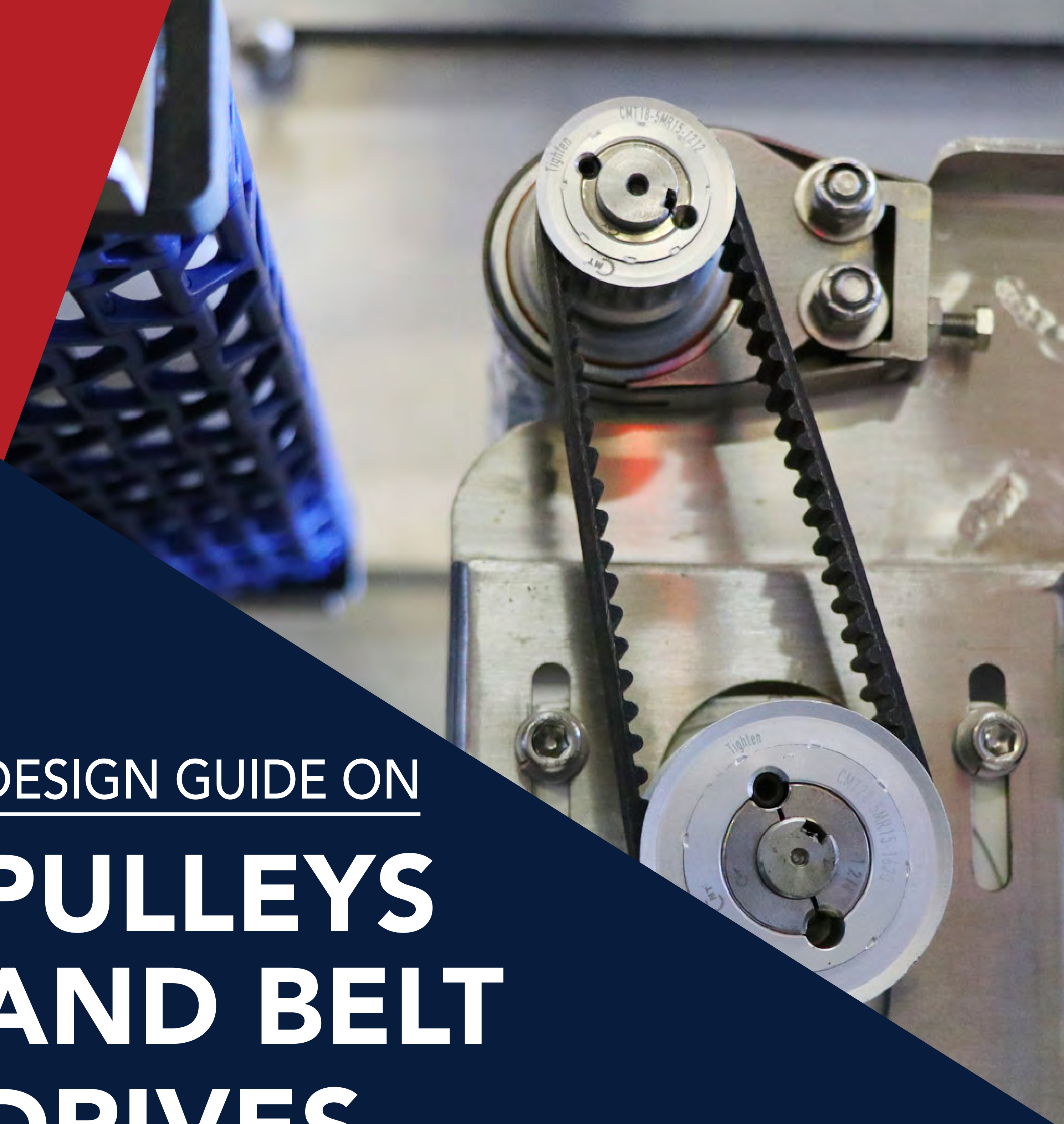
DESIGN GUIDE ON

PULLEYS AND BELT DRIVES



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PULLEYS AND BELT DRIVES DESIGN GUIDE

Belts and pulleys lift loads, use mechanical advantage to apply forces, and transmit power. They also form the basis of industrial conveyors big and small. In this exclusive Design Guide, the editors of Design World review both V and synchronous belt types — including the fundamentals of their operation. Topics on sizing and selection are also covered.

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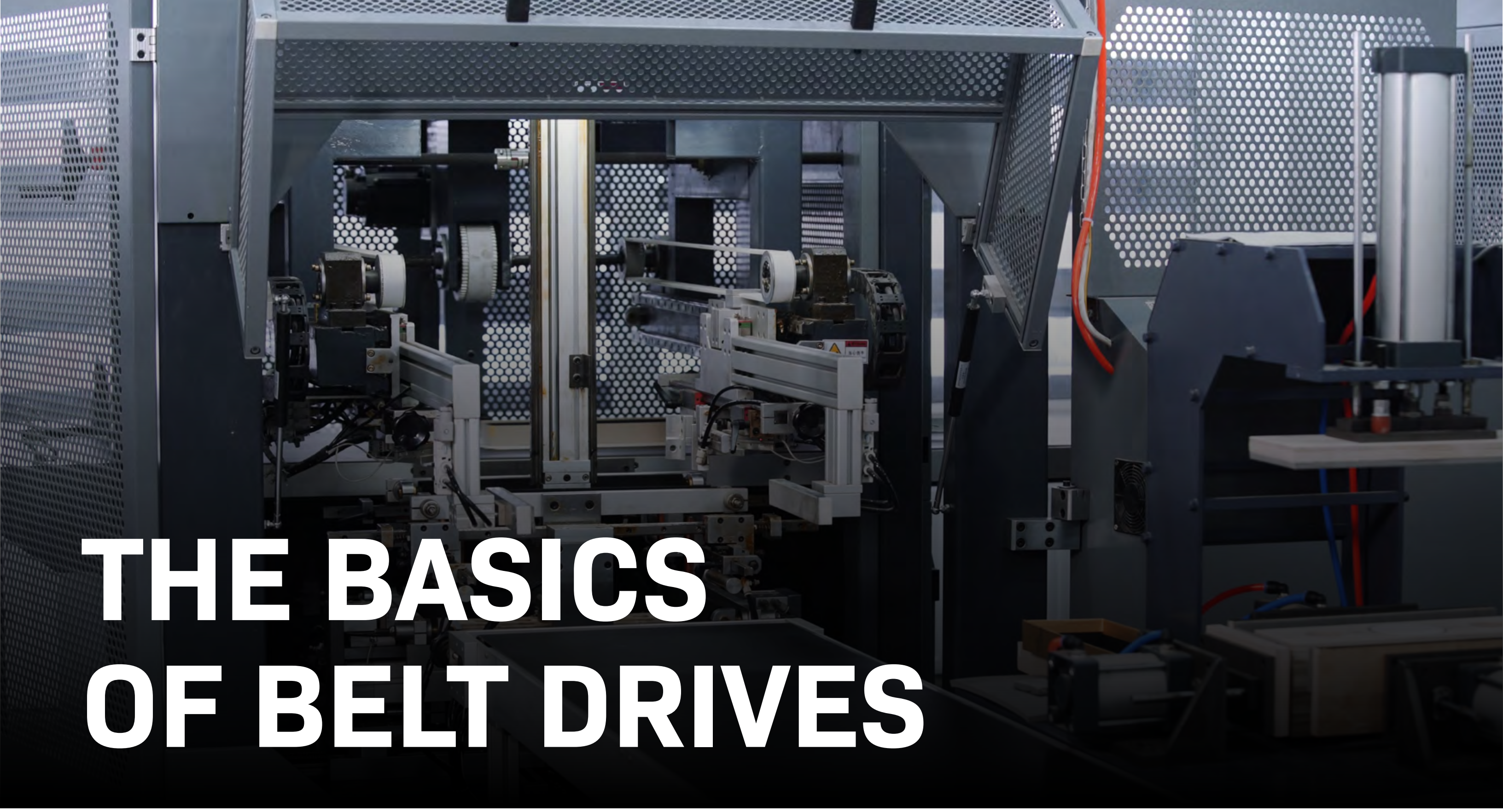

THE BASICS OF BELT DRIVES

Belt drives are indispensable in cartoning (cardboard-box folding) applications. Image via Dreamstime

Belt drives in power-transmission and motion designs consist of rubber, engineered plastic, metal, or (most common) multi-material belts that wrap around drive pulleys — specially grooved or otherwise profiled wheels mounted on a shaft — in turn driven by electric motors. Powered by various motor types, these belt drives run axes transmitting fractional to 7,000 hp or more. Most belt drives in motion designs also wrap the belt around one or more idler pulleys that keep the belt taut and on track.

Custom timing pulleys integrates many custom design features into a single product design. Image courtesy of Custom Machine & Tool Co., Inc.

While industrial belts are generally non-serviceable and can exhibit wear and vulnerability to oil as well as debris contamination, their benefits abound. The main reasons that engineers pick belt drives over other options is that modern varieties require little if no maintenance; they're less expensive than chain drives; and they're quiet and efficient, even up to 95% or more. In addition, the tensile members of today's belts — cords embedded into the belt rubber that carry most of the belt load — are stronger than ever. Made of steel, polyester, aramid, fiberglass, or carbon fiber, these tensile cords render today's belt drives thoroughly modern power-transmission devices.

BELT-DRIVE EVOLUTION OF DESIGN AND PERFORMANCE

Flat belts are the original design for automated machinery — first applied in such designs during the first Industrial Revolution and before. In fact, flat belts were and remain especially important in pump and sawmill operations — and once reigned supreme in driving many axes off common steam-powered line drives through factories. Versions made of leather quickly gave way to rubber and neoprene — hastened by the innovations of the burgeoning automotive industry and new forms of independent pieces of machinery run off electric

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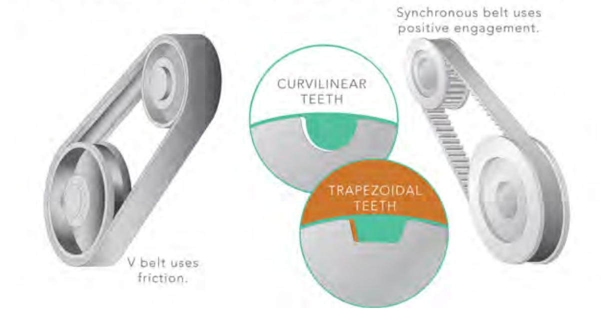
THE BASICS OF BELT DRIVES

V BELT AND SYNCHRONOUS BELT GEOMETRY



Machine designs often employ gear, chain, and belt drives for power transmission. The latter offer several advantages and come in two main subtypes — V belt and synchronous belt drives — to serve different applications.

Recent years have seen convergence of specialty belt drive systems in mass-produced consumer and light industrial tools with the standard belt drives integrated into specialty machine designs. That's because options have proliferated for belts with flat and round profiles as well as those with various V-shaped profiles and toothed belts for synchronous operation. The Association for Rubber Products Manufacturers (ARPM) originating from the Rubber Manufacturers Association (RMA) and the National Industrial Belting Association (NIBA) along with component suppliers dictate the details of how the geometries and performance of these industrial belt drives are standardized and quantified.

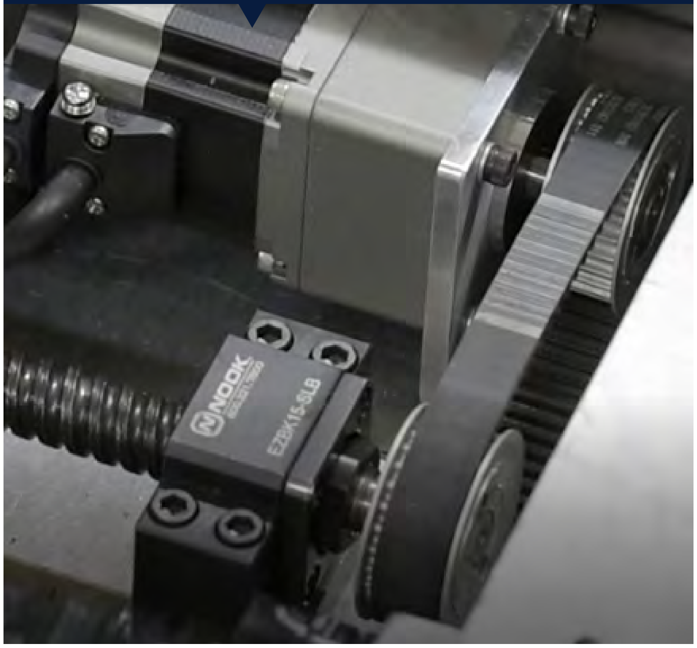
motors. Today, highly engineered flat belts still find myriad uses in conveying and material-handling applications.

However, the faster axis speeds associated with many motor-powered designs necessitated belts with new geometry — so next came V belts having trapezoidal cross sections. Invented by John Gates in 1917, their easier tracking on pulleys and higher friction (which we'll explain more on a moment) also allow high force transmission even at relatively low tension values. Reinforced cords embedded in belt backing — the tension-carrying zone — was another innovation still core to modern belt variations.

Combining flat and V-belt design elements are ribbed or poly-groove V belts — those with a cord-reinforced tension-bearing face and multiple trapezoidal profiles running the inner belt circumference. Drives based on ribbed V belts are exceptionally compact and necessitate lower tensions than flat belts.

As we'll explore in this Design Guide, other innovations came to include the introduction of toothed belts for synchronous chain-like operation; heat-resistant belt insulation layers; elasticized and other highly engineered working belt surfaces; and pre-stretched tensile cords of various materials.

Terminology for belt drives is more consistent than that for other motion components. That said, in some contexts the term sheave is used instead of pulley. The terms sheave and pulley are interchangeable, with few regions and industries differentiating sheave to mean any drive pulley — distinct from idler pulleys that have flat (or simply profiled) outer diameters. Otherwise, sheave can imply a rugged steel or cast-iron drive wheel that's less precisely cast or machined than the pulleys found in motion designs — which are our primary focus in this Design Guide.



