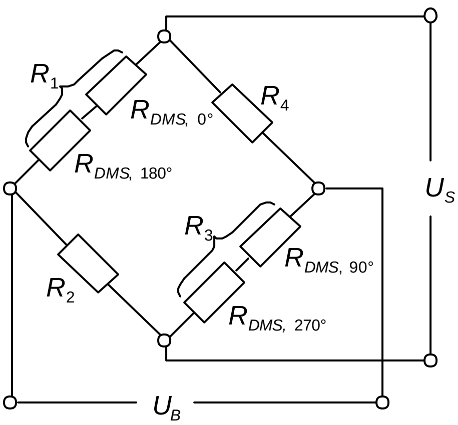


Figure 3 Measurement of the test piece

The four strain gauges were arranged in such a way that occurring cross effects could be compensated (each about 90° displaced). For this purpose, opposite strain gauges were connected in serial to quarter bridges of the used Wheatstone resistor bridge. The remaining two quarter bridges were built with resistors of appropriate resistance R_0 of 700 Ω (Figure 4, U_B bridge voltage, U_S supply voltage).



$$R_1 = R_{DMS,0°} + R_{DMS,180°}$$

$$R_3 = R_{DMS,90°} + R_{DMS,270°}$$

$$\frac{U_B}{U_S} = \frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2 + \Delta R_2} - \frac{R_4 + \Delta R_4}{R_4 + \Delta R_4 + R_3 + \Delta R_3}$$

for $R_1 = R_2 = R_3 = R_4 = R_0$ and $\Delta R / R < 10^{-3}$

$$\frac{U_B}{U_S} = \frac{1}{4} \cdot \frac{\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4}{R_0}$$

for $\Delta R_2 = \Delta R_4 = 0$ and $\Delta R_1 = \Delta R_3 = \Delta R_0$

$$\frac{U_B}{U_S} = \frac{1}{2} \cdot \frac{\Delta R_0}{R_0} = \frac{1}{2} \cdot k \cdot e$$

Figure 4 Used strain gauges Wheatstone resistor bridge [4]

Strain gauges made by HBM (type 6/350 LK 13/C) have been used having a k-factor of 2,07 ± 0,5 %. For the signal conditioning of these strain gauges an analogous DC measurement amplifier was used because of the smaller phase shift of such amplifiers. The amplification S_{DMS} was set to 49,835 $\frac{V}{mV/V}$. The output voltage of the DC amplifier U_{DMS} resulted in:

$$U_{DMS} = S_{DMS} \cdot \frac{U_B}{U_S}$$

Data acquisition was done by a multi-channel signal analyser. This device was also used to calculate the frequency response of the piezo film sensors in relation to the strain gauges. The real and the imaginary part of the complex frequency response were made available for further evaluation.

Test processing

A test series was conducted with various mechanical loads on the test piece. The variation of the mechanical load was reached by the usage of different load masses. Five masses were employed: 2 kg, 4 kg, 6 kg, 8 kg and10 kg.

Using the analogous controlled shaker, a frequency sweep from 20 Hz up to 1 kHz could be used, which was passed in steps of 10 Hz. For this range it was possible to calculate the complex frequency response in relation to the strain gauge outputs.

Discussion of the test results

For the test evaluation, the modulus of the frequency response was calculated from its recorded real and imaginary part. As an example, the following signal sequence could be determined for a mechanical stress applied through 10 kg load mass by using piezo film sensors with epoxy resin (Figure 5).

