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NUMERICAL ANALYSIS OF STAINLESS STEEL DIAPHRAGM FOR LOW PRESSURE MEASUREMENT

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Abstract. Metal membranes are the thin circular plates. For transducers and pressure transmitters, it is assumed that the membrane is loaded with uniform load over the entire surface. In case that the membrane is rigid over the edge, then it is called a diaphragm. In general, the membranes are divided into flat and corrugated. Corrugated diaphragms can resist much higher pressure than flat diaphragms and they are used mainly in the low pressure area. In contact with various aggressive fluids, membranes are most commonly made of high alloy austenitic steel, which have high corrosion resistance, have good spring properties and they are stable at different temperatures. The deflection analyses of corrugated diaphragms are very important in sensitivity of transducers/transmitters. The application of corrugated diaphragms gives possibility to control sensitivity of thin diaphragms by geometrical parameters. In this paper numerical and experimental structural analysis of a thin corrugated diaphragm 19 mm diameter, with variable material thickness and corrugation number is presented. Experimental tests are conducted on a corrugated stainless steel (AISI 316) diaphragm. The measured deflections are compared with numerical results in ANSYS software package. The results showed small deviations between numerical and experimental data, which is very important for further diaphragm application of measurement instruments.

Introduction

Metal membranes are thin round plates which undergo elastic deformation when exposed to pressure or axial load. They are made from metal foils by pressing. In the case of a transducer and a pressure transmitter, it is assumed that the membrane is loaded with uniform load over the entire surface. In the case when the membrane is clamped (locked, welded) along the periphery it is called the diaphragm [1]. The diaphragm receives pressure from one side, which leads to its deformation. When the effect of pressure ceases, the diaphragm returns to its original position.

Membranes in contact with various aggressive environments are usually made of high alloy austenitic steels. These materials are characterized by high corrosion resistance and have good spring properties. Stainless steels AISI 300 series have good fatigue resistance and good creep strength. This series is characterized by high density and modulus of elasticity, high thermal expansion coefficients and the smallest thermal conductivity.

Corrugated diaphragm geometry

According to the constructive solution, the membranes can be straight and profiled. Profiled diaphragms can withstand much higher pressure than flat diaphragms and are used mainly in the low pressure area. The straight membranes exhibit a non-linear relationship between the deflection and the applied pressure. For relatively small deflections, this ratio is approximately linear, whereas non-linearity is created due to larger deflections [2,3].

In small deflections, the profiled membrane is less prone to deflections than the flat membrane of the same surface and thickness. With the profiled membrane, it is possible to control mechanical sensitivity by changing geometry parameters [1,2]: 1) H - depth of corrugations; 2) h - thickness of diaphragm / membrane and 3) n - number of corrugations.

According to Scheeper et al. [2], the elements of the profiled membrane are 1) a solid center that is fixed to the central part (flat) of the membrane; 2) the membrane profile of different shapes and 3) the extreme waves of the membrane.

The existence of an ultimate wave is necessary when connecting the membrane to the case of the transducer. The final wave passes to the cylinder or plane, which serves to attach the membrane - diaphragm. Circular corrugations per profile may be toroidal or sinusoidal, with these others having appropriate channels on the diaphragm carrier and are formed after diaphragm or welding the diaphragm. The thin profiled membrane with small toroidal waves is quite sensitive and is used to measure small pressures.

A great influence on the operation of the membrane shows a preliminary tightening. The corrugated membranes are very sensitive to such tightening, in particular the low rigidity membrane [1]. If the membrane is tight at the initial level, it causes its rigidity to fall, while the spring feature can become rising. Conversely, when tightening the membrane, rigidity increases. This impact will be more prominent if the initial rigidness is minimal, i.e. as thin as possible and if there are minor waves. When fixing the membrane, the construction and accuracy of the clamping surfaces is of great importance, as well as the correct surface treatment of the contact surface and the fixing rings.

