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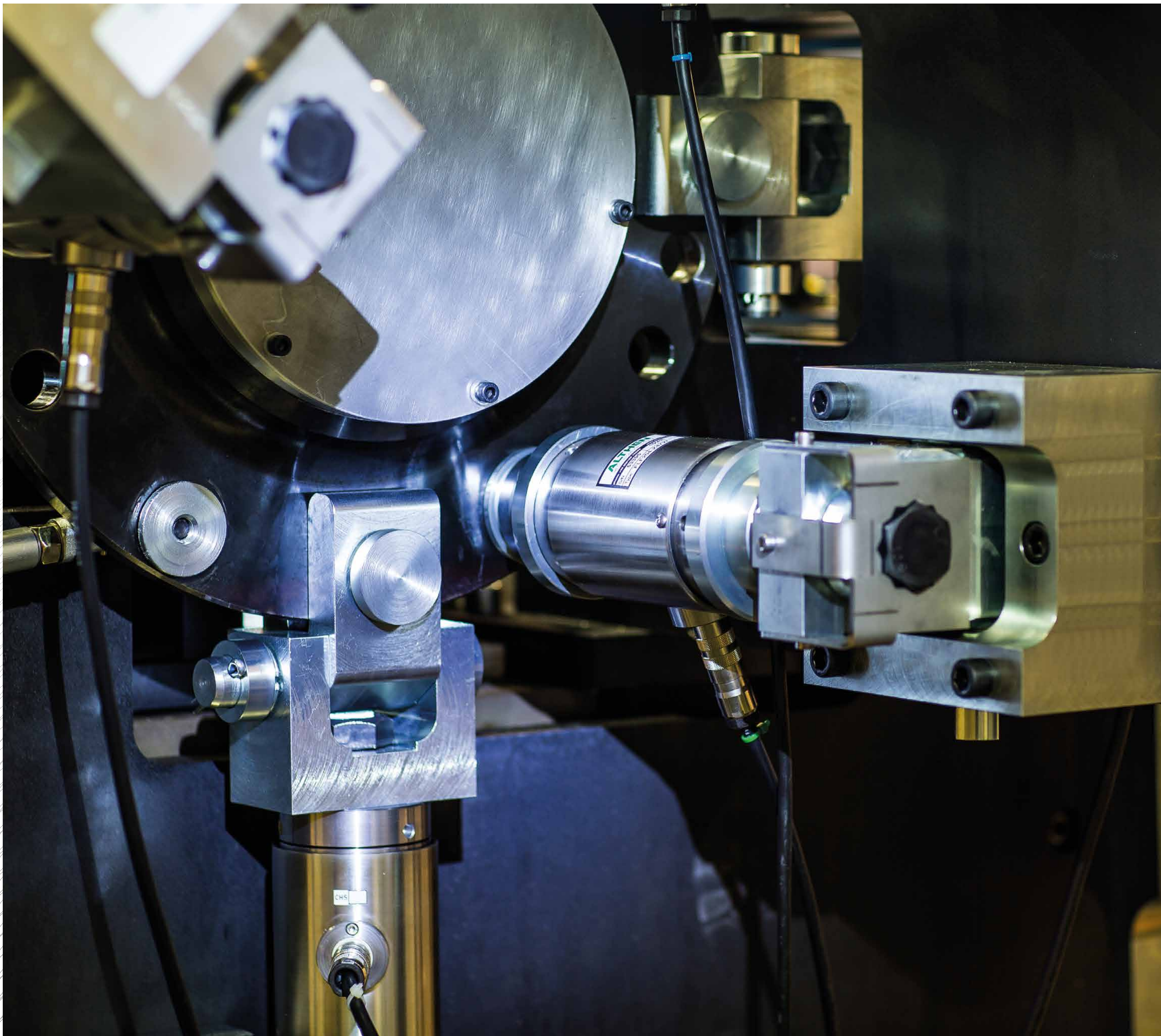
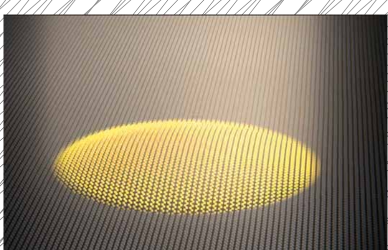
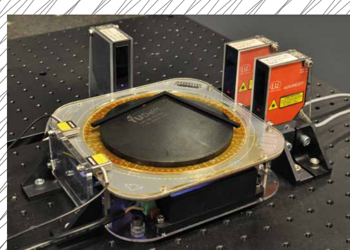


- THEME: **PRECISION BEARING TECHNOLOGY**
- KNOWLEDGE **SHARING**
- **LEVITATING** HIGH-PERFORMANCE MACHINING
- **SERVICE** ROBOTICS





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The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

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The main cover photo (featuring a sensor-bearing calibrator) is courtesy of Ingrid Bussemakers/Nobleo Technology. Read the article on page 5 ff.

