RECIRCULATING, CROSSED-ROLLER OR OVERRUNNING?

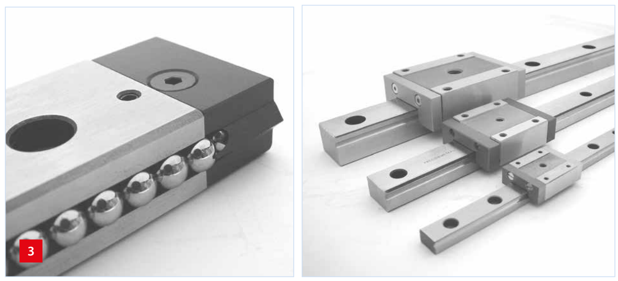
Solutions for mechanical bearings in motion applications mainly come in two types: crossed-roller and recirculating. Both have their pros and cons. In this article, a comparison is made, and a new bearing type is introduced that combines the best of both worlds: the overrunning cage bearing.

Introduction

A linear crossed-roller bearing consists mainly of two pairs of two rails with a roller cage between the rails; see Figure 1. The rollers provide smooth guidance in the desired direction. The rollers are oriented in such a way that the bearing is stiff in all other directions.

A recirculating linear bearing consists of a rail with on both sides recirculation units that guide the rolling bodies of the bearing (these can be either balls or rollers). Due to the recirculation of the rolling bodies, the stroke of a recirculating linear bearing can theoretically be infinite; see Figure 3.

1 *A linear crossed-roller bearing.*



3 *Recirculating linear bearings.*

The rollers are alternatingly oriented under a 90° angle with respect to each other, which gives high stiffness in all directions except the intended direction of motion. The roller cage acts as a separator and (in cases) as a retainer that keeps the rollers spaced apart, preventing roller-to-roller contact and thereby reducing friction, wear and the risk of jamming. Cages can be produced in various shapes and made out of various materials; see Figure 2. Each cage has its own characteristics; for example, easy manipulation (retained rollers), very low friction, resistant to low temperature and/or vacuum, modular and extendable, etc.

When a comparison is made between the two different bearing types, the important properties of a bearing must be known. For high-precision guiding and positioning solutions, as provided by PM (see the company profile), the following properties are important:

- stroke, velocity and acceleration;
- moving resistance;
- accuracy and repeatability;
- stiffness;
- load capacity.

2 *Cages in various shapes and made out of various materials.*

EDITORIAL NOTE

This article was contributed by PM.

Stroke, velocity and acceleration
Stroke, velocity and acceleration vary per application. Both crossed-roller guides and recirculating guides can be used for high-speed and high-acceleration applications. When a large stroke is needed, a recirculating guide is commonly the solution of choice for longer strokes, since the stroke with recirculating guides is determined by the rail length, whereas in crossed-roller guides the maximum stroke is limited by the ratio between the rail and cage length (which should be relatively high to guarantee performance).
When small or medium strokes are needed, both types can be used. In the past, large strokes were difficult to achieve with crossed-roller bearings, but due to developments such as overrunning cages, large strokes are now possible. PM offers linear guide sets with standard stroke lengths, but the company's strength lies in developing customised solutions and supporting customers with technical co-engineering.

Moving resistance
Crossed-roller guides serve many applications, but for high-precision guiding and positioning they are regarded as the solution of choice. Here, the moving resistance of the bearing is a critical factor. More resistance generally leads to less accuracy and repeatability. Factors contributing to moving resistance are:

- friction between surfaces in relative motion;
- elastic deformations caused by preload (Hertzian contacts);
- lubrication viscosity.

In terms of moving resistance, the linear crossed-roller bearing is superior to the recirculating linear bearing due to additional factors that apply for the recirculating bearing. Two examples are given below.