If the contact surfaces of the membrane and the fixing ring are not parallel to each other, deformation may occur during the tightening of the membrane, causing a deviation from its spring characteristics. The errors of the final tightening of the diaphragm are more emphasized, with less diaphragm rigidity. The steel sheet for the formation of the membrane must be made with the exact diameter according to the defined tool. After forming the molded diaphragm, the diameter will be slightly reduced.

In Figure 1, a diaphragm testing circuit is shown.

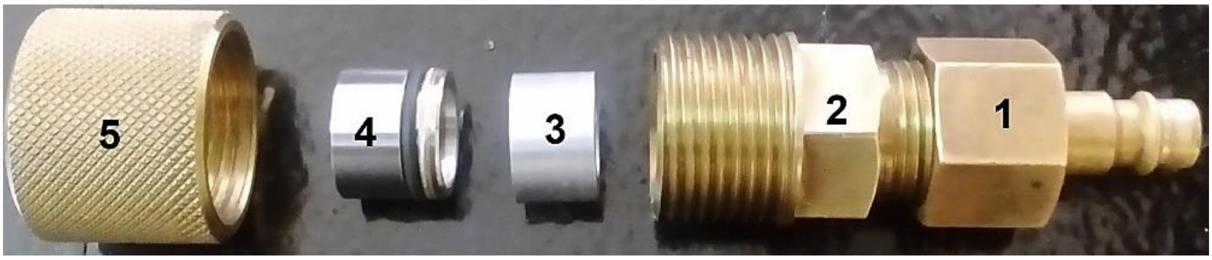


Fig. 1 Diaphragm test assembly: 1- quick coupler; 2 - measuring chamber body; 3-spacer; 4-diaphragm; 5- measuring chamber nut

Circular corrugated diaphragm calculation

In this paper, the methodology of membrane designing will be shown according to the elasticity characteristic. The elasticity characteristic of the profiled membrane is given by the equation Eq. (1) [1]:

$$w_0 = f(p);\ p = A \cdot w_0 + B \cdot w_0^3 \tag{1}$$

In the equation Eq. (1), the first member (A) determines the resistance equivalent to the membrane deflection and can be determined based on the linear solution. The second, cubic member (B) characterizes the resistance of the membrane due to elongation, where it is necessary to consider the deformation of the membrane. This member can be improved by more rigid edges around the periphery [3]. and by changing the value of the coefficients A and B in the equation Eq. (1) the equation Eq. (2) is obtained.

$$A = \frac{E_d}{R_d^4} \cdot h_d^3 \cdot a_d\ ;\ B = \frac{E_d}{R_d^4} \cdot h_d \cdot b_d\ ;\ p = a_p \cdot E_d \cdot \frac{h_d^4}{R_d^4} \cdot \frac{w_0}{h_d} + b_p \cdot \frac{E_d}{1-\nu^2} \cdot \frac{h_d^4}{R_d^4} \cdot \frac{w_0^3}{h_d^3} \tag{2}$$

Values of the coefficients a_d and b_d from the equation Eq. (2) are calculated according to the following equation Eq. (3) [4,5]:

$$a_d = \frac{2 \cdot (q+1) \cdot (q+3)}{3 \cdot (1 - \frac{\nu^2}{q^2})}\ ;\ b_d = 32 \cdot \frac{1-\nu^2}{q^2 - 9} \cdot \left[\frac{1}{6} - \frac{3-\nu}{(q-\nu)\cdot(q+3)}\right] \tag{3}$$

The effects of profiling the diaphragm are determined by the correction factor of the profile form (q) [3,4]. The higher rigidity of the profiled diaphragm causes a higher critical rigidity in the tangential direction. Critical rigidity in the radial direction, which depends on the thickness of the material, becomes equal for both flat and corrugated membranes [5]. The functional link for coefficients a_d and b_d over coefficients k_1 and k_2 is given by the following relationship, i.e. from the equation for the correction factor of the shape of the profile (q) the equation Eq. (4) is obtained:

$$q^2 = k_1 \cdot k_2\ ;\ k_1 = \frac{S}{l}\ ;\ k_2 = 1 + 1{,}5\frac{H^2}{h_d^2} \rightarrow q^2 = (\frac{S}{l}) \cdot (1 + 1{,}5\frac{H^2}{h_d^2}) \tag{4}$$

Based on the above shown, it can be seen that the coefficients k_1 and k_2 depend only on the geometry of the profiled membrane and its thickness, where the coefficient $k_1 \leq 1$. The coefficient k_2 is equal to the ratio of the moment of inertia and axial cross-section of the profiled membrane and can be $k_2 >> 1$.