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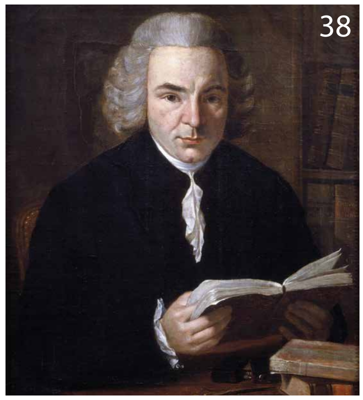
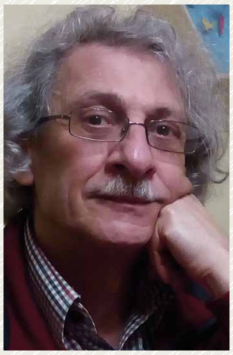
Theme: Precision Bearing Technology



FEATURES

NO TECH WITHOUT **BEARINGS**


(Photo: Wannes Vermeir)

The purpose of a bearing is to transport a load over an interface, subject to certain requirements. The most important of these requirements are that the bearing provides low, well-behaved friction, as well as smooth, precise motion and high stiffness in the directions orthogonal to the motion direction. It can safely be asserted that technology would have been unthinkable without bearings: after all, objects need to be moved relative to one another in a controlled, predictable manner, and bearings play a key role in that.

Bearings and bearing systems evolved over thousands of years from plain and lubricated sliding contacts and later rolling contacts into a wide variety of technologies responding to the ever-increasing demands of industry. In addition to the conventional types that remain the most popular, we have witnessed the steady development of fluid film bearings, both self-acting and externally pressurised (EP). Although the majority of these fluid film bearings still use oil, others use almost all known fluids and some even use air, which is abundant, stable and environment-friendly.

EP gas bearings can maintain a stable air/gas film between the moving surfaces, which smoothens surface undulations by averaging, so that the resulting motion is more precise. Rotary tables, such as those produced by LAB Motion Systems in Belgium, easily achieve less than 50-100 nm axis-of-rotation error. Moreover, the air film is not necessarily bound to one particular surface. This idea inspired IBS Precision Engineering in the Netherlands to swap the roles and so develop a roll-to-roll foil handling in which the rollers do not roll while the foil glides over them separated by the air film.

Then there is the class of passive and, in particular, active magnetic bearings, where the bearing surfaces are kept apart by controlled magnetic, e.g. Lorentz, forces. These bearings can work in a vacuum, maintaining very precise and nearly frictionless motion.
Active and semi-active fluid bearings use ferrofluids, electro- or magnetorheological fluids, or liquid crystals, which influence rheological properties, such as the apparent viscosity of the fluid. These fluids help achieve beneficial effects in the bearing film, in particular regarding stiffness, damping and sealing behaviour. These effects are being researched by Delft University of Technology (TU Delft) in the Netherlands.

This brings us back to the function of a bearing in a contemporary high-performance, often mechatronic, setting. Ultra-high-speed applications demand surface speeds approaching that of sound, while maintaining low frictional dissipation and good stability, i.e. stiffness and damping. However, there are also the ultra-high-precision motion-control applications where error motions at a submicron, often nanometer level are required over very large strokes. This becomes increasingly difficult without mastering the mechatronics' active compensation approach that is enabled by the ever-advancing actuator/sensor technology and system control, i.e. measuring the position of the borne object and feeding it back through the control to a piezo system actuating the bearing film force. This is quite costly and complex however and as such hinders widespread application.

A trend in bearing technology is to combine bearing and drive functionalities, which are separate in conventional machines, in the same system, e.g. in piezo steppers. KU Leuven has been conducting research in this area. TU Delft has recently been researching a non-contacting variant, using the viscous motor principle, by which the air that is eccentrically fed to the air bearing gap drags the borne surface in a controlled and highly dynamic way.

In conclusion, I hope that readers enjoy learning about the various developments in this fascinating and important field of scientific and technological endeavour.

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WHAT BETTER LOCATION TO MEASURE LOAD?