- Forces between the rolling bodies when recirculating (absent in crossed-roller bearings); see Figure 4:

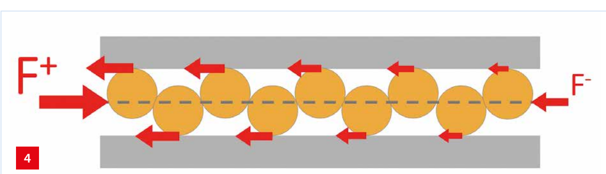
$$\Delta\alpha \approx 2\frac{d_{\text{channel}} - d_{\text{ball}}}{d_{\text{ball}}}$$

$$\alpha \approx n\Delta\alpha$$

- Here, n is the number of balls.

$$\frac{F^+}{F^-} = e^{\mu\alpha}$$

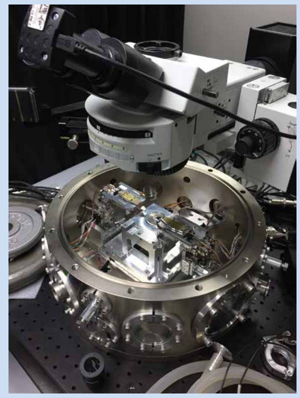
- Disturbance forces of rolling bodies going in and out of pretension (absent in crossed-roller bearings).



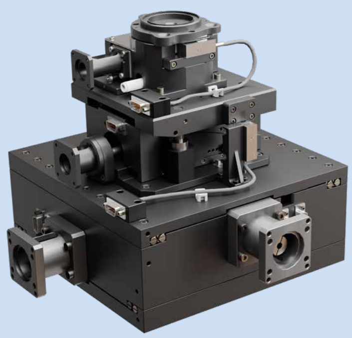
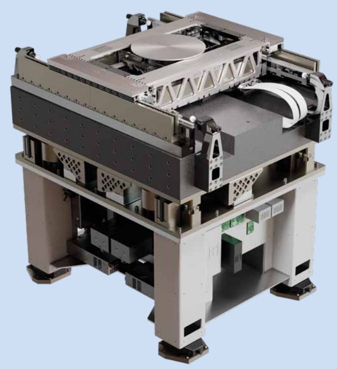
Forces in a recirculating linear bearing.

Company profile: PM

PM was founded in Dedemsvaart (NL) in 1966. For several decades, bearings formed the core activity of the company, with a strong focus on linear motion solutions. Through continuous investment in craftsmanship and precision manufacturing, PM established a solid foundation of knowledge and expertise in bearings. These properties make PM products a key component in high-precision applications, including semiconductor equipment, microscopy and automation.


PM specialises in high-precision equipment.

Throughout the years, PM has evolved into a high-end bearing and mechatronic system supplier, covering the range from precision crossed-roller bearings to positioning systems and complex assemblies. One can think of XYZ-theta platforms in sizes of a shoe box to a cubic meter, as is typical for semiconductor wafer-inspection systems.



Complex positioning systems in different sizes: shoe-box-size (left) and a cubic meter (right).

Next to having a large production and assembly facility for creating the actual hardware, PM also has an R&D and engineering department able to develop solutions from customer requirements. The conceptual engineering process is focused on creating a digital twin of the product, so that its behaviour can be predicted and anticipated as much as possible. Typically, a digital twin is set up by modelling and simulation. However, a bearing as a component has an overconstrained design. This does not make modelling from theory impossible, but the input of practical measurements is very helpful in shaping the digital twin.

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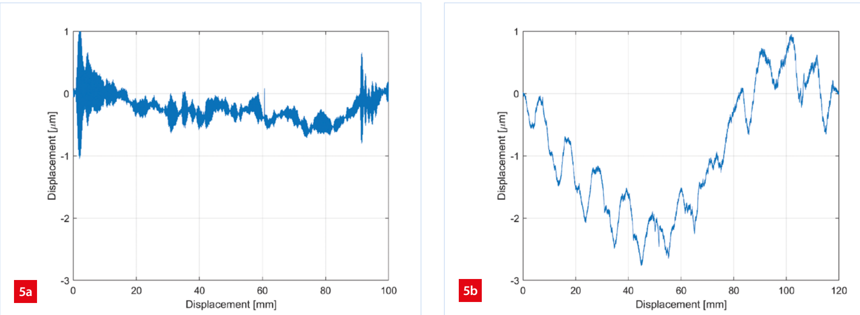
Accuracy and repeatability

Both crossed-roller and recirculating guides have good accuracy and repeatability; see Figure 5.

