The Principles and Applications of Pneumatic Gauging

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HISTORY
The basic principle of blowing a jet from a nozzle against the surface of a workpiece to be measured is thought to have been known to scientists of the 19th century, but the first application of the principle can be traced through technical and potent literature as far back as 1917.

In the application at that time, the medium used was a liquid, and it was not until about 10 years later that a system using compressed air for engineering measuring systems was developed by a company in France. The first well-known application was in the standardizing of jets for carburetors.

The pressing military demands of the 1940s gave increased impetus to the development of air gauging, and by 1948 several systems were available. Industry in the United States was quick to appreciate the benefits that air gauging instruments had to offer, and these were put to extensive use particularly in the automobile industry.

At the metrology division of the National Physical Laboratory (NPL) in England, study of the pneumatic method of gauging began during the 1939-45 war years, and subsequent theoretical and practical investigations were undertaken to obtain design data. Notes written by Evans, Graneek, and Morgan were published by the NPL and are considered to be classic works on the subject.

Principles
By controlling the supply of compressed air to a system, either the flow or pressure characteristics within the system can be interpreted to determine the dimensional relationship between a nozzle and

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the surface of a workpiece. Simple flow or pressure indicators can be used to reliably display the dimensional relationship.

SIMPLE FLOW MEASURING CIRCUIT
A simple flow responsive system is shown diagrammatically in Figure 1a. In this system, compressed air at a constant, closely controlled pressure is passed through a variable flow meter (that is, a float in a tapered glass tube) and then to a suitable nozzle. The air from the nozzle impinges on the surface placed in front of the nozzle, and if the surface is moved toward or away from the nozzle the flow of air changes and the float in the tube moves accordingly.

Calibration can be carried out by applying known displacements to the surface. The graph in shown in Figure 1b shows a typical curve shape, relating air flow to the clearance between the nozzle and the surface.

Figure 1a shows a new flow system with air electronic converter (Michel L. Dechape, “Pneumatic gauging system A.K.A. air gauging system A.K.A. air electric converter,” U.S. Patent No. 7,694,549, Apr. 13, 2010). The calibration graph in Figure 1d shows the linearity of the new flow system.
Figure 2 shows further detail from Dechape’s 2010 patent. Figure 3 compares the essential components of the previous and new air gage systems.
Figure 2

Figure 3
Essential components of the previous (left) and new (right) air gage systems (Dechape figure)
Simple Back Pressure Circuit

*Figure 4a* shows a simple back pressure circuit. In this circuit, compressed air from the pressure regulator passes through a primary restrictor, commonly called the control orifice, before entering the cavity upstream of the escape orifice. Due to the presence of the primary restriction, changes in the restrictive effect of the escape orifice will give rise to changes in pressure in the cavity between the two orifices. Changes in the restrictive effect of the escape orifice are made by moving the surface toward or away from the nozzle face. Changes in pressure inside the cavity can be measured by a pressure indicator such as a Bourdon tube type pressure gauge.

Again, calibration of such a system can be carried out by applying known displacements to the surface. *Figure 4b* shows a typical curve shape relating pressure ($p$) in the cavity to the clearance ($L$) between nozzle face and surface.

One of the disadvantages of this circuit is that it requires compressed air at a constant, closely controlled pressure; otherwise, the readings will vary proportionately to the variations of the input pressure.

Simple Back Pressure Circuit Experimental Rig

An experimental rig with which any air gauging circuit can be studied is shown in *Figure 5a*. The pressure/clearance curves obtained using a 0.55 mm (.02”) diameter control orifice and nozzles of 1 mm (.04”), 1.5 mm (.06”), and 2.0 mm (.08”) are shown in *Figure 5b*. *Figure 5c* shows the three different slopes of output vs. clearance under the same conditions using the new flow system. (Of course, the 0.55 mm control orifice does not apply to the new flow system.)
It will be clear that when the micrometer anvil is in contact with and sealing the nozzles, the pressure indicated on the gauge will be equal to the pressure at which the supply is regulated. Thus, the three curves have the same point of origin on the ‘p’ axis.

Other obvious conclusions that can be drawn from the three curves of Figure 5b are that the curves are not the same but are similar in shape, and the range of measurement is fairly small, say, 0.125 mm (.005”) in the case of the 1.0 mm diameter nozzle.

