euspen's 19th International Conference & Exhibition, Bilbao, ES, June 2019

www.euspen.eu

Recirculating linear ball bearings and their effect on the accuracy of positioning systems

Tim Groothuijsen[1], Dick Laro[1], Theo Ruijl[1]

[1]MI-Partners, Eindhoven, The Netherlands
T.Groothuijsen@mi-partners.nl

Abstract
In this article friction characteristics of linear guides are measured and modelled, in order to predict the system positioning performance of a system equipped with these components. The Dahl and Stribeck characteristics are shown for a number of configurations of the same type of linear guide. It is shown how these guide parameters affect system positioning performance for a positioning stage application, which is used as an example of bearing selection. It is shown that proper guide selection requires detailed knowledge regarding the friction behaviour, and shows how a low friction bearing actually shows less performance for a particular positioning application. By having a database of these parameters for different guide types and configurations, it is possible to select the optimal linear guide during the design of a system. Future work will investigate other aspects of these bearings, such as vibration due to recirculation of rolling elements.

Linear recirculating ball bearings, positioning stages, friction

1. Background

For the development of high-accuracy linear positioning systems with a long stroke, multiple bearing solutions are possible. Examples include magnetic bearings and air bearings, which behave highly predictable and enable highly accurate motion. One possible alternative to these is a linear rolling element guide, which can provide a low-cost, robust solution with high stiffness and load capacity per unit construction volume.

These bearing elements also have downsides such as friction forces and ball passage vibrations, which limit their accuracy. A study was performed at MI-Partners to determine to what level of accuracy a linear motion guide can be used. The focus of this study is on the recirculating type of linear rolling element bearing, also known as a linear motion guide. Non-recirculating linear guideways have the advantage of achieving higher positioning accuracy and higher velocities, while recirculating linear guides have the advantage of being preloaded internally and having the ability to make a long stroke without additional rail length on both sides of the bearing. These guides can be found in, for example, positioning stages for machine tools, pick and place machines, inspection machines, die bonders and 3D printers.

1.1 Identification of linear guide characteristics for positioning accuracy

For machine development, it is important to know how linear guides behave on component level. Rather than detailed investigations into the tribological or contact mechanics aspects, MI-Partners is interested in the positioning performance of systems that use such bearing elements. Relevant parameters in that sense are:

- Friction forces (small and large displacements)
- Dynamic stiffness over frequency
- Accuracy in constrained directions (geometric accuracy and roling element vibrations)

For these parameters, it is especially interesting how these vary by guide configuration such as lubricant, preload, sealing and other configuration details. These measured parameters are required to determine the suitability of a bearing for an application. These parameters are used in addition to parameters that are more readily available from manufacturers, such as stiffness, load capacity, running parallellism and lifetime estimations.

Quantification of the friction parameters that affect the system positioning performance assists in selecting the proper guide for an application. By quantifying the magnitude of this error contribution, it can be compared to other error sources and, if required, measures can be taken in the design to reduce it.

1.2 Measurement methods

Several measurement setups have been developed at MI-Partners to quantify parameters relevant for modelling friction behaviour and rolling element vibrations, using methods described in [1] and [2].

One such setup is shown in Figure 1, which measures force over displacement. This setup is used to measure Dahl and Stribeck characteristics, but can be adapted to measure rolling element vibrations as well. How Stribeck and Dahl curves are related to friction characteristics is described in [3].

The setup is shown schematically in Figure 2. The two aforementioned figures show the guide under test being driven by a linear actuator, which is in closed loop control. Closed loop position control is required as the friction behaviour is a function of the displacement and velocity, which are to be controlled in the experiment in the presence of varying friction force.

The force applied to the guide under test is measured by means of a strain gauge force cell (0.05 N repeatability), the position is determined by means of a linear optical encoder (1 nm resolution).

A flexure mechanism which is only stiff in the driving direction (and compliant in all others), ensures that a force is only applied in the driving direction. This minimizes influence from parasitic forces and torques, caused by overdeterminedness, on the measurement. This flexure also ensures that the actuation force goes through the center of the rows of rolling elements, to minimize moments on the guide under test. This 1-DOF coupling has a stiffness in driving direction that is roughly two orders of magnitude greater than the Dahl stiffness of the guide.

The force cell and encoder are placed as close to the linear guide under test as possible, to avoid errors due to friction or acceleration forces and errors due to elastic deformation from other components.

Another configuration of this test setup enables measurement of the guiding accuracy in the constrained degrees of freedom with respect to calibrated straight edges while moving in the driving direction.

