

LASER DIODE DRIVEN PRESSURE GAUGE

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Abstract: The paper presents the prototype of the membrane pressure gauge with optoelectronic conversion. The main parts of the system are polished metal membrane, plastic (PMMA) 2 m long optical fibres, and the box containing optoelectronic components (laser diode module, beam splitter, photodetectors and op. amps). Pressure changes causing membrane displacement modulate the laser beam conducted by incoming optical fibre. Modulated and reflected beam is conducted through the outgoing optical fibre to the optoelectronic assembly where it is converted into the voltage proportional to the pressure. Two different electronic circuits for the compensation of laser diode light beam intensity fluctuation are compared. The calibration characteristic recorded using mercury filled U-tube manometer in the range from 0 to $0.52 \cdot 10^5$ Pa shows accuracy ± 0.8 % FS.

Keywords: pressure, measurement, reflective fibre-optical sensor

1 INTRODUCTION

Measurements of fast pressure changes under special conditions (strong electromagnetic fields, high medium temperatures or situations in which electric spark is prohibited) which as a measure of pressure change require proportional continuous current or voltage signal, are difficult and sometimes even impossible to carry out by using sensors on the electro-resistant, capacity or inductive principle. However, fast development of optoelectronics (photonics) over the last ten years has provided the market with a series of widely available and inexpensive products such as photoemitters, photodetectors and optical fibres whose usage in the measuring chain enables solving of the given problem. Here, reflection and interference of light waves are the optical phenomena most frequently used in the design of optoelectronic pressure-measuring systems. In [1] for example, the fibre-optic pressure sensor is described on the principle of measuring the intensity of the reflected light from a membrane which is deformed by pressure, and in [2] Fabry-Perot's interferometer connected to the fibre-optic strain sensor that can be adjusted for measuring pressure or temperature.

The described prototype is of reflective fibre-optic type transducer one, constructed for pressure below 10^5 Pa with the aim of gathering experience in designing and producing transducers for absolute pressures of up to $200 \cdot 10^5$ Pa and differential pressures of up to 10^5 Pa at the level of the mentioned absolute pressures.

2 OPERATION OF THE GAUGE

2.1 Operation principle

Operation of the gauge can be monitored according to the scheme presented in Figure 1. Since this is an over-pressure transducer, the membrane is the boundary between the medium under pressure and the ambient. If the pressures of the medium and the ambient are equal, the membrane is straight, and if there is a difference, the membrane is deformed towards the lower pressure. Light emitted from a photo-emitter (laser diode) is conducted by the incoming optical fibre to the membrane and then it is exposed to light. The incoming beam is reflected towards another, outgoing optical fibre which ends in front of a photodetector. As long as the membrane stays in the same position, which means as long as the pressure below it is constant, the detector receives through the optical fibre part of the reflected beam whose value is also constant. If the pressure changes, the membrane is elastically deformed upwards (rising pressure) or downwards (falling pressure). The volume and direction of the membrane deflection change the intensity of the reflected light towards the optical fibre (i.e. the detector). Thus, the output voltage of the detector changes according to the change in pressure. It may be that the volume of reflected light changes not only due to the change in pressure

but also due to the fluctuation of the laser diode radiation intensity. Therefore, the initial beam of light is split into two parts, the first one directed towards the incoming optical fibre, i.e. the membrane and caston detector d2, and the other, cast on detector d1, and meant for control of the light source.

