UNEXPECTED ENCOUNTERS

Rolling-element bearings developed in the last century were a revolutionary improvement over the plain bearings that had been pushed to their limits in applications like electric motors and automobile wheels. Air bearings can likewise be seen to represent the next logical step in bearing design. These may be exploited by mechanical engineers to extend their design capabilities for precision manufacturing systems.

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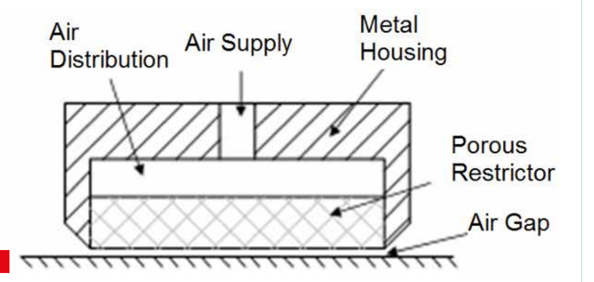
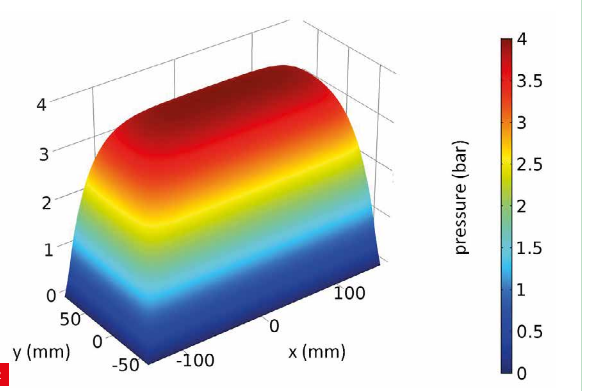
Air bearings use a thin film of pressurised gas to provide a low-friction, load-bearing interface between surfaces. As the two surfaces do not touch, the traditional bearing-related problems of friction, wear, particulates, and lubricant handling can be avoided. The use of air bearings in certain precision systems is well established due to the distinct advantages they offer in precision positioning, such as zero backlash and constant static/dynamic coefficients of friction, so no stick-slip. Thus they have been exploited in applications such as ultra-precision lithography machines and coordinate measuring machines (CMMs).

Low friction also means less heat generation, so less thermal disturbance, and minimal power loss for high-speed applications, such as precision spindles. While any heat generation is of course not zero, relative surface speeds of the order of 30 m/s must be reached before significant heat can be measured.

In the field of air bearings, separation is typically made between aerostatic and aerodynamic bearings. In aerodynamic bearings the cushion of air is formed through the relative motion of static and moving parts; in contrast aerostatic bearings are externally pressurised. This article will focus on the application of aerostatic air bearings, with examples of recent applications where you might not expect to see air bearings.



1 Cross-section of a typical porous air bearing.



2 Simulated air gap pressure distribution for a 150mm x 300mm rectangular porous air bearing.

Surprising load capacities

The fluid film in an aerostatic bearing is achieved by supplying a flow of air through the bearing face and into the bearing gap. This is typically accomplished through an orifice or a porous medium, which restricts or meters the flow of air into the gap (Figure 1). Porous-media restrictors have the advantage of offering greater uniformity and stability (Figure 2). The restriction is designed such that the flow of pressurised air through the restriction is sufficient to match the flow constantly escaping from the bearing gap. The restriction maintains the pressure under the bearing and supports the working load. It is used to optimise the bearing with respect to lift, load, and stiffness for particular applications.

Figure 3 shows the typical load capacity for rectangular (porous) air bearings across a range of bearing sizes. The load capacity can be surprisingly high – for example a bearing just 40 mm x 80 mm in size can support the weight of a typical (European) female and a 150mm x 300mm bearing the 15,000N load of a fully grown rhinoceros. At a load of 11,000 N, such a bearing can provide stiffness (Δload/Δlift) of 1,645 N/μm at a fly height of 5 μm. Or in other words, it will displace 0.6 nm for each extra load of 1 N.

