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# SELECTING SYNCHRONOUS BELTS FOR PRECISE POSITIONING

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Synchronous belts are well known for precise positioning. However, some precision applications require more in-depth engineering to ensure that the belts deliver the needed performance.

In 95% of synchronous belt applications, the necessary precision is obtained without concern about the magnitude of belt elongation, backlash, or play in the system. There are, however, high precision applications that require a careful assessment of the design and selection of components. Robots, X-Y coordinate machines, machine tool drives, printers and plotters, all require a high degree of synchronization precision.

Types of belts

Synchronous belts come in many shapes and sizes. Figure 1 shows the tooth shapes or sections commercially available today: trapezoidal, curvilinear (HTD), and modified curvilinear (GT). Another modified curvilinear design is also shown but is reserved for precision applications and has limited availability.

(a) Trapezoidal

(b) Curvilinear (HTD)

(c) Modified curvilinear (GT)

(d) Modified curvilinear
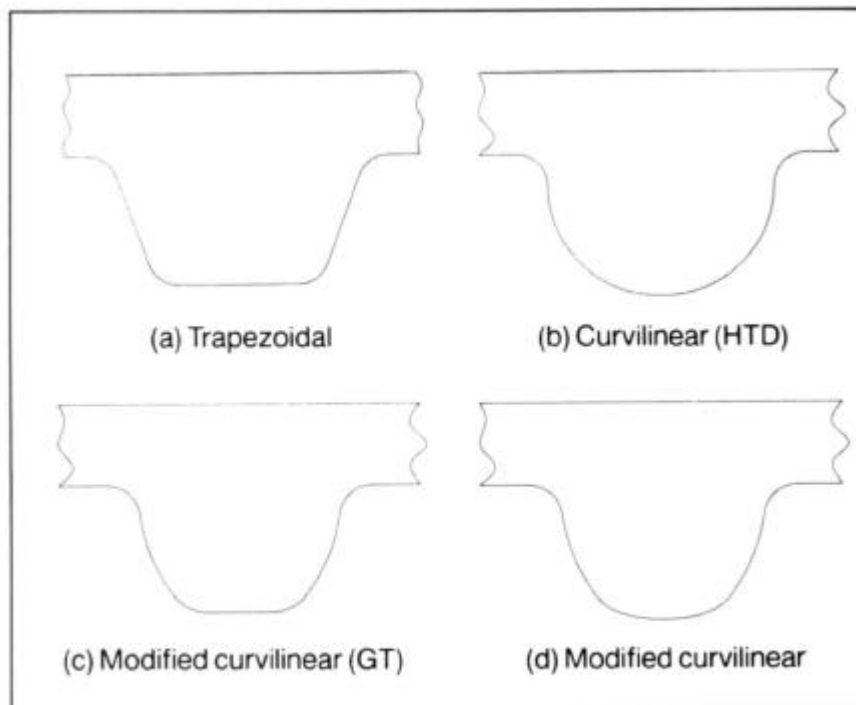
Figure 1 — Synchronous belts are available with several tooth shapes: trapezoidal, curvilinear, and modified curvilinear. The modified curvilinear shape in (d) is used for higher precision applications.

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The three principle dimensions of synchronous belts are:

- Belt pitch is the distance between two adjacent tooth centers as measured on the pitch line. The theoretical pitch line of any synchronous belt drive lies within the tensile member of the belt.

- Pitch length is the total length (circumference) of the belt measured along the belt pitch line.

- Width is the distance across the belt measured at the widest point.

On the sprockets (pulleys), pitch is the distance between tooth centers and is measured on the pitch circumference. The sprocket pitch diameter coincides with the belt pitch line and it is always greater than the sprocket outside diameter, Figure 2.
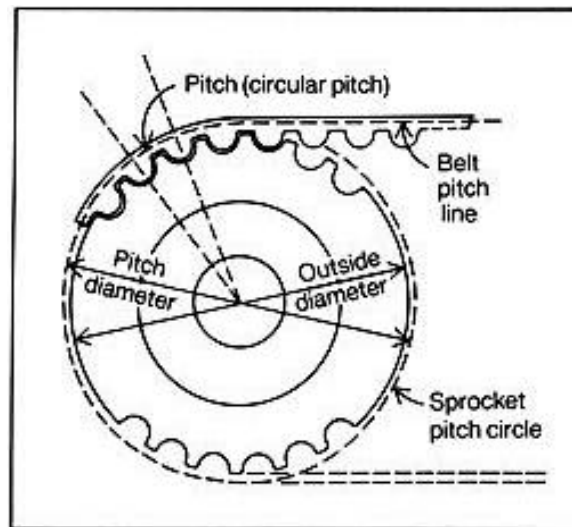
Figure 2—Geometry of a
synchronous belt and sprocket.