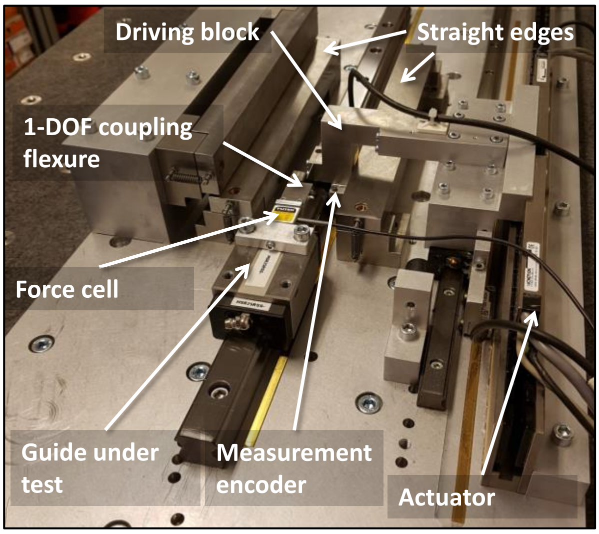

Figure 1: Test setup for measuring force-displacement characteristics.

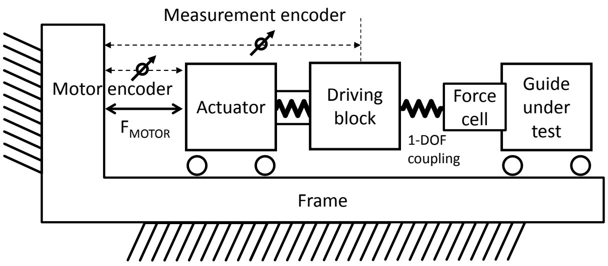

Figure 2: Schematic, idealized representation of setup.

By means of these Stribeck and Dahl measurements, the parameters to fit a Lugre friction model can be found, as shown in [3]. This model can be used to estimate the magnitude of friction effects on positioning accuracy in simplified positioning simulations, which are used to quantify whether a given linear guide type meets the requirements of the application.

1.3 Comparing different guide configurations

In the next two chapters, an example will be shown of the measured friction behaviour along the driving direction of the guide, represented as Stribeck curve (chapter 2) and Dahl curve (chapter 3) measurements.

Many different linear guide configurations have been measured at MI-Partners. Of these, three different variants of the same guide will be shown such that the influence of certain guide configuration parameters can be visualized.

Measurement data will be shown for a single type of recirculating linear ball bearing (railsize 25mm) from the same manufacturer in different configurations, as shown in Table 1. The manufacturer's standard linear guide (guide 1) is compared to a variant without seals (2) and with low friction lubricant (3).

Table 1: Three different guide configurations are compared.

Guide	Seals	Lubricant	Cage
1	Yes	Standard	Yes
2	No	Standard	Yes
3	Yes	Low-friction	Yes

In chapter 4, the positioning performance of the three guides will be compared in a simulation using a Lugre model fitted on the parameters measured in chapter 2 and 3. This illustrates a case of guide selection for a linear positioning system in which both high accuracy tracking and settling are relevant, without large process forces and at lower velocities.

2. Force-velocity characteristics for constant velocity

One of the friction properties that needs to be identified is the force-velocity characteristic at constant velocity, known as the Stribeck curve. The guide is accelerated to a constant velocity. During this constant velocity part of the motion, the force is measured, followed by deceleration. A Stribeck measurement is shown below in Figure 3 for all guide types of Table 1.

A typical Stribeck curve measurement shows a force build up at near zero velocity to the static friction force: The force threshold for continuous motion. In some cases this is followed by a decrease of the force over velocity to a local minimum, called the Stribeck effect. At even higher velocities, the force will increase again due to increasing viscous friction force.

At very low velocities, it can be seen that the guide without seals (2) has much lower static friction. The variant with low friction grease (3) shows the highest static friction.

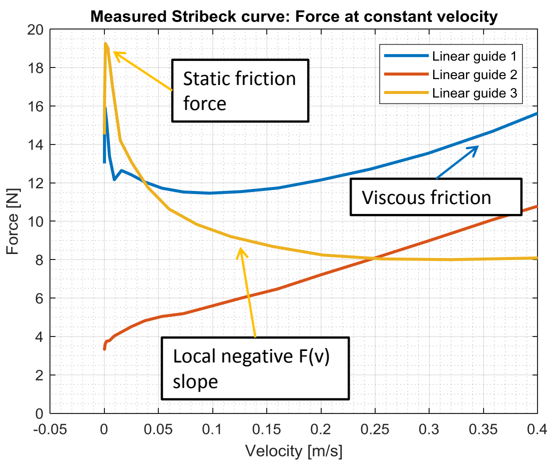

Figure 3: Stribeck measurement for three different guide types.

