

Dynamics of in-process control with non-contact air gauges

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ABSTRACT

Dynamic properties of the air gauges performing in-process measurement are of the great importance because of dynamic error affecting the measurement results. The paper presents the analysis of the air gauges dynamics and some practical recommendation. The investigations proved the dependence of the time constants on the actually measured back-pressure. In practical solutions of in-process control, the air gauge must work in conditions of falling back-pressure since with the material removal dimensions of the machined workpiece go down. Thus, in the area of the smallest values of back-pressure within the measuring range, the time constant value is the largest. Worsening of the air gauge dynamic properties at the end stage of the machining must be considered when the dynamic characteristics of the projected air gauge are calculated.

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1. Introduction

In-process measurements ensure high productquality through real-time quality monitoring, reduce manufacturing costs and increase productivity (Berger et al., 2015). Automated quality control is very important aspect of a manufacturing process (Milo et al., 2015), and the measurement accuracy is particularly important in the new manufacturing era called Smart Manufacturing, Intelligent Factory or Industry 4.0 (Moroni & Petro, 2018). Metrology becomes part of the Cyber-Physical Manufacturing Systems (CPMS) and involves big data analytics (Majstorovic et al., 2018) as well as Internet of Things (Majstorovic et al., 2019). To handle metrological data in multistage manufacturing processes, intelligent systems based on neural networks are applied (Papananias et al. 2019). The intelligent embedded systems have a potential to contribute to more efficient manufacturing and more manageable technological processes (Tomov & Dimitrov, 2019).

Scientists and engineers appreciate many merits of the pneumatic dimensional measurement, among others the simple construction of gauge, cheap maintenance, easy regulation of metrological properties, non-contact measurement, self-cleaning of the measured surface with the outflowing air (in open jet devices) and so on (Curtis & Farago, 2014). In 1960ths and 1970ths, the air gauging was important part of the metrological sciences with numerous publications around the World (Lotze, 1968; Pogorelov, 1971; Zalmanzon, 1971). After some decline in the development, air gauges regained new attention (Schuetz, 2008; Koenig 2017), especially in the context of the in-process control (Menziez & Koshy, 2009; Vacharanukul & Mekid, 2005; Koehn 2015; Rao 2017). In particular, researchers looked for the ways of improvement of static and dynamic characteristics of the air gauges (Jermak 2010; Cellary & Jermak 1997; Jakubowicz & Derezynski 2017), proposed some modifications of the nozzle geometry (Jakubowicz 2020), and evaluated new models of their

work (Bokov 2011; Jermak 2017). However, dynamical properties of an air gauge are considered rather poor, e.g. in documentation *Millimar* (2005) its setting time is declared as 0.3-0.5 s.

Application of piezoresistive transducers and small chambers was described by Rucki et al. (2010), it reduced the time constant and setting time down to few milliseconds (Rucki & Jermak, 2012). As a result, the air gauges became suitable in the applications of high dynamics. This study is dedicated to the accurate determination of the time constant, which is crucial in in-process measurement with air gauges.

2. Typical In-Process Back-Pressure Air Gauging

Typical air gauging measurement during the machining is widely known (Yandayan & Burdekin, 1997). In short, the back-pressure air gauge is monitoring the diameter of machined detail, and after the set value is reached, the spool valve controls the parameter of machining or stops the process. Of course, in case of electronic signal gained from the piezoresistive pressure transducer, it could be processed by computer and used in more sophisticated digital control system as well as in the industrial process database (Sanchez et al., 2020).

It should be noted, however, that when machining shafts, the work of the air gauge starts at larger diameters of the workpiece which provide smaller slot s between the detail surface and measuring nozzle. Subsequently, during the machining process, the material is removed and the slot becomes wider, and corresponding back-pressure falls down. In some range z_p , the dependence of the back-pressure p_k on the slot width s is proportional. The completion of the machining process would correspond with slot s close to the end of this proportional area when the back-pressure p_k is the smallest.