**Belt construction**

The belt is constructed of four components, Figure 3:

- Tensile member - Fiberglass, aramid, steel, or polyester.

- Backing - Neoprene or polyurethane.

- Teeth - Neoprene or polyurethane.

- Facing - Nylon or none.

In isolated cases, other materials are used to meet special operating conditions. The belt manufacturer should be consulted when specifying nonstandard materials, as certain combinations of backing, tooth, and tensile-member materials are not compatible. Also, some materials are not appropriate in certain size belts.

Only two components have a marked effect on precision synchronization - the tensile member and the teeth.

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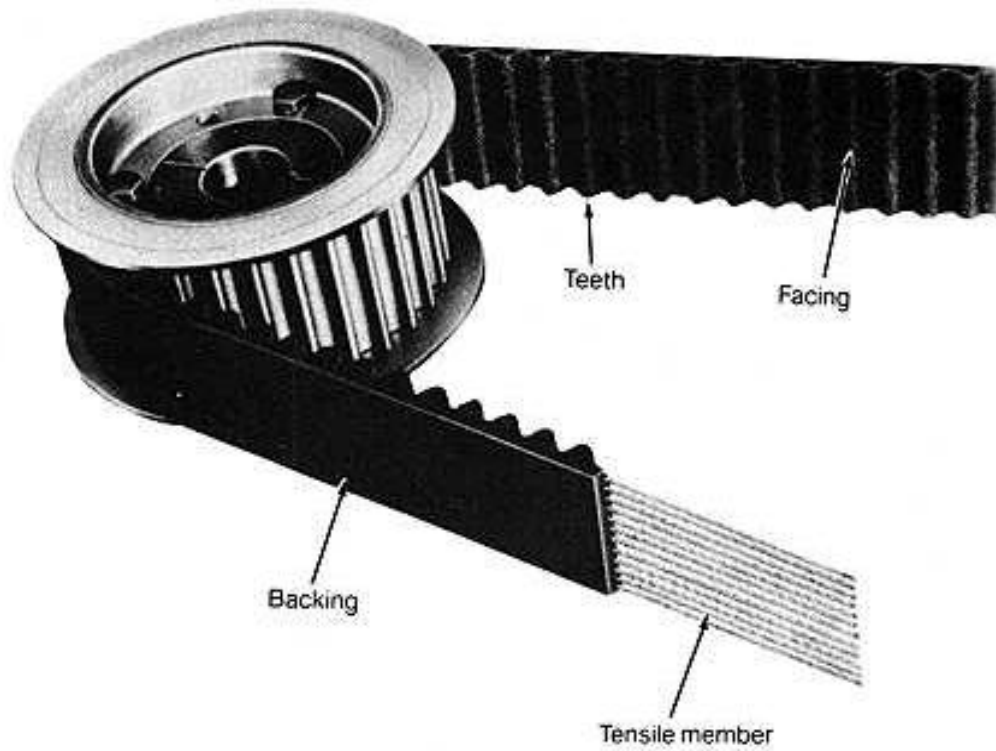
*Figure 3 — The four components of a synchronous belt.*

Tensile member. One of the attributes of tensile members is stiffness, which determines the amount of elastic elongation caused by tension. As defined here, stiffness does not induce the permanent elongation that my occur due to initial stretch, or the stretch caused by fatigue and wear. Characteristics of the major tensile members are shown in Table 1.

Teeth. The use of high hardness tooth materials reduces tooth deformation, but produces a more rigid, hard-to-bend belt.

Belt registration

Registration, as generally defined, is the magnitude of the reaction in one part of a system, compared to an action imparted on another part of the same system.

For example, consider a system composed of one belt and two equal-size sprockets, Figure 4. A force F exerted on sprocket A causes it to turn q deg; this in turn causes a reaction through the belt to sprocket B, which rotates $q - \alpha$.   The error α is caused by losses due to system characteristics such as belt elongation, tooth deformation, improper tension, vibration, pitch discrepancies, or wide tooth-to-groove clearance. The latter causes backlash, or the free play between two mating parts. An example of backlash is sloppy steering in an automobile, where the steering wheel can be turned left or right a small amount with no change in the direction of the automobile.