Recirculating guides may suffer from rolling bodies going in and out of pretension during recirculation, which can reduce dynamic and static accuracy. This effect is less for crossed-roller bearings, offering better accuracy and repeatability.



Bearing flatness over a stroke.
(a) Crossed-roller bearing.
(b) Recirculating ball bearing.

Stiffness

In high-precision mechatronic systems, stiffness is very important: higher stiffness means less deformation under load, which improves accuracy and system dynamics. The stiffness of a crossed-roller bearing is higher than that of a recirculating bearing under equal load, due to the larger contact area. The stiffness of a rail-roller-rail contact is calculated as:

$$k = \frac{\delta P L_c}{\delta_{tot}(P+\delta P) - \delta_{tot}(P)}$$

P = force per contact length
δP = sufficiently small change in force per contact length (e.g., 0.01% of P)
L_C = roller contact length
$\delta_{tot}(P)$ = deformation of a rail-roller-rail contact under force P

The deformation of a rail-roller-rail contact, $\delta_{tot}(P)$, is calculated as [1]:

$$\delta_{tot}(P) = \delta_{roller}(P) + 2\delta_{rail}(P)$$

$$\delta_{roller}(P) = 4P\frac{1-\nu_{roller}^2}{\pi E_{roller}}\left[\ln\left(\frac{4R_{roller}}{a}\right) - \frac{1}{2}\right]$$

$$\delta_{rail}(P) = P\frac{1-\nu_{rail}^2}{\pi E_{rail}}\left[2\ln\left(\frac{2t}{a}\right) - \frac{\nu_{rail}}{1-\nu_{rail}}\right]$$

E_{roller} = Young's modulus of the roller material
ν_{roller} = Poisson's ratio of the roller material
E_{rail} = Young's modulus of the rail material
ν_{rail} = Poisson's ratio of the rail material
R_{roller} = roller radius
t = thickness of the rail segment
a = half-width of the contact area, calculated as $a = \sqrt{\frac{4PR_{roller}}{\pi E_{eff}}}$
E_{eff} = effective modulus, calculated as

$$E_{eff} = \frac{1-\nu_{roller}^2}{E_{roller}} + \frac{1-\nu_{rail}^2}{E_{rail}}$$

The stiffness of a rail-ball-rail contact is calculated as:

$$k = \frac{\delta F}{\delta_{tot}(F+\delta F) - \delta_{tot}(F)}$$

F = force on the rail-ball-rail contact
δF = sufficiently small change in force (e.g., 0.01% of F)
$\delta_{tot}(F)$ = deformation of a rail-ball-rail contact under force F

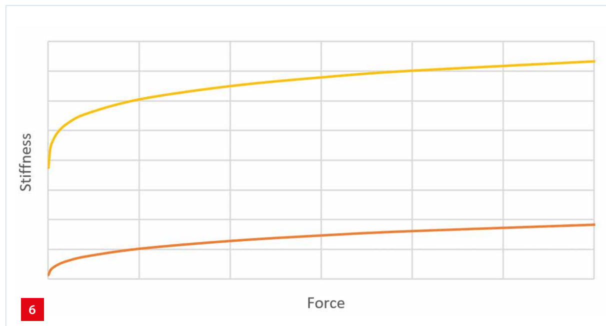
The deformation of a rail-ball-rail contact is calculated as [2]:

$$\delta_{tot}(F) = 2\delta_{ball-rail}(F)$$

$$\delta_{ball-rail}(F) = \frac{a}{2}\ln\left(\frac{R_{ball}+a}{R_{ball}-a}\right)$$