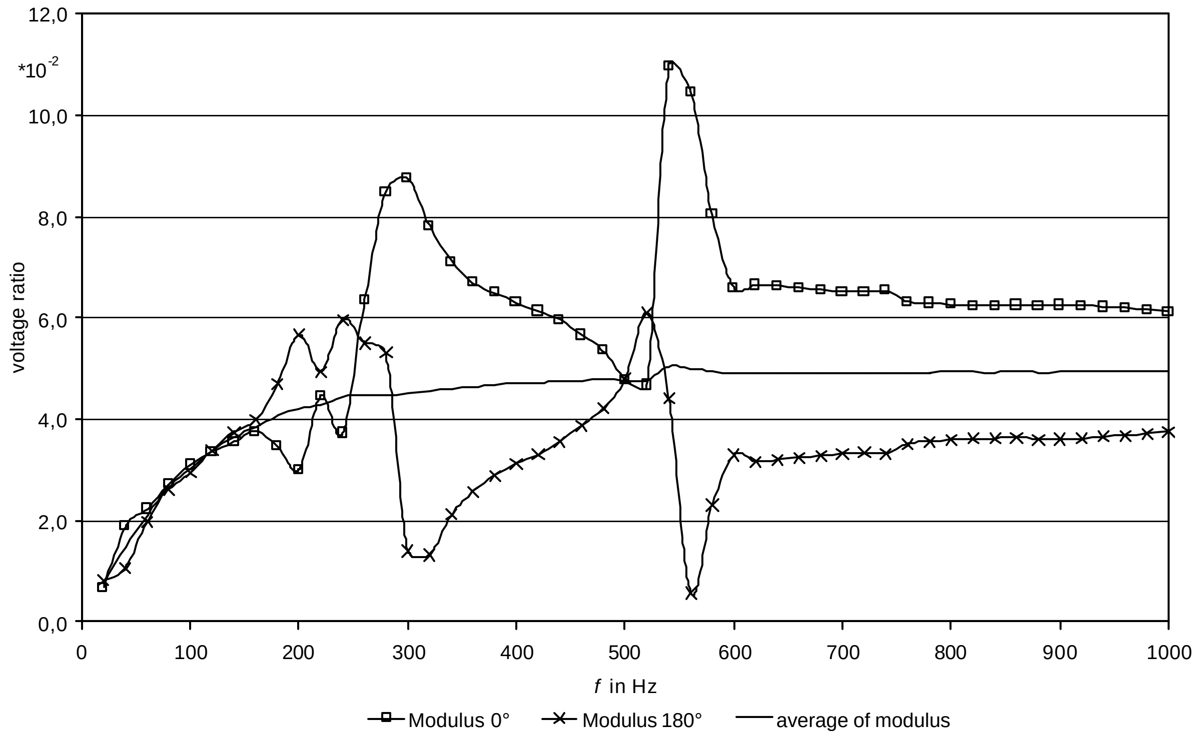


Figure 5 Modulus of the frequency response for film sensors with cover and 10 kg load mass

Figure 5 depicts the high sensitivity of the piezo film sensor to cross movements of the test equipment. This is the result of multi-axle sensitivity to mechanical stress of the PVDF-material used (d_{31} = 23 pC/N; d_{32} = 3 pC/N; d_{33} = -33 pC/N).
These measurement-falsifying signals could be suppressed effectively through averaging output signals from oppositely-applied film sensor pairs (Figure 5). Furthermore, this figure shows that for frequencies above approx. 250 Hz there is a constant value for the frequency response modulus and that for this frequency range it seems to be possible to determine a transmission value between applied strain and sensor output of the piezo film sensor, which is similar to the k-factor of strain gauges.
Likewise, this signal sequence reflects the high pass characteristic of the applied film sensor charge amplifier. This is characterised through the descent of the frequency response at low frequencies (250 Hz down to 20 Hz).