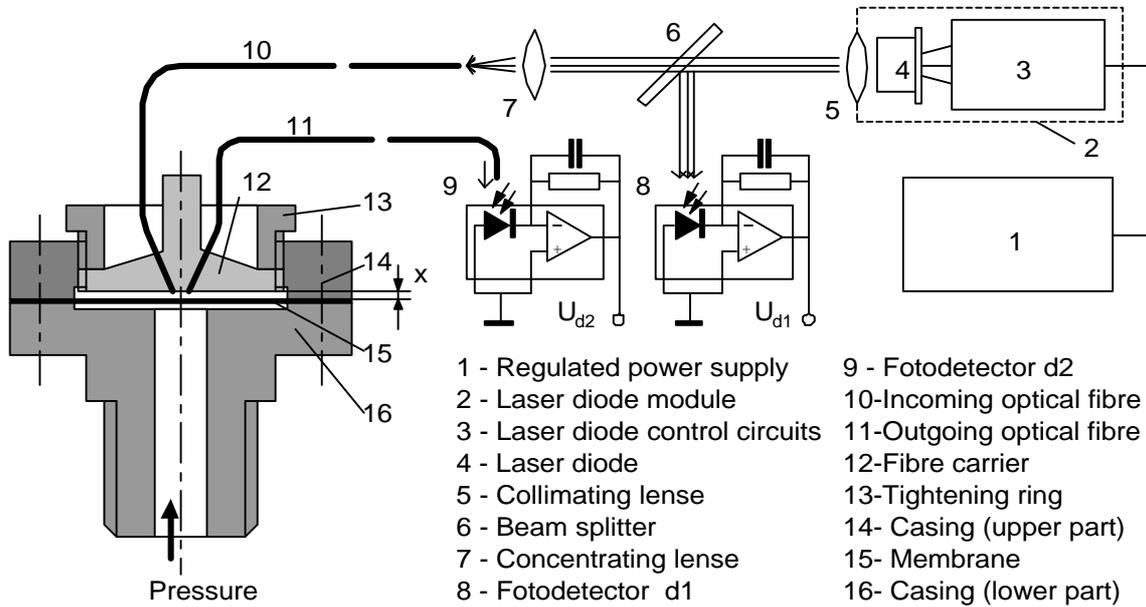


Figure 1. Cross-section of the mechanical part and the optoelectronic circuit of the pressure gauge

The voltage generated by detectors is converted in the electronic part into a single signal which matches the difference in pressures at the sensor membrane. Two alternative electronic schemes (subtraction and division) presented in Figure 2 are tested. The mechanical part of the gauge is connected with the optoelectronic part by 2 m long optical fibres. The casing of the optoelectronic part of the assembly includes the laser module, optical lenses for focusing laser beams into the optical fibre and a beam splitter.

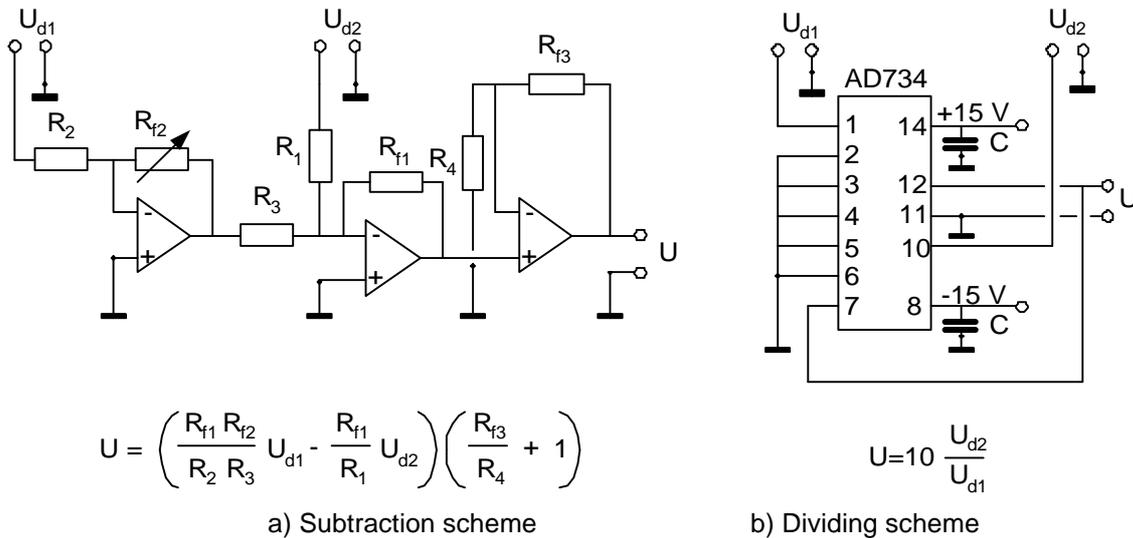


Figure 2. Alternative electronic circuits for laser diode fluctuation compensation