EDITORIAL NOTE

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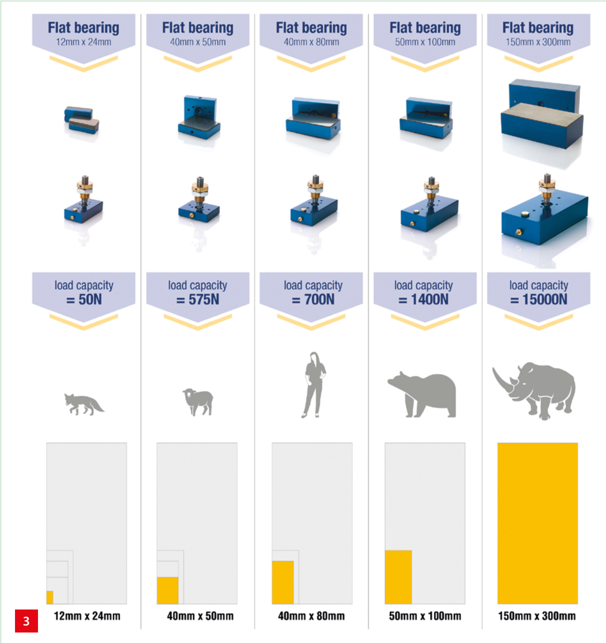
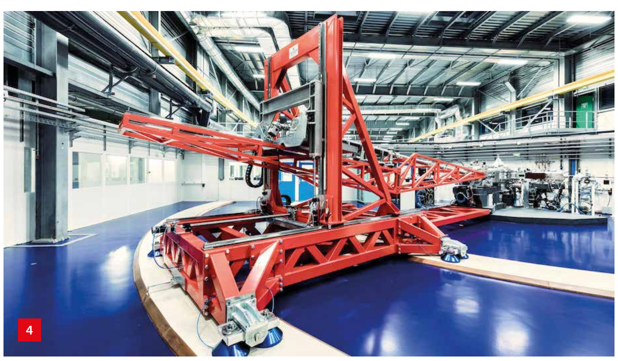


3 *Precision and strength combined; typical load capacity for rectangular air bearings.*

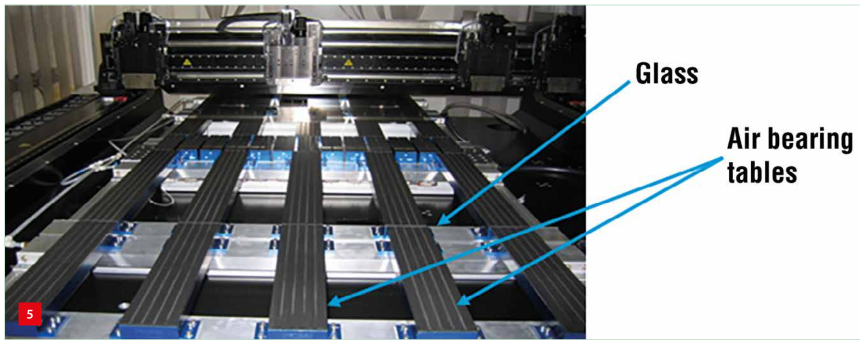
A recent example of an instrument required to move such a large mass with great precision is the new high-resolution soft X-ray spectrometer (RIXS) at the ESRF (European Synchrotron Radiation Facility) in Grenoble, France. This flagship instrument is required to rotate 6.3 ton (62,000 N) of detector continuously through 100° about the sample at a radius of 11 m to capture a precise 3D image. This is achieved on only eight 300mm diameter round air bearings (Figure 4). The designers of this instrument were recently announced winners of the 2018 Europhysics Prize of the Condensed Matter Division of the European Physical Society.