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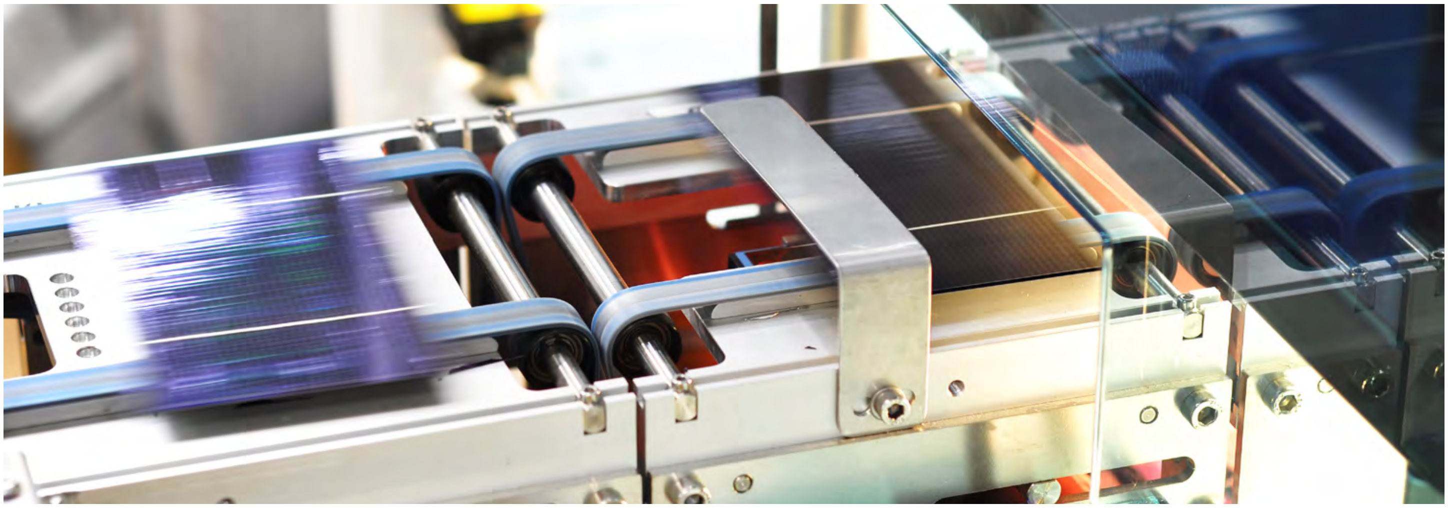
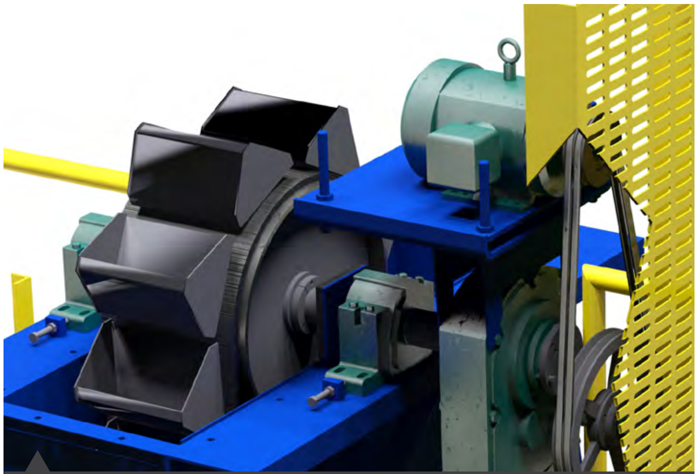
THE BASICS OF BELT DRIVES



Here, flat belt drives on a conveyor support the production of solar cells. Image via Dreamstime

Many manufacturers describe belts and pulleys with five main geometries. Pitch diameter is the drive pulley's diameter. Center distance is the distance between the two pulleys' centers. Minimum wrap angle is a measure of how much the belt wraps around the smallest pulley. Belt length is how long the belt would be if cut and laid flat.

Finally, in the case of toothed belts (also called synchronous belts) the pitch is the number of teeth per some length — so a 3-mm pitch means that the belt has one tooth every 3 mm, for example.



Shown here is a bucket elevator from Feeco International that uses an electric motor through a belt drive with twin V belts for operation.

Power ratings based on belt and pulley size (along with motor output) are adjusted for the belt-drive length and wrap diameters. Traditionally, charts of belt geometries and counts, horsepower ratings, and speed and force capabilities assist design engineers in the specification process. Today, sizing and selection software tools abound to match required values to a machine axis' geometry and torque (output force) and speed requirements. These also provide service-factor adjustments informed by the belt or other component supplier's own historical experience with given industry and application type.

DIFFERENTIATING OTHER LESS COMMON BELT-DRIVE TYPES

Because V belt and synchronous belt drives dominate motion power transmission and motion control (positioning and other precision) applications, we cover them in more depth later in this Design Guide. Following is a brief detailing of the other belt types used in industrial, robotic, and consumer designs.

Modern flat belts are either endless (welded or otherwise closed into a hoop by the manufacturer) or open. Common on grinders, fans, grocery conveyors, and other power-transmission applications, drives based on flat belts rely on precisely set tension for maintaining the proper the friction coefficient between belt and drive pulley.

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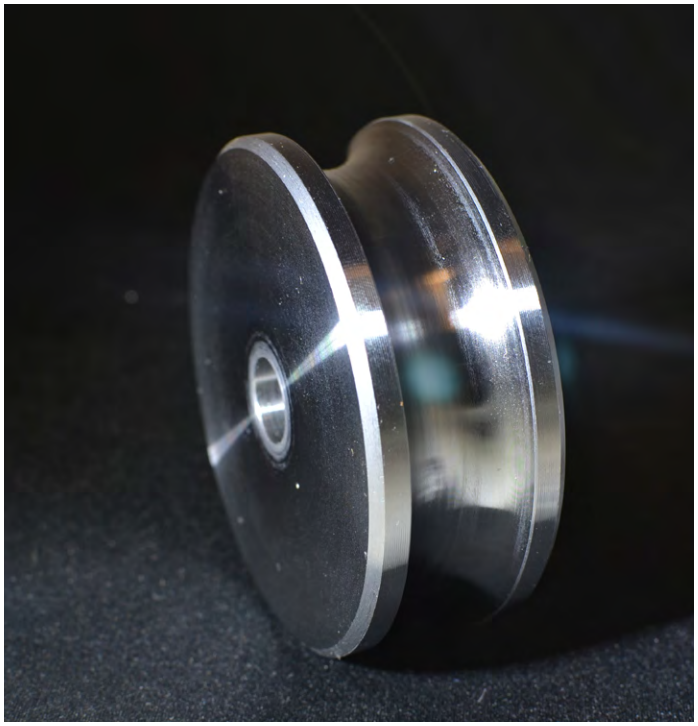
THE BASICS OF BELT DRIVES

Even today, many flat belts are made of natural materials as well as synthetic yarns featuring various filament structures. Flat belts made of polyurethane are common on the ends of conveyors consisting of roller arrays — to gang powered rollers (integrating a motor in its cylindrical body) to passive nonpowered rollers.

Flat belts with polyester tension members excel where high tension (but little stretch) is required; coatings of PVC, polyurethane, and rubber enable high friction for use on high-speed axes running to 22,000 feet per minute.

One specialty type of flat belt indispensable in settings subject to high temperatures and corrosive washdown (or other chemicals) is that made of thin stainless steel. These flat belts are precision welded closed to traverse just a few centimeters to dozens of meters — and often perforated to accept the positive engagement of studded pulleys. Flat metal belts also exhibit no stretch or creep, so allow precision positioning of workpieces — and can protect workpieces sensitive to electrostatic charges with grounding.



This is a typical example of a round belt pulley.
Image courtesy of Custom Machine and Tool Co., Inc.

Round belts (sometimes called O-ring belts or O belts) have a circular cross section; they're common on axes of consumer-grade electronics with moving elements, office-grade printers and scanners, and light industrial equipment such as tabletop robotics with modest to moderate power-transmission requirements.

Most round belts are extruded from neoprene, propylene, or cross-linked urethane (either reground or virgin) and then butt welded together into endless loops. Their elasticity makes them more forgiving of suboptimal installations, but at a sacrifice of power capability. Mating pulleys have semicircular grooves and diameters no less than sixfold the belt's cross section. Texturized O-belts have lower coefficients of friction but are better able to resist abrasion and overheating.

BELT CREEP, SLIP, AND TENSION

Any belts not employing positive engagement (via teeth) can exhibit slip and creep.

Creep is a cyclical elongation of belt (with some measure of elasticity) as it travels around the loaded side to the slack side of its circuit … and is considered normal. Proper tension holds the dimensional changes of creep to within 0.5% of the belt's normal length and cross section. There is a cyclical stressing associated with creep as well as the flexing of belt around its pulleys — which does ultimately limit belt life but doesn't induce dramatic temperature increases.

In contrast, belt slip due to improper tension or (worse yet) improper design can quickly generate heat buildup. Simple measurements taken of belt temperature along with geometry, vibrations, and sound generated (including squealing upon startup) can accurately indicate the amount of tensioning or retensioning required. Belts transmitting high power require greater tensioning or risk slip and other modes of improper operation.

Design tensions are often defined by the ratio of belt drive-side tension divided by that of the slack side — along with a constant wedging design factor (for V belts) and the belt-to-pulley dynamic friction coefficient. As we'll explore in more detail, design tension ratios for V belts tend to be higher than those for flat belts.

CALCULATING MOTOR DRIVE TORQUE FOR BELT-BASED MOTION SYSTEMS

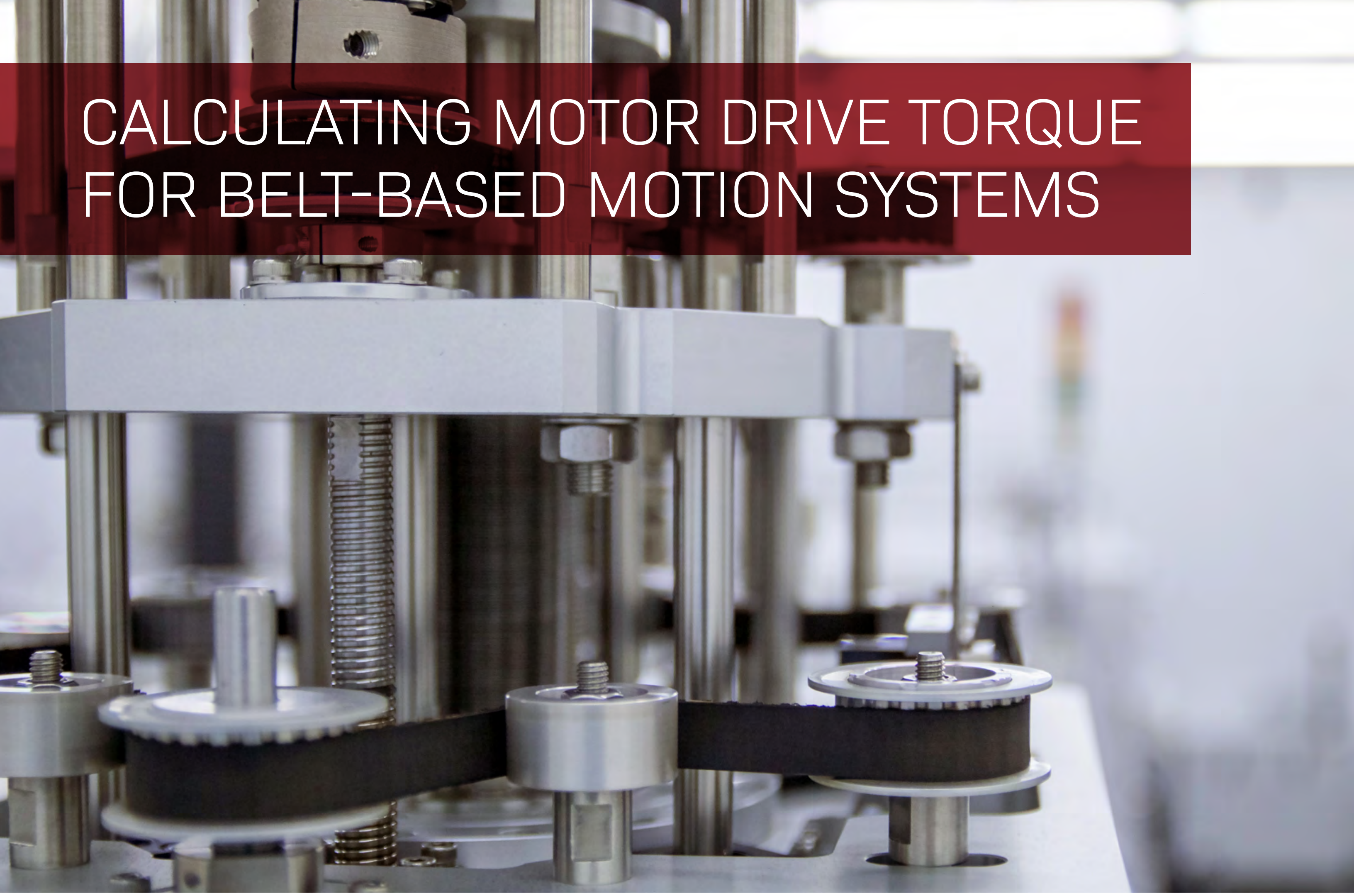


Image via Dreamstime

Belt-driven linear systems are common in applications that require long travel and high speed, such as gantry robots and material handling and transport. The motors of choice for these systems are often servomotors, for their ability to accurately control position, speed, and torque.

Sizing and selecting the servo motor requires determining both the continuous and intermittent drive torques required for the application. The continuous torque is calculated by taking the root mean square of all the torque requirements throughout the application — torque required for acceleration, torque for constant velocity, and torque for deceleration. In most applications, the maximum (intermittent) torque occurs during acceleration.

To determine the root mean square (continuous) torque, we first calculate the torque values required during each phase of the move profile.

