Precision Coupling Basics—Stiff or Stiff Enough?

When selecting couplings for precise motion applications there are often questions about the most suitable approach for optimizing both performance and economy.

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Torsionally stiff line shaft couplings are ideal for linking belt-driven linear actuators which will be used in tandem to support the loads overhead.

Precision flexible shaft couplings come in two basic forms, both of which are designed to operate without backlash or excessive inertia while compensating for inevitable misalignment offsets between motor/gearbox and load. Torsionally stiff couplings are made with metallic flexible elements and with the intent to eliminate as much twisting deflection as possible so that the rotation of both shafts is kept as well synchronized as can be. Vibration-damping elastomer couplings almost always use a plastic buffer between the driving and driven hub to filter out and absorb unwanted vibration and shock loading. Precision elastomer coupling designs also include considerations to eliminate backlash with a preload between the plastic buffer and jaw hubs, but some torsional wind-up is inevitable. As a rule of thumb, metal bellows couplings possess a torsional stiffness approximately ten times greater than that of comparably sized elastomer couplings, but the latter offers its own advantages in terms of helping to ensure smooth running in addition to being somewhat lower in cost. Choosing between the two styles of precision coupling usually starts with an assessment of torsional stiffness requirements.

In each of the following four scenarios, which address the most common precision coupling applications, either type could be determined to be the best choice. One way of beginning the process of deciding between them is to consider a default selection and then qualify it for the individual situation. The most important criteria to consider up front are mechanical advantage, required positional accuracy of the load, rate of acceleration/deceleration, and the inertia ratio between the driving and driven ends of the coupling, each of which has a significant impact on how torsionally stiff the coupling needs to be to keep up with the overall performance requirements.

Ball Screws and Lead Screws

The most common linear motion application for precision couplings is to connect servomotors to ball and lead screws. In these situations, it is typical to have a precise target for positioning accuracy, even down to a few microns or less, since this is the type of linear motion system that's used most often in machine tools and semiconductor wafer handling equipment. Considering this it would be easy to assume that torsionally stiff couplings are always the way to go—and they often are. But perhaps surprisingly, the best choice is more often a precision elastomer coupling. This is because, depending on the linear travel per rotation (lead), the mechanical advantage provided by the screw mitigates the effects of torsional wind-up as it pertains to linear positioning accuracy. Compared with other mechanical motion components, there is also a relatively low input torque required to generate the desired thrust, velocity, and position of the load, which in turn means less torsional strain on the coupling and less wind-up.

For example, consider a typical application for a ball screw with a 10 mm lead, which will require an input torque of 15 Nm to generate the desired 1 ton of thrust in its end use.

Option A: Bellows coupling
Torque capacity: 15 Nm
Torsional stiffness: 23,000 Nm/rad

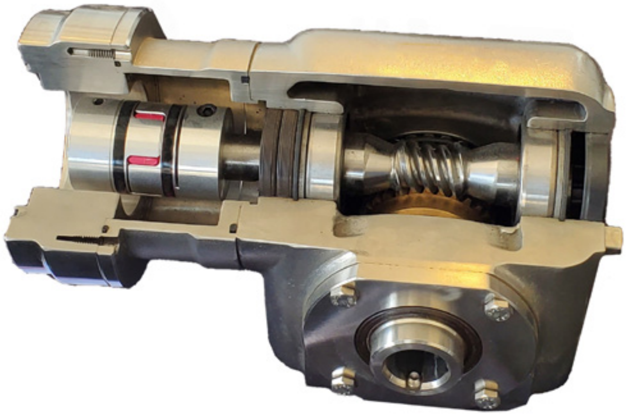
Option B: Elastomer coupling
Torque capacity: 21 Nm
Torsional stiffness: 2,300 Nm/rad

Going through a simple calculation for linear positioning error which is attributable to coupling wind up we see that both couplings hold up quite well.

$$\frac{\text{Torque (Nm)} \cdot \text{Screw lead (mm)}}{\text{Torsional stiffness (Nm/rad)} \cdot 2\pi} = \text{Linear position error (mm)}$$

