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Air Gauging: Still Some Room for Development

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In the paper, history, present state and perspectives of air gauging are presented. The dimensional measurement with pressured air is known for almost 100 years. Its rapid development has taken place mostly in the years of the World War II, and during the next three decades many research papers have been published throughout the World. Some decline in the industrial application of the air gauges took place at the end of 20th century, but nowadays many enterprises rediscover merits of the air operated dimensional measurement.

Keywords

Measurement, Accuracy, Air Gauge, Quality, Mechanical Engineering

Why Air Gauging

"As electronics are increasingly used as the 'brains' of automatic machining, so air-operated gauges will be chosen as the 'eyes,' to assess and signal or send impulses, according to how the process is running." With this sentence Tanner [1] opened his review on history and future of the air gauging in 1958. Despite the incredible development of the measurement techniques, unimaginable 50 years ago, Tanner's introduction is still valid and actual, even though the principle of air gauging is known for a hundred years now.

Nowadays, the quality of the devices and other products sold annually for tens of billions Euro depends directly on the applied measurement techniques [2]. Automation of the machining processes is closely connected with the development of the measurement methods and devices [3]. Especially valuable in that context are non-contact measuring techniques [4], among others air gauges [5]. The quality requirements of the final product force the manufacturers to develop measurement accuracy continually, which leads to the measurement performed in micro and nanoscale [6], [7], and even subatomic measurement [8]. It is obvious that the air gauges where the measured dimension is transformed into the characteristics of the air flow, are unable to perform such a measurement, but they still find their application in the industrial precise measuring tasks like automatic control [9], in-process inspection [10] (both passive [11] and active type [12]), or untypical elements measurement, e.g. extremely long microbores [13].

During the in situ measurement, the unfavorable conditions (vibrations, dirt etc.) take place which make most of the devices unable to be applied. Here, air gauges seem to be certainly advantageous as compared to other measuring tools of any other work principle [14], mainly because of their insensitivity to the above factors, ability to perform non-contact measurement with high accuracy, and the self-cleaning of the measured surface with a stream of pressured air [15], [16].

What Air Gauging Actually Means

Different characteristics of the air flow represent the measured dimension in two main air gauging methods: flow (velocity) or back-pressure measurement [17]. In the first one, the measuring slot (directly dependent on the measured dimension) influences the airflow measured by the rotometer tube (flow type air gauge) or with a Ventury chamber (velocity type). In the second method, the pressured air passes through so-called measuring chamber with an inlet restriction (nozzle or valve), and then goes out through the measuring slot which works as a flapper-nozzle valve. The obvious relation $p_k = f(s)$ between the slot width s and pressure in the chamber p_k is: the wider is the slot, the lower drops the back-pressure. Various kinds of pressure transducers could be applied, which mainly determine the accuracy and especially dynamical characteristics of the air gauge [18].

Thus, the air gauge could be defined as a unit consisting of measuring (outlet) nozzle of diameter d_p, restricting (inlet) nozzle of diameter d_w (or an adjustable valve) and the chamber between them called the measuring chamber [19] where back-pressure p_k is being measured. The measuring nozzle could be inserted into the gauging heads of various constructions and tasks [14], and it receive the information on the dimension of the measured surface. So then, air gauge means both simple probe for one-point measurement of dimensional changes, and pneumatic gauging heads for the multipoint measurement of e.g. round details [20], [21]. Nowadays, air gauging devices are equipped with specialized electronic units to convert the signal from pneumatic into electronic one and to process it, as well as to cooperate with supervising computer system, to create database, to control external devices and so on [22].

How Did It All Begin

Air gauging has been probably for the first time applied for the dimensional measurement at the end of the First World War or shortly after [1]. At the beginning of the 20th century, the rapid development of the motor industry required precise devices for quick dimensional inspection and accurate selection of the details. This task was solved for the carburetor jets by Marcel Mennesson in France who proposed the back-pressure air gauges. By the end of the second decade of 20th century, the devices under the name “Solex” were widely introduced to the market.