Torque required for constant velocity: For a belt drive system, the motor torque required during constant velocity is simply the total axial force (Fa) on the belt multiplied by the radius r_1 of the drive pulley:

$$T_c = \frac{F_a \cdot r_1}{1000 \cdot \eta}$$

Where T_c = Torque required during constant velocity, Nm

F_a = Total axial force, N

r_1 = Radius of drive pulley, mm

η = Efficiency of belt drive system

Notice that the efficiency η of the belt drive system is included in the torque equation. This efficiency accounts for losses such

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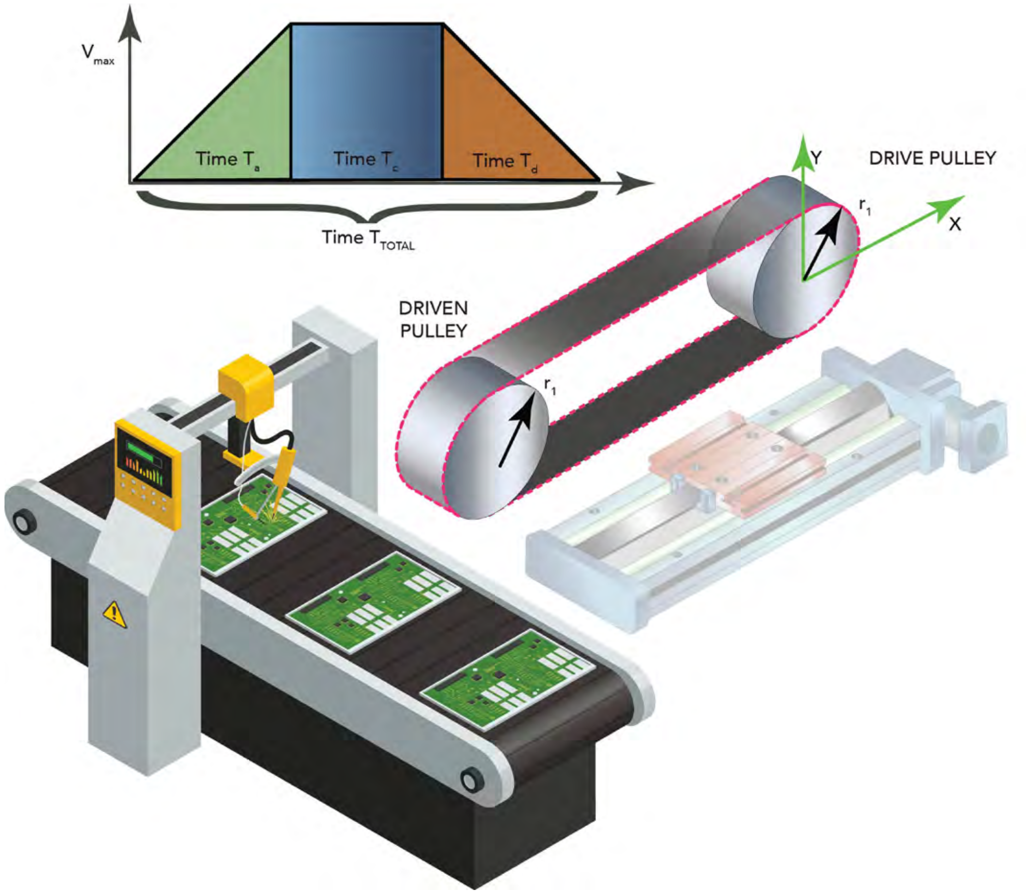
CALCULATING MOTOR DRIVE TORQUE FOR BELT-BASED MOTION SYSTEMS



For the equations in this Design Guide section, we've assumed the drive and idler (driven) pulleys have the same radius, which is often the case for belt-driven linear motion systems.

as friction between the belt and pulleys. Also note that we've assumed the drive and idler (driven) pulleys have the same radius, which is often the case for belt-driven linear motion systems.

Unlike screw drives, which often encounter axial forces due to external operations such as pressing or drilling, belt drives aren't designed to withstand external axial forces. So the total axial force for a belt drive system consists only of the force required to move the load, which is the weight (m·g) of the load (both the external load and the belt) multiplied by the coefficient of friction μ of the guide supporting the load.

$$F_a = m \cdot g \cdot \mu$$

Where m = Mass of moved load — external load plus belt, kg

g = Gravity, m/sec^2

μ = Coefficient of friction of guide

Torque required for acceleration: The acceleration phase of the move profile is typically the period when maximum torque is required from the motor, and this torque value T_a is often taken as the intermittent torque.

The torque required during acceleration includes the torque required at constant speed plus the torque required to accelerate the load.

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CALCULATING MOTOR DRIVE TORQUE FOR BELT-BASED MOTION SYSTEMS

$$T_a = T_c + T_{acc}$$

Where T_a = Total torque required during acceleration, Nm

T_{acc} = Torque required due to acceleration, Nm

The torque due to acceleration is found by multiplying the total inertia of the system Jt by the angular acceleration α:

$$T_{acc} = J_t \cdot \alpha$$

Where J_t = Total inertia of the system, kg·m^2

a = Angular acceleration, rad/sec^2

Total system inertia includes the inertia of the motor (because the motor must overcome its own inertia) as well as that of the coupling, pulleys, and load:

$$J_t = J_m + J_c + J_{p1} + J_{p2} + J_l$$

Where J_m = Inertia of motor — provided by manufacturer, kg·m^2

J_c = Inertia of coupling — provided by manufacturer, kg·m^2

J_{p1} = Inertia of drive pulley — provided by manufacturer, or calculate kg·m^2

J_{p2} = Inertia of idler pulley — provide by manufacturer, or calculate kg·m^2

J_l = Inertia of load, kg·m^2

Although we assumed above that the drive and idler pulleys have the same radius, their inertias may be slightly different, because the drive pulley is toothed and therefore has a slightly larger radius and higher mass than the idler pulley. The inertia values of the motor, coupling, and pulleys are typically specified by their respective manufacturers. However, the inertia of the load must be calculated. Remember that the load includes the mass of both the external load and the belt, because the motor must generate enough torque to overcome the inertia of the belt:

$$J_l = (m_l + m_b) \cdot r_1^2 \; x \, 10^{-6}$$

Where m_l = Mass of external load, kg

m_b = Mass of belt, kg

r_1 = Radius of drive pulley, mm

For the angular acceleration, we assume that the system is accelerating from zero to some maximum velocity, with N being the maximum angular velocity and t being the time to accelerate.

$$\alpha = \frac{2\pi \cdot N}{60 \cdot t}$$

Where N = Maximum angular velocity, rpm

t = Time for acceleration, sec

If the system is accelerating from a non-zero velocity, then the equation would simply incorporate the change in velocity ΔN divided by the time over which the velocity increase occurred Δt.

Torque required for deceleration: The motor drive torque required for deceleration is equal to the torque at constant velocity minus the torque due to acceleration. Td is torque required during deceleration in Nm:

$$T_d = T_c - T_{acc}$$

Now that we know the motor drive torques required during acceleration, constant velocity, and deceleration, we can take the root mean square of these values to determine the continuous torque required by the motor:

$$T_{RMS} = \frac{\sqrt{T_a^2 \cdot t_a + T_c^2 \cdot t_c + T_d^2 \cdot t_d}}{t_{total}}$$

Where T_{RMS} = Root mean square (continuous) torque, Nm

t_a = Time for acceleration, sec

t_c = Time for constant velocity, sec

t_d = Time for deceleration, sec

t_{total} = Total time for move — including any idle time between moves, sec

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ACCOUNTING FOR BELT AND PULLEY INERTIA

For a motor to accelerate or decelerate a load, it must overcome the load's inertia or resistance to change in motion, as explained in Newton's First Law. In belt-driven linear motion systems, the motor must overcome not only the inertia of the applied load but also the inertia of the belt, pulleys, and motor coupling.

The inertia of each component can typically be estimated with sufficient accuracy by using the standard inertia equations for simple shapes. Because inertia depends upon the axis around which the component rotates, we can start by considering the applied load and the belt together, since they both rotate around the axis of the driven pulley.

The applied load and the belt can be modeled as a point mass that rotates around the driven pulley, and their inertia can be calculated as:

$$J_L = mr^2$$

Where J_L = Inertia of belt and applied load, kg·m^2

m = Mass of belt and applied load, kg

r = Radius of driven pulley, m

Belt manufacturers typically provide mass (or weight) information per unit length, so the mass of the belt can be found by multiplying the mass per unit length by the total length of the belt. In calculations, just be sure to use the full circular belt length — not just the length of the stroke. Also remember that the applied load is typically mounted to the belt via a carriage or table, so the mass of this part should be included in the mass of the applied load.

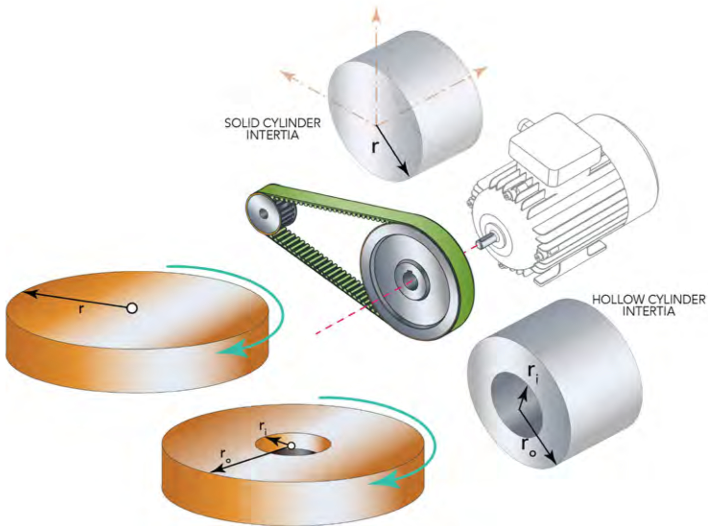
The pulleys and coupling can be treating as solid cylinders that rotate about their own axes, and their inertia can be calculated as:

$$J_p = \frac{1}{2}mr^2$$

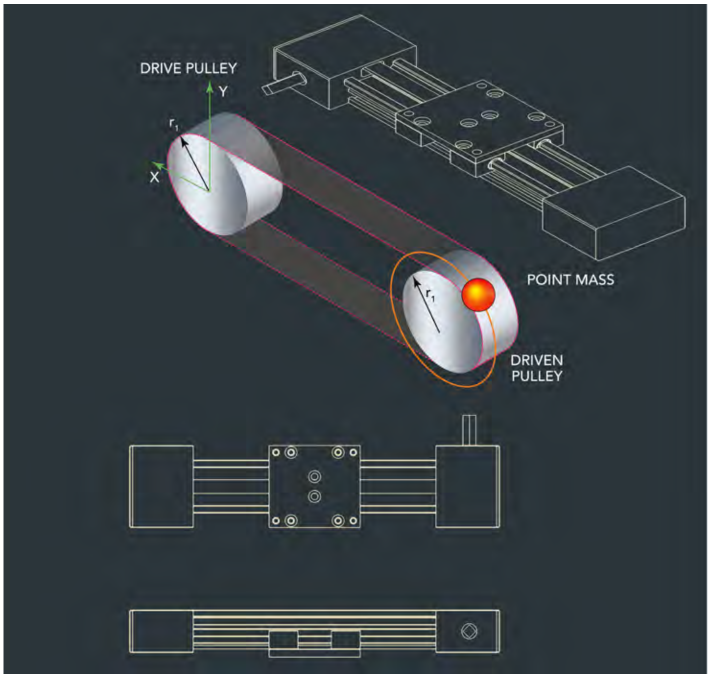
Where J_p = Inertia of solid cylinder — pulley and coupling, kgm^2

m = Mass of cylinder, kg

r = Radius of cylinder, m



Pulleys can serve to change a belt drive's speed.



The belt and load can be considered a point mass that rotates around the driven pulley.

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ACCOUNTING FOR BELT AND PULLEY INERTIA

Keep in mind that although the pulleys may have the same diameters (and radii) if one pulley is toothed (driven) and the other is smooth (idler) … as is the case in many belt-driven actuators, they will have different masses and therefore different inertias.

Although the solid cylinder approximation shown above is typically sufficient, more accurate inertia values for the pulleys and coupling can be found by considering that these components have a center bore and using the inertia equation for a hollow cylinder:

$$J_{ph} = \frac{1}{2} m\left(r_o^2 + r_i^2\right)$$

Where J_{ph} = Inertia of hollow cylinder — pulleys and coupling, $kg \cdot m^2$

m = Mass of cylinder, kg

r_o = Outer radius, m

r_i = Inner radius, m

It's common for belt driven systems to use a gearbox to increase torque, reduce speed, and reduce the inertia of the load reflected to the motor. In this case, the total inertia of the moved mass (applied load, belt, pulleys, and coupling) should be divided by the square of the gear reduction, and then the inertia of the gearbox should be added. This will give the total inertia reflected back to the motor, which can be used for motor sizing and selection.

$$J_{total} = \frac{J_L + J_{p1} + J_{p2} + J_c}{i^2} + J_g$$

Where J_{total} = Total inertia reflected to motor, $kg \cdot m^2$

J_L = Inertia of belt and applied load, $kg \cdot m^2$

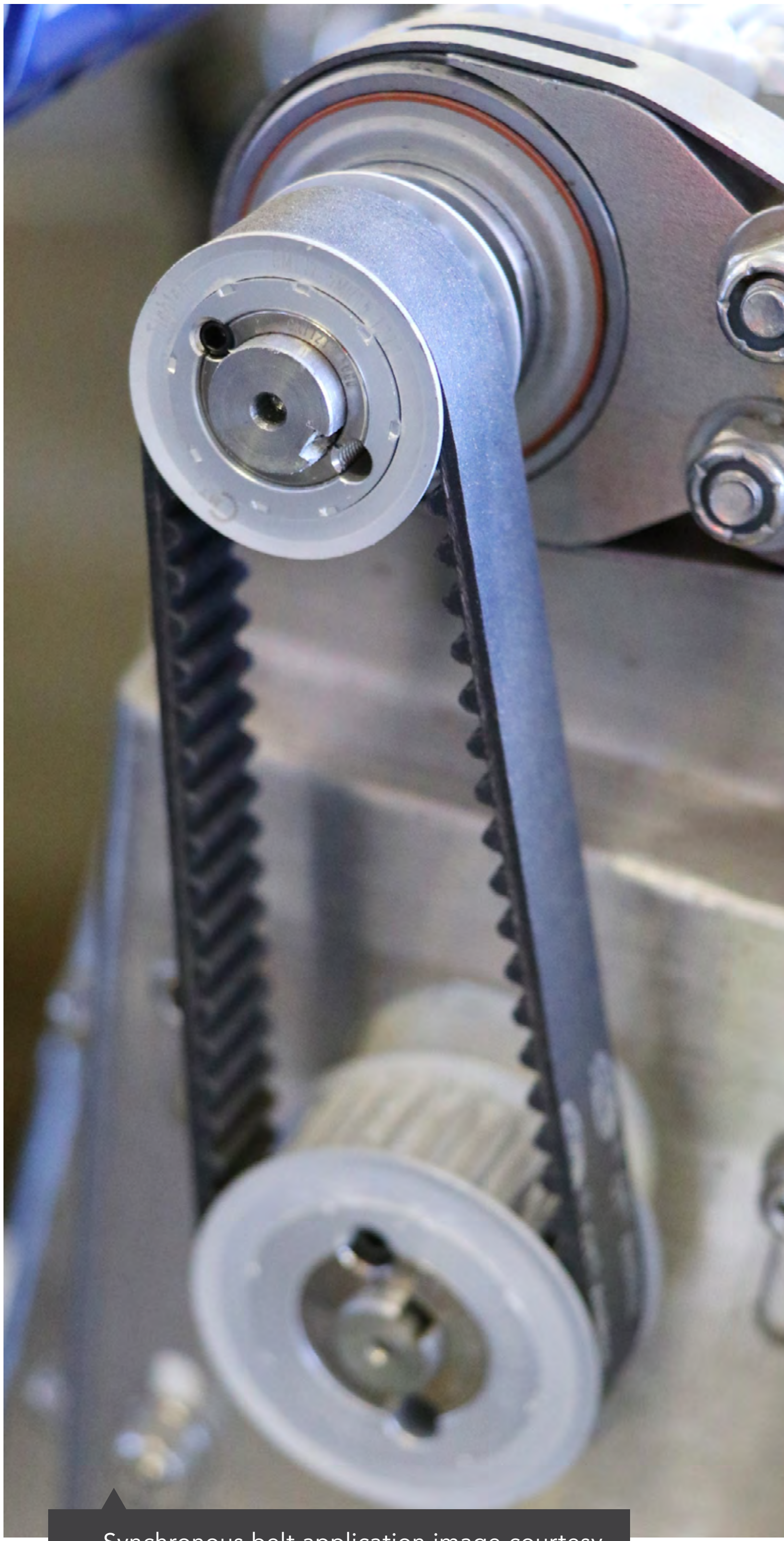
J_{p1} = Inertia of first pulley, $kg \cdot m^2$

J_{p2} = Inertia of second pulley, $kg \cdot m^2$

J_c = Iinertia of coupling, $kg \cdot m^2$

i = Gear reduction

J_g = Inertia of gearbox, $kg \cdot m^2$



Synchronous belt application image courtesy of Custom Machine & Tool Co., Inc.