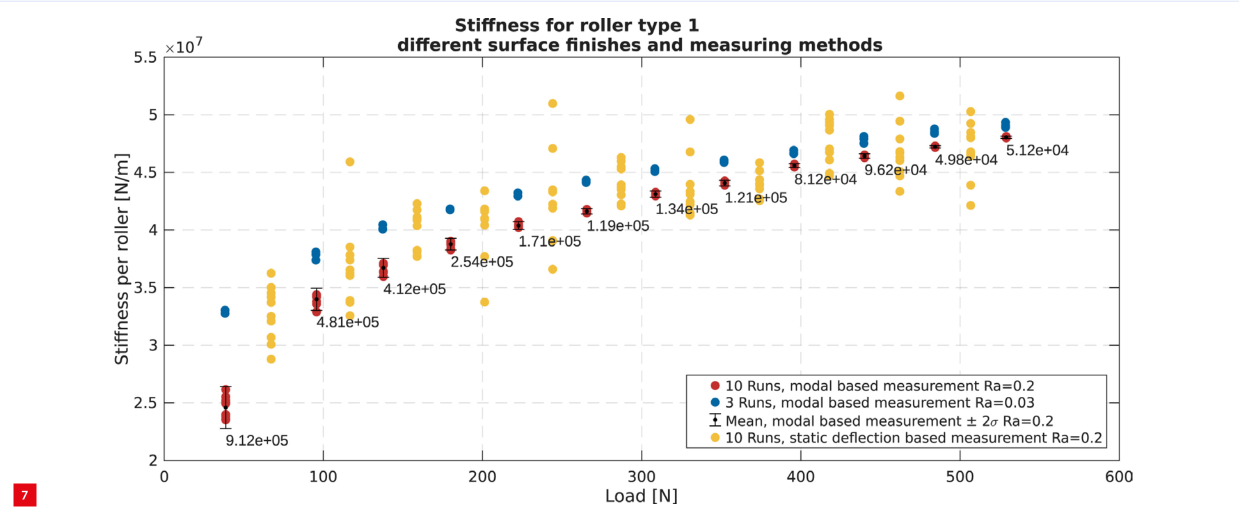
R_{ball} = radius of the ball
a = contact radius calculated as $a = \left(\frac{3R_{ball}F}{4E_{eff}}\right)^{1/3}$

When the stiffnesses under the same force of a rail-roller-rail contact and a rail-ball-rail contact are compared, this results in the graph of Figure 6.



Stiffness of bearing contacts: rail-roller-rail contact (yellow) and rail-ball-rail contact (orange).

Another interesting aspect of using two rails (crossed-roller bearing) compared to one rail and a recirculating bearing is that the surface of the rails is more easily machined to a very low roughness. PM has the capability to grind rails to SF (super finish) quality. Studies show that a low roughness is beneficial for increased stiffness. Figure 7 shows stiffnesses derived from modal measurement results, for roughness values of R_a = 0.2 μm (red) and R_a = 0.03 μm (blue). The graph also shows static measurements based on deflection. It is clearly seen that these show a large spread, demonstrating that modal analysis/measurements are a more stable method to determine bearing stiffness.



Stiffness measurements for a crossed-roller bearing. (Source: [3])

Load capacity

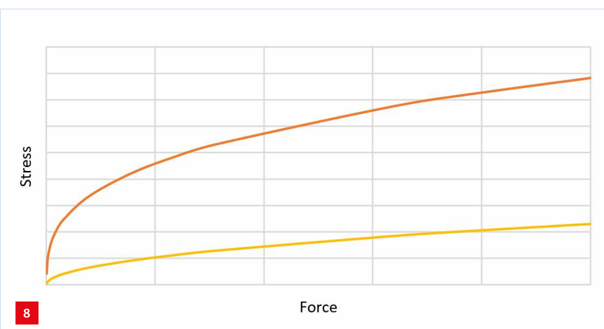
In high-precision mechatronic systems, stiffness is very important: higher stiffness means less deformation under load, which improves accuracy and system dynamics. The stiffness of a crossed-roller bearing is higher than that of a recirculating bearing under equal load, due to the larger contact area. The stiffness of a rail-roller-rail contact is calculated as:

$$p = \left(\frac{P * E_{\mathrm{eff}}}{\pi * R_{\mathrm{roller}}}\right)^{1/2}$$

For a rail-ball contact, the maximum contact stress is calculated as [4]:

$$p = \frac{1}{\pi}\left(\frac{6FE_{\mathrm{eff}}^2}{R_{\mathrm{ball}}^2}\right)^{1/3}$$

When the maximum contact stress under the same load of a rail-roller-rail contact and a rail-ball-rail contact are compared, this results in the graph of Figure 8.



