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A METHOD OF MEASURING MOVING ELEMENT DISPLACEMENTS IN MICRO-HYDRAULIC VALVES WITH THE USE OF OPTICAL FIBERS

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This work presents a fiberoptic technique used to measure displacements of moving elements in micro-hydraulic valves. Fiberoptic sensors coupled with a reflection method have proven to be perfect for touchless measurement of movement for elements hard to measure by other methods due to their small size and presence of a hydraulic oil. The article presents results of experiments revealing correlation between the measurement signal and element movement as well as sample displacement changes in time of the moving element in non-equilibrium states – for both, a stable action and self-exciting vibrations of the element.

Keywords: microhydraulics, micro valves, fiber optic, displacement, vibration, measurement

1. Introduction

In the present world of miniaturization, it is a common trend to apply novel solutions to all sorts of machinery drive systems. One of them – hydraulic drive systems are characterized by high power density, i.e. ability to transfer high levels of power with a relatively small size and mass of the drive system elements. Traditional massive pneumatic or electromagnetic drive systems can be replaced by miniaturized hydraulic systems of equal power transfer capacity and broad automation potential. Considerations mentioned above contribute to dynamic growth of a new technical field known as high-pressure micro hydraulics–hydraulics, where the flow is less than $2\,\mathrm{dm}^3/\mathrm{min}$. Some examples of micro-hydraulic systems as well as a global review of miniaturized micro-hydraulic elements produced by various companies were described in detail in Łomotowski (2013).

High-pressure micro hydraulics is a relatively new field of technology that still requires a range of scientific studies. It turns out that some of the rules governing classic large-size hydraulic systems might not apply to micro hydraulics. Examples of effects possibly significant for high-pressure micro hydraulics are non-isothermal flow (Kollek *et al.*, 2011; Kollek and Łomotowski, 2012) and obliteration (Kudźma *et al.*, 2011).

The liquid pressure and rate of flow are the two basic parameters measured while researching micro-hydraulic systems and elements. When conducting research on micro-hydraulic elements, other parameters may have to be measured as well; for example, measuring displacements of parts moving inside the studied micro valves in equilibrium and non-equilibrium states can broaden knowledge about processes taking place inside the elements. This should lead to eliminate the disadvantageous vibration. The vibration of moving parts inside valves, which may gradually destroy the cooperating elements, may derive from external factors; for example the vibration can be propagated from an element located in valve surroundings which have contact with the valve body. The effects of external mechanical vibrations on hydraulic valves and theoretical analysis of the contribution of selected vibration insulators to reduction in the hydraulic valve housing vibrations was carried out in Stosiak (2011). An effective method of reduction of the influence of external vibrations on the hydraulic valve is an application of special insulators for valve housing (Kudźma and Stosiak, 2013; Stosiak, 2011). The application of insulators leads to valve housing vibrations reduction in a wide frequency range (Stosiak, 2011). The other type of vibration is self-excited vibration which derives from unstability of dynamic systems (Misra *et al.*, 2002). An example of a hydraulic element where stability loss can occur what leads to self-excited vibration, is a relief valve (Licsko *et al.*, 2009; Łomotowski, 2013). Measuring the displacement of the working valve closing element allows for obtaining more information about the valve static and dynamic properties. The gained knowledge leads to designing correctly high-quality micro-hydraulic elements.

Measurements of moving part displacements in micro-hydraulic components are difficult for several reasons. The basic problems are small hydraulic valve dimensions and the presence of the oil, which leads to the decision of including fiberoptic technology in the measurement methodology employed. The measurement method involving fiberoptic sensors founds its way to wide use in industrial, military and biomedical systems (Yasin *et al.*, 2008; (Harun *et al.*, 2010; Shen *et al.*, 2010). Its advantages include but are not limited to: non-contact measurement ability for very little displacements, very good dynamic properties (wide measurement frequency range) and very small dimensions of the sensors themselves (Cao *et al.*, 2005; Yasin *et al.*, 2008; Harun *et al.*, 2010). These factors exactly, as well as the fact that light can be transmitted through hydraulic oil, contributed to making a decision on choice of the fiberoptic method for measuring micro valve closing elements displacements.

