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STEP RESPONSE OF THE AIR GAUGE

In the paper, the results of investigations on the dynamical properties of air gauges have been presented. The basic parameter that underwent examinations has been the step response. It has been found that there is a difference between rising and falling signal response and that the whole pneumatic canal influences the behavior of the air gauge. The achieved response time values have been compared with the results of calculations based on the amplitude-phase characteristics.

Keywords: air gauging, step response, dynamical properties, dimensional measurement

1. INTRODUCTION

The air gauges are well known devices for length measurement, used for decades [1], though nowadays not many works are published. The pressure (especially, so-called high pressure) gauges work as flapper-nozzle valves, and the air pressure in the measuring chamber indicates the changes in length of the measured detail. Figure 1 shows the investigation set which enabled to achieve the static characteristics of the air gauge. The air of stabilized feeding pressure p_z goes through the inlet nozzle 1 (Fig. 2) with the diameter d_w, and in the measuring chamber 2 its pressure p_k depends on the diameter of the measuring nozzle 3 (d_p) and on the displacement s. The function $p_k = f(s)$ is close to linear in a certain area which may be used as a measuring range z_p.

The dynamical properties of air gauges are important for metrology, because they are applied in systems of in-process control (dynamical measurement) and in measuring automatons (quick measurement). Perfect reproduction of the input signal is not possible, so some dynamic error is inevitable. The dynamic error $\delta(\omega)$ of a system is defined in literature [2] using the magnitude ratio $M(\omega)$:

$$\delta(\omega) = \mathrm{M}(\omega) - 1, \tag{1}$$

where: $M(\omega) = \dfrac{B}{KA} = \dfrac{1}{\sqrt{1+\omega T}}$ – magnitude ratio, B – amplitude of the steady response, K – static sensitivity, A – input signal amplitude, ω – circular frequency, T – time constant.

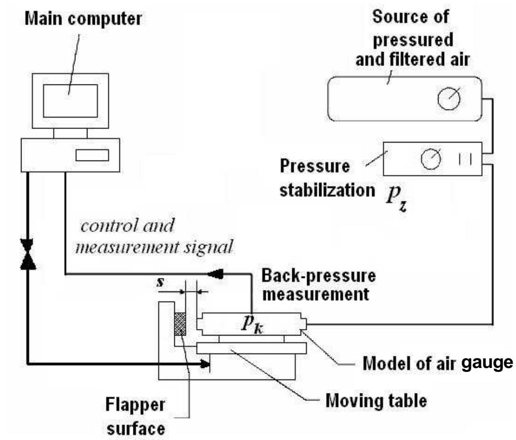

Fig. 1. Investigation set for air gauge static characteristics measurement.

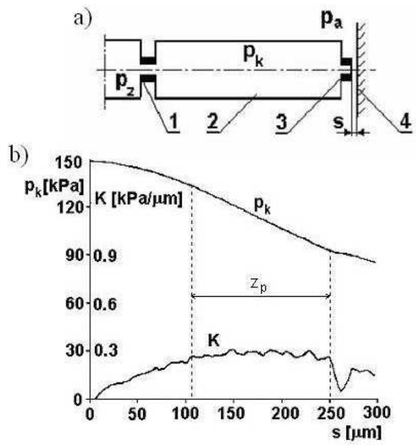

Fig. 2. a) Model of the measuring chamber, b) example of the static characteristics.

The rate of response of a system to a change in input is estimated by use of the step function input. The system parameters of time constant T (for first-order systems), and natural frequency ω_n and damping ratio ζ (for second-order systems) are used as indicators of system response rate. Knowing the dynamical parameters of the measuring device, it is possible to improve its dynamical metrological properties [3].

2. STEP FUNCTION INPUT

To simulate the step response of the air gauge, full closure of the measuring nozzle was carried out. In this way maximal change of the measuring pressure signal p_k is achieved. When the measuring nozzle is closed, the pressure in the chamber 2 is maximal and equal to the feeding pressure $p_{k\,\max} = p_z$. When it is fully open, the pressure $p_{k\,\min}$ would depend on the diameters of measuring and inlet nozzles (d_p and d_w). For example, the air gauge with d_p = 1.200 mm and d_w = 0.900 mm with feeding pressure p_z = 150 kPa will have $p_{k\,\max} = p_z$ = 150 kPa and $p_{k\,\min}$ = 32 kPa.