For the new flow system, Figure 5c, the three plots start at zero output for zero clearance and show that the sensitivity of the system is proportional to the diameter of the nozzle and their number (plug gauges...
can have two, three, or four nozzles to increase sensitivity and other reasons). Furthermore, the system is linear to at least 0.25 mm (.01”), which translates to 0.5 mm (.02”) for a diameter measurement.

**Area of the Escape Orifice**

Before any further theoretical study of air gauge circuits is carried out, the area of the escape orifice should be considered, as follows:

When the clearance between the surface and the nozzle face is zero, no air escapes from the nozzle, and the area of the escape orifice is zero.

When the clearance between the surface and the nozzle face is very large, the area of the escape orifice is \( \pi D^2 \), where \( D \) is the diameter of the nozzle.

Between these extremes, especially where the clearance is small and where air gauging can be employed, the area of the escape orifice is \( \pi L(D - L/L) \), that is, the area of the curved surface of the cylinder shown in Figure 6.

![Figure 6](image)

**Area of the Escape Orifice**

(Burrows figure)

**Linearity and Sensitivity**

If the experimental rig shown in Figure 5a is used for more detailed study, it can be shown that between certain limits ‘\( p \)’ is inversely proportional to the area of the escape orifice. In fact, between certain useful limits the pressure/escape orifice area relationship is linear within 1%. If a lower order of linearity is acceptable, say within 2%, the measuring range is very usefully extended. These are conditions that are met by good commercial air gauge systems. Note: To operate in this small 1% linear range requires complex precision machining of the gauge head.

With the new air electric converter, which is linear from zero clearance to full scale, there is no complex machining, and for a plug gauge, its diameter, if measured accurately, can be used as the “Lo Master,” needing only one “Hi Master” to perform the calibration.
If the experimental rig is used to obtain figures for plotting pressure against the escape orifice area using a number of different sizes of the control orifice, it will be found that sensitivity increases as the diameter of the control orifice decreases; that is, for small control orifices the change in pressure is greater for a given change in escape orifice area. This is important because some commercial systems incorporate a variable control orifice, the use of which enables sensitivity (magnification) to be set precisely.

Simple back pressure circuits should not be considered for new applications.

Differential Back Pressure
The circuit shown in Figure 7a is a differential back pressure circuit in which accuracy is maintained regardless of some variation in the regulator performance that controls supply pressure. This is now obsolete.

Figure 7b shows a differential back pressure circuit with solid state differential pressure transducer, which is the gold standard of differential back pressure air electronic converters (Michel L. Dechape, “Pneumatic gauging circuit,” U.S. Patent No. 4,550,592, Nov. 5, 1985).

Practical Flow Responsive System
A practical flow responsive system that was in common use is shown in Figure 8. This also employed variable orifices for sensitivity and datum control. This is practically obsolete. Newer readout instruments display actual values or deviations from mean value in actual metric or British units.
Applications
In addition to simple dimensional measurement, air gauging was developed to an extent where it was used to control precise and complex machining and other processes. In 2013, air gauging is still alive and kicking and has many advantages over any other gauging system when it comes to in-process gauging, such as for grinding or lapping, or in harsh environments such as heat, cold, caustic, explosive, or nuclear. The instrumentation can reside in a safe environment and send the air supply to the open jet or gauging cartridge via stainless steel tubing. Using the new flow system allows unlimited length without degrading the accuracy of the system.

Now, many applications for air gauging have been taken over by electronic gauging, but some forms of measurement are still ideally performed pneumatically, and it is these that we can usefully consider.

In view of the recent improvements in air electronic converters, the trend will be reversed once engineers and designers realize the potential in simplified tooling and the ability to perform measurements that were not possible even with electronic gauges. The lower cost, the ruggedness, and the previously mentioned advantages of air gauging should make it possible.

Measuring Head
So far, only air gauge circuits and indicators have been considered, but it is the measuring head, by means of which the variable being measured is made to control the air flow, that adapts the system to any specific problem of measurement.

Air Plug Gauges
The simplest form of air gauging head in common use is the air plug gauge. Many thousands of air plug gauges are in daily use providing industry with an economical and easily used facility for the precise comparative measurement of internal diameters.