2. Displacement and the mechanical vibration measurement method using fiberoptic technique

According to Samian *et al.* (2009) there are three types of fiberoptic displacement sensors, and they take advantage of three different phenomena: changing wavelength, changing light ray intensity (amplitude sensor) and change in phase shift (phase sensor). The displacement measurement method associated with light intensity change is the best for conducting dynamic measurements as it is relatively cheap and the results are easy to interpret, even though the method is a little less accurate. Most of the time, this method relies on a mirror that reflects light towards a photosensor. Appropriate shifting of the mirror changes the reflected light intensity, and consequently the measuring signal. This method has been used in many different variations as published in Cao *et al.* (2005), Yasin *et al.* (2008), Samian *et al.* (2009), Shribak *et al.* (1996), Harun *et al.* (2010), Shen *et al.* (2010) to mention a few. The authors of these publications propose applicable mathematical models (for the relationship between measuring signal and mirror shifting) and they confirm the models by means of experiments. Both, single and multimode optical fibers are used for the proposed methods.

The work by Cao *et al.* (2005) treats about two situations: one, where two optical fibers are connected so that the first fiber conducts the signal from transmitter and the second fiber directs the signal toward photosensor; two, where more transmitting and receiving fibers have been connected.

The work by Harun *et al.* (2010) presents a setup with a single transmitting fiber and two receiving fibers, whereas the work by Yasin *et al.* (2008) depicts one transmitting fiber against sixteen receiving fibers.

Figure 1 shows a simplified optical system diagram of the construction described in the works by Samian *et al.* (2009), Shribak *et al.* (1996) and Shen *et al.* (2010) that employs only one multimode optical fiber for both the sending and receiving signals. For this design, a multimode coupler is used to connect the transmitter, receiver and fiber pointed at the moving mirror. The presented research was conducted while sensors were in a dry environment, however the authors of the work by Shribak *et al.* (1996) stated that the filling of the space between the fiber tip and the mirror with a light-absorbing liquid of an appropriately selected refraction index would be a good method for increasing the measurement range as well as the sensitivity of the measuring system. That, in turn, evoked an idea that sensors immersed in the hydraulic oil should work very well as long as the oil meets specific requirements.

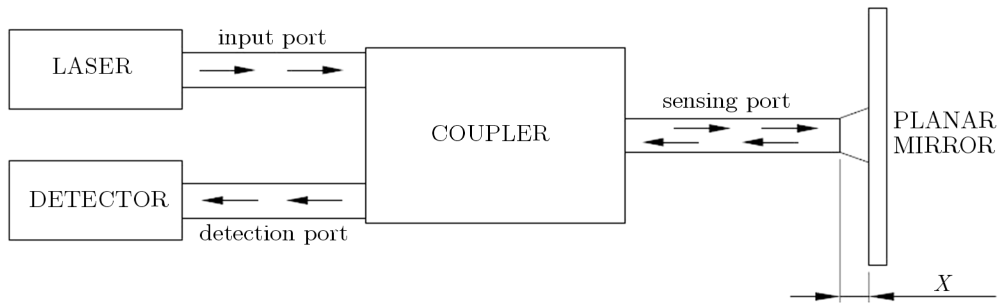

Fig. 1. Simplified diagram of the optical measuring system

According to Samian *et al.* (2009) and Shribak *et al.* (1996), the total correlation between the measuring signal, i.e. the reflected light power and the mirror displacement is not linear in the entire measurement range. However, the range where that correlation is very close to linear can be found. Fiberoptic displacement sensors work in that range.