THE ENDURING IMPORTANCE OF V BELTS

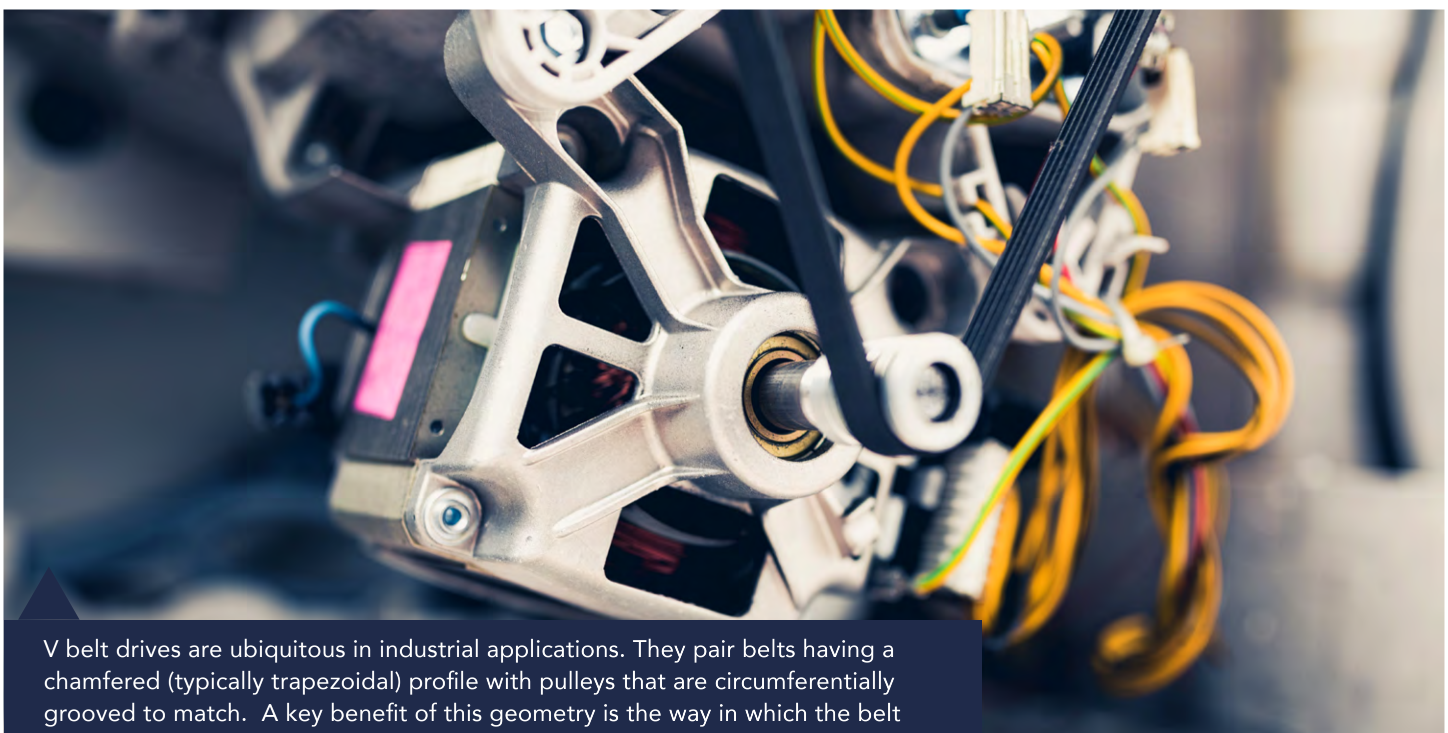
Shown here is a V ribbed pulley from Custom Machine & Tool Co., Inc. for low-horsepower drives. V ribbed pulleys are suitable for compact designs and machines requiring low vibration — as well as applications requiring low noise transmission. Images courtesy of Custom Machine & Tool Co., Inc.

Power transmission in linear motion designs is often through rotary-to-linear mechanical devices, chain drives, or belt drives. The earliest belt iteration — and one that's still economical today — is the friction-based V-belt design. These pair a wedge-shaped belt with a pulley (often on an electric motor's geared output shaft) to provide reliable operation in myriad end-user and industrial designs.

Modern V belts — sometimes called friction belts — are rubber, urethane synthetic, and neoprene designs with either a V or trapezoidal profile. The latter increases the amount of contact between V belts and pulleys to minimize tension needed to transmit torque. Even so, polyurethane outperforms rubber thanks to its higher resistance to chemicals and adaptability to specialized profiles.

Polyurethane also boosts the shear strength of the teeth on synchronous belts covered later in this Design Guide.

The V belt's most important element — its tension-bearing top — includes fiber cords for strength to bear the actual traction load. Modern tension-member cords are often aramid, polyester, fiberglass, or even steel. Prestretched variations help minimize stretch. The cords embed into the main belt material that serves to hold the belt body together and shed heat. The working side of V belts — which engages the pulley — is a compression section designed to wedge into pulley grooves for reliable shock-damping engagement. In many instances, a rubberized fabric cover protects the belt surface and prevents slipping (which in turn prevents overheating tension cords).



V belt drives are ubiquitous in industrial applications. They pair belts having a chamfered (typically trapezoidal) profile with pulleys that are circumferentially grooved to match. A key benefit of this geometry is the way in which the belt wedges into the pulley groove with increased tension for a corresponding increase in belt-and-pulley surface friction. That in turns minimizes slippage and boosts allowable torque transmission. Shown here is a small V belt drive on a motor-driven axis inside a consumer-grade washing machine. Image via Dreamstime

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THE ENDURING IMPORTANCE OF V BELTS

One additional note here: Though V-belt slip is usually detrimental, it can be a helpful behavior on axes that are truly jammed — serving to protect more expensive components in the drivetrain.

Though they're versatile and forgiving, improperly sized friction-based belt drives can slip (tangentially on the pulley — a form of lost motion) and creep axially. That can make for unreliable speed output. Here are some things to remember if a V-belt drive makes the most sense for a motion axis: Output torque depends on belt resistance to tension and belt-pulley adherence. The latter is why oils and greases must be kept away from belt drives — or threaten drive failure due to slipping.

The special case of cogged V belts: Not to be confused with toothed (synchronous) belts covered later in this Design Guide are cogged V belts. These have notches on the working (pulley-contacting) belt surface to:

• Allow airflow for cooler operation

• Boost flexibility — to travel around pulleys with smaller diameters than otherwise allowable

These notched V belts — available in a wide array of classic and narrow configurations — often have a raw-edge design (sans cover) for more space in the belt cross section for load-carrying cord. Any standard V belt that is cogged will have a name with an X suffix — such as BX or 3VX, for example.

Though most associated with heavy power-transmission applications, V belts do in fact find use in precision motion designs as well. Embrace the oxymoron: Static motion

Shown here is a custom multi-groove V-belt pulley attached with a standard keyway.

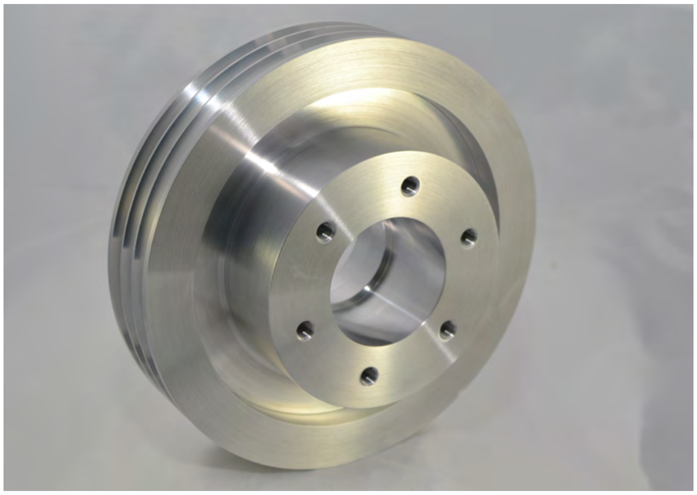
Image courtesy of Custom Machine & Tool Co., Inc.

designs — those that only depend on consistent end-of-move positioning — can tolerate the errors of friction-belt drives. In contrast, dynamic motion designs require axes that move predictably over their complete strokes — even if load varies during operation. Here, engineers typically specify low-backlash toothed belts (covered in the next section of this Design Guide) needing shallow clearance for pulley engagement. Single V belts for these motion applications often take the form of light-duty or fractional horsepower V belts denoted by 2L, 3L, 4L, or 5L codes with the latter dimensionally resembling so-called *classical* A and B-coded V belts.

MORE ON COMMON V BELT STANDARDS

Be prepared to specify V belts by cross section (including the belt's top width, V angle, depth of engagement, and depth) and overall pitch length … defined as a circumferential length along a belt's pitch line. Then suitable V belts are narrowed further by which have sufficient power ratings (determined by rpm and sheave speed) to satisfy design demand of nominal horsepower (to be transmitted or output at the motor) with application of a service factor.

Sound complicated? In fact, industry has simplified much of this work with references that list specific V-belt service factors that adjust for typical levels of special application demands … as well as losses from variable loads and rpm, heat, detrimental



Shown here is a custom-manufactured multi-groove V-belt pulley from Custom Machine & Tool Co., Inc.

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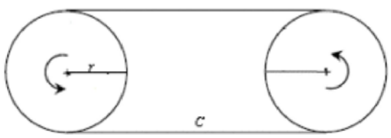
THE ENDURING IMPORTANCE OF V BELTS

HOW TO CALCULATE DATUM LENGTH

Case 1: Pulleys with equal diameters

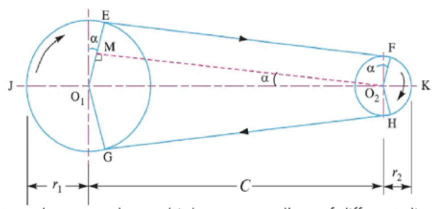


Belt length is based on …
- The center-to-center distance between pulleys and
- The arc of contact between the belt and the pulleys— dependent on the relative pulley diameters.

When the belt's only purpose is to transmit power, pulleys of equal diameter are used on each end of the belt. In this case, the arc of contact is 180° on each pulley. This means that the belt has contact with exactly one-half of circumference of each pulley, or the equivalent of one full pulley circumference. To determine the belt datum length, simply add the pulley circumference to twice the center distance between the pulleys.

$$L_D = 2\pi r + 2C$$

Case 2: Pulleys with unequal diameters



When the belt is used to reduce speed or multiply torque, pulleys of different diameters are used. When the pulley diameters differ, the arc of contact is less than 180° on the smaller pulley and greater than 180° on the larger pulley. In this case, the formula for belt datum length requires determining the arc of contact on each pulley, as well as the length of belt between pulleys on both the top and bottom.

$$L_D = arcGJE + EF + arcFKH + HG$$

As shown in the figure, arc GJE is greater than 180° and arc FKH is less than 180° as determined by the angle **α** — or more specifically by the sine of **α** which is given as:

$$\sin \alpha = \frac{r_1 - r_2}{C}$$

The arc GJE equals half of the larger sheave circumference, plus twice the length given by sin **α**:

$$arcGJE = r_1\left(\pi + 2\frac{(r_1 - r_2)}{C}\right)$$

Similarly, arc FKH equals half of the smaller sheave circumference, minus twice the length given by sin **α**:

$$arcFKH = r_2\left(\pi - 2\frac{(r_1 - r_2)}{C}\right)$$

Note that MO_2 is equal in length to EF and GH, so we can solve for MO_2 to determine the length of belt between the pulleys. Using the Pythagorean theorem, we get:

$$MO_2 = \sqrt{(O_1O_2)^2 - (O_1M)^2}$$

Which can be expressed as:

$$EF = MO_2 = C - \frac{(r_1 - r_2)^2}{2C}$$

Adding arcGJE, arcFKH, and twice the length EF (for the belt between pulleys on both top and bottom):

$$L_D = \pi(r_1 + r_2) + \frac{(r_1 - r_2)^2}{C} + 2C$$

Or, in terms of diameter:

$$L_D = \frac{\pi}{2}(d_1 + d_2) + \frac{(d_1 - d_2)^2}{4C} + 2C$$

environmental conditions, and shock and vibration.

V belts with so-called classical geometries just mentioned are a rugged if moderate-efficiency option. In the U.S., standardized geometries are coded A and B (most common) as well as lesser-used C, D, and E having progressively larger cross sections. Narrow V belts are named with progressively higher numbers for progressively larger belts — and have V suffixes. Double-sided V belts are those with a double-angle or so-called hexagonal geometry for winding through and driving serpentine drive arrangements; these are coded AA, BB, CC, and so on. These codes are listed in specification software and manufacturer catalogs as well as printed on the belts themselves … usually followed by a dash and then a number denoting the total working length of the belt in inches. Even International Organization for Standardization standards such as ISO 8419 (dictating the standards for narrow V belts) lists values in millimeters that reflect these standards first established in Imperial units.

Of course, the latter (length) code does not appear on adjustable V belts — those made of a series of interlocking sections joined by tabs or other fasteners like industrial chain. These linked belts (suitable for even high-power and high-speed axes to many thousands of rpm) are sold in open sections that are cut to length and then closed by the installer in the field.

Another V-belt design is that of ***joined*** V belts. Unlike ribbed V belts (covered earlier in this Design Guide) that have a common foundation of thickness sufficient to feature reinforcement

(continued)

THE ENDURING IMPORTANCE OF V BELTS

throughout, joined V belts have discrete trapezoidal sections. These sections are themselves reinforced but joined by just a thin layer of tension material. Such joined V-belts are easier to specify than matched sets and far less problematic than separate arrays of V belts running in parallel — especially on axes subject to intermittent forces and speeds. That's especially true on axes that might otherwise require a dozen or more V belts in parallel for sufficient power transmission.

Axes run off 2-hp or smaller motors under the control of variable speed drives (never prompting more than fivefold speed increases) accept V belts having 4L, 5L, A, or B notations. Axes with more dramatic speed variations necessitate other V belt that's also standardized and coded — in this case, with four-digit values and a V (for narrow) suffix.

SPECIFYING V BELTS BY HORSEPOWER AND GEOMETRY

Standards established by the Rubber Manufacturers Association (RMA) and the Mechanical Power Transmission Association (MPTA) inform specification approaches that first satisfy design horsepower requirements. Using this approach, a service factor applied to nominal (rated) motor or axis horsepower (to accommodate friction, vibration, heat, and other losses) ensures reliable and efficient belt-drive operation. These service factors are published for machine and drive types typical to various industries.