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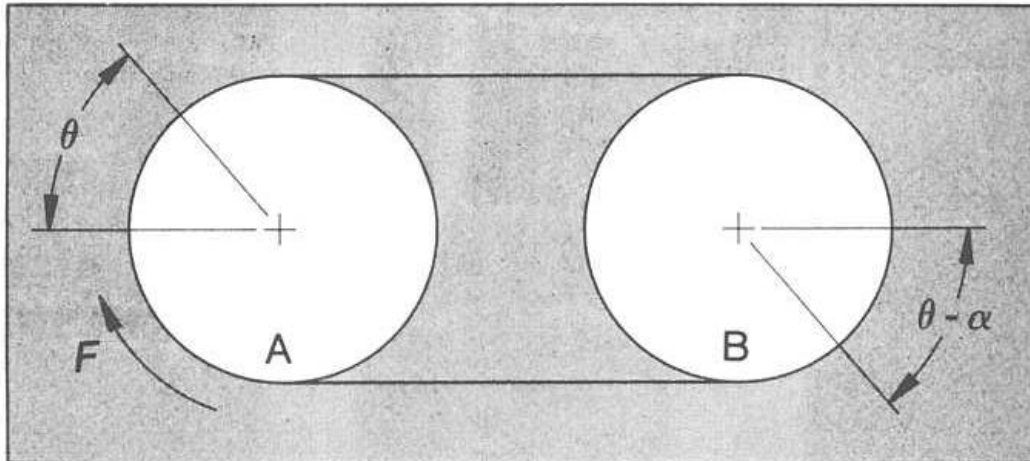
Figure 4 — An example of registration error. The rotation of sprocket B lags behind that of sprocket A due to system losses.

Tooth clearance. In any synchronous system, the clearance between belt teeth and mating sprocket grooves is the principal indication of backlash in the system. Each type and size of synchronous belt has its own characteristic tooth clearance dimensions.

Clearance values alone, however, do not represent a quantitative measure of backlash, because other factors also play a part. In fact, it is not possible to make a true comparison between the backlash of a trapezoidal tooth drive and the curvilinear tooth drives because of the difference in sprocket-to-belt tooth fit. Figures 5, 6, and 7 show the clearances for unloaded belts. Under load, a trapezoidal belt tooth contacts the sprocket in the root radius and upper flank areas only, while the curvilinear types permit greater flank contact between the belt tooth and sprocket groove.

Table 1 — Relative Characteristics of Common Tensile (Cord) Members

Material	Cost	Elongation	Flexibility	Strength[1] (psi)	Shock Load Capacity	Changes in Belt Length Due to Temp. Changes	Typical Uses
Polyester	Lowest	High	Very High	155,000	Very High	Significant	Small urethane belts such as MXL and XL.
Fiber Glass	Medium	Low	Medium	195,000/ 310,000	Medium	Insignificant	Rubber trapezoidal and curvilinear belts.
Aramid (Kevlar, Flexten, Nomex, etc.)	High	Very Low	Medium	360,000	High	Insignificant	Modified curvilinear belts (GT). Optional in other belts.
Steel	Highest	Very Low	Lowest	350,000	Medium	Insignificant	Optional.

[1]Based on equal material cross section, not belt size.

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Because the main stresses in a trapezoidal tooth timing belt are concentrated in a stress line at the base of each tooth, a high degree of tooth wear takes place as the belt operates, reducing belt life. The curvilinear tooth profiles overcome this condition because they have greater tooth flank contact with the groove and the small stress line area is eliminated. This increases belt life and reduces tooth distortion caused by the drive torque.

In addition, the trapezoidal belt exhibits a chordal effect as it wraps around small sprockets. This effect is reduced in the modified curvilinear design because each tooth is supported all along its flank. This design improves meshing, reduces vibration, and resists belt tooth deformation.

On a drive having low installation tension, small sprockets and light loads, the backlash experienced with a modified curvilinear design has significantly less backlash than the trapezoidal design.

The modified curvilinear system is a refinement of the curvilinear (HTD) system, which was developed for high torque applications but is not acceptable for some degrees of precision indexing or registration drives. The curvilinear design requires substantial clearance between belt-tooth and sprocket-groove to perform its intended function. As smaller diameter sprockets are used, the amount of clearance required to operate properly is increased. Thus, the clearance of a curvilinear drive using small sprockets can be four times greater than the clearance of an equivalent trapezoidal belt drive.