The ratio of the H/h_d profile is one of the basic geometrical parameters of the membrane by which its properties are determined. With the increase in the wave depth, the membrane becomes round, and the spring feature more linear. Increasing the wave depth causes a smaller deflection, but only at the beginning of the characteristic. Also, the change in the number of waves n at the same wave depth slightly changes the characteristics of the profiled membrane [6].

Finite element analysis

In this paper, a diaphragm from the stainless steel AISI 316 was used. The membrane had a constant diameter of Ø19mm, with a variable number of corrugations and variable metal thickness. The input parameters for the diaphragm are radius (working area) Rd=8.5 mm; Young`s modulus of elasticity $E=1{,}93{\cdot}10^5$ N/mm$^2$; Poisson`s ration of the material $\nu=0{,}3$; Diaphragm thickness h_d=0,025mm/0,050 mm; Corrugation depth H=0,3; Number of corrugations n=4/5

The geometry of the profiled membrane of the toroidal shape with 5 and 4 corrugations, 19 mm in diameter, consist of distance from the rigid center is given as follows: 6; 8.5; 11; 13.5 and 16 mm for 5 corrugation membrane. The idea is to make a sensitivity analysis by controlling geometric parameters such as the depth of the corrugations and the thickness of the diaphragm. The parameters of the profiled membrane (shape, depth and number of corrugations) are determined by the designer, and then, based on the combination of parameters, determines the optimal design requirements. The height of the corrugation formed depends on the thickness of the material and the applied pressure.

In order to confirm the results obtained by theoretical method, the FE analysis (using ANSYS mechanical) of the profiled membrane of the constant diameter, variable thickness and the number of corrugations was used. In the analysis of the circularly profiled diaphragm the theory of plates and shells was used [7]. For the calculation, the characteristics of AISI 316 that were taken into account are: 1) density (7,96 103 kg / m3), 2) tensile strength (460-860 MPa), 3) yield strength (205 MPa), 4) hardness (160- 190 RB). Finite element analysis method was used in the calculation [8, 9]. The simulation results of displacement in mm for the maximum material yield strength of 205 MPa are shown in Figure 2.