2.2 Design of the mechanical part of the gauge

The mechanical part of the pressure gauge has already been presented in Figure 1. In the axially symmetric casing there is a rigidly fixed round elastic membrane made of 12CrNi177 material, of 42 mm working diameter and 0.4 mm thick. On its upper side the membrane has been polished so as to increase the reflection of light. The ends of the incoming and outgoing optical fibres are located in the

optical fibre carrier. By twisting it, the optical fibre carrier can be set at a certain distance from the membrane and fixed in that position by a tightening ring. The distance x between the optical fibre carrier and the membrane changes depending on the current volume of pressure below the membrane. However, the adjusted volume of x of the membrane free of overpressure is one of the major parameters in the operation of the whole system. Since this parameter is impossible to calculate, it has to be obtained by experiment. Because of that, the described design allows its change.

Checking of the allowed membrane deflection for overpressure $Dp = 50 \text{ kPa}$ and the calculation of the resonant frequency have been carried out according to the known relations [3], provided that the allowed deflection does not exceed 1/3 of the membrane thickness. For the selected dimensions the obtained allowed deflection is $132.4 \text{ }\mu\text{m}$ and the resonant membrane frequency is 14 kHz .

2.3 Optical and electrical characteristics of fibres, laser diode and photodetectors

The selected main components of the optoelectronic part of the gauge are the laser module (the unit of the laser diode and its electronic control) by an unknown Chinese manufacturer, plastic optical fibres Super ESKA [4] produced by Mitsubishi Rayon Co; Ltd., Japan, and optodetector OPT211[5], produced by BURR-BROWN, USA. Although their detailed technical characteristics can be found in the listed references or on Internet, their selection should be explained in a few words.

On the whole, they meet a section of the following (sometimes even mutually conflicting) requirements: availability, price, absolute optical or electrical properties, compatibility of these properties and something that may be defined as suitability of the component for the development of a prototype.

Thus, e.g. the laser module has the wavelength of the emitted light ranging from 630 to 680 nm and power less than 1 mW . This light is of visible red colour and relatively harmless for the eye, which is essential in developing products which require a number of experiments.

Two essential properties are provided by the optical fibre: materials that they are made of and physical geometry. The optical fibre material determines the frequency characteristic. The frequency characteristic shows transmission losses depending on the wavelength (i.e. frequency) of the colour of light passing through the optical fibre. The core of the used optical fibres is made of polymethylmethacrylate (PMMA) so that the losses are the least at 560 nm (green light) - 0.160 dB/m and 660 nm (red light) - 0.25 dB/m . Losses at greater wavelengths rise drastically, e.g. at 950 nm (infrared radiation) they amount to 4 dB/m . Obviously, the selected optical fibre material and the laser module emission wavelength match well. Compared to glass optical fibres, whose transmission losses in the domain of visible light are 100 times less, plastic optical fibres are rather opaque. However, using those whose length does not exceed 100 m is considered to be acceptable. The core of the optical fibre has a diameter of $970 \text{ }\mu\text{m}$, and is clad by fluoride coating with a certain content of carbon polymers $30 \text{ }\mu\text{m}$ thick. All this is enveloped by an opaque protective coating of polyvinylchloride (PVC) so that the overall diameter of a plastic optical fibre amounts to 2.2 mm . The allowed tensile strain amounts to 50 N . Numerical aperture of the optical fibre is 0.47 . These dimensions, including also a smaller allowed bending radius (20 mm), harmless handling (no need for protective glasses) as well as simple polishing of the ends, renders the experimental work easier and simpler.