In the modified curvilinear tooth design, Figure 7, the belt-tooth depth has been reduced and belt-tooth flank angle increased, to produce a tooth form and sprocket groove profile that will mesh properly, while allowing the minimum clearance possible and retaining the benefits of the curvilinear tooth form.

Table 2 gives the relative clearance values for the different tooth designs.

Table 2 — Clearance values for various pitch sizes and belt designs

| Timing belts		Curvilinear (HTD) belts		Modified curvilinear belts	
Pitch (in.)	Clearance (in.)	Pitch (mm)	Clearance (in.)	Pitch (mm)	Clearance (in.)
1/5	0.0040-0.0050	3	0.0065-0.0094	3	0.0010-0.0050
3/8	0.0055	5	0.0080-0.0140	5	0.0022-0.0065
1/2	0.0055	8	0.0150-0.0200	8	0.0085
7/8	0.0055	14	0.0290	14	0.0150

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Pitch discrepancies. Discrepancies in the belt or sprocket pitch can also cause registration error.

Because of the manufacturing method for most synchronous belts, tooth-to-tooth variations are seldom seen within a single belt. Usually the tooth-to-tooth pitch is consistently long or consistently short due to the entire belt being long or short. If the length deviation is great enough, the belt will not mesh with the sprockets. Some specialty belts, such as long length belts, may exhibit pitch error, the magnitude of which can only be measured by test.

Sprocket specifications should list tolerances for pitch accuracy, helix angle, eccentricity, draft and diameter. These dimensional tolerances must be carefully considered, along with the belt, on precision applications.

Vibration. In a belt system, vibration is a cyclical oscillation in the driven unit or the belt when there is uniform or stopped motion in the driver unit. An example of this can be seen in Figure 4. If the motion of A suddenly stops, B continues to move until the counterforce of belt tension overcomes this forward motion, stops, then moves in the opposite direction, continuing to oscillate until damped, Figure 8. This type of vibration can be reduced by selecting a belt with a high stiffness characteristic.
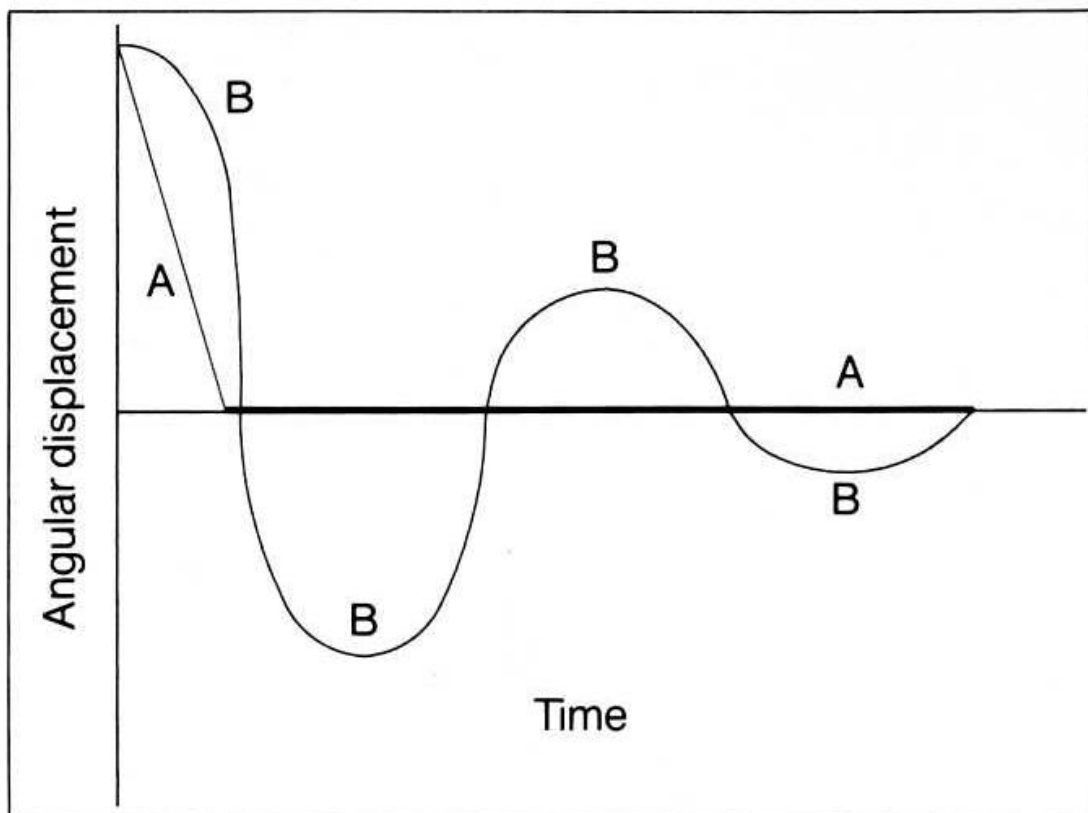
Figure 8 — Vibration in the two-belt system of Figure 4. When sprocket A stops, sprocket B oscillates through several cycles before coming to a full stop.