The configurations of the air gauges that underwent the investigations, are given in Table 1 along with their static sensitivity K.

Table 1. Examined configurations of the air gauges.

d_p	1.2 mm	1.2 mm	1.4 mm	1.4 mm
d_w	0.7 mm	0.9 mm	0.7 mm	0.9 mm
K	0.51 kPa/μm	0.33 kPa/μm	0.75 kPa/μm	0.38 kPa/μm

2.1. Full Closure Response

When the measuring nozzle is closed immediately, the pressure p_k in the measuring chamber is rising from 32 kPa up to 150 kPa. However, it rises a little above the value of 150 kPa and is stabilizing for some time, oscillating around it (Fig. 3).

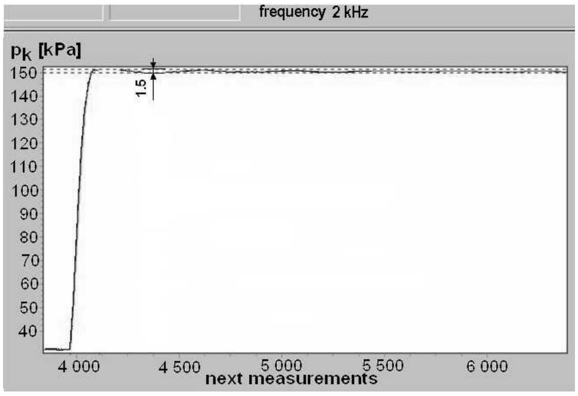

Fig. 3. The graph of the air gauge step response (immediate full closure).

On the one hand, these oscillations do not exceed ±5% of the stabilized value of $p_{k\,\max} = p_z$ = 150 kPa. Thus, they may be omitted, and the air gauge response time may be considered the time when the ±5% area is reached. For the mentioned configuration (d_p = 1.200 mm and d_w = 0.900 mm), this time is T_u = 0.0399 [s] (see

Fig. 4). On the other hand, however, it is interesting to examine the source of this phenomenon.

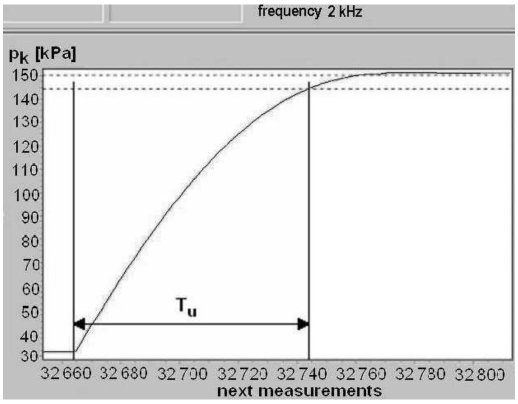

Fig. 4. The setting time T_u.

Most probably, the source is the whole pneumatic line between the stabilizer and the measuring nozzle (see Fig. 1). After the nozzle is immediately closed, the strike wave goes through the measuring chamber and inlet nozzle through the feeding line into the stabilizer, and then goes back. It should be expected that a longer line would generate the back-pressure oscillations with a longer period. Exactly this was observed after including into the feeding line the element of volume $V = 500$ cm^3. The Figure 5 shows the responses of the exactly same system, but without and with added volume V.

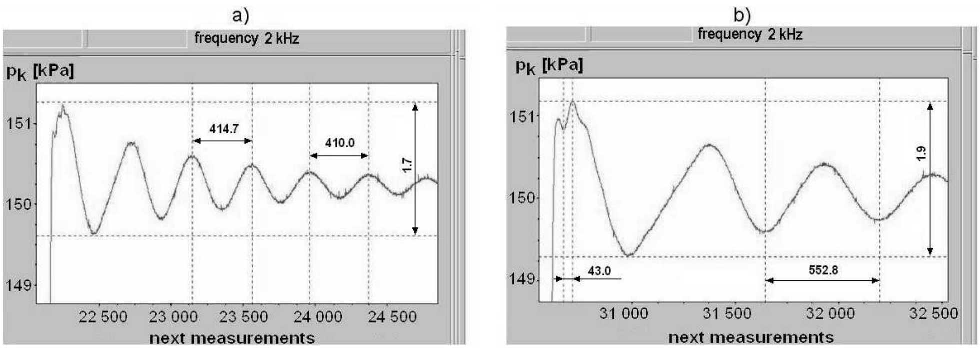

Fig. 5. The back-pressure p_k oscillations: a) without added volume, b) with added volume $V = 500$ cm^3.