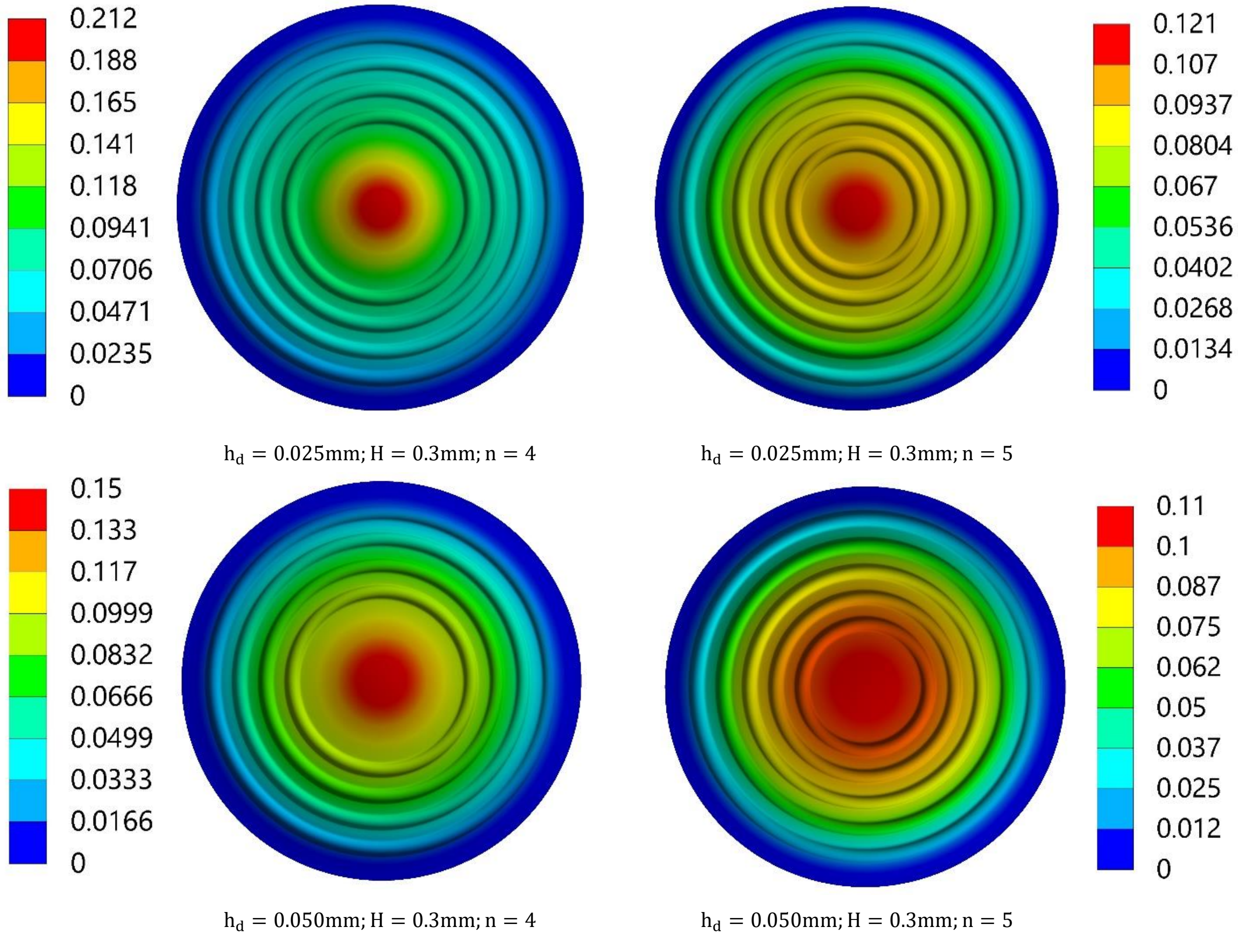


Fig. 2 Displacement field for corrugated diaphragm 19mm diameter

FE analysis shows that if the diaphragm is thicker, the sensitivity is lower. Otherwise, if the diaphragm is thin, the sensitivity of the diaphragm increases, which can lead to degradation or even damage to the diaphragm at high pressure. The analysis confirmed that the change in the number of waves at the same depth slightly changes the characteristics of the profiled membrane, which can be seen from Figure 2.

Measurement

After theoretical and FE analysis, experimental measurement of the diaphragm was started. The diaphragm was placed in the clamping tool (Figure 2) and was tested at various pressures. Pressure is carried out using the Mensor APC 600 pressure calibrator, which sets and maintains pressure with a 0.1mbar accuracy. The Iskra NP37 electronic comparator was used to measure the deflection, with the accuracy of the vertical shift of 0.001mm. The needle on the comparator has a needle of a certain mass and exerts pressure on the surface of the diaphragm. By giving the pressure with the Mensor, the diaphragm rises and the needle registers a move, or a corrugation. Figure 3 shows the model of measuring corrugations of the diaphragm.