Stiffness

The typical fly heights for loads on porous air bearings are of the order of 10s to 100s of µm. In some applications vertical positioning and stiffness in the z-direction is critical. The flat-panel display manufacturing industry, for example, has stringent requirements for the handling, processing and inspection of the glass. Precision, non-contact handling of the glass is required for both optical inspection and for LCD printing (Figure 5).



4 *RIXS spectrometer of the ESRF ID32 beamline. The detector can sweep a 100° circle segment about the sample moving on 300mm diameter round air bearings. (Credit: ESRF/ Stef Cande)*



5 *Flat-panel display glass processing unit showing air bearing tables for glass transport.*

Here, air bearings with so-called vacuum pre-loading are used to control the vertical height within ±5 µm. In such air bearings, regions of sub-atmospheric pressure ('vacuum holes or grooves') are distributed within the bearing region and used to reduce the levitation height and improve the out-of-plane stiffness [1]. The vacuum channels act as the equivalent of a preload, reducing the sensitivity to variation in the transported substrate, with zero additional mass. Similar techniques are also used in photovoltaic solar panel processing.

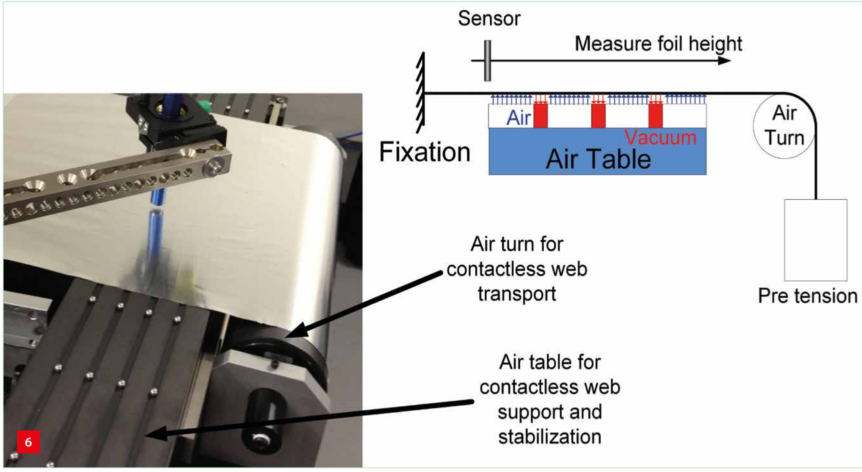
Roll-to-roll

The development of flexible devices for use in consumer electronics has recently attracted much interest. In addition, Internet-of-Things technology requires low-cost ubiquitous and disposable electronic devices. Roll-to-roll (R2R) manufacturing is a highly productive manufacturing process that can be used to print electronics and resolve issues of cost and flexibility [2].

Three main process parameters are important in R2R manufacturing: 1) web tension; 2) web position/speed; and 3) printing force. As printed electronics become more sophisticated and more integrated, these parameters require higher accuracy. Furthermore, newly developed functional inks for printed electronics are typically very sensitive; thus contact with the printed surface should be avoided wherever possible.
The application of air bearings in R2R processes offers improvements in the accuracy of the web positioning and speed. Avoiding web contact also offers reduced damage and contamination on sensitive foils.

Non-contact conveying

Conveyor air bearings, or air tables, normally used for transport of rigid substrates, may be applied for web transport. In such air tables, vacuum grooves are used to pull the supported web towards the air bearing, improving stiffness and stability at a given fly height. Using a capacitive sensor and a metal-coated foil as shown in Figure 6, fly height and deformation of a flexible foil can be investigated. In this instance a 300mm wide, 50µm thick foil has been assessed.