In normal conditions of the experiment, the period of the back-pressure damped oscillations in the closed measuring chamber was 205 ms, which corresponds to a frequency $f = 4.88$ Hz. When the additional volume V is added, the period of oscillations becomes longer, up to 276 ms ($f = 3.61$ Hz). Moreover, some other oscillations become distinguishable at the top of the first wave (Fig. 5b), which appear like disturbances in Fig. 5a. The frequency of those superposed oscillations may be approximated as $f = 46.5$ Hz, which is about ten times higher than the oscillation caused by the pneumatic line. Most probably, this high-frequency oscillation is caused by the strike waves inside the measuring chamber, between the inlet and measuring nozzles (1 and 3 in Fig. 2a).

Turning back to the setting time T_u, it is noteworthy that the high-frequency oscillation superposed on the damping oscillations appeared in each experiment with full closure response and it affected the value of the time constant T and setting time T_u. Considering the air gauge as a first order dynamical system, its step response should be described with the formula

$$y(t) = KA(1 - e^{-t/T}). \tag{2}$$

The best fitted function for the case shown in Fig. 4, is the following:

$$y(t) = 32 + 118 \times (1 - e^{-t/0.0195}), \tag{3}$$

where $T = 0.0195$ [s], $p_{k\,\min} = 32$ [kPa], $p_{k\,\max} = p_z = 150$ [kPa].

However, this function reproduces the experi-mental graph with a maximal error of 8.8% (Fig. 6). In the graph, the delay in the pressure rising after 0.003 s is clearly seen. It may be caused by the superposition of the high-frequency oscillations, described above, on the graph, and it affects the whole process causing such a large difference between theoretical and experimental results.

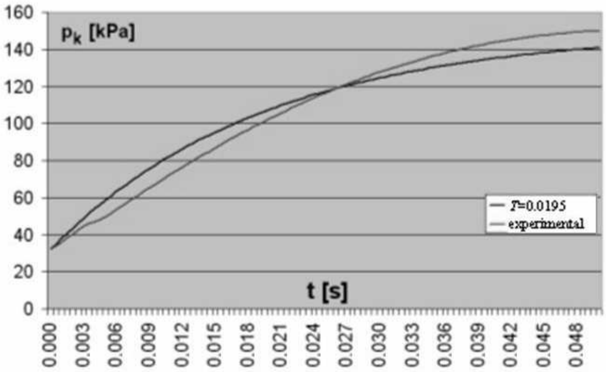

Fig. 6. Theoretical and experimental step response.

During the measurement with the air gauge, the full closure of the measuring nozzle never takes place. The changes of the dis-placement s always appear (or should appear) in the linear part of the static characteristics, marked z_p in Fig. 2b. However, it always generates the strike waves which affect the step response graph and cause a divergence between the theoretical and experimental results.

2.2. Full Opening Response

No such phenomenon appears in the back-pressure p_k changes after the immediate full opening of the measuring nozzle. It is seen in Fig. 7 that the pressure drop process is smooth and undisturbed. It may be described by formula

$$y(t) = 32 + 118(e^{-t/0.0165}), \tag{4}$$

where $T = 0.0165$ [s], unlike in formula (3) for rising pressure. The maximal error of this approximation does not exceed 2.3%. The value of $p_{k\,\min} = 32$ kPa is stable, no oscillations appear, because no strike waves go back into the measuring chamber.

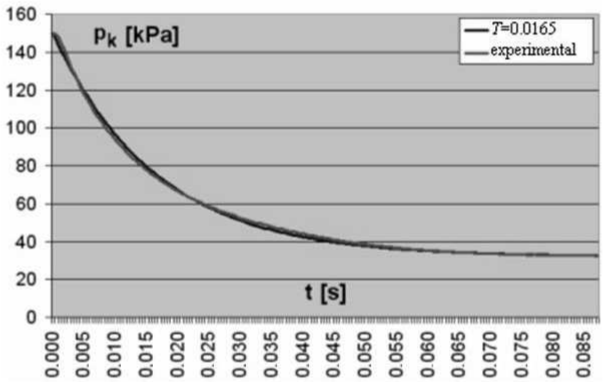

Fig. 7. The step response for pressure drop.

