Analyzing amplitude and phase response of differential pressure sensors using a dynamic pressure source.

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Abstract

State of the art differential pressure sensors for process instrumentation are characterized by a nominal measuring range of Δp_N = 10 mbar at a nominal static pressure of p_{Stat} = 160 bar and an uncertainty of measurement ≤ $2 \cdot 10^{-3}$. Environmentally robust pressure sensors based on silicon deformation bodies require static and dynamic overload protections as well as metallic media separation diaphragms (Fig. 1). Depending on the application the silicon pressure sensor has to be protected against temperature, humidity or corrosive media, although a desired upper cut-off frequency of the complete acoustic system has to be achieved. With adapted electro mechanic network topology analysis, the amplitude and phase response is estimated for differential pressure sensors. To develop reliable overload protection systems and determine the nominal frequency range the dynamic amplitude and phase response, tested by a dynamic pressure source, is essential. Complete characterization requires a dynamic pressure source which is a development of our institute (Fig. 2).

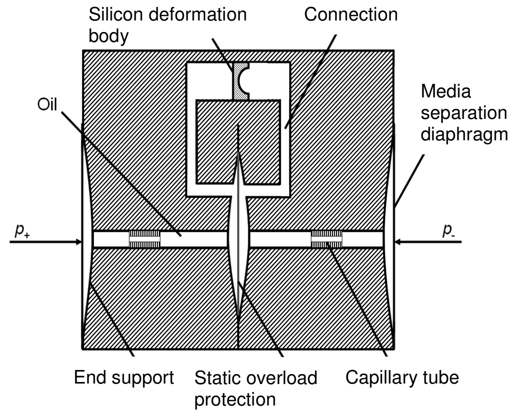

Fig. 1 Differential pressure sensor with overload protection [5].

Introduction

For a nominal measuring range of Δp_N =10 mbar, the capacitive or piezoresistive principle is used for differential pressure measurement, as well as the resonance analysis of thin silicon beams. In all cases a 15 µm – 30 µm thin silicon plate is used as deformation body in order to detect the differential pressure. The dynamic amplitude and phase response changes with extended capillary tubes or static pressure overload protection diaphragms. Usually, the upper cut-off frequency of silicon pressure sensors without housing and overload protection is in the range of 10 kHz – 100 kHz depending on the pressure range the sensor is designed for. Sensor packaging in general affects the nominal frequency range [1]. This also applies to other physical working principles, like thin film or ceramic pressure sensors. The influence of packaging and overload protection on the sensors frequency response has long been object of research at our department. To be able to prove theoretical results, we built a dynamic pressure source whose design, specific values and applications will be discussed below.

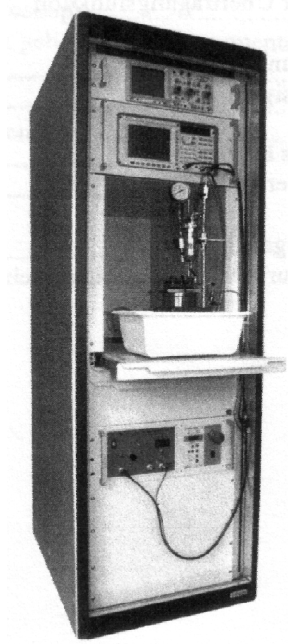

Fig. 2 Dynamic pressure source [6].

Tab. 1 Dynamic pressure source, typical values

Frequency range	1-10.000	Hz
Amplitude	15	mbar
Amplitude maximum	700	mbar
Amplitude uncertainty	<0,1	dB
Operating temperature	20	°C
Reference sensor	701A	Kistler
Reference sensor linearity	0,5	% FSO