AUTHORS' NOTE

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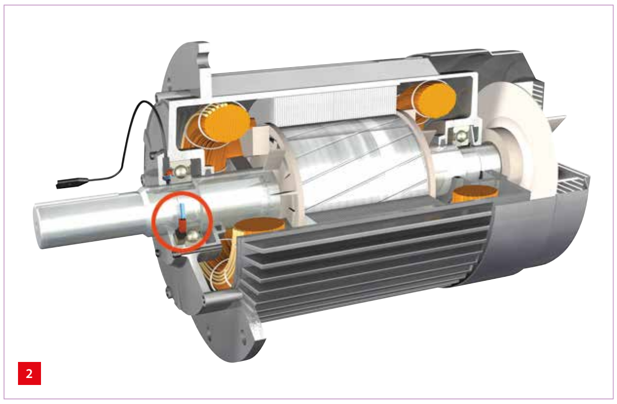
Sensor bearings, e.g. roller bearings fitted with load sensing, hold great promise for the improved functionality of the systems in which they are used. Load-sensing bearings, however, require external calibration. This article outlines the design and realisation of a calibration tool for this purpose. The tool covers up to five degrees of freedom, i.e. the ones that the bearing constrains. The primary design challenge was to create a system that is capable of applying up to 100 kN radial and 50 kN axial force, measure and control the force with an accuracy better that 5% and use electrical actuation.

FRANK SPERLING, RIK HOUWERS, GERARD DUNNING AND ROB LANSBERGEN

Introduction

Sensor bearings (Figure 1), i.e. the combined function of a roller bearing with the sensing of physical properties such as position, velocity, vibration, temperature and load holds great promise for the improved functionality of nearly all systems that use bearings, from heavy industrial equipment to automobiles. Load sensing in a roller bearing is a particularly attractive proposition, as the roller bearing is usually located where practically all of the forces and loads that the two bodies exert on each other are 'concentrated', i.e. where the force lines travel through a defined small number of Hertz contacts. This is much like the typical application shown in Figure 2.



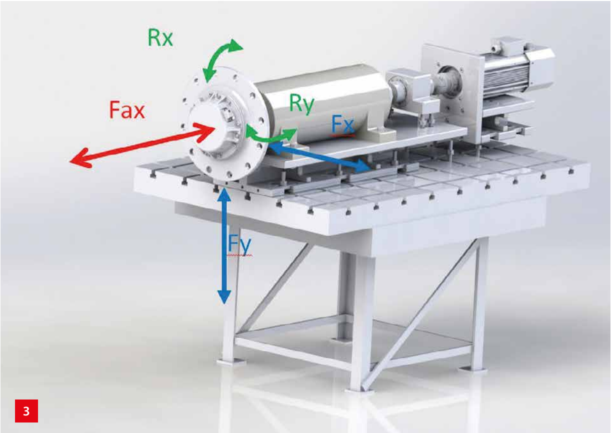
So what's the best location to measure these forces? Several concepts for load sensing have been developed through the years – the first patents are from the early 1990s – and practically all of them rely on strain measurements inside the bearing body. Since a bearing is inherently statically overdetermined, these strains do not uniquely map to the external forces. In addition, thermally induced strain and stress also impact the strain measurement. What's more, measuring strain with strain gauges also implies a relative measurement. Hence, all of the above makes an external calibration of the load-sensing bearing unavoidable.

1 *Typical sensor bearing.*

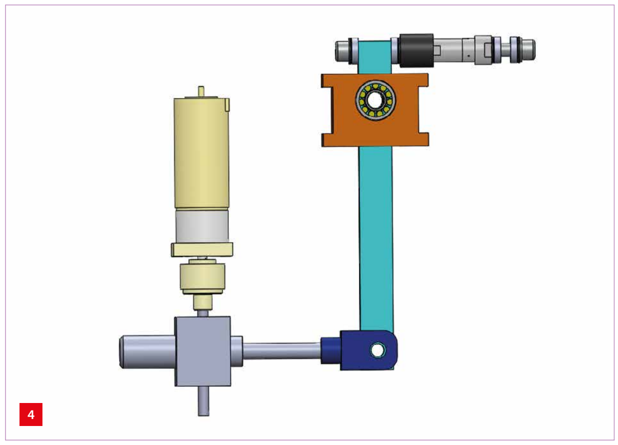
2 *Typical sensor bearing application.*

For a proper calibration tool, the following primary requirements were defined:

1) The tool should allow a rotating bearing to be loaded in five degrees of freedom (DoFs): two radial DoFs, x and y; one axial, z; and two rotations, Rx and Ry (the DoFs and loading directions are depicted in Figure 3).
2) The maximal loading forces are 100 kN in radial direction and 50 kN in axial direction, and maximum torques are 10 kNm.
3) The measured forces should have an accuracy better than 5%.
4) Actuation should be done electrically, preferably with low power.