Power ratings are well documented for all standard V belt and pulley sizes and speeds. But arc and length correction factors (along with the belt-installation center distance and speed ratio covered in a moment) affect this basic power rating. Center distance is often presumed for set pulley combinations. That said, long pulley-to-pulley center distances yield high power ratings and shorter yield lower ratings.

Next, the driven-to-drive pulley speed ratio (based on any difference in their diameters) is calculated to yield output belt speed (sometimes called rim speed). High speed ratios magnify the effect of center distance changes on drive power ratings. Then the maximum output rpm or fpm (based on the axis geometry, pulley construction, and level of balancing) is calculated — with multiplane dynamic balancing increasing this value. Finally, work output for a given time (based on horsepower x 1.341) yields a value expressed in kilowatts.

One last design consideration for machines employing V belts is the level of balancing required. Refer to *Balancing the pulleys of belt drives* later in this Design Guide for more on this topic.

WHAT ARE V-BELT PITCH LENGTH AND DATUM LENGTH?

The length of a V-belt can be specified in several ways — including outside length, effective length, and pitch (or datum) length. Outside length is measured around the belt's outer diameter with no tension but is only an approximation and is not useful for sizing or selection. Effective length is measured at the effective outside diameter of the sheaves (pulleys) — the location on the sheave at which the groove's top width is measured. Alternatively, the pitch length is measured at the pitch diameter of the sheaves. Both effective length and pitch length are measured with the belt tensioned by a specified amount.

Pitch length is difficult to directly measure because it's based on the belt pitch line. According to ISO 1081:2013, the pitch line is "any circumferential line which keeps the same length when the belt is bent perpendicularly to its base." In other words, the pitch line is the line internal to the belt that doesn't change length when the belt is in use. The diameter that is formed on the sheave by the pitch line of the belt is the sheave pitch diameter.

A belt's pitch line typically corresponds to the location of its internal tensile cord. But improvements in belt construction have moved the tensile cord to a location higher in the belt. This resulted in changes to the belt's pitch length, and in turn, to the sheave's pitch diameter. (This design change gives the tensile cord a larger moment arm and more support below it for transmitting forces to the sheave walls.)

To accommodate the changes in belt pitch length, and thus sheave pitch diameter, the datum system was introduced. For most belts and sheaves, the dimensions formerly referred to as pitch length (belts) and pitch diameter (sheaves) are now called datum length and datum diameter.

In terms of sheave dimensions, the pitch diameter is now equal to the outer diameter for most standard sheaves. The datum diameter, however, is slightly less than the outer diameter. This is important when calculating the length of a belt because the datum length, which is the norm for standard V-belt measurements today, is based on the datum diameter of the sheave. In contrast, the formerly used pitch length calculation was based on the sheave's pitch diameter.

SYNCHRONOUS BELTS FOR POSITIONING AND MORE

Note the white synchronous belt on the conveyor's blue slider plate. Image via AdobeStock

Where friction belts are insufficient for a motion design — as on positioning table, conveyor, and printing-machine axes needing true synchronous operation, for example — toothed synchronous belts excel. Such belt drives are also indispensable in compact designs that need power-dense linear drives in awkward or compact design envelopes.

As with V belts, be prepared to specify synchronous belts by length and axis power demand. Here, additional factors include the teeth's maximum shear strength (dictated by their cross section as well as pulley-engagement dynamics). On the topic of teeth engagement, remember that synchronous belt drives need tooth clearances at the engagement with pulley grooves … so teeth can enter and exit channels sans interference. That's why most synchronous belts exhibit some backlash. In addition, a synchronous belt's tooth shear strength must be high enough to withstand maximum application torque demand. As with V-belt selection, service factors can help engineers pick synchronous belts having shear strengths to withstand an application's worst expected shocks and loading.

Despite the extra considerations, synchronous belts are indispensable in precision motion designs. A mature technology is belting with teeth of a trapezoidal shape (not to be confused with V belts sporting trapezoidal cross sections) — although modified iterations are suitable for very precise positioning. More common in new designs are rounded profiles carry more load than belts with trapezoidal teeth. The belts do this in two ways: 1) They have inherently higher tooth shear strength and they 2) More evenly spread load over the belt's tensile cords.

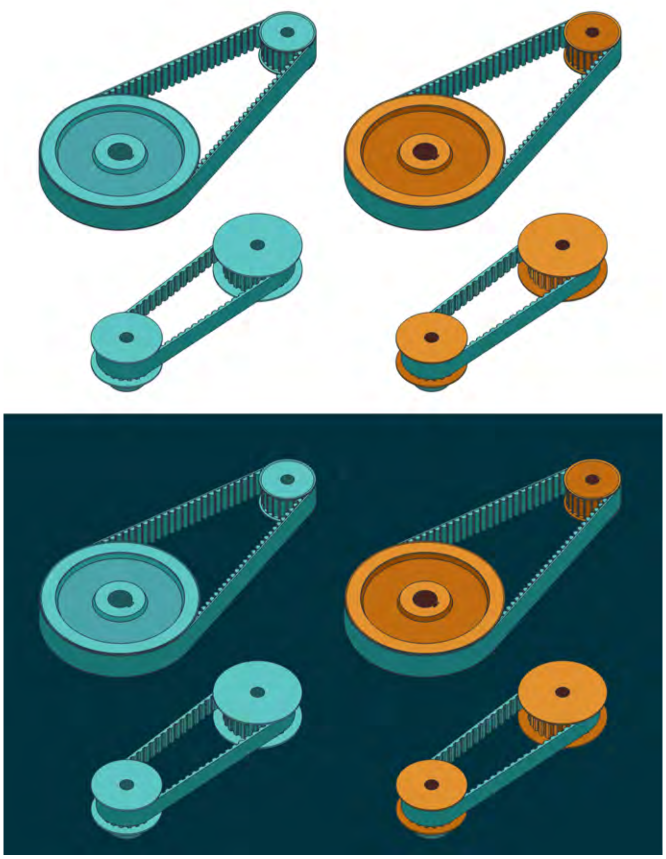


Image via Dreamstime

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SYNCHRONOUS BELTS FOR POSITIONING AND MORE

Standard synchronous-belt products sport MXL, XL, L, H, XH, XXH, and other codes to indicate set geometries. Generic labels for synchronous belts with round-profile teeth are variations on the term high-torque drive or HTD for short — with the latter a trademark of belt and rubber-components manufacturer Gates Corp. In some cases, belts with round-profile teeth can triple horsepower ratings.

Another design — belts with curvilinear teeth — help optimize pulley-tooth engagement and pressure angles to boost overall power transmission. Many such belts go into automotive applications, which come with tensile cords and in sizes unsuitable for industrial designs.

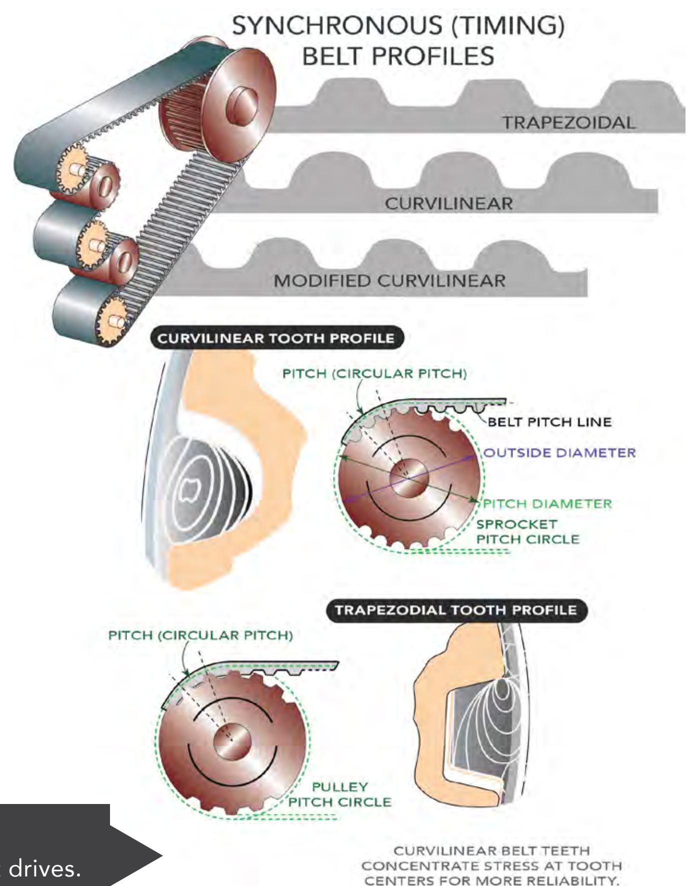
Notice the specialty profile of this synchronous belt and mating pulley. Design example courtesy Custom Machine & Tool Co., Inc.

APPLYING SYNCHRONOUS BELTS IN MOTION DESIGNS

Roughly a quarter of all industrial motors pair with belt drives. Most common are synchronous or high-torque drive belts where efficiency or accuracy are objectives. Applications from consumer-grade home printers to heavy industrial conveyors use these synchronous belts, because unlike V belts with trapezoidal cross-sections, they don't slip.

Many motion applications demand customized timing belts and sprockets — often taking the form of urethane, double-sided, mini-pitch, and made-to-order (MTO) belts and sprockets. Double-sided belts have covered teeth to transfer up to 100% of the maximum rated load from one or both belt sides. These come in trapezoidal timing-belt configurations and HTD curvilinear tooth profiles. Some can run to 14,000 rpm with speed ratios to 10:1, which is enough to replace gearsets in some cases.

Double-sided belts also excel as serpentine drives in riding mowers with counter-rotating blades, printing presses, and textile machines. Urethane belts maximize motion transfer, especially when incorporating polyester or aramid tensile members. Their tooth profile is a miniature version of belt with standard 40° angle teeth. Speed ratios reach 8:1 and torque output reach a couple lb-in. These belts excel on positioning axes, thanks to their low torque and minimal backlash — especially in printers and copiers that need clean operation.



Curvilinear tooth profiles do offer some distinct advantages in motion applications employing belt drives.

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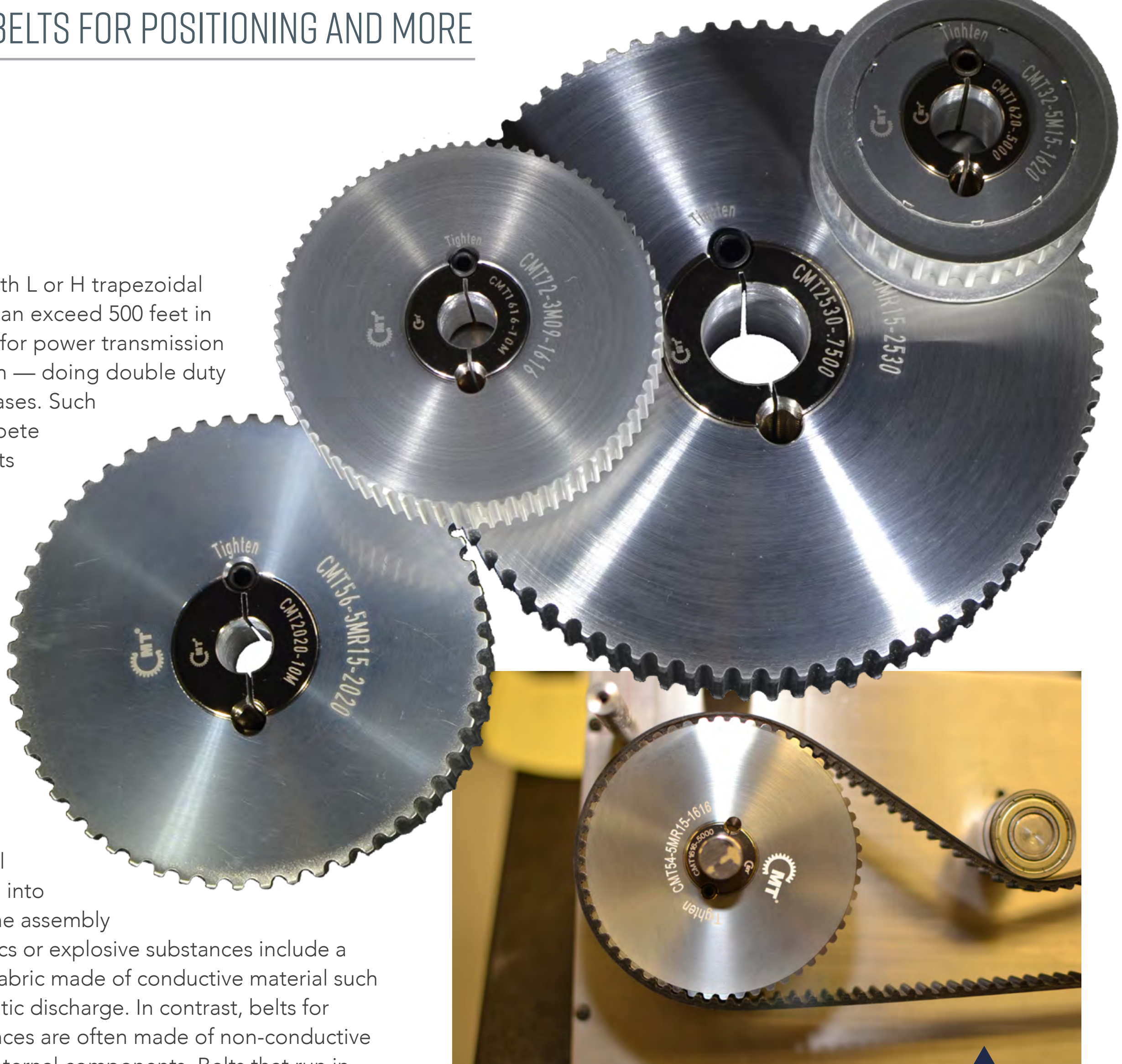
SYNCHRONOUS BELTS FOR POSITIONING AND MORE



Long belting (usually with L or H trapezoidal tooth or HTD profiles) can exceed 500 feet in some cases. They work for power transmission and axis synchronization — doing double duty as conveyors in many cases. Such synchronous belts compete with rack-and-pinion sets in machine tools and X-ray equipment as a viable drive for linear strokes. One caveat: These belts spliced transmit a quarter less horsepower than comparable endless toothed belts.

Made-to-order (MTO) belts take myriad forms, but most are trapezoidal and HTD. Those that go into applications involving the assembly or transport of electronics or explosive substances include a body and tooth-facing fabric made of conductive material such as carbon to prevent static discharge. In contrast, belts for power tools and appliances are often made of non-conductive materials that insulate internal components. Belts that run in harsh environments incorporate oil-resistant and temperature-resistant compounds.

Tensile members in synchronous belts serve two functions — help the belt withstand shock loads and maintain a set length for proper tooth meshing and positioning accuracy. Steel tensile cords were once most common, but now aramid and glass fiber cords dominate.