Contact stress in bearing contacts: rail-roller-rail contact (yellow) and rail-ball-rail contact (orange).

Combining characteristics: overrunning cage as an alternative

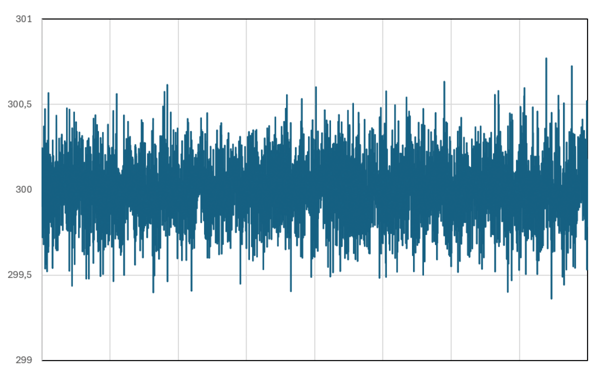
When large strokes need to be combined with the presented advantages of the crossed-roller bearings, a solution with overrunning cages can be used. An overrunning cage is a linear cage that extends outside the rail; an example is shown in Figure 9.

When the carriage moves, a different set of rollers will be in contact with the rail, depending on its position. In contradiction with the recirculating bearings, the rollers do not circle back to the front of the rail but stay in line.

Example of an overrunning cage.

Stroke, velocity and acceleration

With this solution, the stroke can be extended to virtually the same as that of bearings. Acceleration levels are equal as well. When it comes to velocity (and especially velocity constancy), a first thought may be that, when using overrunning cages, the negative effect of the rolling bodies going in and out of pretension may be the same as for the recirculating bearings. However, by shaping the outer ends of the rails in a specific way, the effect of pulling the rollers in pretension can be drastically reduced. Figure 10 shows a graph of the velocity ripple.



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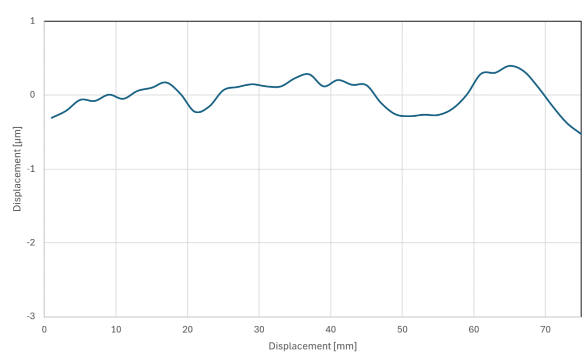
Velocity ripple in an overrunning cage; horizontal axis is time (range unknown).

These measurements are done on stage encoder level. A rather large contribution can be seen at distinct and relatively high frequencies. It is very doubtful if these frequencies represent actual mechanical behaviour. It is more likely to be electronic noise. In following research, measurements on the tool point will be performed to measure the actual behaviour and to justify filtering of these results.

Accuracy and repeatability

The flatness over the stroke is shown in Figure 11.



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Flatness of an overrunning cage.

Comparing this to the displacement plots of the crossed-roller bearing and the recirculating bearing, it can be seen that it is close to the crossed-roller bearing. It may be noticed that this plot shows less frequency content. This is due to the measurement increments in this case. It is expected the same frequency content is present in this case as well.

Stiffness

In nearly all cases, there are more rolling bodies in contact with the rails than in a recirculating bearing. So, next to the increased stiffness of the rollers compared to the balls, the surplus of rollers increases the overall stiffness even more.

Conclusion

The traditional crossed-roller bearing has characteristics in both stiffness and flatness that are very interesting. However, the stroke/size ratio is not practical for larger strokes. In that case, the recirculating bearing is often chosen. This is mostly equipped with balls and has a shorter contact length, making its characteristics less attractive. With the intermediate solution of crossed-roller bearings with linear overrunning cages, the advantages of stiffness and flatness are still there, but a larger stroke can be made. When developing a new application, PM advises to always thoroughly investigate which bearing type suits best the application.

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