Bellows Couplings

PROPER SELECTION FOR OPTIMAL PERFORMANCE

By Andrew Lechner

For many years bellows couplings have been near the top of the list of flexible coupling choices for high-performance motion systems. Their high torsional stiffness, low moment of inertia and minimal restoring forces under misalignment make them a preferred choice for maintaining tight control over the load. This is especially critical when considering that the flexible coupling most often represents the point of least stiffness in an electromechanical system. In this way, couplings have a significant effect on the stability of the

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R+W America covers the basics through advanced sizing formulas and theories surrounding the design and application of precision couplings for servo motors. (Courtesy of R+W America.)

entire system, as well as the positional accuracy of the load.

When not selected properly, however, bellows couplings can lead to frustrating failures and costly machine downtime. This article seeks to explain some of the natural behaviors exhibited by bellows couplings as well as the proper selection procedures. It will also point out some of the pitfalls associated with bellows coupling selection and serve as a guide to proper application.

Most commercially available bellows couplings utilize a stainless steel tube which has been hydroformed to create deep corrugations. These serve to make the bellows flexible across axial, angular and parallel shaft misalignments while maintaining the torsional rigidity inherent to a metallic tubular structure with a relatively large outside diameter. In shaft coupling applications, the stainless steel bellows absorbs the slight misalignments created by perpendicularity and concentricity tolerances between the mounting surfaces of the two components being connected. They also serve to absorb any axial force created by, among other things, thermal expansion of the motor shaft during operation, all the while minimizing torsional deflection and maintaining constant velocity. Exact transmission of velocity, angle and torque, if not maintained, would compromise performance of any servo motion system.

But all of this work places stress on the bellows—particularly parallel misalignment between the two shafts while transmitting torque. Lateral misalignment compensation causes the bellows to flex into an "S" shape, with an angular bend at each end of the bellows, concentrating stress primarily on the end-corrugations closest to the mounting hubs. Excessive misalignment over time can work-harden these areas of the bellows, making them brittle as they flex around their circumferences. Enough torque can eventually cause the hub to tear away from the bellows, often during an emergency stop or an aggressive acceleration, but quite possibly during normal operation as well.

While improved concentricity of the mounting faces of the coupled components (i.e., closer shaft alignment) can reduce lateral misalignment and ensure against such failures, it is important to note that this mode of failure is closely related to torque as well. High misalignment reduces the torque capacity of couplings. Just as a misaligned coupling will not normally tear until torque is applied, a coupling which is aligned precisely can often transmit more torque than expected.

Since such a continuum exists between misalignment and torque, manufacturers of bellows couplings continuously face the challenge of properly rating couplings for the correct combinations of misalignment and torque. Some manufacturers, as in any industry lacking a set standard for such ratings, are more conservative in their ratings, and others more liberal. This is evident in the variety of ratings for peak torque versus maximum misalignment values across manufacturers of couplings whose products are otherwise structurally similar.

The more conservative have selected a shaft misalignment range in line with what the majority of electromechanical systems can readily handle: approximately 0.1–0.2 mm. Some are rated for slightly more misalignment and others slightly less, but generally speaking, peak torque ratings will be found to be similar across bellows couplings with this range of misalignment ratings and a similar outside diameter. The associated torque ratings normally assume that the maximum misalignment condition will exist in the application.

This approach has worked for many years and normally allows for the coupling to fit well into assemblies involving the appropriately sized components. But not all coupling manufacturers use such a rating system. Some, for example, will offer inflated torque ratings along with shaft misalignment tolerances in line with the norm for the industry, with the fine print stating that significant torque de-ratings must be applied if any significant use is to be made of the coupling's flexibility. Designers should be aware of such potential pitfalls as

Table 1—According to torque

In most cases couplings are rated according to the peak torque to be regularly transmitted.

The peak torque may not exceed the rated torque of the coupling.

By rated torque we mean: the torque that is continuously transmittable within the specified acceptable speed and misalignment ranges.

The following calculation has proven itself to be a good rule of thumb:

$$T_{KN} \geq 1{,}5 \cdot T_{AS} \quad \text{(Nm)}$$

T_{KN} =	rated torque of coupling	(Nm)
T_{AS} =	rated torque of coupling	(Nm)

Table 2—According to acceleration torque

For precise rating, the acceleration torque and moments of inertia of the entire machine have to be taken into consideration.

In the case of servo motors ensure that their acceleration or deceleration torque is greater than their torque by a multiple.