Bellows coupling: 0.001 mm
Elastomer coupling: 0.010 mm

Naturally, the bellows coupling outperforms the elastomer coupling in the same 10:1 proportion as the difference in torsional stiffness. While there are many applications for ball screws that would require that the coupling contribute something as small as one micron (0.00004 in.) to linear position error, most everyday applications run very well with coupling wind up contributing the 0.010 mm caused by the elastomer coupling under full load, which is still less than half a thousandth of an inch. This is especially true when linear encoders are being used to control the final positioning of the load and prompt motors to adjust accordingly. As the ball screw lead increases, so too does the linear position error attributable to the coupling, but the rough order of magnitude stays the same. The elastomer coupling is most often the right choice except in cases of the most extreme of positional accuracy requirements.



Vibration-damping couplings are normally the practical choice when driving the inputs of precision gearboxes.

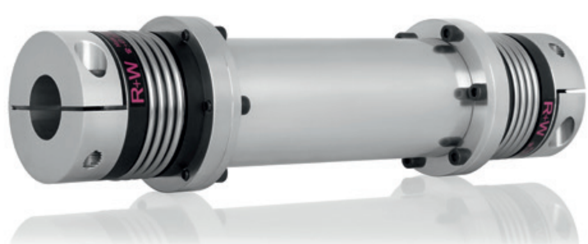
Belt-Driven Linear Modules

Used more for speed of material handling than for the high thrust and precision positioning of ball screw drives, belt-driven linear actuators might initially be considered to require relatively low torsional stiffness in the couplings that connect them to their driving components. The opposite is true in many cases. For the same reason that they are used for higher rates of travel and with less emphasis on thrust beyond acceleration, there is no mechanical advantage between the input shaft of the actuator and the resulting linear motion. This is also why precision gearboxes are almost always needed to assist the motor in producing sufficient acceleration torque and overcoming load inertia, whereas ball screw systems rarely need them. In these situations, the coupling sits at the business end of the drive line, rotating in a one-to-one ratio with the pulleys that create the linear motion. This also makes torsional wind-up much more conspicuous.

In many cases, the base level X axis of a positioning system built on belt-driven linear actuators is also running in tandem with a second actuation module, which helps to support the moment loading created by the additional componentry and payload moving overhead. Instead of powering the second actuator with a separate motor, drive, and gearbox, it is usually much more economical to synchronize these X and X' axes mechanically with line shaft couplings. To keep the carriages of the two modules inline and prevent binding against their linear guides, it is important that they be synchronized throughout the motion profile.

One possible configuration involves center driving the two actuators with a motor and dual output gearbox mounted between them, and a line shaft coupling connecting each of the two gearbox output shafts to its respective actuator shaft. This minimizes the impact of torsional wind-up by, in theory, having equal wind-up between the two line shaft couplings, provided that they have the same overall length, and that the torque loading is approximately even between the two actuator carriages. But this method is not without its own challenges. Center driving the two modules requires that an additional framework be available for mounting the gearbox, which is often not there. It is also more costly than using a simpler gearbox on one end, where it can be supported by the frame of the actuator itself, and with a single line shaft coupling linking the two modules. Determining whether this easier method is feasible is often a matter of weighing the torque load on the line shaft coupling against its torsional stiffness and the resulting positioning error. Going slightly oversized with the line shaft coupling often helps to make this possible. It is also important to note that the X and X' actuators are linked at the carriages by their shared load, and together with their respective linear guides, assist in keeping everything moving together. But when coupling wind-up causes excessive drag in the driven actuator, the ability of the linear bearings to carry along smoothly is lessened. A good rule of thumb is typically to keep this would be position error under 0.2 mm.

Considering another common set of parameters for a gantry style system with 1.5 m between modules and a drive pulley radius of 50 mm, wind-up and positioning error between bellows and elastomer couplings might look like something like this:



Option A: Bellows coupling line shaft
Applied torque: 60 Nm
Torque capacity: 150 Nm
Torsional stiffness: 16,000 Nm/rad

Option B: Elastomer coupling line shaft
Applied torque: 60 Nm
Torque capacity: 150 Nm
Torsional stiffness: 3,600 Nm/rad

$$\frac{\text{Torque (Nm)} \cdot \text{Pulley radius (mm)}}{\text{Torsional stiffness (Nm/rad)}} = \text{Linear position error (mm)}$$

Bellows coupling error: 0.19 mm
Elastomer coupling error: 0.83 mm

In this example a bellows type line shaft is necessary to maintain smooth running, although in other situations the torque loading is sufficiently low enough that elastomer type couplings are up to the task.