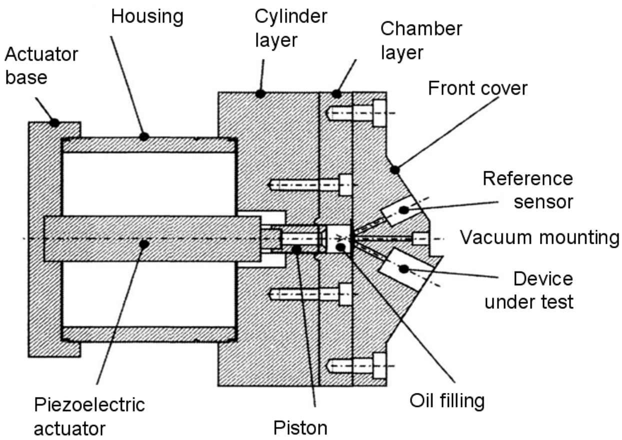

Fig. 3 Pressure source, mechanical design [3].

Dynamic pressure source – mechanical design and concept

The dynamic pressure source consists of a network analyser and a piezoelectric stack actuator, which is driven by a high voltage amplifier up to 1000 V. The actuator is used as a force source connected to a piston and a steel diaphragm (Fig. 3). The pressure p in the hermetically sealed chamber layer increases proportionally for small diaphragm deflections. A network analysis for harmonic pressure excitation is possible. A piezoelectric pressure sensor is used as a reference to detect the generated harmonic pressure amplitude in a wide frequency range from quasi static behaviour up to 10 kHz. A charge amplifier provides the needed reference voltage $\underline{U}_R$ to control the generated pressure amplitude to a user defined level. The device under test and the reference sensor are mounted at the same front cover of the chamber layer (Fig. 3). The pressure in the unregulated operation mode is limited by the allowed maximal actuator excitation ξ_{Max}. The pressure amplitude and phase response $\underline{U}_R/\underline{U}_q$ of the dynamic pressure source typically follows a low pass characteristic with resonance at the actuator resonance frequency. The signal of the reference sensor $\underline{U}_R$ and the device under test $\underline{U}_T$ are compared as long as the pressure source generates a detectable pressure (Fig. 4).
This typical characteristic is suppressed in the regulated operation mode - the signal analyzer uses the signal of the reference sensor $\underline{U}_R$ in a closed loop control to obtain a constant pressure amplitude p (Fig. 5). The piston, with a sealing diaphragm, compresses the oil filling in the chamber layer. A properly deaerated oil filled chamber is crucial to achieve the maximal pressure amplitude. With every new measurement setup a vacuum pump is connected to the front cover to deaerate the oil filled chamber, because dissolved gas in the oil filling considerably increases the acoustic compliance.

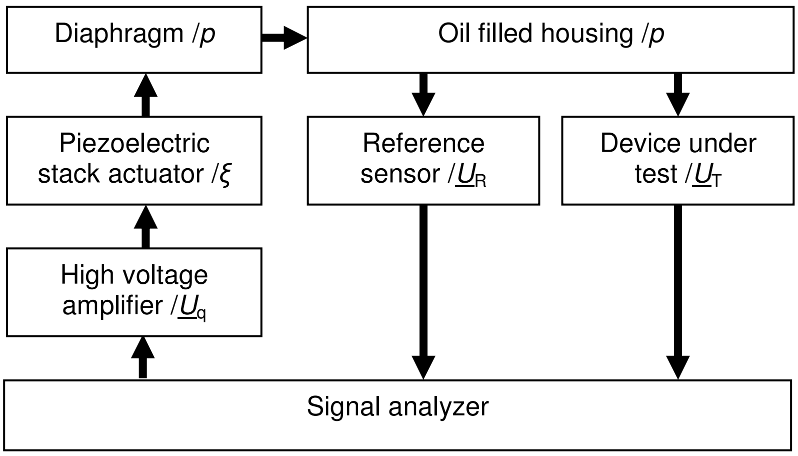

Fig. 4 Dynamic pressure source, block diagram.