3 *The sensor-bearing calibrator and its five DoFs.*



4 *Basic concept: a double lead screw and lever – the grey unit at the short end of the lever is the force sensor measuring directly at the bearing housing plate.*

Ad 3) Since a typical load-sensing application does not require the same kind of accuracy that a dedicated measurement device has – often the data is used for monitoring, remaining lifetime prediction or vehicle dynamics enhancements – the measured signals should show a good resolution and linearity, while absolute accuracy can be typically in the 1-10% range. As a consequence the calibration procedure, i.e. a calibration device, needs to have an accuracy and reproducibility that is a fraction of that number; in this case, 5% accuracy was specified.
Ad 4) Nobleo's customer expressed the explicit desire to avoid the use of hydraulic systems in order to eliminate the cost and volume of large hydraulic pump units and the risk of oil leaks and spills.

Concept

In order to achieve the desired force levels at acceptable (motor) power levels and to make the system as safe as possible for use, the first concept decision was to design with high system stiffness in mind, since the amount of energy required to deform an elastic system with a prescribed force is inversely proportional to its stiffness, i.e. the extreme case of an infinitely stiff mechanism requires zero power to create a force. Stiffness in this sense refers to the total amount of elastic energy stored in the system when a bearing is loaded with a prescribed force and is expressed in terms of the force over displacement at the bearing.

The force is measured by a load cell (preferably as closely as possible to the bearing load), the displacement is calculated from the actuator motion (i.e. the encoder) and the kinematic transmission ratio of motor revolutions to bearing displacement. As such, the stiffness includes the transmission system, hinges and supports, the frame and the bearing being tested.

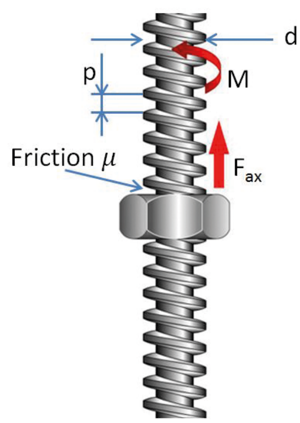
On the other hand, an upper limit to the stiffness is also given by the (allowable) motion inaccuracies of a revolving bearing, estimated at max 10 µm. A stiffness, measured at bearing level, of $C = 1{\cdot}10^8$ N/m was set as a design goal, resulting in an estimated (repetitive) error force from the bearing with an amplitude of 1 kN, which is well within the 1% of the required measurement range.

Electrical actuators typically provide a moderate torque at high revolutions, so the motion transformer from a rotary motion torque (order of magnitude 0.1-10 Nm) to a translational force (100 kN) calls for high gearing ratios and triggered exploration of various concepts of special motion transformers.

The basic concept of a double lead screw system with a lever (as shown in Figure 4) is straightforward. The motor axis rotates a vertical screw, which in turn rotates a nut on the horizontal (lead) screw jack. Finally, a lever (5:1 or 7:1) is used. The lead screw and screw jack suffer from friction limiting their efficiency and the achievable force trans-

Transmission ratio

Friction forces limit the transmission ratio. In an ideal, friction-free case; a motion transformer's force transmission ratio is identical to the reciprocal of its kinematic transmission ratio. However, for a leadscrew system employing sliding friction the achievable force transmission is limited by the Coulomb friction.



$$M_{fric} = F_{ax}\,\mu\,\frac{d}{2}$$

The transmission ratio with friction:

$$\frac{F_{ax}}{M} = \frac{2\pi}{\underbrace{p + \mu d \pi}}$$

'virtual pitch' limited by friction

UNEXPECTED ENCOUNTERS

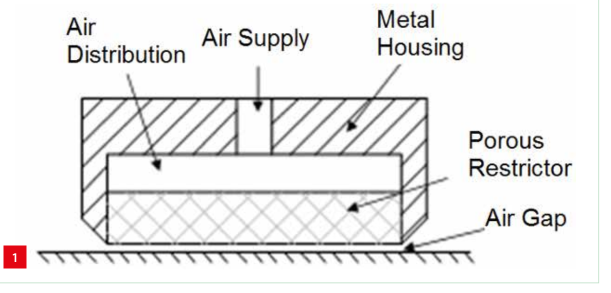
Rolling-element bearings developed in the last century were a revolutionary improvement over the plain bearings that had been pushed to their limits in applications like electric motors and automobile wheels. Air bearings can likewise be seen to represent the next logical step in bearing design. These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