Similarly, in case of machining of inner cylinder surface, the in-process measurement starts with smaller slots and ends with larger ones, since the machining is causing the removal of the material. E.g. during the honing process, the inner diameter of cylinder grows larger, and the measured slot width s grows larger, too. The slot between the measuring nozzle and the inner cylinder surface is illustrated in Figure 1. The diameters of inlet and measuring nozzles are denoted d_w and d_p , respectively. The area between them is called the measuring chamber, where the back-pressure p_k dependent on slot width s is measured. The stabilized feeding pressure of the air gauge is denoted p_z , and its value, along with nozzles geometry, determines the metrological characteristics of the air gauge (Derezynski & Jakubowicz, 2016).

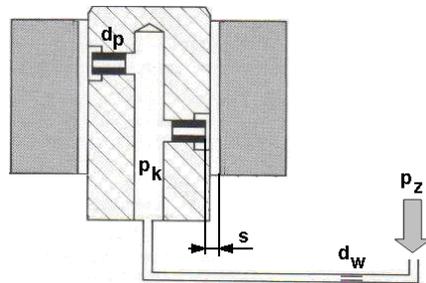


Figure 1. Slot width s in measurement of inner diameters

In the example of the Figure 1, it is seen that the volume of measuring chamber between restriction d_w and measuring nozzle d_p is relatively big. It naturally affects the dynamical properties of the air gauge, according to the formula (Zelczak, 2002):

$$T = \frac{v_k \rho_0 \tau_0 R g}{p_0} \frac{1}{\left(\frac{\partial G_2}{\partial w_{2sr}} \frac{\partial w_{1sr}}{\partial p_k} \right) - \left(\frac{\partial G_1}{\partial w_{1sr}} \frac{\partial w_{1sr}}{\partial p_k} \right)} \quad (1)$$

where: v_k – volume of measuring chamber, ρ_0 – mass density, τ_0 – temperature, R – gas constant, g – acceleration of gravity, G_1 and G_2 – kinetic energy of the air stream in the inlet and measuring nozzles, w_{1sr} and w_{2sr} – mean velocity of the air in the inlet and measuring nozzles.

In order to reduce the time constant, smaller volumes of measuring chambers should be applied. It was proposed, e.g. in (Jermak & Rucki, 2016) where three measuring nozzles were not joined in one measuring chamber, but worked independently with three small measuring chambers. The measuring head was placed on the flexible rod, and the data analysis was based on the original algorithm, which calculated the roundness of the measured detail from three independent signals. This device was designed for quality control performed

offline, after a part is produced (Gao et al., 2014), when the material is no longer removed. However, in most in-process applications, the air gauges produce the control signal when the proper amount of the material is removed and the gauge works in the end area of its measuring range z_p . This area corresponds with larger slot width s and smaller back-pressure p_k .

3. Materials and Methods

Measurement of the air gauge dynamic characteristics was performed with the specially arranged laboratory set described in details by Jakubowicz, Rucki & Siemiatkowski (2019). It consisted of mechanical sine input in form of eccentric shaft, electrical motor with settable rotational speed to control the input frequency, and the electronic signal processing and computational unit. Three main sources of uncertainty were considered, namely, mechanical generation of the sine input $s(\omega t)$, pressure transducer indications p_k , and further signal processing with estimations, smoothening, averaging, interpolation and similar procedures. Overall system uncertainty in determination of time constant T for coverage factor $k = 2$, which corresponded with approximately 95% level of confidence, was calculated as $U_{95} = 0.001$ s (Jakubowicz, Rucki & Babic, 2019).

Configurations of air gauges used in experiments are described in Table 1. The examined air gauge with $d_p = 1.200$ combined with $d_w = 1.200$ mm (denoted D2 in Table 1) and $d_w = 0.625$ mm (denoted D5 in Table 1) provided the multiplication of $K = 0.15$ kPa/ μ m and $K = 0.88$ kPa/ μ m respectively. Therefore, the measuring ranges z_{pD2} and z_{pD5} correspond with different ranges of back-pressure, as it is seen in Figure 2. Both combinations were joined with the measuring chambers of reduced volume v_k 0.402 and 3.921 cm³.