Figure 1 presents a simplified diagram of displacement sensors which can offer measurement accuracy within millimetres, micrometres or even nanometres – depending on the optical fiber used and lights source intensity. An interesting configuration is described in the work by Shen *et al.* (2010), where a broad spectrum light source offering smooth intensity choice change was used along with a special collimator which enabled broadening the testing range. The sensor could work in the 5-30 cm range.

A layout described by Samian *et al.* (2009) and Shribak *et al.* (1996), Fig. 1, that is a part of distance measuring fiberoptic sensors, is used to measure moving element displacements inside one of the micro-hydraulic valves. This model allowed for developing a measuring technique, where displacements of an element having a few millimetres in size, entirely immersed in the hydraulic oil, could be measured in the 0-100 μm range. Optical fiber GI 50/125 was used to evaluate the displacement.

A micro pressure relief valve was the object of research with a fiberoptic-based technique attempted to be used to measure displacements of a few-millimetre-long moving element entirely immersed in the hydraulic oil. Figure 2 presents a simplified draft of such a valve and its operating principle. The adjusting screw x_s controls the set pressure, i.e. the force the closing element exerts on the valve seat. The valve remains closed until the opening pressure set with the adjusting screw is reached in the inlet channel P. When the pressure is exceeded, the valve opens and the liquid is allowed to flow to the outlet channel T. As long as the defined rate of flow is maintained, the pressure in the approach channel P remains close to the level set with the adjusting screw, and the valve remains open. Hence, this valve is a sort of a pressure regulator that can be unstable and succumb to self-exciting vibrations if construction parameters are maladjusted.

The tested valve seat diameter is 2 mm. The valve has been designed to work with liquids flowing at rates up to 1 dm^3/min and 16 MPa of maximum setting pressure.

Figure 2 presents some construction changes that were implemented in order to make measurements of displacements of the closing element possible. An optical fiber embedded in a metal pipe is inserted into a hole drilled in adjusting screw 1. A mirror is glued to closing element 2.

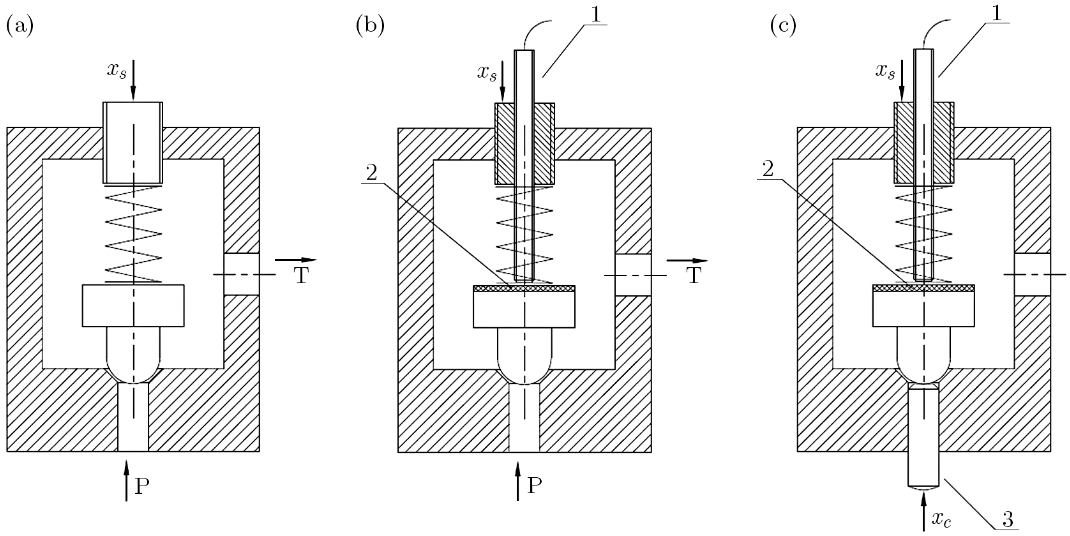

Fig. 2. Method of measuring displacements of the moving element: (a) simplified relief valve diagram; (b) fiberoptic testing probe 1 and mirror 2 installed in the relief valve for the displacement measurements; (c) relief valve, equipped with fiberoptic testing probe 1, mirror 2 and calibrating probe 3, during calibration

Laser light sent from the transmitter is directed at the mirror, so it can travel across the valve and go back to the receiver – light sensor. A multimode 2×1 coupler is used so that a single fiber can transport the transmitted and reflected beams simultaneously. The longer the distance between the closing element and the seat, the shorter the distance between the optical fiber and the mirror, and the higher power of the laser beam returning to the detector that, in turn, produced a proportional electric signal.