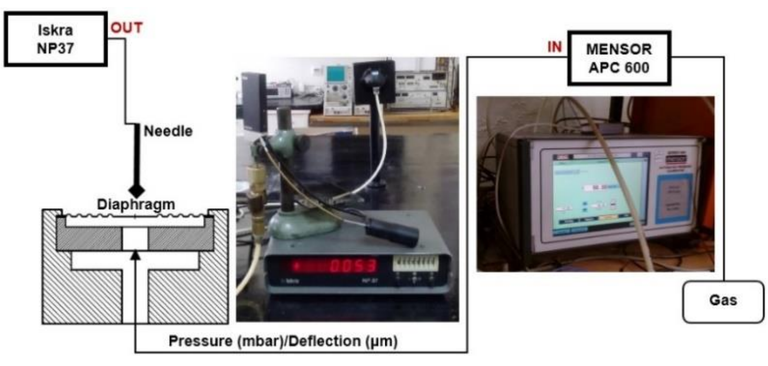
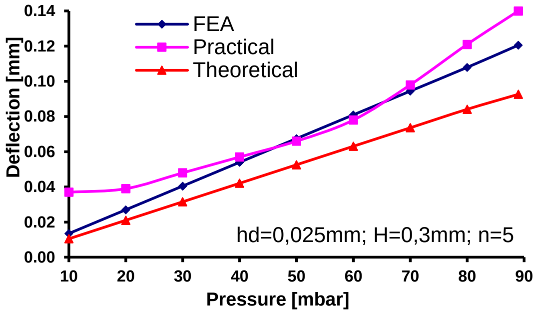


Fig. 3 Diaphragm deflection scheme

Results and discussion

The sensitivity of the profiled membrane affects several parameters, such as the width and height of the corrugation, the shape of the corrugation and its density. However, the greatest impact is the depth of the membrane corrugation. Linearity is an elastic property that is defined by the extent of the linear part of the relationship due to large displacements. In Figure 4, a comparative analysis of the results obtained by theoretical, experimental and FE analysis was given, for a 19mm diameter membrane, with a 0.3mm depth of corrugation and a thickness of 0.025mm / 0.05mm. The measurement showed that the thin membrane has a good linearity for the range of 30mbar ÷ 70mbar, but it is also very sensitive. During the experimental work, a measurement uncertainty of 10 mbar was diagnosed, which can depend on the weight of the needle and operation of the new diaphragm. Also, as a medium, a gas that is compressible is used, which affects the slower and non-linear response of the diaphragm.



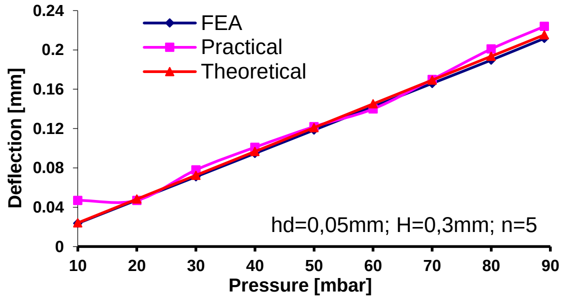


Fig. 4 Pressure vs deflection for 19mm diameter

The thicker membrane has shown linear spring characteristics in the wider range of 20mbar ÷ 90mbar. Here as well, the delay of the diaphragm response was noted at a pressure of 10 mbar for the above mentioned reasons. The theory and FE analysis coincide in the case of a thicker diaphragm that is more rigid and gives a better linear response to the system. For this low pressure range of 10mbar ÷ 100mbar, an optimal depth of corrugation 0.3mm can be adopted.

Conclusion

- In this paper, the sensitivity of the profiled membrane was examined by the variation of geometric parameters.
- Based on the results, it has been concluded that the number of corrugations does not have much to do with the characteristics of the profiled diaphragm.
- The depth of corrugations is an efficient parameter that affects the behavior of the profiled diaphragm.
- The obtained experimental results indicate that there are certain abnormalities in the diaphragm response primarily due to the use of the overlapped diaphragm and the compression medium.
- The profiled diaphragm of thickness 0.05mm has a better linear spring characteristics and gives a good response to the pressures of 10mbar ÷ 100mbar.
- To improve the measurement of diaphragm damage, oil should be used instead of gas.

Acknowledgment

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