Table 1. Examined configurations of air gauges

No.	d_p [mm]	d_w [mm]	K [kPa/ μ m]	v_k [cm ³]	p_k range [kPa]
2D2	1.200	1.200	0.15	0.402	105-140
9D2	1.200	1.200	0.15	3.921	105-140
2D5	1.200	0.625	0.88	0.402	70-115
9D5	1.200	0.625	0.88	3.921	70-115

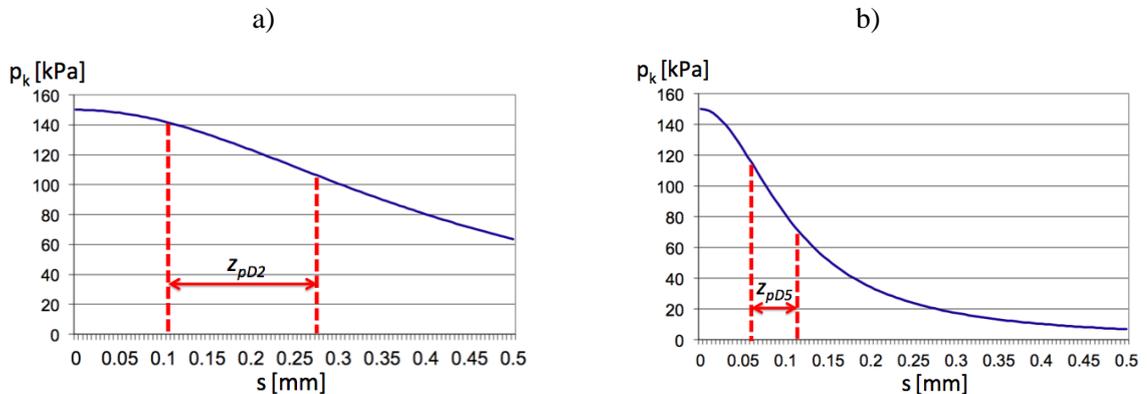


Figure 2. Static characteristics of the examined air gauges: (a) with $d_p = 1.200$ and $d_w = 1.200$ mm; (b) with $d_p = 1.200$ and $d_w = 0.625$ mm.

In previous studies, it was demonstrated that under certain conditions, dynamics of the small chamber air gauges could be described in terms of the first-order system (Rucki & Jermak, 2012). Thus, it is possible to calculate the phase shift as following (Figliola & Beasley, 2006):

$$\varphi(\omega) = -\arctg(\omega T) \quad (2)$$

and

$$\varphi(\omega) = -\arctg\frac{Q(\omega)}{P(\omega)} \quad (3)$$

Hence, the sine response of the system could be described by formula:

$$y(t) = C e^{-t/T} + \frac{KA}{\sqrt{1+(\omega T)^2}} \sin[\omega t - \varphi(\omega)] \tag{4}$$

In Figure 3a, there are presented graphs of the theoretical phase shift calculated according to the formula (3) and the experimental one. It should be noted that for the examined case the 5% dynamic error is reached for the frequency $f_{0.95} = 2.6$ Hz shown in the amplitude-frequency characteristics in Figure 3b. This value corresponds with $\omega = 16.3$ and $\omega T = 0.33$. In that extend, the working frequency below 2.6 Hz is the object of interest. The analysis proved that in the point of $\omega T = 0.33$, the difference between the experiment and first-order dynamic system was smaller than 8%.

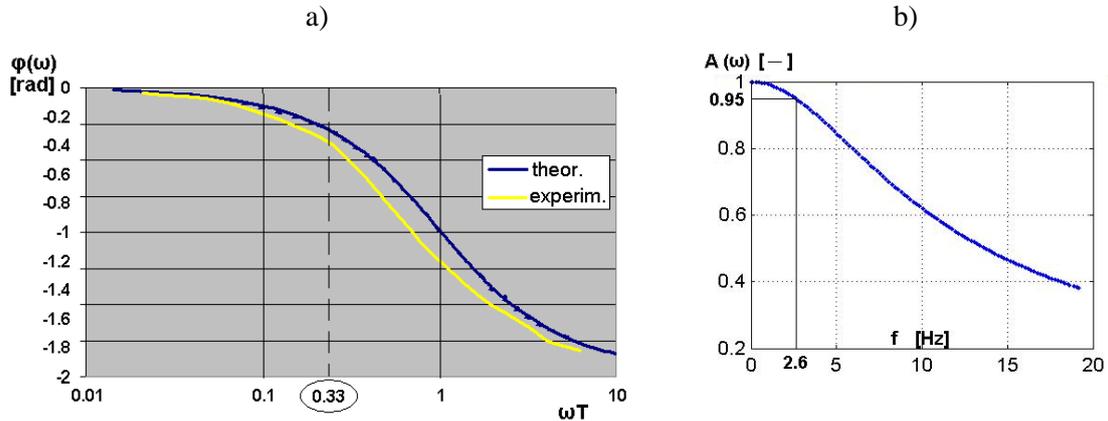


Figure 3. Dynamic characteristics of the examined air gauge with $d_p = 1.200$ and $d_w = 0.625$ mm: (a) Phase characteristics; (b) Amplitude-frequency characteristics.