Specified performance

Under the assumption, that no oil displacement is caused by the device under test, figure 5 shows the pressure amplitude for the closed loop control mode. The maximal pressure amplitude depends on the used frequency range and the properties of the high voltage amplifier. To prevent a depolarisation of the stack actuator an offset voltage of 500 V was applied. The pressure peak amplitude of 700 mbar is achieved by an alternating voltage of 500 ± 278 V.

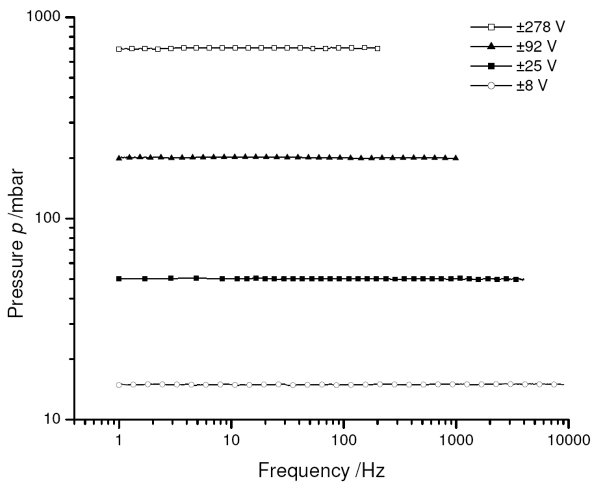

Fig. 5 Dynamic pressure source, peak values.

Successful application example: Micro housed pressure sensor

The development of this miniaturized differential pressure sensor is based on an electro acoustical network topology. The sensor design is a result of the project MATCHDRUCK (Fig. 6). The first approach, without media separation diaphragm, is based on the amplitude response of the acoustic network $\underline{p}_{Si}/\underline{p}_{2+}$ (Fig. 8). Acoustic mass, compliance and friction are determined by component dimensions. The comparison of simulation and measurements of the acoustic network shows good agreement (Fig. 7). The detailed cross section shows the contour of the diaphragm and the oil filled gap (Fig. 9).

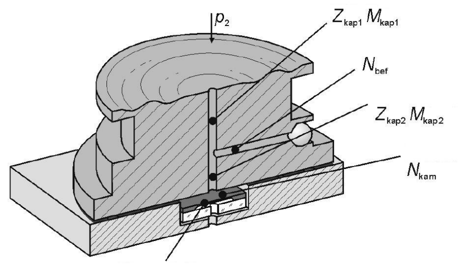

Fig. 6 Capillary system of a micro housed silicon differential pressure sensor, project MATCHDRUCK [3].

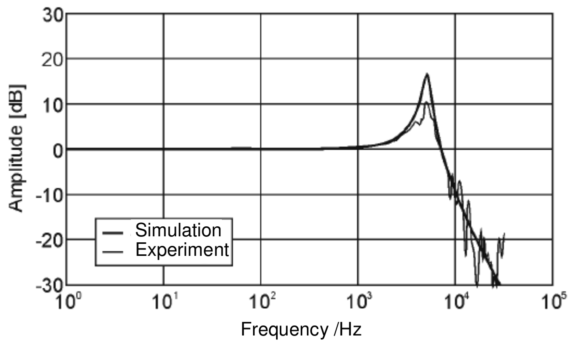

Fig. 7 Comparison of simulation and measurement of the amplitude response of the acoustic network [3].

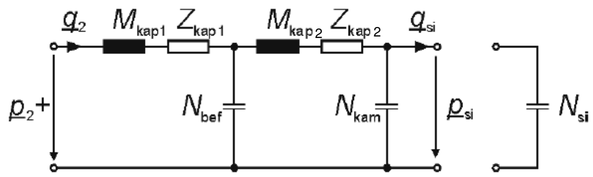

Fig. 8 Network topology for positive pressure excitation [2], [3].