Under normal working conditions, the closing element moves away from the seat as a result of the liquid pressure acting on it. The fiberoptic technique gives ability to measure displacement changes in time. The required beforehand calibration can be done with separate calibrating shaft (3) presented in Fig. 2c. The shaft moves the closing element away from the seat to create a gap of required size. Following the calibration, the calibration shaft can be removed from the inlet channel, and the channel can be reconnected to the system without affecting the optical fiber position.

It is worth mentioning that the calibration should take place before each measurement as not only the reflected signal power depends on the closing element position, but also on the optical fiber holding the testing probe setting.

Figure 3 depicts two cooperating elements that play the key role in the optical fiber based measurements of the studied micro valve.

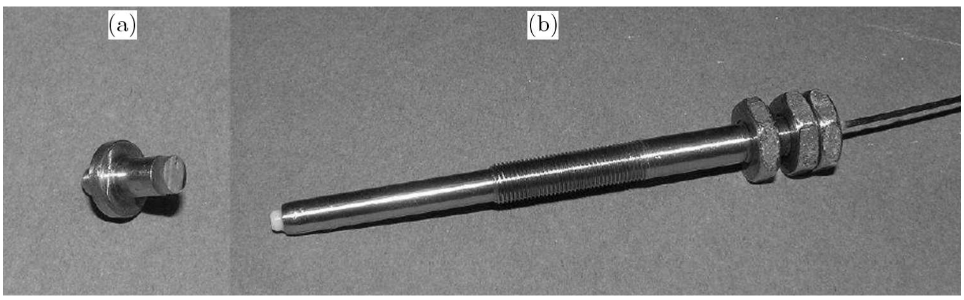

Fig. 3. Cooperating elements: (a) mirror-equipped element whose movements are measured, (b) testing probe with optical fiber installed in its core

It is noteworthy that both the mirror-equipped closing element and the optical fiber holding testing probe work in a low-pressure environment (that comes from the liquid flow resistance met on its direct way to the tank). This is very advantageous as it facilitates sealing off the testing probe, and it minimizes the risk of forcing the optical fiber out of the testing probe with the pressurized liquid.

Measuring the closing element displacements involves:

- specially adapted micro valve
- optical fiber 50/125 μm in diameter
- 850 nm-wavelength VCSEL diode of 0,5mW (transmitter)
- Si-PIN diode with 500 μm of active area
- multimode 2×1 coupler with 50/50 split coefficient
- micrometer gauge (for calibrating the measuring system)
- electronic circuitry changing the light signal from the sensor to an electric signal readable by the oscilloscope
- Tektronix TDS224 oscilloscope
- Universal micro hydraulics testing station (Łomotowski, 2013)

3. Calibrating the measuring system

Calibration is imperative in order to obtain information about displacement magnitude. While the valve is working at the micro valve testing station, calibration can be done before or after taking displacement measurements. The calibration should be done at the same conditions as during measurements (e.g. the same temperature of the hydraulic oil). Figure 4 shows the studied micro valve during its calibration.