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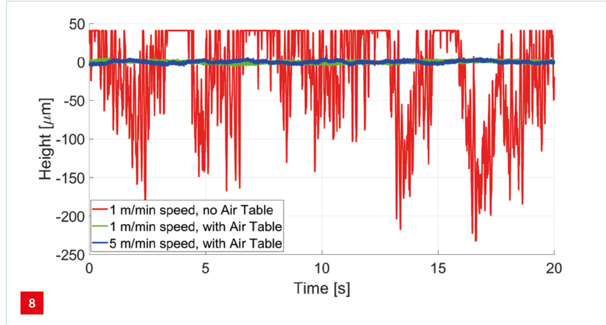

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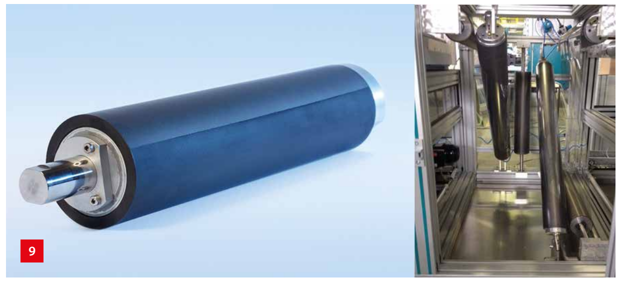
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6 *Air table measurement set-up.*

7 *Air table with vacuum grooves (left). Foil fly height above the air table (right) in the tension direction using 2 bar air pressure, 0 to –0.3 bar vacuum (i.e., below ambient).*

8 *Foil height over time with and without air table support.*

9 *Cylindrical air turn (left) installed in an R2R line (right).*

10 *Foil fly height as a function of position over a 300mm diameter air turn.*

Figure 7 shows the fly height and form in the length (tension) direction of the foil, as a function of vacuum pressure with the air bearings pressurised to 2 bar. This data confirms that at optimal vacuum/pressure settings, a foil height variation < 5 μm over 55 mm can be achieved in the tension direction. The height variation in a lateral direction was less than 15 μm, measured over 200 mm of foil width.

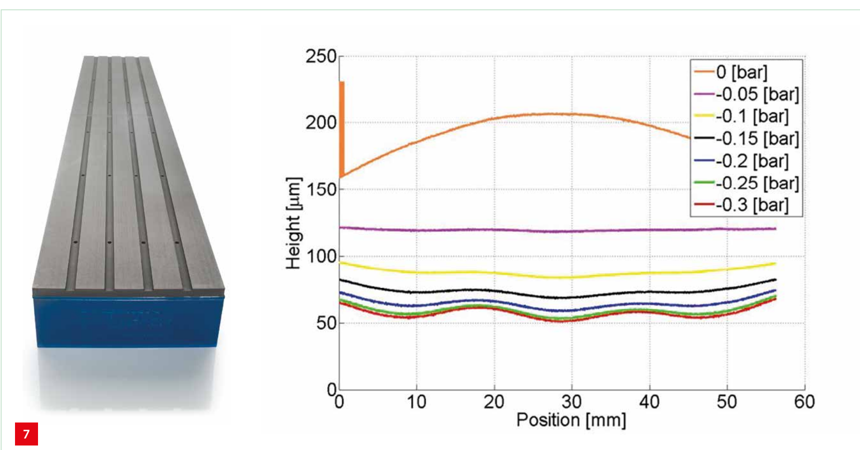
To test the capability of the air table to reduce vibrations in a moving foil, measurements were completed in cooperation with Eight19, Cambridge, UK. Integrated in an R2R line, the foil height was measured with a capacitive displacement sensor. Without support by the air table, vibrations of more than 250 μm were seen in the foil (Figure 8). With the air table, these vibrations were reduced to < ±5 μm. The measurement was repeated with 1 and 5 m/min foil velocity. No significant difference between these measurements was seen. Such foil stabilisation has important advantages for applications such as inkjet printing where foil stabilities in the vertical direction below 50 μm are often required.