The conventional open jet air plug gauge is an essentially simple device. Compressed air from the air gauge indicating unit is passed to the plug gauge and is allowed to issue from two or more jets in the periphery. The traditional design of a two-jet air plug is shown in Figures 9a and 9b.

When the air plug gauge is inserted into a hole, the air escaping from the jets is limited by the clearance between the jet faces and the hole. The small changes in clearance, arising when the air plug gauge is inserted in successive holes of differing sizes, produce changes in the flow rate or back pressure in the circuit.

Calibration is carried out with master holes, that is, two setting rings, the diameters of their bores being known to a high degree of accuracy. One Min Master determines the lower limit and a Max Master the upper.

With the new flow system, which is linear from zero clearance to full scale, jet recession is no longer needed (Figure 9b compared with Figure 9c), bringing new advantages such as easier design and less expensive machining.
With the plug gauge made .002” to .004” (50 to 100 microns) smaller than the minimum diameter, drilling the jets directly through the body of the plug is sufficient. The larger clearance will ease insertion of the plug and minimize wear.

The biggest advantage is that the diameter of the plug can be used as the Min Master by pinching the tubing to the plug to simulate a zero clearance. The finished diameter of the plug should be measured to a high degree of accuracy to be used as the Min Master. Only one Max Master is required to complete the calibration.

For measuring holes smaller than 2.5 mm (.1”) diameter, the hole itself can be used as the escape orifice. The output will be proportional to the square of the diameter of the measured hole.

Again, by calibrating the system with a master hole, it will provide measurements indicating the amount of oversize or undersize of each hole being gauged.

**USE OF AIR ELECTRONICS**
Currently, and for many years, the terms air electric or air electronic converters have been used for instruments doing air gauging and producing an electrical signal proportional to the measurement.

It started with using a position transducer (LVDT, RVDT, …) in back pressure nonelectric instruments to measure the displacement of the membranes (or Bourdon tubes or bellows) used in those instruments to respond to pressure changes related to part size.

This allowed the display of results on an electronic column to simulate the original flow system and provide an electrical signal for further processing by the rudimentary equipment of the 1970s.

However, this addition to the original back pressure systems did not cure the problems (hysteresis, wear, friction, vibrations, and temperature effects, common in the early mechanical systems having several moving parts), and in some cases it made it worse.

The first truly air electronic converter, shown in Figure 7b, was patented in 1985 (U.S. Patent No. 4,550,592). This version of air electronic converter has no moving parts, outside of a zero and a spread adjustment. It is a differential back pressure system. Its solid-state electronics produce analog and/or digital outputs proportional to the measurement made with open jet, air plug gauge, or air gauging cartridge.

In 2010, a new air electronic converter was patented (U.S. Patent No. 7,694,549). This new principle, shown in Figures 1c and 2, provides a larger, linear range of measurement than back pressure systems, from zero clearance to .010” (.25 mm) for a single open jet or .020” (.5 mm) for a diameter
measurement. With no pressure drop in the circuit, the air pressure at the nozzle(s) remains constant regardless of the clearance. This is not the case with existing back pressure systems.

This new principle does not require a closely controlled input pressure, nor any special air filtering. Other advantages are:

- No fixed or adjustable orifices that could become clogged or be tampered with,
- No moving parts that can wear and cause erratic measurements,
- No maintenance required,

all of which contribute to the reliability, repeatability, and stability of the instrument. Electronic circuitry provides fast-responding analog and/or digital outputs for direct connection to instrumentation or computerized gauging systems and machine tool controls.

Other examples of air electronic measurement applications are (shown in Figure 10):

- Diameters, in/out
- Thickness
- Parallelism
- Squareness
- Conicity, in/out
- Center distance
- Taper
- Concentricity
- Matching, bore/shaft
- Flatness
- Gap gauging
- Orifice sizing/matching
- Leak testing
- Continuous wire gauging
- Continuous wire coating gauging
Advantages of Air Plug Gauges

Air plug gauges have the following advantages:

- They are of simple construction (no moving parts).
- Their cost is even lower when made for the new flow system.