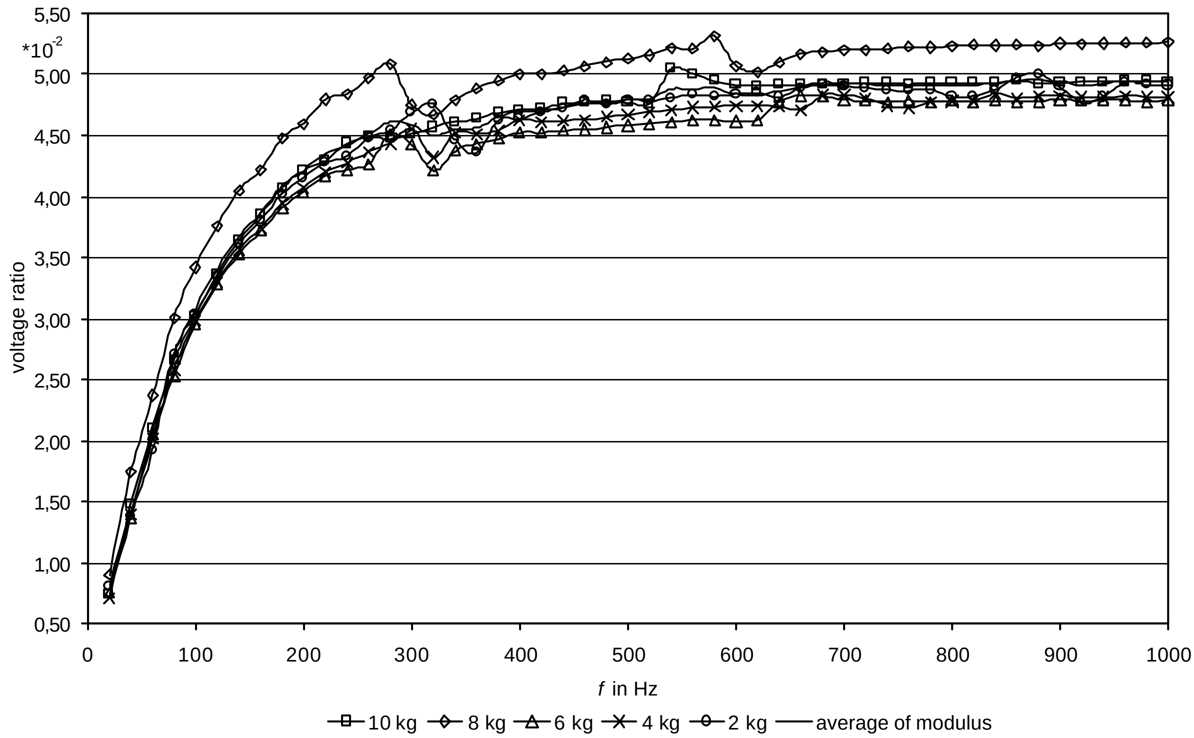


Figure 6 Modulus of the frequency response for film sensors with cover and different load masses

Figure 6 shows the distribution of the frequency response for piezo film sensors without epoxy resin cover during tests with different load masses.
As in Figure 5, there is once again a constant value for the frequency response modulus for frequencies above approx. 250 Hz. Additionally, for different mechanical stresses there were very similar values for the modulus. For this frequency range it was possible to calculate an averaged value of 0,0475.
For piezo film sensors without epoxy resin cover it is also possible to calculate an averaged value of the frequency response modulus. This value amounts to 0,0661. Again, this is valid for frequencies above 250 Hz (Figure 7).