At high velocities, it can be seen that the standard guide and the guide without seals have roughly similar slopes, but different force levels. The guide with the low friction grease (3) has low viscous friction, which is beneficial when used at high velocities.

Also notable is that certain variants (1 and 3) have a local negative *F(v)* slope at low velocities, which makes these guides more vulnerable to limit cycling when integral control is used, which is discussed in [5].

The low friction grease guide (3) shows the importance of specifying the application to the guide manufacturer when requesting a low friction linear guide: Low friction grease in this case strongly reduces viscous friction, but seems to lead to higher static friction, which can result in reduced positioning performance as well.

Removing all the seals seems to result in a large reduction in static friction, but is only possible in a clean environment. Removing the rolling element cage as well decreases it even further (not shown), but introduces risk of increased wear and increased vibration levels due to rubbing contact between rolling elements and reduced lubrication, which can decrease performance again.

The mechatronic systems used in the example of chapter 4 do not perform long strokes and high velocities are not reached. As such, static friction is the most important property, low viscous friction is less important for such a system. A standard guide or one without seals would be preferred, provided that the environment is sufficiently clean.

The stribeck curve only gives information about friction force as a function of constant velocity. What is interesting for the fine positioning application in chapter 4 is how the friction behaves for small displacements. Such behavior is represented by the Dahl curve, shown in the next chapter.

3. Force-displacement characteristics for small displacements

The Dahl curves show the non-linear force-displacement behavior in the motion direction of the guide for small displacements. Figure 4 shows the Dahl curve for two different amplitude levels. The Dahl curves are measured in closed loop by making very slow back-and-forward motion, such that acceleration and viscous forces become negligible and only hysteretic stiffness force is observed.

For the 40 µm amplitude (innermost) curve, linear guides 1 and 3 behave as a hysteretic stiffness. Linear guide number 2 has exceeded its breakaway force for this displacement magnitude. Note that these hysteresis loops include more than just rolling element prerolling stiffness, it includes all the components, such as seals and cages, if present.

This is a nonlinear stiffness: with increasing displacement amplitude, the effective stiffness decreases. The area inside the loop is a measure for damping, and can be used to estimate the modal damping of a Dahl resonance on this stiffness. In [6] it is shown how to quantify this effective stiffness and damping from a Dahl measurement.

It can be seen that the stiffness value is different for each guide. When displacement magnitude is increased, breakaway occurs. Note that the removal of seals strongly decreases breakaway force (by approximately 12 N in Figure 4), and also lowers the effective Dahl stiffness of the bearing.

The Dahl curves are shown for even smaller (1 µm) amplitude displacements in Figure 5. What can be gathered from this data is that the small displacement stiffness of these guides is not strongly affected by the lubricant. This is in contrast to the large-scale motion behavior characterized by the Stribeck curve, which is strongly affected by the chosen lubricant. Removing the seals reduces the effective stiffness for 1 µm displacments in the driving direction from 4.5e5 N/m to 2.6e5 N/m.

The term effective stiffness relates to total force difference divided by total position difference, due to the nonlinearity of the stiffness. Using the standard linear guide (1) as an example, the 40 µm displacement from Figure 4 yields a stiffness of 2.3e5 N/m and the 1 µm displacement from Figure 5 yields 4.5e5 N/m. For very small displacements the stiffness eventually reaches a constant value (e.g. 10 nm yields 7.5e5 N/m in this case). Note that this is much lower than the tangential stiffness of the Hertzian contact, as the elements can rotate elastically. In general, smaller displacement amplitudes yield higher effective stiffness and lower effective damping.