After passing through the incoming optical fibre, the laser beam is reflected on the membrane and after passing through the outgoing optical fibre it falls on the photodetector. Such a beam is rather attenuated and a sensitive detector is necessary for converting it into an electrical signal. Out of many possible solutions, a chip (transparent 8 pin – DIP) OPT 211 was selected, which consists of silicon photodiode and precise low-noise FET operative amplifier. The photodiode and amplifier assembly in the same chip pre-insures minimum electrical noise in the outgoing voltage signal, dark error amounts to less than $\pm 2 \text{ mV}$. The outgoing signal is very high and at the red light wavelength of 650 nm amounts to 0.45 V/mV . Non-linearity is $0.01\% \text{ FS}$. The photosensitive surface has the shape of a $2.9 \times 2.9 \text{ mm}$ square which corresponds to the requirements of the used plastic optical fibres and laser diode, and at the same time provides good reproduction of signals up to the frequency of 50 kHz .

3 GAUGE ADJUSTMENT

The stability of the outgoing signal over time can be practically defined as short-term (skidding of the signal within several hours) and long-term (time period of several months or years). The biggest problem of assuring short-term stability is related to the change of ambient temperature. The temperature changes the characteristics of the electronic components e.g. the wavelength of the light emitted from the laser diode, thus changing its intensity. Long-term stability is threatened by reduction

of membrane reflexivity due to corrosion, limited lifetime of the photoemitter and detector and the ageing of the plastic material of the optical fibre. PMMA optical fibres have been used worldwide for about 5 years, and have been intended for operation at the temperatures ranging from -30 to $+85$ °C and no change in optical properties has been noticed yet. The service lifetime (MTTF at the temperature of 30 °C) of the diode laser modules amounts to 20,000 hours and of the photodetectors even far more.

For the purpose of studying the linearity of conversion of the reflective membrane displacement into an electrical signal, a gauge such as presented in Figure 3 (a) has been designed. It may be noticed that it is composed of the optical fibre carrier, fixed casing and micrometer. The body of the micrometer and the optical fibre carrier are rigidly connected with the casing. The polished head of the micrometer screw has optically replaced the polished membrane. If the screw head is brought into contact with the optical fibre carrier (displacement $x = 0$), the outgoing signal U from the electronic part (using subtraction scheme) is 4.8 V. By moving away the micrometer screw head in increments of 0.01 mm from $x = 0$ to $x = 3.5$ mm a reflection curve presented in Figure 3 (b) has been obtained.

It may be noted that it has its minimum at $x = 1.3$ mm and that the first steeper and falling part is less non-linear than the second rising part of the curve. The advantage of the falling part is, apart from less non-linearity, also greater sensitivity of displacement conversion into an electrical signal. This curve is the basis for defining a permanently set distance x between the optical fibre carrier and the polished upper side of the membrane in the mechanical part of the sensor presented in Figure 1. The adjusted distance x is 0.85 mm. It is perfectly clear that this distance will decrease as the pressure rises, and according to the presented reflection curve the output voltage will increase.