4. Pressure-Dependent Time Constant

It was found that for the vessels with pressured air, in the process of emptying there is dependence of the time constant on the actual pressure in the vessel (Koscielny & Wozniak, 1995):

$$T = \frac{1}{M} \left(1 - \frac{p_a}{p_0} \right) \tag{5}$$

where: p_a, p_0 – atmospheric pressure and pressure in the vessel, respectively; M – factor of proportionality.

When such pressure dependence $T = f(p_k)$ is considered, the approximation with exponential function is much closer to the experimental results and fits to them with the error smaller than 3%. Figure 4a presents the graph of function $T = f(p_k)$, and Figure 4b shows how new approximation fits to the experimental results.

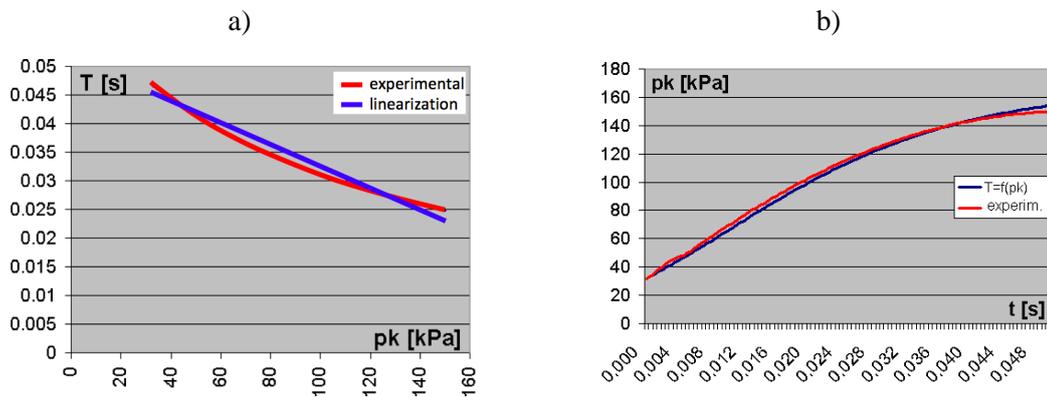


Figure 4. Dependence of the time constant on the air gauge with $d_p = 1.200$ and $d_w = 0.625$ mm: (a) Graph of the function $T = f(p_k)$; (b) Calculated step response considering the function $T = f(p_k)$ in comparison to the experimental data.

For the practical reasons in industrial applications, the function $T = f(p_k)$ can be linearized. Using the Least Square method, as it is shown in the Figure 9a with blue line, the linearization error is ca. 7%. However, exact analysis of the laboratory measurement results provided interesting observations specified below.

The functions of $T = f(p_k)$ for each examined air gauge configuration, appeared to be dependent on measuring chamber volume v_k with some distinguishable similarity. Figure 5 presents the graphs of time constants dependent on the back-pressure and slot width for the air gauges specified in the Table 1. It is seen that smaller volumes of measuring chambers and smaller multiplication K of the air gauge provide smaller sensitivity of time constant T to the actual back-pressure p_k .

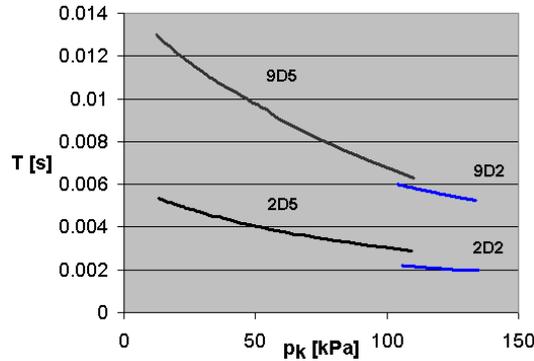


Figure 5. Examples of the $T = f(p_k)$ functions for the examined air gauges configurations.