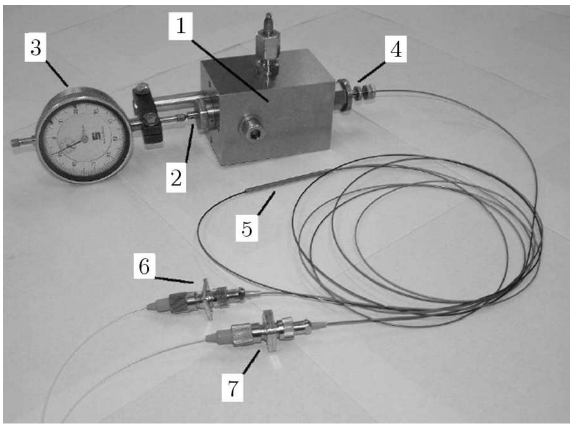

Fig. 4. Studied micro valve during calibration: 1 – micro valve body, 2 – calibration shaft for displacing the closing element, 3 – micrometer gauge for measuring closing element displacements in relation to seat, 4 – testing probe (measuring shaft) containing optical fiber, 5 – fiberoptic coupler, 6 and 7 – coupler-transmitter and coupler-receiver connectors

Table 1 contains a sample of measuring system calibration results for two different testing probe positions. In both cases, the increase of testing signal after opening the valve was measured in relation to its value at the time of valve closed position.

Three measurement sets were performed in each case because of marked external interference with the testing signal. Among other things, some micro valve manufacturing flaws and impurities in the hydraulic oil adversely affected light travel through the valve causing interference.

Table 1. Calibration results for two settings of the initial distance from the mirror to the optical fiber

Setting 1				Setting 2			
x [μm]	u_1 [mV]	u_2 [mV]	u_3 [mV]	x [μm]	u_1 [mV]	u_2 [mV]	u_3 [mV]
10	4	10	6	10	8	6	8
20	8	12	10	20	16	16	18
30	14	18	16	30	26	22	24
40	22	22	20	40	32	24	30
50	28	28	28	50	38	36	40
60	34	32	32	60	44	46	46
70	38	38	36	70	52	50	52
80	42	40	40	80	62	58	62
90	44	44	42	90	72	64	70
100	50	44	48	100	78	72	76

It has been noted that the calibration relationship between the closing element displacement and testing signal measured in volts is approximately linear. Figure 5 depicts calibration results for two different testing probe positions with associated linear approximations.

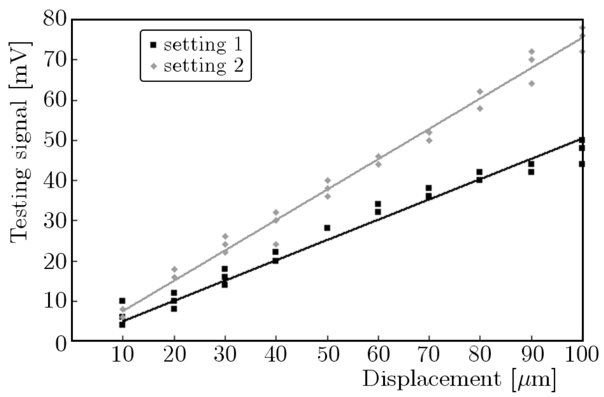

Fig. 5. 5: Sample calibration results for two different testing probe settings (x axis – displacement in μm, y axis – testing signal in mV)

For the calibration represented by results obtained during setting 1, the relationship can be expressed with formula $(3.1)_1$; for the calibration represented by results obtained during setting 2, the relationship can be expressed with formula $(3.1)_2$

$$x\,[\mu m] = 1.967u\,[\mathrm{mV}] \qquad\qquad x\,[\mu m] = 1.322u\,[\mathrm{mV}] \tag{3.1}$$

In order to estimate the repeatability and linearity of measurement results, based on three sets of results, the regression coefficient confidence level can be estimated by means of the method of least squares.

In the first case, for the confidence level of 95%, the regression coefficient falls between 1.9091 and 2.0243, therefore the coefficient deviation is 2.9%.

In the second case, for the confidence level of 95% the regression coefficient falls between 1.2977 and 1.3464, therefore the coefficient deviation is 1.8%.