The analytical solution for media separation diaphragms is more complex and requires an approach with distributed parameters. A model of a media separation diaphragm was developed by SINDLINGER (Fig. 10). The complete amplitude response $\underline{p}_{Si}/\underline{p}$ results from the multiplication of the amplitude response of the media separation diaphragm $\underline{p}_{2+}/\underline{p}$ and the capillary network $\underline{p}_{Si}/\underline{p}_{2+}$. A dynamic pressure source makes it easy to verify these results. The effect of media separation diaphragms has a low pass characteristic and reduces the nominal frequency range (Fig. 11). At least one media separation membrane is needed for relative pressure sensors. For differential pressure sensors, a symmetric design with two media separation diaphragms is required. This makes the estimation of the frequency response more complex, because different amounts of oil in the gap between diaphragm and end support affect the upper cut-off frequency additionally. The sensor development process needs the analytical as well as the empirical results to improve the characteristic amplitude and phase response of a pressure sensor.

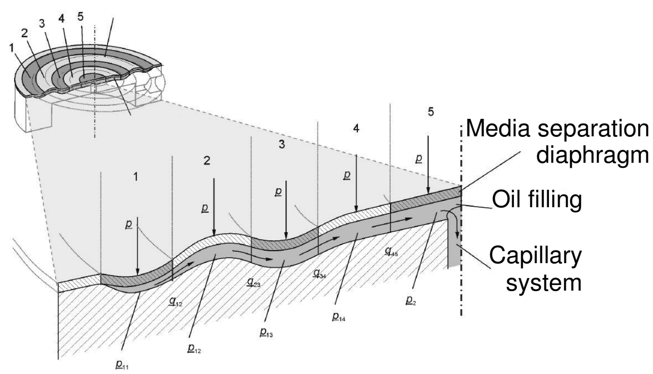

Fig. 9 Media separation diaphragm with oil filling [3].

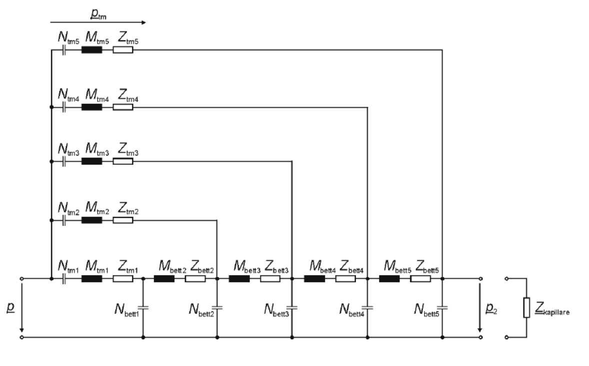

Fig. 10 Network topology for media separation diaphragm with n= 5 distributed parameters [3].

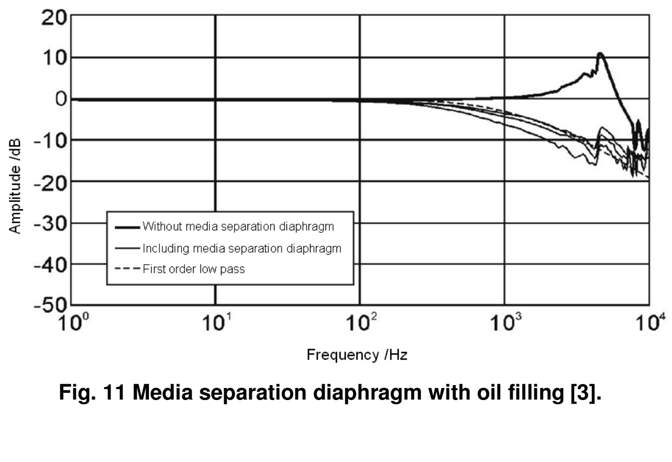

Fig. 11 Media separation diaphragm with oil filling [3].