Engineers can even customize the twist of members to alternate or go left or right to satisfy tracking requirements. Another option is thick or backed belts to convey or grip objects in tandem with mating belt drives. Backings can also extend belt life and address vibration.

The pulley-bushing detail shown above is the Concentric Maxi Torque assembly. A mechanical shrink fit clamps down on the shaft via a setscrew axial to the shaft — which serves as a lever to force the tapered bushing into the matching taper in the hub. As the lever forces the two tapers together, the slot in the bushing compresses, thus clamping the pulley to the shaft with a mechanical shrink fit.

If needed, that same setscrew can be removed and used in the bushing's opposite hole to act as a jack — releasing the shrink fit and allowing for removal or repositioning. Images courtesy of Custom Machine & Tool Co., Inc.

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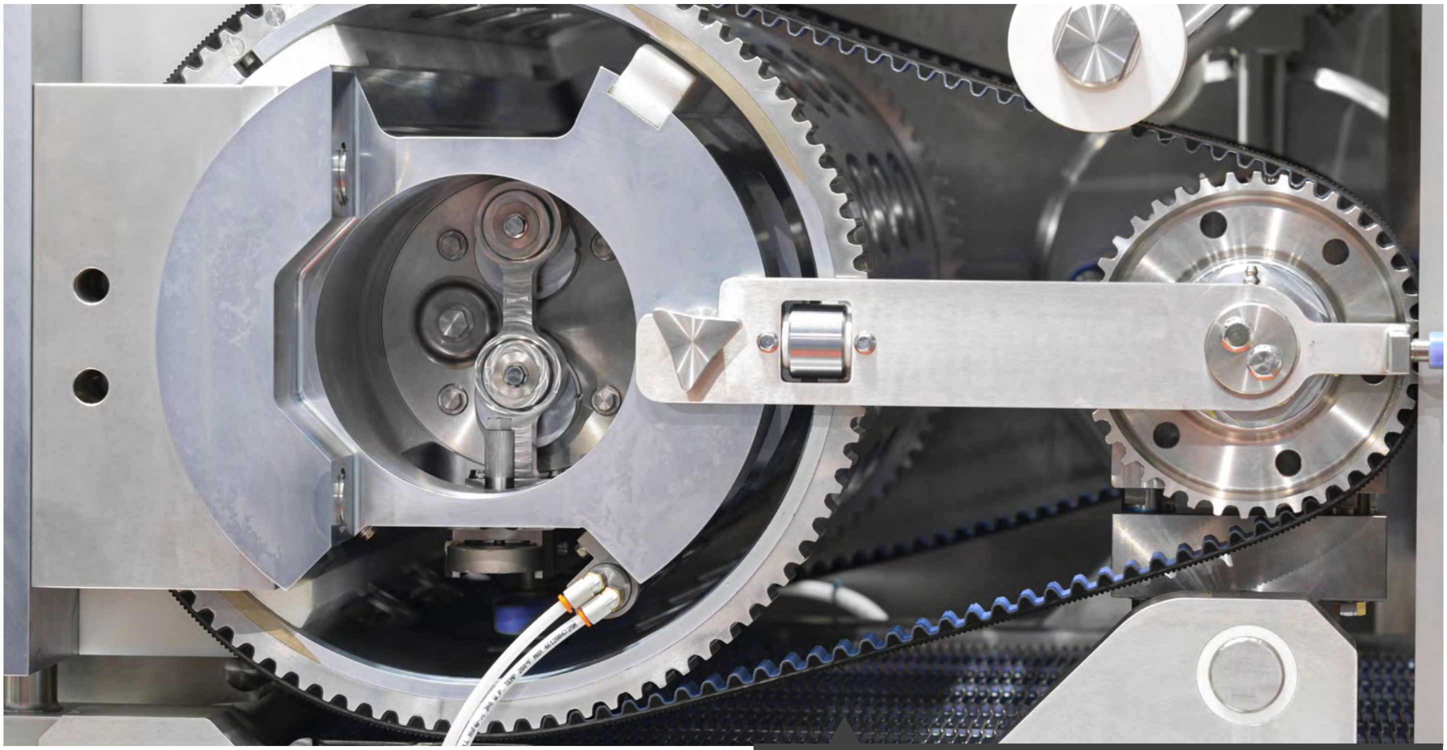
SYNCHRONOUS BELTS FOR POSITIONING AND MORE



This is another synchronous (toothed) belt drive — here on a machine to rotate a drum for the forming of chicken nuggets. Image via Dreamstime

For industrial applications, most synchronous belt sprockets are made of either cast or ductile iron. That said, steel excels in designs that run at speeds exceeding those safe for iron pulleys, even to 20,000 fpm. Likewise, aluminum pulleys run at high speed and have low inertia to boot. Another lightweight option is non-metallic pulleys — common in lawn equipment and power tools that transmit little torque and have relatively short design life. Other synchronous-sprocket options include specialty tooth profiles for better positioning accuracy or custom hub mounts and flanges.

PROPERLY DESIGNING AND SPECIFYING SYNCHRONOUS BELT DRIVES

Some general guidelines are applicable to all timing belts, including miniature and double-sided synchronous belt variations. First, engineers should always design these belt drives with a sufficient safety factor — with ample reserve horsepower capacity. Design tip: Take note of overload service factors. Belt ratings are generally only 1/15 of the belt's ultimate strength. These ratings are set so the belt will deliver at least 3,000 hours of useful life if properly installed and maintained. The pulley diameter should never be smaller than the belt width.

Sourcing matching flanges and belts for pulley stock is made easier and less time-consuming in a one-stop shop.
Image courtesy of Custom Machine & Tool Co., Inc.

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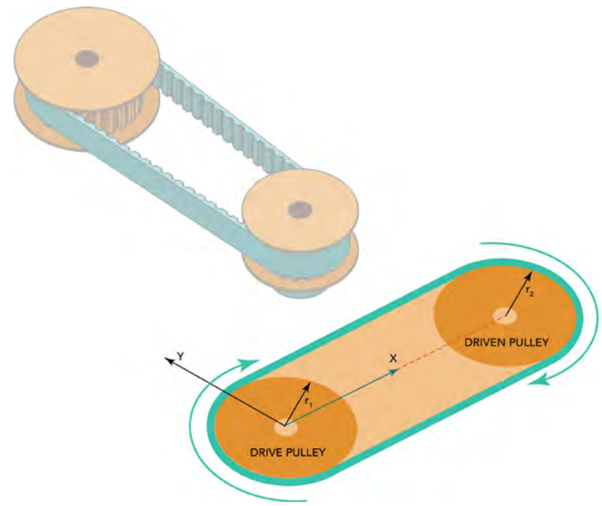
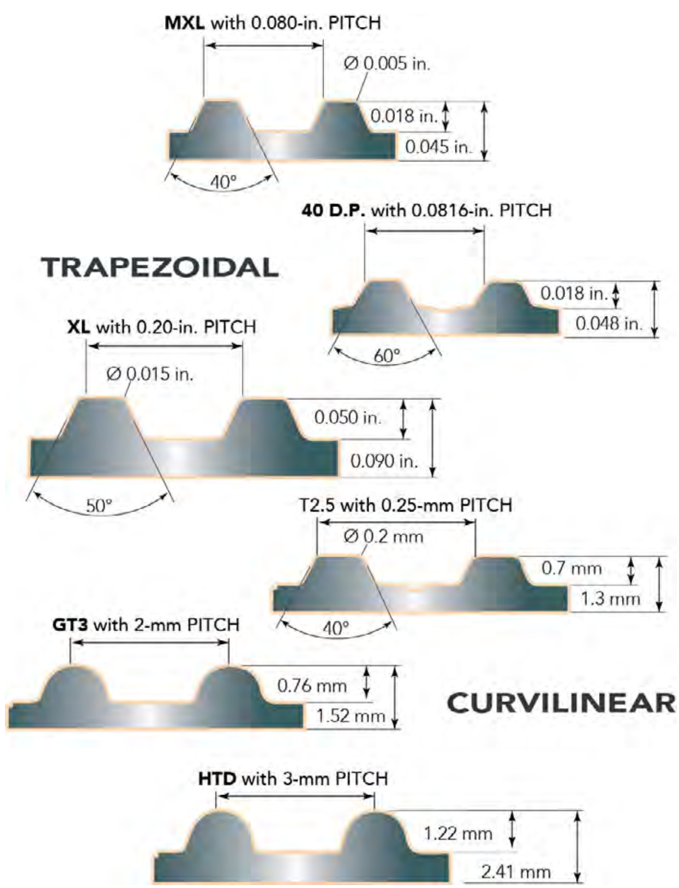
SYNCHRONOUS BELTS FOR POSITIONING AND MORE



The belt and load are typically modeled as one point mass rotating around the driven pulley. Pulleys of the same diameters may have different inertias if one is toothed, and the other is smooth.



As mentioned, belts are quieter than other power-transmission drive options … but not silent. Noise frequency increases proportionally with belt speed, and noise amplitude increases with belt tension. Most synchronous belt noise arises from the way in which belt teeth entering the pulleys at high speed repeatedly compresses trapped pockets of air. Other noise arises from belt rubbing against side flanges; in some cases, this happens when the shafts aren't parallel.

Synchronous belt pulleys are made of metal or plastic, and the most suitable choice depends on required precision, price, inertia, color, magnetic properties, and the engineer's preference based on experience. Plastic pulleys with metal inserts or metal hubs are a good compromise.

Tip: Make at least one pulley in the belt drive adjustable to allow for belt installation and tensioning. Also note that in a properly designed belt drive, there should be a minimum of six teeth in mesh and at least 60° of belt wrap around the drive pulley. Other tips:

Pretension belts with the proper recommended tension. This extends life and prevents belt ratcheting or tooth jumping.

- Align shafts and pulleys to prevent belt-tracking forces and belt edge wear. Don't crimp belts beyond the smallest recommended pulley radius for that belt section.
- Select the appropriate belt for the design torque.
- Select the appropriate belt material for the environment (temperature, chemical, cleaning agents, oils, and weather). Belt-and-pulley systems are suitable for myriad environments, but some applications need special consideration. Topping this list are environmental factors.

Dusty environments do not generally present serious problems if the particles are fine and dry. In contrast, particulate matter can act as an abrasive and accelerates belt and pulley wear. Debris should be prevented from falling into belt drives. Debris caught in the drive is generally either forced through the belt or makes the system stall. In either case, serious damage occurs to the belt and related drive hardware.

Light and occasional contact with water—during occasional washdowns, for example—has little serious effect. However, prolonged contact with constant spray or submersion can

(continued)

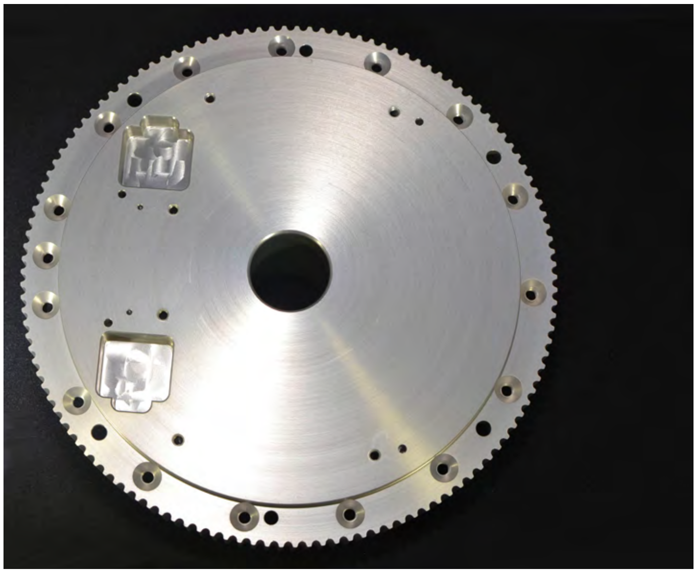
SYNCHRONOUS BELTS FOR POSITIONING AND MORE

significantly reduce tensile strength in fiberglass belts and make aramid belts break down and stretch out.

In the same way, occasional contact with oils doesn't damage synchronous belts. But prolonged contact with oil or lubricants, either directly or airborne, significantly reduces belt service life. Lubricants cause the rubber compound to swell, break down internal adhesion systems and reduce felt tensile strength. While alternate rubber compounds may provide some marginal improvement in durability, it's best to prevent oil from contacting synchronous belts.

The presence of ozone can be detrimental to the compounds used in rubber synchronous belts. Ozone degrades belt materials in much the same way as excessive temperatures. Although the bumper materials used in belts are compounded to resist the effects of ozone, eventually chemical breakdown occurs, and they become hard and brittle and begin cracking. The amount of degradation depends on the ozone concentration and generation of exposure.

Rubber belts aren't suitable for cleanrooms, as they risk shedding particles. Instead, use urethane timing belts here … keeping in mind that while urethane belts make significantly less debris, most can carry only light loads. Also, none have static conductive construction to dissipate electrical charges.



Custom synchronous pulley example courtesy Custom Machine & Tool Co., Inc.

FURTHER READING ON SYNCHRONOUS BELT DRIVES

[Trapezoidal, curvilinear, or modified curvilinear?]
[The best timing belt tooth profile for high-speed applications]
[Ratcheting in synchronous belt drives]

Most synchronous belt noise arises from the way in which belt teeth entering pulleys repeatedly compresses trapped pockets of air. Image via Dreamstime

SYNCHRONOUS BELT FAILURES: SIX WAYS THEY CAN OCCUR

Notice the belt drive (red) running along the top of this through-machine conveyor carrying bag of potatoes. Image via Dreamstime

Synchronous belts can transmit high torque without the potential for slip, due to positive engagement between the teeth of the belt and the grooves of the pulley. But the performance of synchronous belt drive systems can be affected by installation errors, unexpected application conditions, or the use of components that aren't suitable for the operating requirements. Here are six ways that synchronous belts can fail and their most common causes.

Flanged pulleys provide tracking for synchronous belts by resisting the lateral forces from the belt as it tries to move from side to side on the pulley. But in some cases, the belt can ride along the flange and exert significant force on it, resulting in wear on the edge of the belt. Common causes of edge wear are parallel misalignment, using a belt that is too wide for the selected pulley, or using pulleys that are damaged or have a rough surface finish.

Cracking: Belt cracking usually occurs parallel to the teeth, in the areas between the teeth called land areas. Cracking is often associated with temperature issues – either a temperature that is too low at startup or too high during operation, causing the material to harden and crack due to bending. Other causes of belt cracking are a skewed pulley assembly or exposure to chemicals.

Tensile break: This type of failure is typically due to crimping or severe shock loads to the belt. Crimping often produces a tear straight across the belt and can be caused by mishandling of the belt, inadequate tension, a pulley diameter that is too small, or debris in drive system. Shock loads often result in an angled tear across the belt and can be accompanied by tooth shear.