These results confirm the correct choice of the measurement method. Accuracy of the measurements is hard to evaluate since the setup for mirror-equipped closing element displacements was pretty rough itself. Although the testing probe position was adjusted with an accuracy of $10\,\mu$m, setting the gap between the mirror and the optical fiber tip was not necessarily that accurate. The valve has been manufactured by conventional standards. In spite of demand for high quality control, the valve was still produced in quality levels allowing for shape and size deviations ranging tens of micrometers.

4. Micro valve testing at the micro-hydraulic station

Working in a hydraulic system, the displacement measurements of the relief valve closing element were taken at a universal micro-hydraulic element testing station (Łomotowski, 2013). Figure 6 depicts the hydraulic system put together for the purpose of conducting our study.

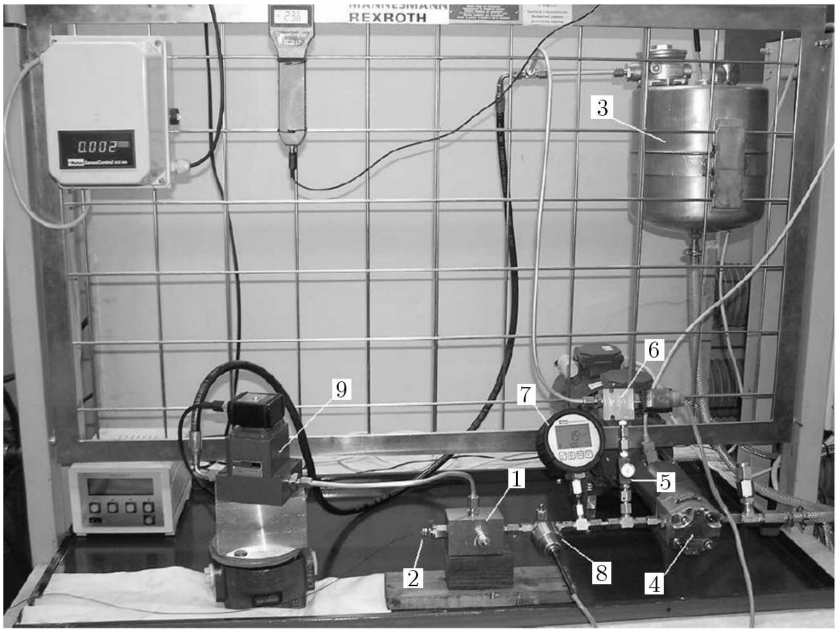

Fig. 6. The hydraulic system for measurements of the micro valve closing element displacements

Figure 7 shows the studied hydraulic system diagram. The system consists of the following elements (marked with numbers corresponding to Figs. 6 and 7):

1 – tested micro relief valve adapted to allow taking the closing element displacement measurements with the fiberoptic method

2 – testing probe holding the optical fiber used to transport the displacement measuring signal back to the measurement system

3 – hydraulic oil tank

4 – micro pumps motorized with a variable-speed revolution motor allowing for smooth pumped oil flow changes from 0 to 1.1 dm^3/min

5 – throttle valve

6 – electromagnetic shut off valve

7 – digital manometer of measuring range 40 MPa

8 – pressure strain gauge of measuring range 25 MPa

9 – flow quantity meter of measuring range 2 dm^3/min

The very essence of the measurements is registering the displacement changes in time of the valve closing element lift following an appropriate step change in the flow directed at the micro valve. Different actions can be obtained depending on the opening pressure set and the