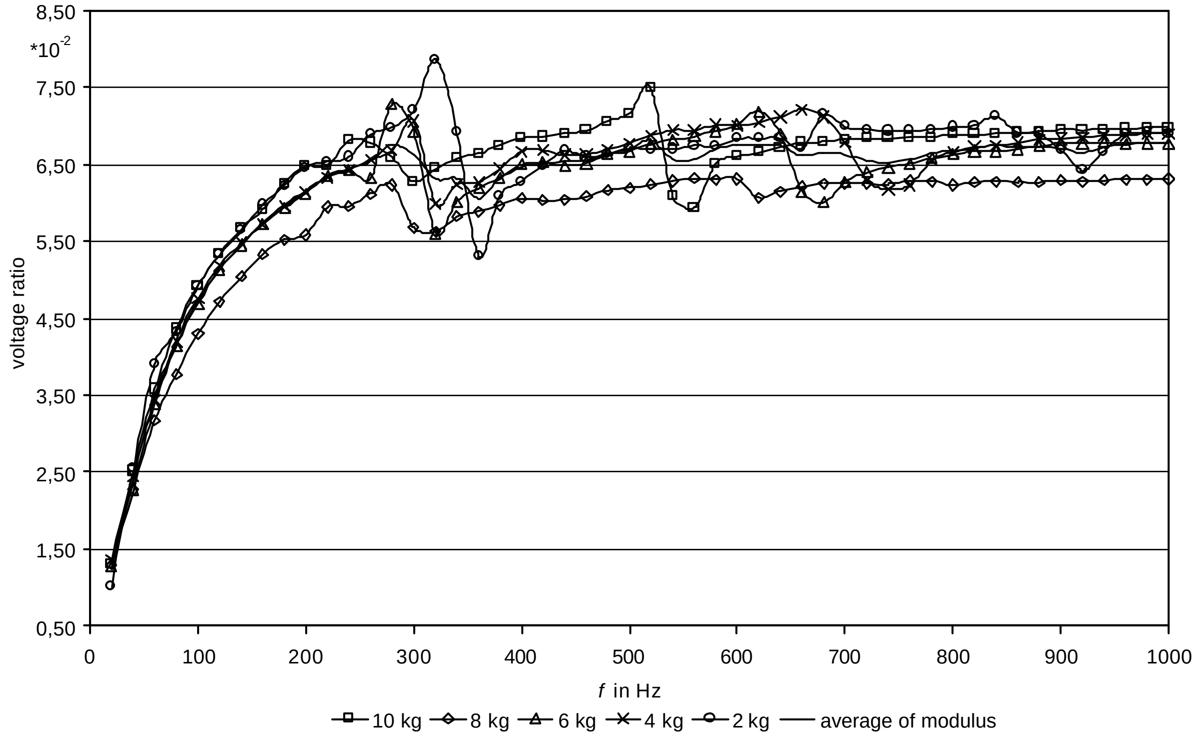


Figure 7 Modulus of the frequency response for film sensors without cover and different load masses

Considering the equations for the Wheatstone resistor bridge used and for the strain gauge amplifier, the following equation for the transmission value of the piezo film sensors S_{piezo}, which is similar to the k-factor, could be derived (Figure 4):

$$\frac{U_{piezo}}{U_{DMS}} = \frac{U_{piezo}}{S_{DMS} \cdot \frac{U_B}{U_S}} = \frac{S_{piezo} \cdot e_{piezo}}{S_{DMS} \cdot \frac{1}{2} \cdot k \cdot e_{DMS}}$$

$$\text{assuming that}: e_{piezo} = e_{DMS} = e$$

$$S_{piezo} = \frac{1}{2} \cdot k \cdot S_{DMS} \cdot \frac{U_{piezo}}{U_{DMS}}$$

The following transmission values S_{piezo} for the piezo film sensors used were calculated: 2,45 $\frac{V}{mm/m}$ with the epoxy resin cover and 3,41 $\frac{V}{mm/m}$ without the epoxy resin cover.

The inequality of these values shows that the assumption $e_{piezo} = e_{DMS} = e$ is not correct and that the usage of the epoxy resin cover reduces the applied stress of the piezo foils because of the stiffer sensor design and resulting higher degree of force bypassing. The consequence is the reduction of the piezo film sensor output as shown. The comparison of the averaged frequency response modulus confirms this effect. There is a reduction of approx. 28 % due to the cover (0,0475 with the epoxy resin cover, 0,0661 without).

The calculated transmission values S_{piezo} are only specific values of the chosen piezo film sensor design.

Furthermore, the comparison of the results shows that the cross sensitivity of the sensors decreases through the usage of the epoxy resin cover and thus the stiffened sensor design.

This is derived from the smoother graph progress and the lower output variation in Figure 6 in contrast to Figure 7.

Conclusions

It could be shown that for high frequencies above 250 Hz, PVDF film sensors have similar transmission functions to conventional strain gauges. For this frequency range it was possible to calculate a specific transmission value S_{piezo} for the piezo film sensors used.

Due to the high cross sensitivity of the PVDF foils used, it was necessary to eliminate the existing cross signal parts in the film sensor output. This was achieved through the averaging of signals from oppositely-applied sensor pairs, which was very effective.

The influence of the used epoxy resin cover was also evaluated. Due to the stiffer sensor design, it could be discovered that the cover leads to a reduction of the piezo film sensor output of approx. 28 %, whereas the cross sensitivity is decreased.

As a short summary it can be said that the difficulties regarding the mechanical design of the given piezo film sensors in automotive crash recognition systems were identified.

[1] http://www.mirow.de

[2] http://www.msiusa.com/piezo/index.htm

[3] Seifart M.: *Analoge Schaltungen.* Verlag Technik, Berlin, 1994.

[4] Keil, S.: *Beanspruchungsermittlung mit Dehnungsmeßstreifen.* CUNEUS Verlag, Zwingenberg a.d. Bergstraße, 1995.