However, it was not until 1932 when the air gauging process was first analyzed and described scientifically. In April 1932 Marcel Mennesson presented to a sitting of the French Academy of Science a paper presenting the basic principle of linear dimensional measurement with the pressured air [23]. A supply of air at constant pressure, regulated to within 1 mm of water, flows through a calibrated orifice into a vessel and then through the second orifice outside. The measured object was placed in front of the second orifice, and the pressure between those two orifices was measured by the water manometer. Five years later at least 6 scientific papers highlighting the air gauges were presented at the symposium of the French Society of Mechanical Engineers [24]. Among others, such interesting applications as the measurement of materials strength and surface conditions were discussed. Long before the outbreak of the World War II, numerous application of the air gauges were invented, but the War pressed the industrial world to develop a wide variety of the air gauges.

In 1947, E. Göthel [25] worked out an approximate theoretical air flow relations, but still recommended empirical calibration of the instrument. In 1950, R. Molle tried to summarize the laws governing pneumatic metrology [26]. By the end of 50ths, over 30 companies produced various types of the air gauges throughout the World, and they were widely implemented in the industrial enterprises of the Communist countries [27]. It seemed, however, that any further development of air gauges was very difficult or even impossible, mostly because of the long response time of the devices. The investigations on the improvement of the air gauge dynamics were undertaken worldwide [28], [29], [30], and an analog computer was used to simulate dynamic air gaging [31].

Rise and Decline

During the 60ths and 70ths, the air gauges became an important part of the metrological sciences. Numerous researches were undertaken to work out the theoretical background for gas dynamics and other phenomena that took place in the flow-through elements [32], [33], [34], [35], [36]. Fundamental theoretical formulas were proposed to approximate the parameters of air gauges and their characteristics [37]. In general, however, it was admitted that the exact solutions of the formulas is unreachable, so every model contained some simplifying assumptions. Nevertheless, new devices were developed, supplied with higher pressure of 150÷300 kPa [38], able to keep the required measurement accuracy of several micrometers and the settling time of few seconds. Differential and bridge systems were introduced in order to reduce influence of the feeding pressure instability and temperature changes on the measurement accuracy [14]. As the highly automatized manufacturing systems emerged, the application area of the air gauges grew wider, so the complicated measurement and control systems based on the pneumatics arose [39], [40]. A typical air gauge-based measurement automaton was able to inspect up to 1000 details per hour [27].

The last two decades of the 20th century, however, revealed less interest expressed to the air gauging, because many new measuring methods and measuring machines were developed. Some additional problems appeared with the inclusion of the air gauges into the new computer-based measurement systems. Conversion of the pneumatic signal into digital measurement information seemed to be the main obstacle [41]. Liquid columns did not satisfy the customers any more. Mechanical manometers based on Bourdon tube, diaphragms or bellows required additional devices like potentiometers to obtain electrical signals. Moreover, the dead volume of those devices generated too long settling time, up to few seconds, which became inacceptable for the industrial applications [42].

Even though it was the time of development of piezoresistive pressure transducers [43], researchers turned their attention and efforts to the new measuring methods, leaving air gauging aside. Very few papers were published at that period on the air gauges, compared to the variety and number of previous works. In the meantime, piezoresistive transducers gained the temperature compensation providing quick and accurate measurement with an electronic output ready to be processed [44].

Renaissance of the Air Gauging

The undisputable merits of the air gauges made them not to be eventually replaced by other measuring techniques. In the beginning of the 21st century they became a subject of scientific interest again [45]. Leading producers of measuring tools introduced into their catalogues the air gauges equipped with piezoresistive pressure transducers, leaving alone such companies like Solex or Neberding that never gave up on the air gauging.

New investigations lead to the development of the new constructions of the air gauges providing better metrological characteristics [46]. The examples of new solutions could be the air gauges with corrected nozzle [47], polygonal orifice [48] or conical nozzles [49]. Simple but effective solutions are asymmetrical injectors [50] or double-nozzled solutions [51].