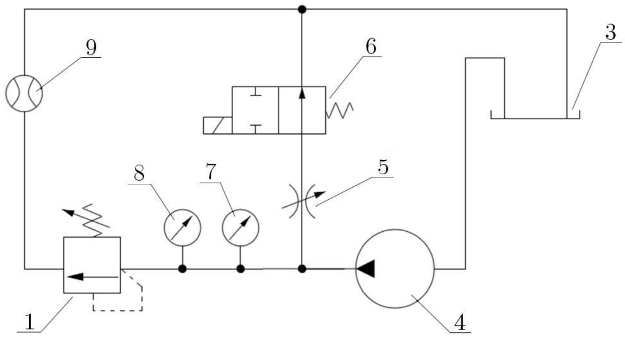

Fig. 7. Diagram of the hydraulic system for measurements of the micro valve closing element displacement

flow rate directed at it. In order to achieve the desired action, micro pump (4) has to be set to an appropriate revolution rate that yields a desired rate of flow, then electromagnetic shut off valve (6) has to be overrun to close. As a result, the entire pumped liquid flows toward the pressure relief valve. In addition, pressure strain gauge (8) enables recording of pressure changes in time.

Figure 8 presents the recording system that consists of: (1) fiberoptic coupler, (2) transmitter electronic module power supply that also converts light signals from the sensor (receiver) to electric signals readable by the oscilloscope, (3) device that converts pressure sensor signals to electric signals readable by the oscilloscope, (4) oscilloscope, (5) computer recording signals from the oscilloscope in files.

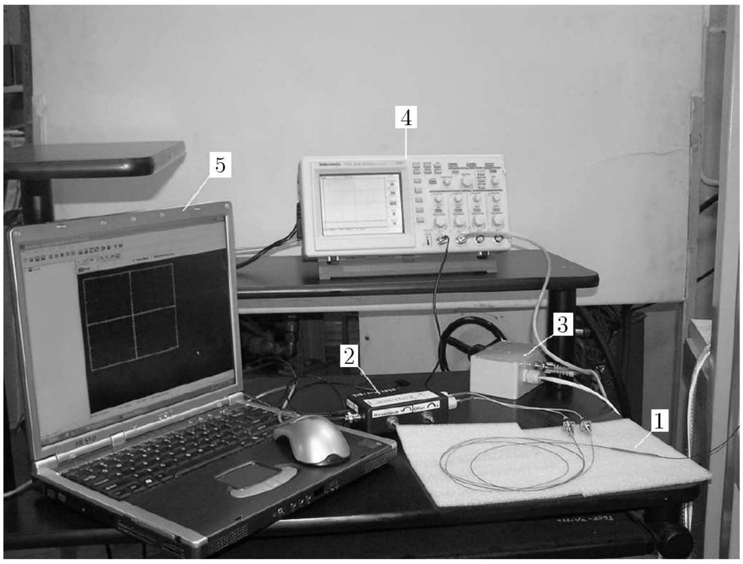

Fig. 8. The measuring system for the micro valve closing element displacement

The studied valve was built in the way that allowed for changes in some construction parameters in order to test for the best parameter choice for the best performance. Figure 9 presents valve closing element timing associated with correctly selected construction parameters. In this case, the valve action is stable. Figure 9 shows unaltered recording and the same recording filtered by the moving average method. Original recording show some deviations from the equilibrium caused by measurement system noises, impurities movement in the hydraulic oil causing changes in the reflected light luminosity as well as slight closing element vibrations caused by the liquid flowing around it.

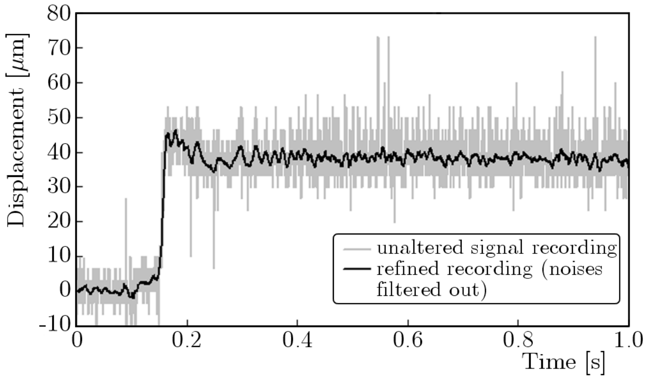

Fig. 9. Exemplary course of the micro valve closing element displacements during a step change in the flow directed at the valve – unaltered signal recording and refined recording (noises filtered out)