THERESA SPAAN-BURKE

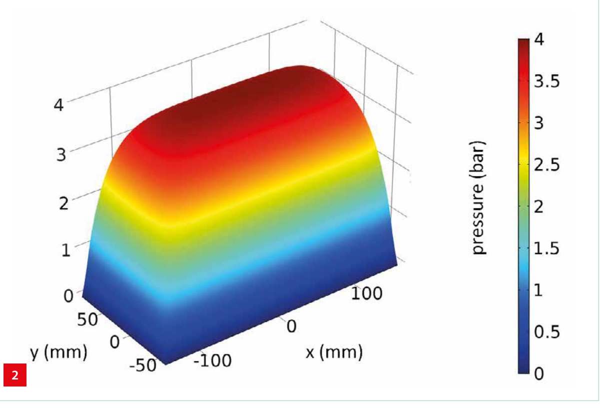
Air bearings use a thin film of pressurised gas to provide a low-friction, load-bearing interface between surfaces. As the two surfaces do not touch, the traditional bearing-related problems of friction, wear, particulates, and lubricant handling can be avoided. The use of air bearings in certain precision 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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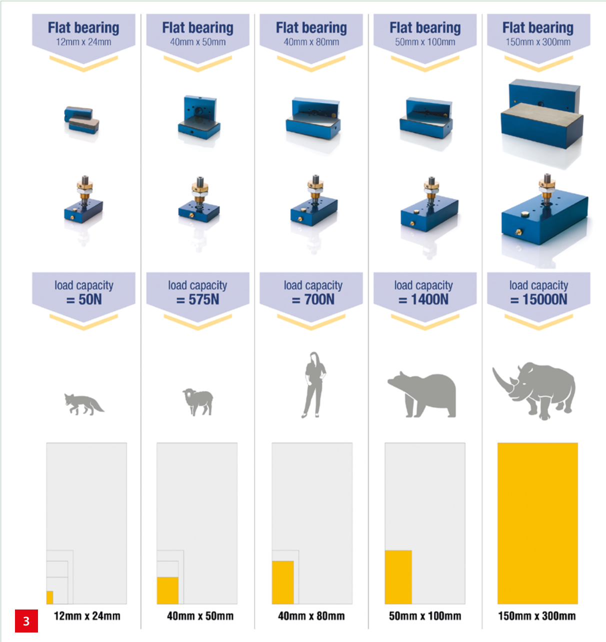
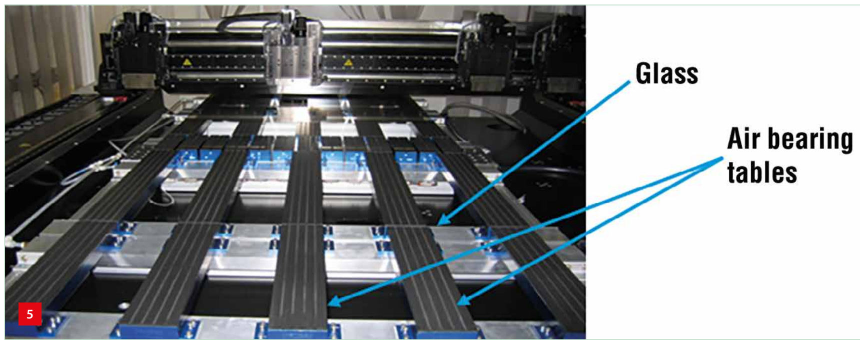
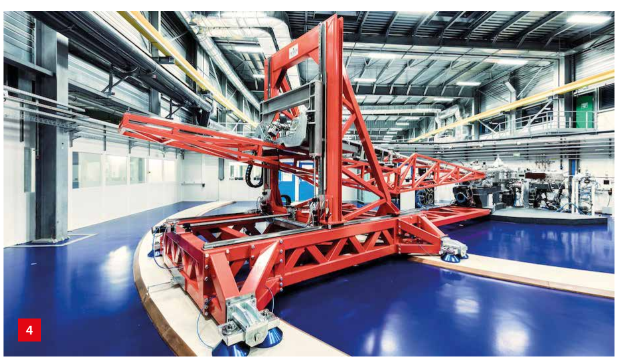




A recent example of an instrument required to move such a large mass with great precision is the new high-resolution soft X-ray spectrometer (RIXS) at the ESRF (European Synchrotron Radiation Facility) in Grenoble, France. This flagship instrument is required to rotate 6.3 ton (62,000 N) of detector 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).



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.

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

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.*