S_A = Shock or load factor

S_A = 1 (uniform load)

S_A = 2 (non-uniform load)

S_A = 3-4 (Shocking load)

Values for S_A = 2-3 are usual for servo drives on machine tools.

$$T_{KN} \geq T_{AS} \cdot S_A \cdot \frac{J_L}{J_A + J_L} \quad \text{(Nm)}$$

T_{KN} =	rated torque of coupling	(Nm)
T_{AS} =	max. acceleration torque on the driving element	(Nm)
	- or max. deceleration torque of the load	(Nm)
J_L =	machine moment of inertia (Spindle + slide + workpiece + half of coupling)	(kgm^2)
J_A =	motor's moment of inertia	(kgm^2)

Table 3—According to torsional stiffness

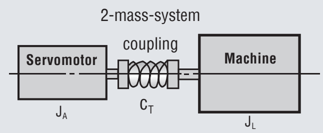
Transmission errors due to the torsional load:

$$\varphi = \frac{130}{\pi} \cdot \frac{T_{AS}}{C_1} \quad \text{(degrees)}$$

φ =	torsional deflection	(degrees)
C_1 =	torsional stiffness of coupling	(Nm/rad)
T_{AS} =	max. torque	(Nm)

Table 4—According to resonace frequency

For the mech. substitutional model of the 2-mass-system the following is valid:



As a value of practice the following is valid: $f_e \geq 2 \times f_{er}$

$$f_e = \frac{1}{2 \cdot \pi} \sqrt{C_T \cdot \frac{J_A + J_L}{J_A \cdot J_L}} \quad \text{(Hz)}$$

C_1 = torsional stiffness of coupling (Nm/rad)

f_e = mechanical resonance frequency of the 2 mass system (HZ)

f_{er} = mechanical frequency of the drive (HZ)

misinterpreting the published capabilities and inadvertently selecting an undersized product. Fortunately, most manufacturers of bellows couplings seem to have settled on combinations of ratings that allow for a reasonable level of shaft misalignment to exist, without yielding a maximum torque rating that would cause the coupling to be too large for the assembly into which it will be installed. Further, some manufacturers offer coupling designs with additional corrugations and even double flexures, which allow for a magnification of the lateral misalignment compensation within a given torque rating while still maintaining a relatively high level of torsional stiffness. In general, proper bellows coupling selection should normally begin with a torque calculation.

A quick, safe and easy bellows coupling selection would be to take the peak torque capacity of the servo motor, multiplied by any applicable gear reduction ratio, and multiplied by a safety factor of 1.5. The appropriate bellows coupling would then be required to have a torque rating greater than or equal to that of the calculated torque (Table 1).

A more precise calculation takes into account the moments of inertia and actual torque required to accelerate the load by first overestimating the required torque of the application through the use of generalized service factors, and then reducing the torque value by taking into account the moments of inertia of the drive and the load. Inertia mismatch can be critical to coupling longevity, as reflected load inertia in aggressive start/stop or reversing applications can produce significant spikes in torque, often beyond those estimated through the use of current limits into the drive amplifier. Selection by torque is most common; however, calculating the required torque rating of the coupling is a step that can be skipped by those more experienced with bellows couplings, in the event that their position accuracy requirements would result in a torsional stiffness value corresponding to a torque rating far in excess of the actual power requirements of the application (Table 2).

As previously noted, the flexible coupling is normally the most compliant of components in any mechanical motion system, making its torsional stiffness a critical factor in terms of maintaining positional control over the load. Possessing the highest torsional stiffness of any commercially available servo motor coupling, bellows couplings are routinely employed in applications with very high-precision positioning requirements. Calculating torsional deflection angle based on the torsional stiffness of the coupling takes a very simple formula (Table 3).

There are some rare cases, however, in which servo loop gains set high enough can result in a mechanical frequency that will excite the natural frequency of the coupling. In these cases, elevating the coupling torsional stiffness is required in order to avoid a situation where the rate at which the coupling springs back from a torsional impulse does not match that at which the next impulse would take place. While auto-tuning features in most modern servo drives have eliminated this potential problem for most applications, in some cases this would still be necessary, and the following calculation allows for proper coupling selection based on mechanical resonant frequency (Table 4).

Properly selected bellows couplings result in the best possible control over the load in any high-performance servo application. Sequentially, the selection criteria generally begins with ensuring that the coupling will have sufficient torque rating to accelerate the load, followed by checking that coupling misalignment tolerances are inline with practical expectations of the accuracy with which coupled shafts will be aligned. In general, higher misalignment tolerances can be achieved at potential compromise to torsional stiffness, though in most applications bellows couplings have ample torsional stiffness to begin with. In those cases where a coupling with a good mechanical fit has marginal torsional stiffness in light of stringent requirements, shaft alignment must be addressed in order to accommodate the very high stiffness requirement. Contact a coupling expert for future servo coupling requirements and ensure that optimal performance will result.

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