Air plug gauges have the following advantages over solid GO/NOT GO plug gauges:

- No operator skill or judgment is necessary because air plug gauges are used in conjunction with an indicating instrument, and any user will obtain the same indicated reading for a given size of hole.
- Larger clearance between the air plug gauge body and a hole at the low limit of size reduces wear on the gauge, and limited wear has no significant effect on air plug gauge performance.
• Errors of form can be detected with an air plug gauge that are not possible to be detected with solid plug gauges, such as taper, bell mouthing, barreling, ovality, and lobing (using a three-jet plug) (see Figure 11).
• Air plug gauges made for the new flow system have a range of ±0.01” (±0.25 mm), compared with most gauging that is in the range of ±0.002 (±50 microns).

**Figure 11**
Errors of Form in Holes
(Burrows figure)

**Hole Straightness Gauging**
Many modern mechanical assemblies demand that holes should be closely controlled for straightness as well as diameter. An air plug gauge for gauging hole straightness is shown in *Figure 12.*
Effect of Surface Roughness
If air from the jets of an air plug gauge impinges on the rough surface of a bore, the size is measured approximately midway between the peaks and valleys of the surface roughness. This subject is controversial. First, machined parts held to close tolerances are somewhat unlikely to have a rough finish. Second, the Masters used to calibrate the gauging system could be machined with the same tool to match the finish of the parts to be gauged, nulling this effect. Lastly, air cartridges can be used, making it a contact-type gauging, or as follows:

For the measurement of bores with rough surfaces, contact-type gauging elements are interposed between the jet faces and the bore surfaces, and the size of the bore that is functionally important is measured, for example, the smallest diameter formed by the peaks of the surface roughness.

Contacting elements are also interposed between the jets and the surfaces, where the surfaces being measured are porous.

Indirect Pneumatic Gauging Devices
It has already been said that open jets have the disadvantage of small measuring ranges. This is not really true. Their range is much larger than the tolerances used in quality control of machined parts, and air gauge indicators can be used for larger ranges if a gauging cartridge is used. Such cartridges employ a contacting stylus, the inner end of which is tapered and forms the restriction in an escape orifice. The position of the stylus and consequently the position of the taper in the orifice causes changes in the area of the orifice. Changes in the rate of the taper change the measuring range of the cartridge.
If necessary, measuring ranges up to 10 mm (.4”) can be obtained easily with this type of cartridge, which is available but rarely used. These cartridges look and have the same size as electronic probes (LVDTs or LVRTs), and if air gauging is in use for some measurements, the air cartridges should be used in place of electronic probes, which are more expensive, more fragile, and require other electronics.

One area where these long-range cartridges can replace electronic probes is in harsh conditions such as high temperature, toxic environment, or explosive gases. The cartridges are made of stainless steel, and the air supply from the air electronic converter (in another room) can be brought in with stainless steel tubing. All of that equipment can withstand anything.

**Other Applications Where Air Gauging has Advantages**

In addition to gauging hole size and geometry, air gauging has other applications where it is still a most suitable medium, for example, for the noncontact thickness gauging of soft and fragile materials such as plastic film and thin foils.

**Centerless Grinding Machine, Honing Machine, and CNC Machine Control:** Noncontacting open jets can be machined as an integral part of a honing machine mandrel, and these can be fed with air from an air electronic converter. Outputs from the converter can be used to control the operation or stop the machine at a predetermined size regardless of tool wear. The advantage of air gauging under these abrasive conditions is quite clear.

**CONCLUSIONS**

Pneumatic gauging is a reliable and precise system of measurement. It served industry well for a long period before electronic gauging became a reliable and economical workshop system.

The advances in measuring the flow of the air using the new principle make air gauging much more valuable than it has ever been, for the following reasons:

- Linear measurements over a range four times that of previous systems.
- Easier tooling design and machining. (Lower cost.)
- Easy to operate (no adjustments and no maintenance).
- Air consumption is one-fifth that of previous systems. (Cost reduction.)
- No need for air preparation or precise regulation. (Cost reduction.)
- Precise and repeatable measurements. (Microinch resolution.)

There is no application where pneumatic gauging is not suitable (unless compressed air is not available). The only requirement is to design the appropriate gauge head and fixture and use the best air electronic converter.