From the Figure 5, following correlations can be derived.

As it could be expected, the time constant T is highly dependent on the measuring chamber volume and can be reduced ca. 50% when v_k is reduced from ca. 4.0 cm^3 down to 0.4 cm^3 . However, for the same volume v_k , decrease of the inner nozzle diameter d_w from 1.2 down to 0.6 mm, and subsequent increase of the multiplication K from 0.15 up to $0.88 \text{ kPa}/\mu\text{m}$ has substantial effect on the time constant. This effect is twofold. On the one hand it depends on actual back-pressure p_k , so that larger measured slot s within the same measuring range is measured with longer time constant T . On the other hand, the entire curve of $T(s)$ is placed a little higher for smaller d_w providing higher time constant for the same s and respective back-pressure p_k . In the examined cases, at $p_k = 110 \text{ kPa}$, black curves are placed little higher than the blue ones.

The most important observation is related to the curvature of $T(s)$ for different configurations of air gauges. In general, larger volumes v_k provided higher dependency of time constant on the back-pressure. In case of 2D2 configuration, the differences in time constant T for different p_k values are small and could be neglected. However, in case of 9D5 such a difference is more than 100%, from 6 up to 13 ms. In all cases, however, declination of the $T(s)$ curve is increasing with the increase of s and respective p_k .

Figure 6 shows schematic in-process control of the grinding with air gauges. After each stroke, the initial slot width s is enlarged with Depth Of Cut (DOC) value, causing respective back-pressure drop $\Delta p_k = p_{k1} - p_{k2}$. When the control system registers the final value p_{kf} , the grinding is finished.

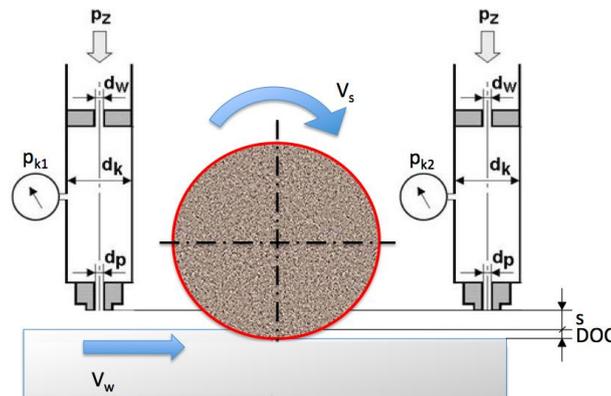


Figure 6. Scheme of the in-process measurement of the grinded plate

However, with larger slot width corresponds smaller back-pressure, which take place at the end of the machining process. In that very moment, the dynamics of the air gauge is the worst. Increased time constant provides the maximal possible dynamic error. Control device could identify the proper dimensional signal p_{kf} too late, and the process could go too far, removing too much material.

5. Conclusions

The theoretical analysis and experimental researches on dynamics of air gauges led to the conclusion that its time constant could be reduced down to several milliseconds. That could be reached when the pressure transducer has very small time constant, e.g. piezoresistive one with $T = 0.1$ ms. Next, the measuring chamber volume should be reduced down to few cm^3 or even less than 1 cm^3 . Under such a conditions, the air gauge reach time constant of several milliseconds and could be treated as a first-order dynamic system.

Obviously, smaller measuring chambers provide smaller time constants. It was proved, however, that the time constant of the high-multiplication air gauge is larger than that of low-multiplication ones. Moreover, the time constant depends on the actual value of back-pressure. In-situ measurement during the technological process requires high dynamics of the measurement device especially in the final stage of the machining. For the air gauges, that means the range of the lowest back-pressure, where the time constants are longest. The largest dynamic error in the most responsible moment of measurement could cause that the system would generate the control signal too late.

Thus, in-process application of air gauge demands more thorough analysis of time constant in the conditions of falling back-pressure, for its smallest values. It is important especially in case of high-multiplication air gauges with larger volumes of measuring chambers. Small volumes, e.g. less than 1 cm^3 , and low multiplication of the air gauge provide the time constant almost insensitive to the back-pressure changes.

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