Porous-media air bearings are often used in cleanroom applications. Results of tests done by the manufacturer indicate that the porous air bearings produce less than 1,000 particles > 0.1 μm per m^3 of exhausted air.

Contactless rollers

Cylindrical porous-media air bearings, or air turns, can be used as replacement idler rollers, i.e. non-driving contact rollers, for web transport, as shown in Figure 9. A web can be wrapped over the air turn, in the same way as with a roller. In this case, the air layer not only supports the foil without contact but also serves to flatten out any wrinkles as seen in Figure 10.

For traditional rollers, foils such as PET can become charged by the order of 5 keV as they pass over an individual roller. Such static build up has to be compensated to prevent disruption to processes. For such air turns, as the foil does not touch the roller, no charging occurs. This removes the need for static discharge bars to be applied before printing actions that can be sensitive to a charged foil, such as inkjet printing.



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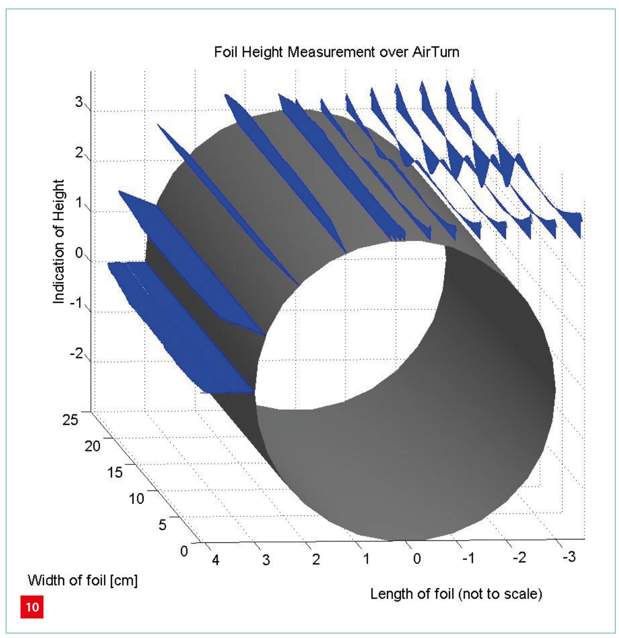