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Stiffness. The dynamic elongation of a belt, as well as the stiffness, can be best quantified by the use of EA or spring rate charts. Simply stated, the EA product is Young's Modulus (E) times the Cross Sectional Area (A). A 1-inch-wide belt is placed on a test apparatus and its elongation is measured under various tension loads. Several belts of the same size and construction are tested and the average elongation is plotted on the EA chart, Figure 9. The deviation from this curve by any single belt can be as great as ±30% due to normal material variations.
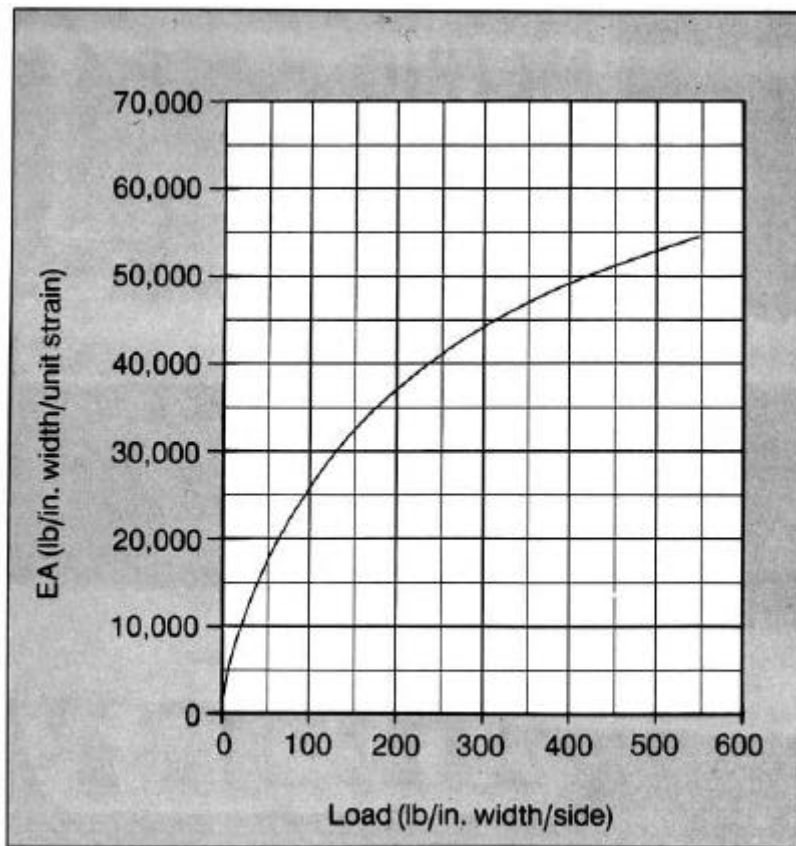

Figure 9 — EA chart shows spring rate for 14 mm pitch belt in tension.

EA=Young's Modulus X Cross Sectional Area, or

$$EA = \frac{T \times L}{E_1 \times W}$$

where:

EA = Force per unit strain per inch of belt width (lb/in./in./in.)
T = Belt working tension (lb). This is tension in the belt due to torque, centrifugal force, pretension, or a combination thereof.
L = Span Length (in.)
E_1 = Elongation of span length (in.)
W = Belt width (in.)

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If the calculated elongation is excessive, it can be improved by making one or more of the following changes:

- Reduce the belt working tension.
- Reduce the span length.
- Increase the belt width.
- Increase the installation tension.
- Choose a belt with a higher stiffness tensile member.

Design examples

Selecting belt drives for maximum precision has its trade-offs in terms of dollars, space, and weight. In addition, nonstock parts are often required to meet critical design parameters. The drive designer must weigh these factors when the original parameters are established. If questions arise concerning precise positioning and synchronization using synchronous belts, do not hesitate to contact a synchronous belt manufacturer for additional information.