Excessive tooth wear: Tooth wear is a normal result of the positive engagement between the belt and pulley and is mitigated by belt materials that are wear-resistant. However, excessive wear can result from either too much or too little tension, misalignment, excessive loading, debris in the drive system, a damaged pulley, or a pulley that is out of spec or does not have sufficient hardness. Under normal operating conditions, tooth wear generally does not affect the service life of the belt.

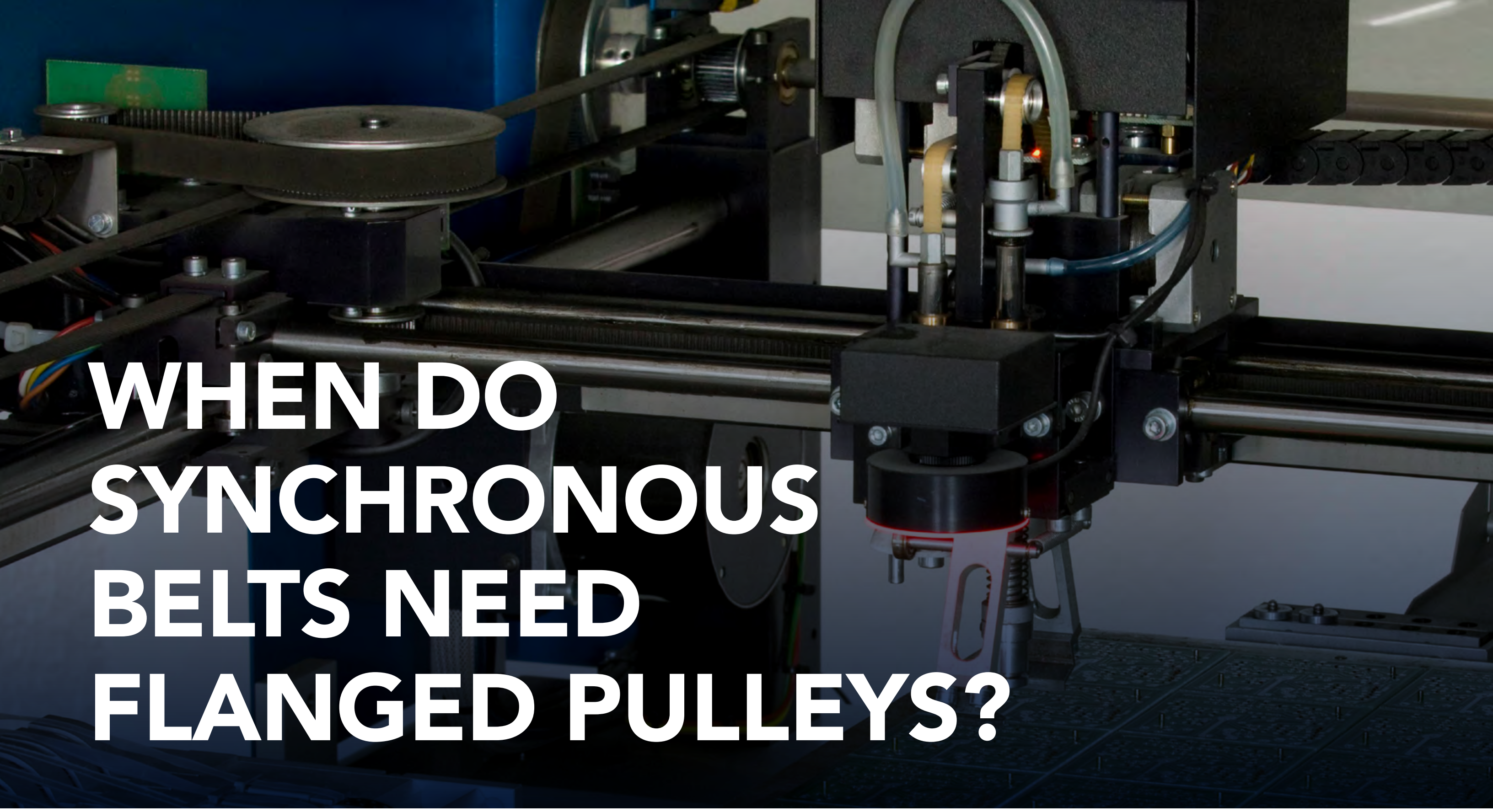
Tooth shear: Tooth shear is a catastrophic failure that can be caused by shock loads or misalignment. It can also be a result of insufficient tension, which causes a condition known as self-tensioning — which in turn makes the belt teeth ride out of the pulley. When this happens, the load is no longer carried at the roots of the teeth, but rather further down the tooth flanks. This causes the teeth to bend and rotate, which can cause them to tear at their base and separate from the belt.

Ratcheting: Ratcheting is a condition in which belts jump or skip teeth on the pulley. The primary cause of ratcheting is insufficient belt tension. One of the benefits of synchronous belts, when compared to V-belts, is that once the tension is properly set, they do not require re-tensioning.

While synchronous belt failures can occur in many forms, pulleys generally fail in one of two ways: **tooth wear or flange failure**.

Abnormal or excessive pulley tooth wear is typically due to use in an abrasive environment, although pulley misalignment, excessive loading, and improper tension can also be causes. Pulley flange failure is most often a result of angular or parallel pulley misalignment.

WHEN DO SYNCHRONOUS BELTS NEED FLANGED PULLEYS?



Shown here are track-roller linear guides and drive belts on flanged pulleys along with screw drives on piece of semiconductor manufacturing equipment.

Synchronous belts transmit power via positive engagement between profiled teeth on the belt and pulley. Although this tooth engagement (along with proper belt tension) prevents the belt from ratcheting, the belt is free to track or move side-to-side on the pulley.

To prevent the belt from riding off the pulley, and to resist the lateral forces caused by the belt's side-to-side motion, synchronous belt drive systems typically require one or more flanged pulleys.

> *The orientation of tensile cord twist can cause a belt to track to one side of its pulleys. To reduce this tendency, synchronous belts often use tensile cords with both S and Z twists*

CAUSES OF BELT TRACKING

The tensile cords in a synchronous belt are twisted in either an S (righthand) or a Z (lefthand) twist pattern. The direction of the twist determines to which side of the pulley the belt will tend to track. To reduce this tendency, synchronous belts often use tensile cords with alternating twists.

However, even when tracking due to tensile cord orientation is minimized, synchronous belts may still favor one side of a pulley — typically the side that provides a shorter center distance, and therefore, a lower tension.

Belt tracking can also be caused by varying loads, primarily due to distortion of the tensile cords. But varying loads can also cause angular misalignment between pulley shafts (which is also sometimes a product of mounting inaccuracies) and deflection in the drive system structure, both of which contribute to a belt's tendency to track to one side.

It's important to prevent the belt from causing significant forces against the pulley flanges, which can result in belt edge wear or flange failure. The tracking force is typically higher for shorter belts than for longer belts because the helix angle of the tensile cord decreases as the belt length increases. Similarly, wide belts tend to track with more force than do narrow belts.

The relationship between belt width and pulley diameter also affects tracking forces: smaller diameter pulleys (relative to belt width) tend to cause belts to track with higher forces than do larger diameter pulleys. Manufacturers advise against using pulleys with diameters less than the belt width because this can result in excessive tracking forces.

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WHEN DO SYNCHRONOUS BELTS NEED FLANGED PULLEYS?

WHEN TO USE FLANGED PULLEYS ...

The general guideline provided by manufacturers is that in all synchronous belt drive systems, at least one pulley should have flanges. Alternatively, for short-span drives with two-pulleys, each of the pulleys can have a flange on one side. When the span (center distance between shafts) is eight times or more the diameter of the smaller pulley, both pulleys should have flanges.

Most synchronous belt drive systems should include at least one flanged pulley.

For serpentine configurations, which use more than two pulleys, proper tracking becomes even more critical, since there are more instances of belt-pulley engagement. In these arrangements, flanges should be included on every other pulley. Alternatively, each pulley should have a flange on alternating sides.

When belts are used on pulleys with vertical shafts — in other words, the belt is running on its side — gravity tends to pull the belt downward, so vertical shaft systems should have at least one pulley with flanges on both sides, and the remaining pulleys should be flanged at least on the bottom side.

In conveying applications, it may not be possible to use flanged pulleys due to the product's orientation on the belt. In these cases, a flanged pulley can be used as a back-side idler, placed either near the lead pulley (for unidirectional travel) or midway between the two pulleys (for bi-directional travel).

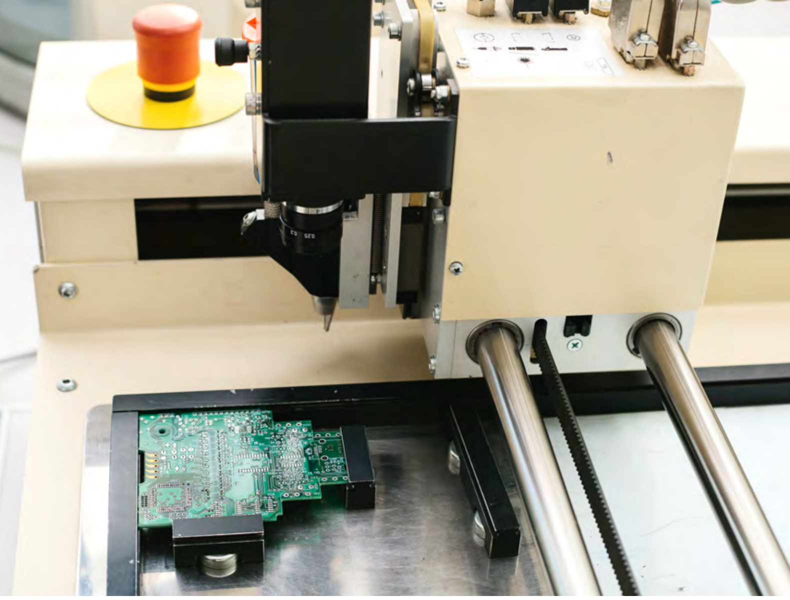
WHEN FLANGED PULLEYS MAY BE UNNECESSARY ...

In some cases, it's possible for synchronous belt drives to run properly without flanged pulleys. Considering the factors discussed above, large diameter pulleys can sometimes be used without flanges if the flange face is sufficiently wider than the belt. In addition, idler pulleys generally don't need to be flanged, but they can include flanges if lateral control of the belt is required.

Flanged pulley image courtesy of Custom Machine & Tool Co., Inc.

FURTHER READING ON SYNCHRONOUS BELT DRIVE PULLEYS

How to specify pulleys for synchronous belt drives
How to measure synchronous (toothed) belt tension
Tooth shear in synchronous belts and how to avoid



Belt-driven actuators can provide long lengths and high speeds.

BELT-DRIVEN ACTUATORS FOR A WIDE RANGE OF APPLICATIONS

Belt-driven actuators are the workhorses of the electromechanical world, offering longer stroke lengths and faster speed capabilities than screw driven designs, with less inertia and better resistance to contamination than rack and pinion drives. And although linear motors boast better positioning accuracy than belts, the price-performance ratio of a belt-driven actuator is difficult to beat.

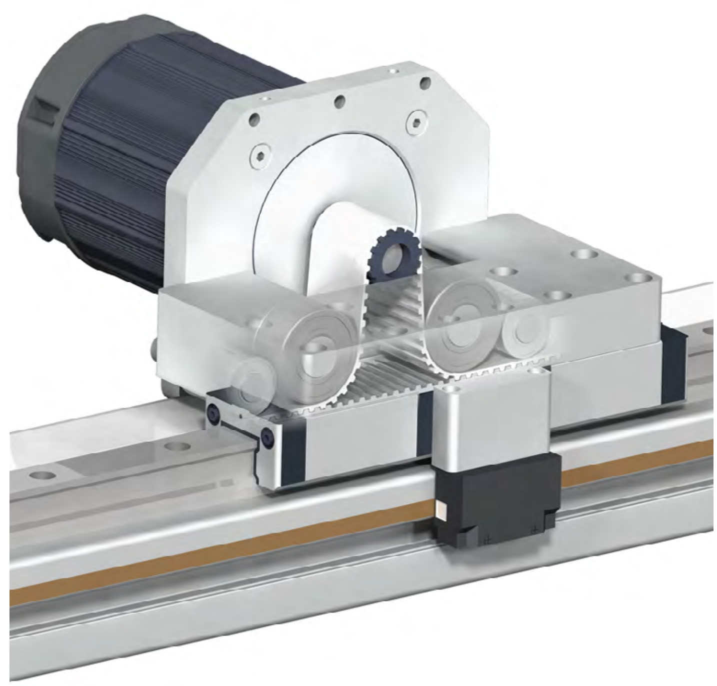
TRADITIONAL BELT-DRIVEN ACTUATORS: SIMPLE AND COST-EFFECTIVE

Belt-driven actuators have been used for decades in applications ranging from high-speed transport to basic positioning. The most common designs using an aluminum extrusion housing for protection against contamination, or an open-frame design for lower weight and reduced cost. Belts are commonly made of steel-reinforced polyurethane, paired with recirculating ball linear guides or wheel-based guide systems.

Despite their inherent versatility, belt drive actuators continue to evolve, with manufacturers introducing new designs to reduce size, weight, and cost — making them better able to compete with leadscrew actuators.

To achieve this, recirculating ball or wheel-based guides are replaced with plain bearing guides made of plastic or composite, and carriages are made of aluminum or even thermoplastic. Although plain bearings have lower load capacities than steel ball or roller-based linear bearings, they do offer a benefit in harsh environments … withstanding debris and chemicals better than their steel counterparts. And because these lower-cost versions aren't meant for high-accuracy positioning, non-reinforced neoprene belts are often suitable.

Here's an example of an omega module. Because the belt is in tension only around the driven pinion, backlash is eliminated, and repeatability can rival that of some ballscrew actuators. Image credit: Bell-Everman



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BELT-DRIVEN ACTUATORS FOR A WIDE RANGE OF APPLICATIONS

In these designs, not only is material cost significantly reduced, but weight and inertia are also kept to a minimum. That means the driving components (including motor and gearbox) can also be downsized for further reduction of overall system cost.

BELT-DRIVEN ACTUATORS AS CANTILEVERED AXES

For applications where the carriage is stationary and the actuator body is the moving part, the traditional configuration, with the motor driving a pulley at the end of the actuator — is less-than ideal. This is because in the carriage-fixed, body-moving scenario, the entire motor-gearbox assembly must be moved along with the actuator body and mounted load.

To address these applications, some manufacturers have introduced belt driven actuators that incorporate the pulleys into the carriage, so the motor-gearbox assembly mounts directly to the stationary carriage. Removing the motor-gearbox mass — which can be significant — from the moving part of the actuator reduces the driven load and the reflected inertia. This, in turn, allows the actuator to move at higher speeds and accelerations, for more dynamic motion profiles.