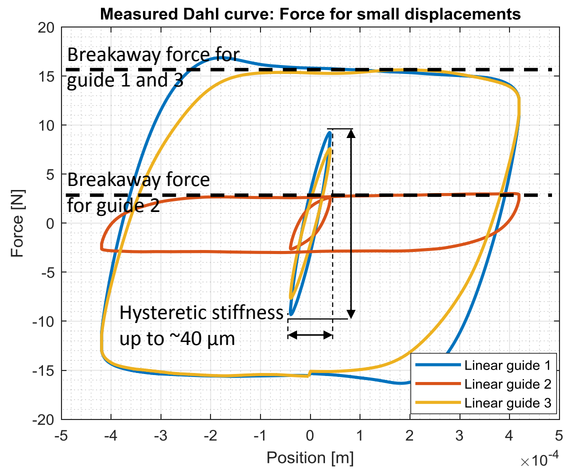

Figure 4: Dahl curves for three different guides and two displacement amplitudes: Approximately 40 µm and 420 µm amplitude.

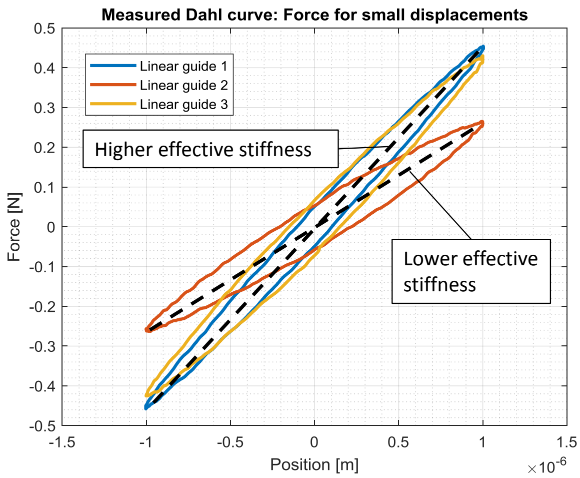

Figure 5: Dahl curves for three different guides, displacement amplitude of 1 µm.

It should be noted that this small displacement stiffness is also relevant for motion control stability. For small displacements, a stage on linear guides will have a frequency response that represents the hysteretic stiffness of the guides up to a certain frequency, rather than the mass of the stage. This can result in a different feedback gain than expected, with associated stability and performance issues. How Dahl stiffness affects the system dynamics is shown in [7].

4. Effect on mechatronic system performance

The linear guides characterized in the previous sections are compared for closed loop performance by using a Lugre model (fitting procedure shown in [2]) based on the Dahl and Stribeck measurements. Such a model captures the behaviour of the Stribeck curve, the pre-sliding behaviour and breakaway, as well as frictional lag. This model may have limitations in predicting the exact time-displacement curve [2], but is useful to predict the magnitude of friction effects as mentioned in paragraph 1.1. As an example, a 40 kg positioning stage is equipped with four of the measured bearings. The simulated applications use a 60 Hz PID with lowpass as feedback controller. Ideal mass feedforward is used, such that only the disturbance effects from friction are visible. No feedforward is used for the friction forces. Two applications are considered:

- A fast positioning system performing a forward and return move of 50 mm in 100 ms, in which both tracking and settling performance are required.
- A fine positioning application, making small steps of 10 µm in 3 ms for each move, for which fast settling is required.

Before the forward motion, the guide has moved 50 mm in the return direction and has been stationary for one minute to achieve a repeatable starting condition in terms of direction of friction, spread of lubricant and setting of rolling elements.

The simulation results for the fast positioning stage is shown in Figure 6. It shows that the peak positioning error for this motion trajectory depends on the static friction of the linear guide and the stiffness of the feedback controller. The guide without seals has the least static friction, and as such the lowest peak error.

Between 0.025 s and 0.150 s, viscous friction strongly affects the positioning error, which means guide 3 has a small error in this time interval. If a linear viscous damping feedforward is used, the wave shape in the error in this time interval disappears. Guide 3 initially settles faster, but when the error has decreased to very small (µm) magnitude, the other two guides catch up and eventually reach the required position faster.

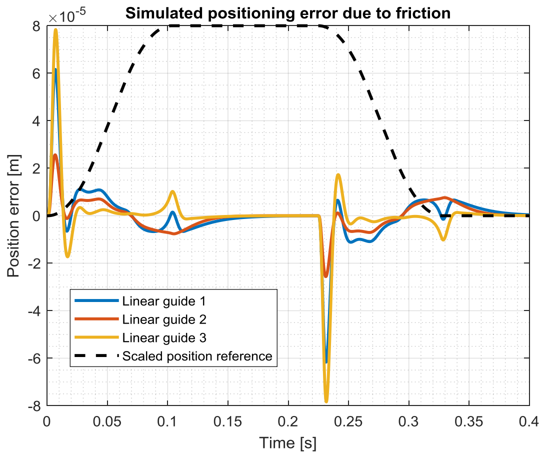

Figure 6: Simulation results showing positioning error for 50 mm displacement. The black dashed line is the position reference, scaled in amplitude to fit in the plot.