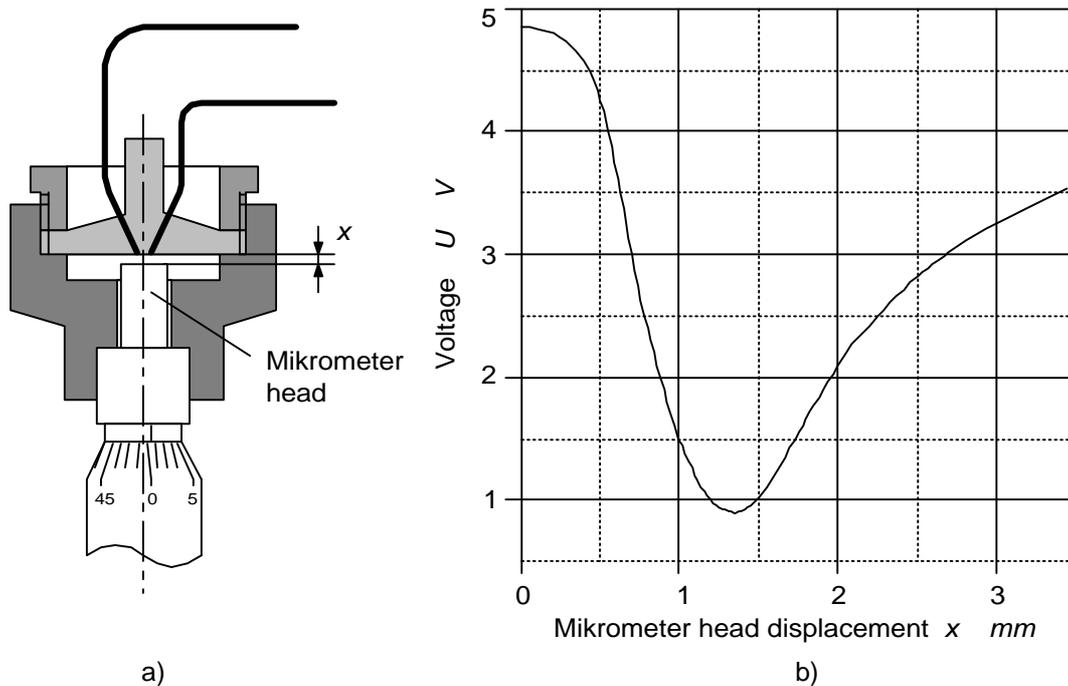


Figure 3. Reflection curve recording using the micrometer

If the output voltage from the photodetector $d1$ is denoted with U_{d1} and the output voltage from photodetector $d2$ with U_{d2} , it may prove that the voltage at the output from the electronic part, U , is determined by relation:

$$U = \left(\frac{R_{f1}R_{f2}}{R_2R_3} U_{d1} - \frac{R_{f1}}{R_1} U_{d2} \right) \left(\frac{R_{f3}}{R_4} + 1 \right) \quad (1)$$

In the given design of the device, the values of the resistor are $R_1=R_2=R_3=R_4=R_{f1}=10k\Omega$, and $R_{f3}=100k\Omega$. equal to those in Figure 2a. Resistance is the only one that can be changed R_2 . Its value influences the output voltage U and its sensitivity to laser beam intensity fluctuation. Determining of

the most suitable value of this resistance for a given suitable value of the distance between the membrane and the optical fibre carrier, e.g. for $x = 0.85 \text{ mm}$, is a procedure which includes recording of the output voltage for different adjustments of the laser diode beam intensity. The real value of resistance R_{f2} is the one that provides equal output voltage for a sufficiently wide range of laser beam intensity fluctuation at constant value of the distance x . In the concrete case $R_{f2} = 2.43 \text{ kW}$.

The alternative compensation circuit uses division of signal U_{d1} and U_{d2} , the way to ensure insensitivity to light source fluctuation proposed in [6]. Here the Analogue Device's multiplier/divider analogue chip AD734 [7] were used. Resulting measuring output signal has the form:

$$U = 10 \frac{U_{d2}}{U_{d1}} \quad (2)$$

Having $x = 0.85 \text{ mm}$, intentionally provoked laser module voltage supply fluctuation between 3 and 4.5 V (33%), caused 8% change of resulting measuring signal U using either compensation circuit alternative.

4 CALIBRATION CHARACTERISTIC

With fix positioning of the optical fibre carrier at a distance of 0.85 mm from the membrane and by using the subtraction circuit, the calibration characteristics have been recorded by controlled change of air pressure below the membrane. The obtained sensor characteristic is presented in Figure 4.