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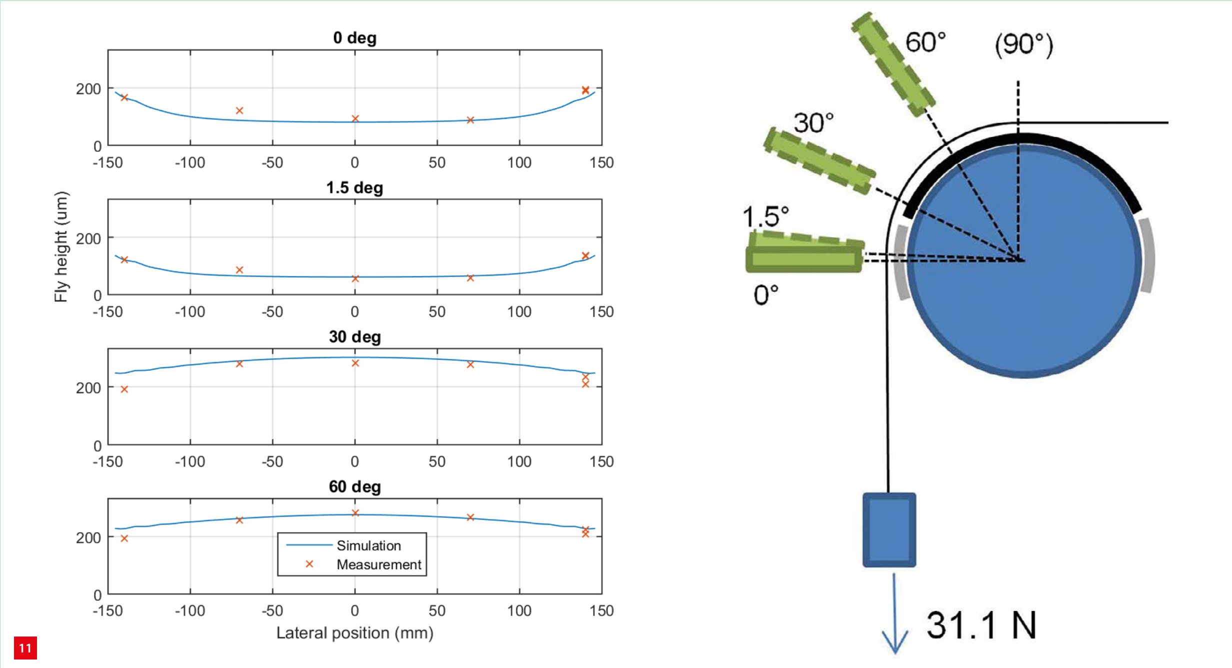
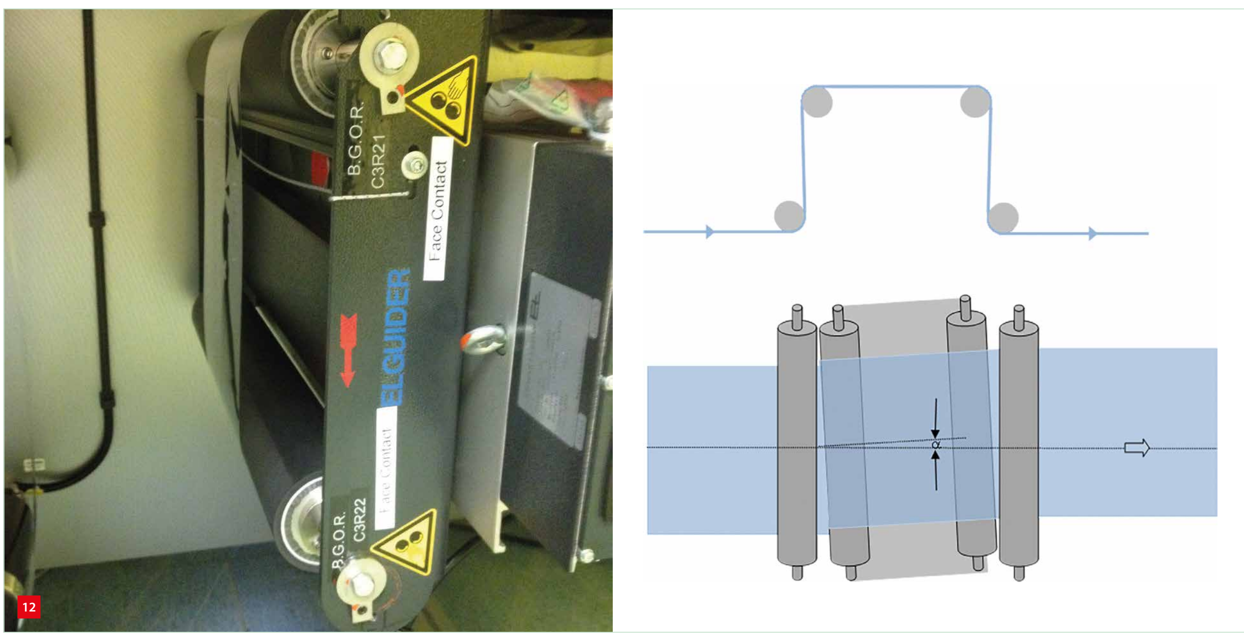


Detailed investigation of the form of the foil as it moves over the air turn has allowed for simulation models to be developed. From these models optimum configuration of the air bearings has been identified for in-line use, including air turns with dual zones (Figure 11).
Not only plastic foils can be supported by air turns. Transport of paper is also possible. Here, the permeability of the paper should be considered. Higher permeability leads to a higher percentage air loss through the paper, which will in turn reduce the fly height and stiffness. Thus the paper tension when contact occurs is directly linked to the permeability. However, papers have been found to be supported at tensions of 50 N or more for a range of papers (tested to 52 g/m^2) and speeds of 10 m/min.