Figure 10 presents a time interval record of the closing element displacement in the valve with construction parameters chosen incorrectly. In this case, the valve action is unstable. Considerable self-excited vibrations can be observed in the valve. Figure 11 presents results of vibrations Fast Fourier Transform – the original record and the transform. It is noteworthy that valve vibrations are so intensive that the closing element knocks the seat. Such operation is unacceptable because the cooperating parts can quickly get damaged, and because of powerful pressure pulsation. Unstable valve action can easily be recognized as it causes a characteristic noise.

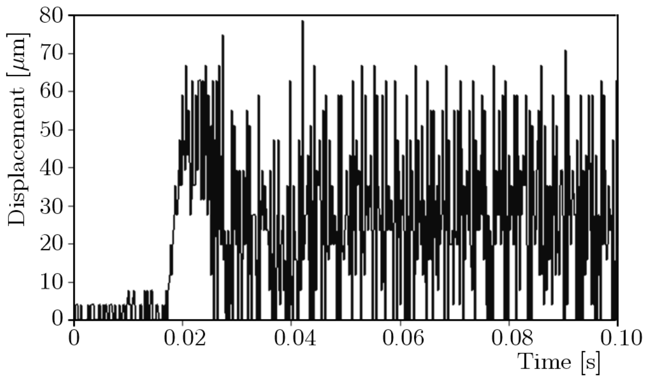

Fig. 10. Exemplary course of the micro valve closing element displacement during a step change in the flow directed at the valve – unstable valve action

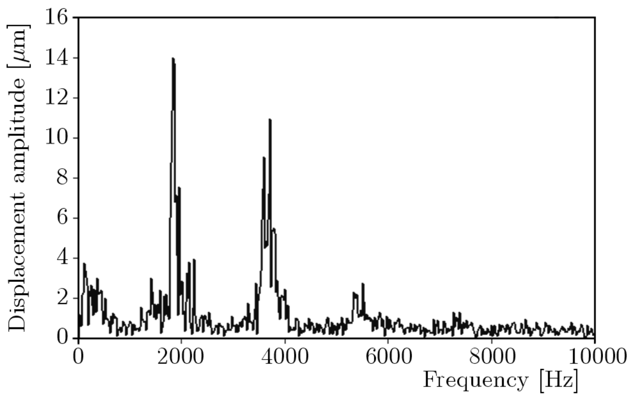

Fig. 11. Exemplary valve vibration frequency analysis during an unstable action

It is clearly seen that the base frequency of self-excited vibrations is 1830 Hz. The first higher harmonic can clearly be noticed. No vibrations occur above 6000 Hz.

5. Conclusions

Fiberoptic technology enables measuring displacements of small moving elements entirely submerged in a hydraulic oil. The presented method can be applied to study micro-hydraulic systems elements – micro valves in particular. This method of taking vibration frequency measurements is highly accurate. It is also important that the method provides ability to record the constant-displacement component; therefore, it is possible to measure the way the micro valve moving element displacements shape in time in valves working in both the equilibrium state and in non-equilibrium state. Researchers collecting information this way can broaden their knowledge about valves functioning and phenomena associated with it. That knowledge should contribute to establishing criteria for designing high-quality micro-hydraulic valves correctly.

Thanks to very good dynamic properties of the measuring method, fiberoptic displacement sensors can be used, among others, in automatic control of elements in micro-hydraulic systems. For example, a micro-hydraulic directional valve equipped with a fiberoptic sensor can give out measurements that influence more precise settings for the slider travels.

A very good measurement method has been presented in this article. Nevertheless, the method requires further development involving a system built entirely with high-quality components. The presented calibration results are based on a very rough displacement setup, yet the results repeatability is good. Future attempts should be made on system components produced with higher accuracy. Required displacements should be executed with better precision, e.g. with a piezoelectric actuator (Harun *et al.*, 2010).

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