Gearbox Inputs

Another area in which it might be assumed that torsional stiffness should be maximized is on the input shafts of gearboxes being used to generate precise motion. Depending on the gear ratio, using a bellows coupling on the input is often but not always overkill. This is even in the case of precision gear drives with very low backlash ratings. Consider again the difference between backlash and torsional windup. Where backlash is completely lost motion which must be compensated for, torsional windup in precision couplings still allows for a high level of position repeatability in both directions. Loaded in one direction and then relaxed, the elastomer coupling system returns to a zero position, and will go on to behave in exactly the same way in the other direction, providing a mirror image in the resulting position when the same load is applied. This is often more manageable than the lost motion associated with backlash.

Using the same example couplings and 15 Nm input torque as above, and with a 9:1 reduction ratio:

$$\frac{180}{\pi} \times \frac{\text{Torque (Nm)}}{\text{Torsional stiffness (Nm/rad)}} \times 60 \div 9 = \text{Output position error (arc min)}$$

Bellows Coupling: 0.249 arcmin
Elastomer Coupling: 2.49 arcmin

Assuming the load at the output of the gearbox has a diameter of 500mm, the difference in the position of its outer rim between an elastomer coupling torque load of 0 Nm and 15 Nm is only 0.18 mm. While the ratio also mitigates the impact of backlash at the output in the same way, it is still permanently lost motion. While within its rated torque capacity the coupling torsional stiffness is treated as linear as torque load is applied, and if there is minimal variance in torque load applied at different load position targets, there is also a proportionally reduced difference in the load position as it pertains to coupling wind up. Unlike the gear teeth themselves, the coupling is also virtually guaranteed to start at a zero position with regard to directional loading and position error when first installed and commissioned, making it much more predictable. For precision gearbox inputs, consider elastomer couplings first and move on if more stiffness is needed.

Direct Coupling Servomotors and Gearheads to Their Loads

When motors and gearheads need to direct drive roller shafts, lever arms, indexing tables, or any other mechanical device that is intended to be rotated into position, coupling torsional stiffness plays an outsized role in machine performance. As the radius of the load increases, the positioning error resulting from coupling wind up increases rapidly. After all, one degree of wind up in a coupling driving an arm with a radius of 1 m results in a position error of 17.5 mm at the end of the arm. Considering that rotational moment of inertia is a function of the square of the radius of the load multiplied by its mass, abrupt deceleration of an object with a large radius into position can also cause a large amount of overtravel when torsionally softer couplings are being used. Even smaller diameter loads can become problematic when driven by couplings with insufficient torsional stiffness when gearboxes are not used to support the inevitable inertia mismatches between servomotors and their driven machine components. Gearboxes address inertia mismatch by the square of their ratio, meaning for example that a 5:1 gearbox reduces the influence of reflected inertia on the motor shaft to a twenty-fifth of what effect it would have without a gearbox. Since servo drives are normally seeking to rectify the velocity and position of the motor shaft every several milliseconds, overtravel of a load pulling the shaft forward which is delayed by wind up in a torsionally soft coupling can make it impossible for the system to keep up, resulting in high-frequency oscillations and failure to operate. Therefore, when selecting couplings that will be directly used to manipulate a driven load with a significant radius or moment of inertia, especially when load position targets need to be reached rapidly, torsionally stiff couplings are normally the best option.

In each of these typical application areas, there are exceptions to the rules that guide the default selections. But knowing where to start can save a lot of time and prevent getting lost in the sea of different precision coupling options that exist on the market today. Even within the two basic categories of torsionally stiff and vibration-damping precision couplings, multiple designs of flexible elements exist to address varying needs for misalignment compensation levels and to optimize torsional damping. More choices still exist beyond that to include a wide variety of hub types to suit different installation situations. As always when selecting precision drive components, it's best to contact manufacturers for guidance as to the ideal choice.

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