Contactless web steering

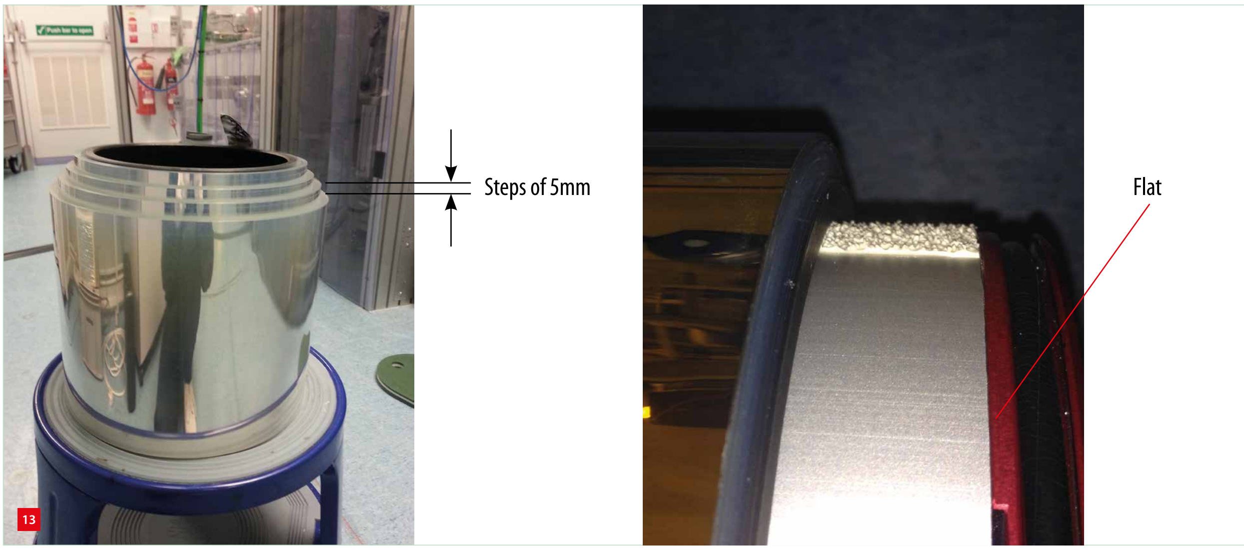
Steering units are commonly used in R2R lines to maintain the lateral position, orthogonal to the travel direction. Such units are typically composed of four rollers, where the front side of the web is made to come in contact with two of the rollers (see Figure 12). The central rollers in the steering frame can be replaced by air turns to avoid frontside contact. Using an edge sensor, the lateral position of the web can be tracked.

Trials have been carried out by IBS where the web response to 5mm stepwise changes in the sensor position have been applied. The web was shown to be stable within the required ±0.2 mm. 5mm steps in reference position were clearly visible



11 *Measurement of foil shape as a function of the position on a dual zone air turn.*

12 *Typical steering roller configuration (right upper and lower image). Air turns retrofitted to a standard steering frame (left).*



13 *5mm steps can be clearly seen in foil wound using a steering frame retrofitted with air turns (left). The sharp edge of wound foil shows effective steering control (right).*

in the roll after winding, as shown in Figure 13. In addition, the steering range was seen to be increased from approx. 3 to 20 mm. The steering response to a step in the reference position, as measured by the edge sensor, was seen to be significantly faster.

Conclusion

Porous-media air bearings provide a unique technology for the delivery of precision machines and processes for industrial manufacturing. Whilst well established in the precision engineering field, they offer a surprising range of new avenues for exploitation.

Acknowledgements

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