Application of the piezoresistive pressure transducers allowed to integrate the air gauges with the measurement system and quality control [22]. An example of such solution could be the new PNEUTRONIK device developed by Institute of Advanced Technologies (Cracow, Poland) in cooperation with Division of Metrology and Measurement Systems (Poznan University of Technology, Poland) [52]. The concept found its continuation and further development in the advanced measuring device PneuStar based on air gauge. The device was awarded with the Golden Medal at the Warsaw Exhibition of Innovations and Inventions (IWIS 2010) and Silver Medal at Brussels Innova Eureka Competition.

Thanks to the development of the computing techniques, complicated and extended calculations and simulations became possible to be performed. Thus, the existing methods of exact prediction of a static characteristic dependent on the geometrical features of the projected air gauge underwent the reevaluation. Based on the ε–k model, the flow through the air gauge elements (orifices and chamber, and measuring slot) was described and simulated, and compared with the empirical data [53]. To calculate the static characteristics, most of the known models were included into comparative analysis, and it was found out that the closest to empirical data was the model based on the second critical parameters of the nozzles [54]. It is recommended for accurate theoretical calculation of the air gauge static characteristics, especially in the precise measurement.

Since the dynamical characteristics had been one of the main obstacles in air gauges development [55], some steps were undertaken to solve the problem. The time constant of a typical piezoresistive transducer is ca. 0.1 ms, thus the application of the piezoresistive transducers instead of clumsy mechanical analog manometers eliminates the slowest element of the system [18]. This way the time constants of few milliseconds became achievable, and the air gauges found their way to many contemporary measurement systems to perform the tasks requiring high dynamic characteristics. It was found, however, that the proposed simplified models of air gauge dynamics could introduce the dynamic error even of 50%. Additionally, it was proved experimentally that the time constant of the air gauge is dependent on the actual back-pressure and differs in different areas of the measuring range. As the measured displacement gets larger, the dynamics of the air gauge gets worse, and its time constant could become even 100% longer [56]. This knowledge is of extreme importance especially for the in-process control, where the slot is widening because of the material removal during the machining. The research papers prove that the air gauges are still applied in in-process inspection. For example, Shiraishi et al. [57] described the air gauge measurement during turning operation, and Pudovkin et al. [58] investigated the in-process air gauging, too, but they did not consider the problem with the time constant changes.

Nowadays, the air gauges are applied also in the form measurement to evaluate roundness or cylindricity. Several companies included such a devices into their offer, and further investigations are ongoing. The team of Division of Metrology and Measurement Systems (Poznan University of Technology, Poland) worked out a dedicated device for the roundness measurement in three intersections of the cylinder (tolerance of T_D = 10÷15 μm) [59]. The patented measuring head with built-in air gauges ensures the amplification of K = 0,5 kPa/μm in the range of z_p = 100 μm, and time constant T of few milliseconds. The single circle is measured in 10 seconds, and the collected data are processed by the computer.

Similarly, high dynamic characteristics is required in the measurement of the profile [60] or surface topography [61]. Menzies and Koshy [62] applied the air gauge to the porosity identification. The examined surface is moved along the measuring nozzle, and it works excellently with any kind of the measured material. The response time of the pressure transducer is 2 µs which ensure good dynamics of the entire system. Also some biomedical applications made use of the flapper-nozzle systems [63].

Conclusion

During about a century of their application and development, the air gauges did not change much in principle. In fact, they were improved continuously together with the developing technology and were able to meet more and more strict requirements. The advantages of air gauging seem still not to be exploited fully both in typical measurement or inspection tasks and in new application areas. Apart of the possibility to describe the phenomena and to calculate the characteristics more accurately, or to apply new precise transducers with high dynamics, some constructional changes can be introduced to achieve still better metrological characteristics.

It seems rather impossible to improve air gauges accuracy better than 0.1 µm, despite of some attempts undertaken [64]. However, there are plenty of industrial applications where the measurement uncertainty and dynamic properties of the air gauges could be considered very good. Along with non-contact measurement, good dynamic characteristics and high resistance to the environmental conditions, accuracy and reliability of air gauges will be decisive factors of their application in the future. Thus we can say, like some 60 years ago Tanner did, “The compressed air industry can foresee the ever-increasing use of air gauges” [1]. ■

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