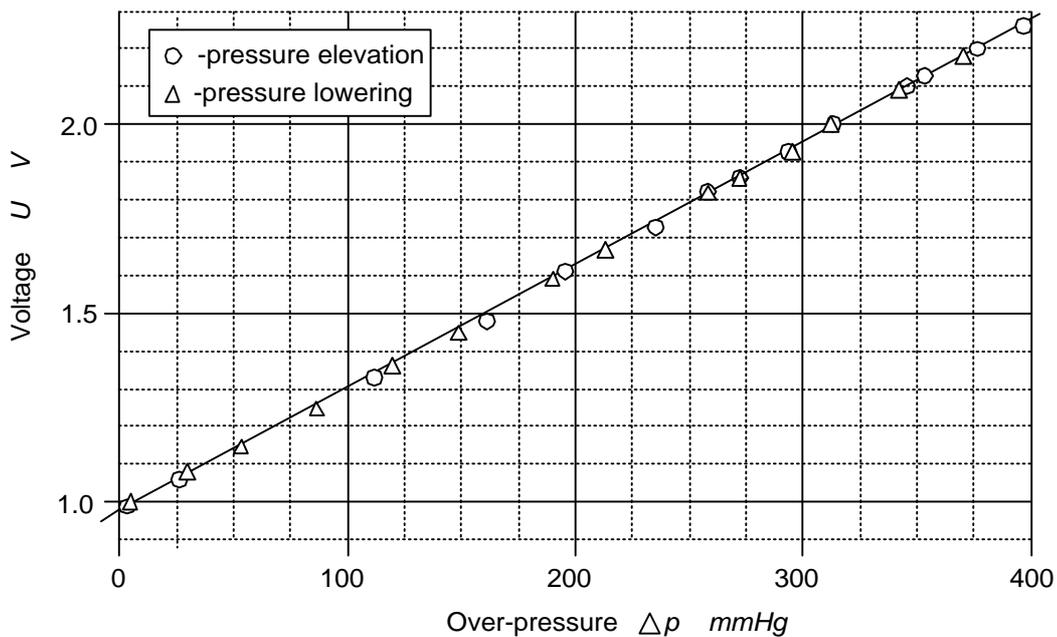


Figure 4. Optoelectronic pressure gauge calibration characteristic

The reference manometer was a glass, mercury filled U-tube. Calibration was carried out so that the same air pressure was conducted from the tank under sufficiently high pressure simultaneously to below the sensor membrane and to one branch of the mercury manometer. The pressure was raised and lowered in the range from 0 to 400 mmHg (0 do $0.52 \cdot 10^5 \text{ Pa}$), simultaneously recording the output voltage in Volts. The mercury temperature was approximately equal to the ambient temperature (20°C). The ambient pressure was 1024 hPa. The maximum voltage deviations from the line which represents the linear approximation of all the measured points (obtained by the minimal square method) amount to +0.63 % and - 0.8 % FS.

5 CONCLUSION

The design and testing of the prototype of the membrane over-pressure gauge with optoelectronic conversion has been described, whose main characteristic is connecting of the casing with the membrane and of the electronic part by plastic (PMMA) 2 m long optical fibres. The obtained accuracy of the whole system in the range $Dp = 0 - 0.52 \cdot 10^5 \text{ Pa}$ amounts to +/- 0.8% FS.

Besides advantages, introduction of optical fibres causes also problems. The most significant is the problem of fixing the ends of the optical fibre in the optical fibre carrier and the optoelectronic box. Current condition of technology is such that fix contacts are preferred over those that can be disconnected. The reason for this is that even the tiniest displacement of ends causes fluctuations in the light beam intensity, and depending on the subsequent amplifiers this may mean unacceptably great interference. Interference is also caused if plastic optical fibre is pressed or bent with greater force. It is also important that the box with laser module and detectors is absolutely darkened. It has been determined that electronic compensation for the fluctuations in the laser diode light intensity by subtracting the signal is equally efficient as by dividing the signal. Further improvements of the described device are necessary and possible due to inherent advantages of using light and optical fibre for pressure measurements.

NOMENCLATURE

R	- electrical resistance, W
U	- voltage, V
x	- distance, mm
Dp	- pressure difference at the membrane, Pa
MTTF	- Mean Time to Failure
FS	- Full Scale

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