The investigations have been repeated for other configurations of the air gages and there has always been a difference between the time constant T for rising and falling step function input. It is very possible that the difference is caused by the fact that the time constant T itself is not constant, but is to some extent dependent on the values of measured back-pressure $p_{k\,\min}$ and $p_{k\,\max}$. Investigations on thermometric sensors described in literature [4] led to the conclusion that a *dynamical parameter* should be introduced instead of *time constant*. It seems reasonable to continue modeling of air gauge dynamical properties based on a non-linear model. Analogically to thermometric sensors, such a model for air gauge could contain the *dynamical parameter* T_d dependent on actually measured back-pressure p_k and stabilized value p_{ku} (minimal $p_{k\,\min}$ for falling pressure or maximal $p_{k\,\max}$ for rising one):

$$T_d \frac{dp_k}{dt} + p_k = p_{ku}. \tag{5}$$

Thus, some investigation should be performed in order to find out the relationship between the dynamical parameter and the values of pressure.

3. SINUSOIDAL FUNCTION INPUT

The time constant T can be calculated also from the experimentally achieved amplitude-phase characteristics. The input signal (displacement s) is changed periodically with a known frequency, and the amplitude of back-pressure p_k is being registered. This method has been proposed by Soboczyński [5] and is based on the following formula:

$$T = \frac{\sum_{i=1}^{n} \frac{1-A^2(\omega)}{A^2(\omega)}}{\sum_{i=1}^{n} \left(\omega \sqrt{\frac{1-A^2(\omega)}{A^2(\omega)}}\right)}, \tag{6}$$

where: $A(\omega) = \dfrac{A(\omega_i)}{A(\omega_o)} = \dfrac{1}{\sqrt{1 + T^2\omega_i^2}}$ – the ratio of amplitudes for changed input oscillations and for the initial pressure (established in static conditions), T – time constant.

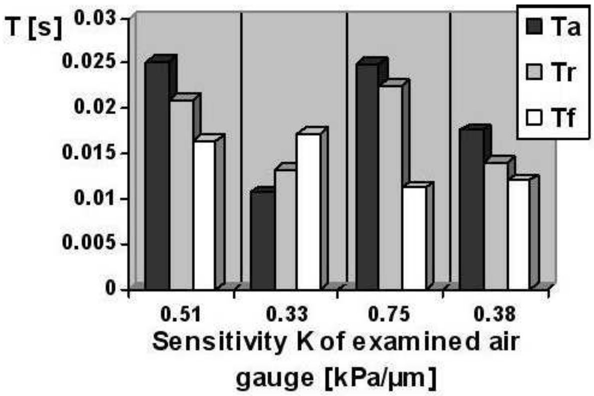

Fig. 8. Comparison of the time constant achieved with different methods for air gauges with various sensitivity.

The measurement of the amplitudes of back-pressure p_k dependent on the input signal circular frequency ω for the configurations specified in the Table 1 has been performed and presented in the work [6]. The graph in Fig. 8 shows the comparison of the calculated time constant T_a (based on the amplitude-phase characteristics) with the T_r (for rising pressure after full closure of the measuring nozzle) and T_f (for falling pressure after full opening).

It is seen that the results differ for different configurations of the air gauges, values of T vary from 0.011 up to 0.025 seconds. It must be emphasized that the time constant calculated from the amplitude-phase characteristics T_a is either the highest or lowest one, while the time constant T_r for rising value of the back pressure p_k lies always somewhere between T_a and T_f. These differences are caused by the fact that the full closure and full opening does not operate in the linear part of static characteristics of the examined air gauge (the measuring range marked z_p in the Fig. 2). In the next stage of investigations, the research set will be built to generate the step response within the bounds of the measuring range z_p.

4. CONCLUSIONS

Dynamical properties of the air gauge are very important in the inspection process. The examinations of the step response of typical back-pressure air gauge led to the conclusion that its behavior is very close to that of a first-order dynamical system. The time constant of the pneumatic system does not exceed several hundredths of a second. However, the step response achieved from the full closure of the measuring nozzle (maximal input signal) is affected by the damping oscillation caused by strike waves in the pneumatic feeding line and in the measuring chamber. The differences between the time constant achieved in different ways indicate the need of non-linear dynamical modeling. Further investigations will pay attention to the dependence of the *time constant* on parameters of a dynamical signal and will thoroughly examine the step response in the linear part of air gauge static characteristics.

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