Successful application example: Overload protected differential pressure sensor

A static differential pressure up to Δp=160 bar loaded to a sensor with nominal measuring range of Δp=10 mbar requires a reliable static overload protection mechanism. This overload diaphragm connects the high- and low-pressure side indirectly and absorbs the displaced oil between the media separation diaphragm and its end support (Fig. 1).
Narrowed capillary tubes are implemented to lower the upper cut-off frequency to protect the silicon die from pressure transients. The mechanical design and the network topology for a differential pressure sensor with static and dynamic overload protection are shown in figure 12 and 13. The calculated electro acoustic network provides an acceptable estimation of the measurements with dynamic pressure excitation in the frequency range of 10 mHz - 1 kHz. The harmonic amplitude is limited to 10 mbar (Fig. 14), while the desired amplitude and phase characteristic is achieved by calculating the acoustical flexibilities, frictions and masses. These values are constant for a limited frequency range [2].

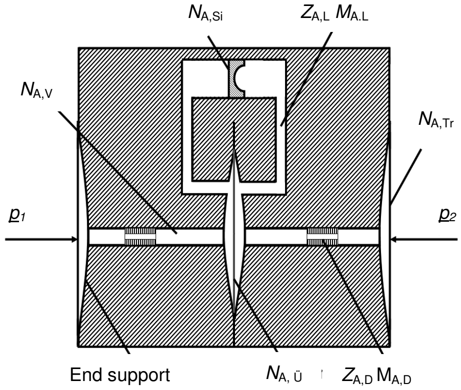

Fig. 12 Differential pressure sensor, network components [5].

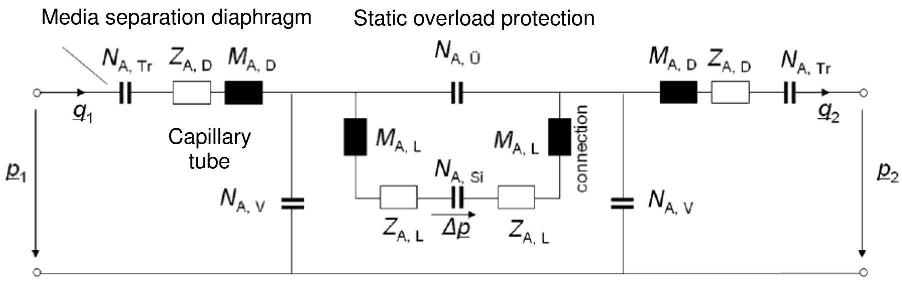

Fig. 13 Network topology for differential pressure sensors with overload protection for static pressure [2],[5].

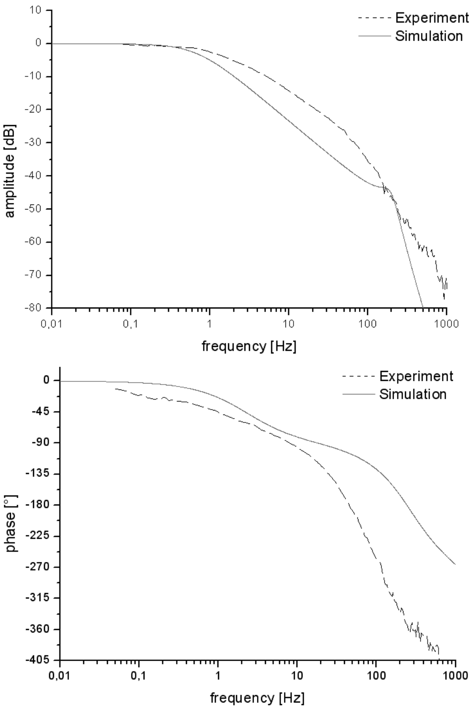

Fig. 14 Dynamic amplitude and phase characteristics $\Delta p/p_1$ of a differential pressure sensor [5]

Conclusion

The theoretical network analysis of pressure sensors is a recommended design method. In combination with applied load tests, reliable and robust overload protected pressure sensors are available. Further development of cost reduced overload protection mechanisms requires dynamic pressure excitation as well as adapted network calculation. Finally optimized overload protection mechanisms can reduce the sensor measurement uncertainty, because of adapted packaging dimensions.

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