The simulation results for the fine positioning application are shown in Figure 7. For steps within the pre-sliding regime, it is mostly the Dahl stiffness that determines the performance. What can be seen is that the controller cannot properly follow this fast setpoint and that the bearing stiffness exceeds the proportional stiffness of the controller. The integral part of the feedback controller will slowly push the guide to its position. The linear guide with the smallest Dahl stiffness (guide 2) shows the lowest peak error and fastest settling.

There are many factors that affect the mechatronic performance of the investigated system. For the motion profiles shown in this chapter and focusing on performance in the free direction, a guide with low Dahl stiffness and low breakaway force would be preferred, which would be guide 2. It also shows that the low friction lubricant guide (3) actually has the worst performance for this application, which was perhaps not expected based on the description of the guide.

While protective measures such as seals can improve the robustness of a bearing by keeping contaminants outside and lubricant inside the bearing, there is a performance price.

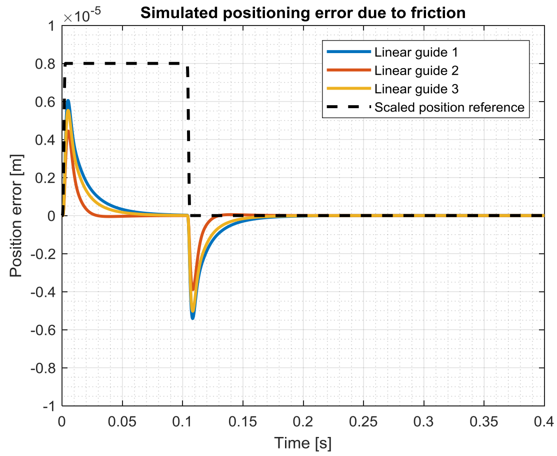

Figure 7: Simulation results showing positioning error for 10 µm displacement. The black dashed line is the position reference, scaled in amplitude to fit in the plot.

5. Conclusion

From these measurements, the different configurations of one type of linear guide can be compared in terms of static friction, Dahl stiffness and viscous friction. The small displacement Dahl stiffness is determined mostly by the mechanical components such as the rolling elements and seals, not by the lubricant. It also scales with preload [6], but this aspect is not shown in this article. The lubricant, as expected, has an effect on the breakaway force level (although this effect is not strongly visible for the two specific guides with different lubricant shown in this study) and a large effect on viscous friction forces that dominate at high velocities.

During the design of a high-speed die bonding module for example, low static friction and fast settling were relevant, viscous behavior was less important and sealing was desired. In that design, linear guides of type 1 were chosen after it was shown that the required system performance could be reached with these linear guides.

In this article it is shown how measurements of linear guide properties such as friction, at component level, can be used to predict positioning performance of stages equipped with these guides. If neccesary, this information can be used for design changes in order to meet the required performance. By building a database with such properties, this knowledge can be used in early stages of the design. This way the optimal linear guide can be chosen for a customer's application.

References

[1] Symens W, Al-Bender F, Swevers J, van Brussel H 2002 Harmonic analysis of a mass subject to hysteretic friction: experimental validation. *Proc. of the ISMA 2002*. Vol.**3**, pp.1229–1239.

[2] Altpeter F 1999 *Friction modeling, identification and compensation* PhD thesis (École Polytechnique Fédérale de Lausanne, Lausanne)

[3] Al-Bender F 2010 Fundamentals of friction modeling. *Proceedings, ASPE Spring Topical Meeting on Control of Precision Systems 2010* pp. 117-122

[4] Armstrong-Hélouvry B, Dupont P, Canudas de Wit C 1994 A survey of analysis and compensation for machines with friction. *Automatica* Vol.**30**.No.**7**.pp.1083-1138

[5] Radcliffe, C J, Southward, S C 1990. A property of stick–slip friction models which promotes limit cycle generation. *Proceedings of the 1990 American control conference, ACC, San Diego, CA* (pp. 1198–1203).

[6] Al-Bender F, Symens W 2005 Characterization of frictional hysteresis in ball-bearing guideways. *Wear* **258** *pp.1630–1642*

[7] Symens W, Al-Bender F, Swevers J, van Brussel H 2002 Dynamic characterization of hysteresis elements in mechanical systems. *Proceedings of the 2002 American Control Conference Anchorage, AK* pp. 4129-4134