> *Cantilevered modules — also called omega modules because the belt forms the shape of the Greek letter omega Ω — allow the motor-gearbox combination to mount directly to the carriage, where the pulleys reside.*

BELT DRIVEN DESIGNS THAT RIVAL BALLSCREW CAPABILITIES

While some manufacturers have focused on reducing costs and making belt driven actuators more suitable for simple positioning tasks, other manufacturers have taken the opposite view in terms of performance, developing belt drive designs that mimic rack-and-pinion configurations. These designs allow belt driven actuators to achieve positioning accuracy that rivals some ballscrews without the length and speed limitations inherent to ballscrew driven systems.

One such design uses two belts — a stationary belt (analogous to the rack in a rack and pinion system) and an active belt that rides through the actuator's carriage ... in turn containing a driven pinion with an idler roller on each side.

The benefit of this dual-belt, rack-and-pinion-like design is that the belt is only in tension as it rides around the pinion, so stiffness is constant along the entire length and belt stretch is greatly reduced. It also reduces or eliminates backlash, so these belt-driven designs can achieve unidirectional repeatability as high as ±10 μm — much better than a traditional belt system and approaching that of some ballscrew drives.

In addition to new actuator designs, advances in belt geometries and materials have also allowed new applications for belt driven actuators. For example, curvilinear and modified curvilinear tooth profiles provide higher thrust force capabilities than the traditional trapezoidal tooth profile, while Kevlar-reinforced belts provide better shock and impact resistance — and less stretch for a given force — than traditional steel-reinforced belts. Plus, new tooth geometries can reduce belt noise due to meshing between the belt and the pulleys.

BALANCING THE PULLEYS OF BELT DRIVES

Precision machining of custom timing pulley to reduce inertia.
Image courtesy of Custom Machine & Tool Co., Inc.

Objects traveling circular paths generate a conceptual centrifugal force that pull the objects outward from center. In real-world machine designs, any unevenly distributed mass about a rotational axis will cause variable centrifugal forces — in turn inducing vibration and accelerated mechanical-component wear. In belt-driven designs, the process of balancing aims to recenter pulleys' lopsided centers of gravity. This process is especially important for correcting the inherent imperfections of pulleys cast and machined using traditional manufacturing methods.

As a pulley rotates, centrifugal forces act on the pulley, and if its mass is not evenly distributed around the axis of rotation – that is, if it's unbalanced — these centrifugal forces will also be unbalanced and cause the pulley to vibrate. (Uneven mass distribution can be due to imperfections in machining or inconsistencies in the material structure.)

Pulley vibrations can transfer to the support bearings and other components of the machine, causing premature or even catastrophic failure. Therefore, pulleys used in belt drive systems almost always undergo some form of balancing.

Single-plane or static balancing: According to the Mechanical Power Transmission Association (MPTA), single-plane balancing should be performed on all belt drives. Systems balanced this way can be conceptualized as a disc having center mass aligning with a center mounting-shaft axis. Any voids or excess masses cause imbalance.

So virtually all pulleys undergo static balancing after manufacture. This ensures that the pulley's weight is equally distributed around its center of rotation.

As its name implies, ***static balancing*** can be done while the object is at rest and is relatively easy to demonstrate through a simple experiment. Rotate the pulley by hand and let it come to rest on its own. Mark the point at the very bottom center of the pulley. Rotate it again and let it come to rest. If it stops with the same point at the bottom center, then its weight is not balanced … and the pulley is heavier at the sinking point.

Correcting this problem is typically done by:

- Removing mass from the heavy point (which is commonly achieved by drilling a small hole in the pulley) or
- By adding mass to a point 180° opposite the heavy point.

Static balancing is typically sufficient for pulleys that travel at

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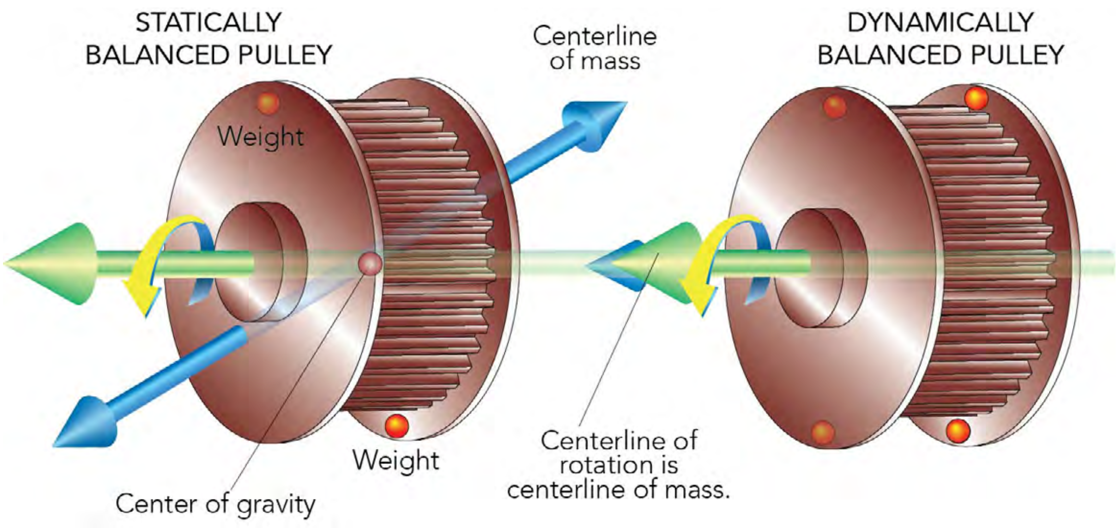
BALANCING THE PULLEYS OF BELT DRIVES

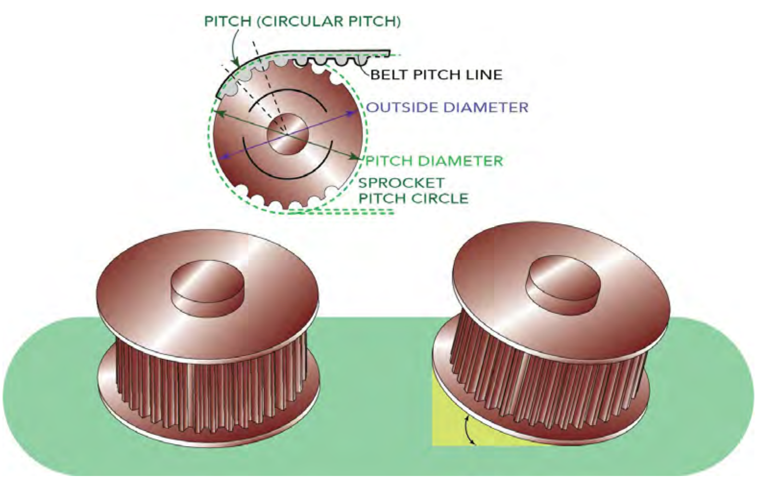


For a statically balanced pulley, weight is evenly distributed around the center of rotation, but the center of mass does not coincide with the center of rotation. For a dynamically balanced pulley, the center of mass coincides with the center of rotation.

6,500 ft/min. (33 m/sec) or less. For speeds above this, or when the pulley diameter is less than seven to 10 times the face width, dynamic balancing is recommended.

Dynamic balancing: Also called two-plane balancing, this goes one step beyond static balancing and ensures that the pulley's center of mass is on the same axis as its center of rotation. It's possible for a pulley to be statically balanced but dynamically unbalanced (although the reverse is not true) so dynamic balance must be measured while the pulley is turning.

Because it involves forces in two planes, dynamic balancing requires that masses be added in two planes to counter the imbalances and prevent pulley vibration. The measure of unbalance is given in units of g-mm (oz-in.) based on the mass of the pulley and the eccentricity (the distance between the center of mass and the center of rotation). The MPTA provides guidelines for both static (one-plane) and dynamic (two-plane) balancing in their standard, MPTA-B2c-2011: Standard Practice for Sheave/Pulley Balancing.



Angular misalignment of pulleys can cause belts to track to one side.

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BALANCING THE PULLEYS OF BELT DRIVES

The classic illustration of inertia is a figure skater spinning on the ice. When her arms are outstretched, a part of her mass is far from the axis of rotation, and therefore she spins at a relatively slow speed. But if she pulls her arms in close to her body, her rate of spin increases because her entire mass is now close to the axis of rotation. The same phenomenon affects the motion of belt-driven systems.

Note: Regarding centripetal and centrifugal forces, there is much debate in science, physics, and engineering circles about which is correct to reference when discussing forces on a rotating body.
Image via Dreamstime

ON A RELATED NOTE: MAKING SYNCHRONOUS BELTS QUIET AND BALANCED

Synchronous belts are common in precision motion systems — providing smoother operation and better high-speed performance than chains and lacking the problems of slipping and stretching that can plague V-belts in precision applications. But one downfall of synchronous or toothed belts is the noise they produce. Although quieter than a chain drive, a synchronous belt can still generate noise that is unacceptable for some applications and environments.

The noise from a synchronous belt is for the most part caused by the very feature that makes synchronous designs a better choice than chains or V belts — meshing between the belt and the pulley.

First, the simple impact of the belt engaging with the pulley creates noise often compared to a slapping sound, which is especially prominent at lower belt speeds.

Second, as belt teeth engage with pulley grooves, air is trapped between the two components and then evacuated, making a sound that can be likened to air escaping from a balloon. This phenomenon is a significant contributor to belt noise at higher speeds.

Another factor that contributes to synchronous belt noise is belt tension. Synchronous belts are typically operated under high tension and therefore, easily resonate (like a plucked guitar string). Belt and pulley materials can also play a role in noise.

For example, polyurethane belts typically exhibit more noise than neoprene (rubber) materials, and polycarbonate (thermoplastic polymer) pulleys tend to be noisier than metal pulleys.

Noise generated by pulleys is also related to the dimensional accuracy of the pulley, which determines the smoothness of meshing between belt teeth and pulley grooves.

Add together the effects of these various factors, and it's easy to end up with a belt driven system that produces uncomfortable or even detrimental amounts of noise — especially when multiple belt systems are operating in

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BALANCING THE PULLEYS OF BELT DRIVES

proximity. But there are ways to reduce the levels of noise produced by synchronous belts.

From a sizing and design standpoint, the noise generated by a synchronous belt is directly related to the belt width and belt speed. Belts with larger widths tend to resonate more, and higher belt speeds generate not only more noise but also higher frequency noise. Noise is also inversely related to the diameter of the pulley. Therefore a few easy ways to reduce noise — if the application allows — are to reduce the belt speed, use a smaller width belt, or use larger-diameter pulley.

From a mounting and operating standpoint, noise can be reduced by ensuring the pulleys are properly aligned, since angular misalignment (parallelism of the pulley shafts) can lead to contact between the belt and the pulley flanges. And if the belt isn't properly tensioned, there can be unnecessary interference between the belt teeth and pulley grooves, which is another factor that contributes to unnecessary noise.

Some manufacturers offer synchronous belts that are designed to be low-noise. From a manufacturing standpoint, noise can be addressed by applying a nylon covering to the toothed side of the belt, which reduces noise that occurs during meshing. And cutting grooves into the pulley provides a low-pressure path for air to escape as the belt and pulley mesh.

Another low-noise modification is to alter the geometry of the tooth profile to improve the rolling action as the belt teeth mesh with the pulley. One such design uses what is referred to as an "offset double helix pattern" for the belt teeth. In this design, the belt has two sets of teeth side-by-side but offset by 180° so the frequency of noise generated by one set of belt teeth (one side of the belt) is 180° out of phase with the frequency of noise generated by the other side, effectively canceling the noise.

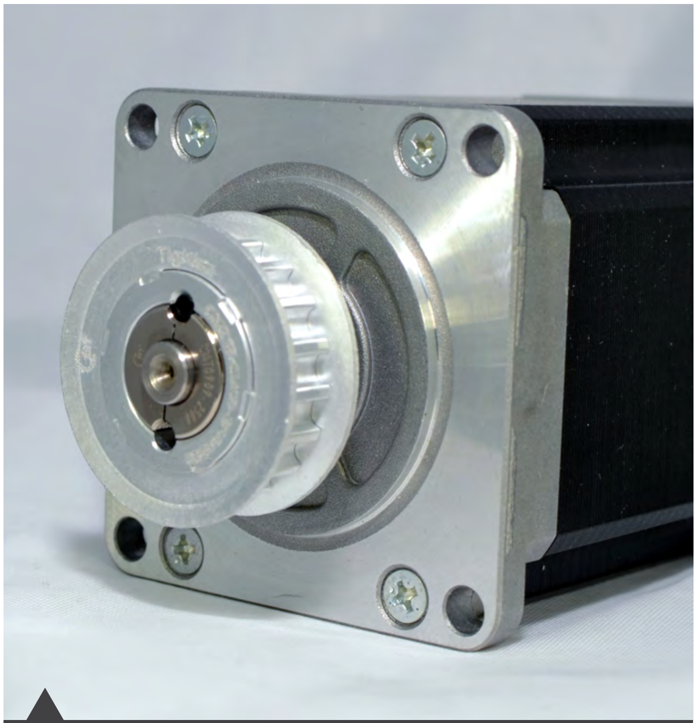
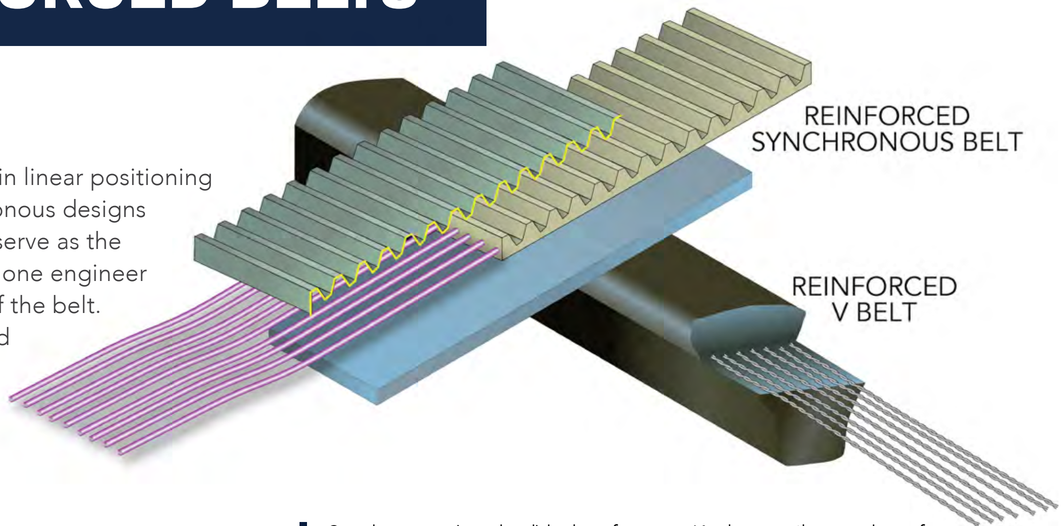


Image courtesy of Custom Machine & Tool Co., Inc.

WHEN TO CONSIDER KEVLAR-REINFORCED BELTS



Synchronous (toothed) belts often use Kevlar tensile members for resistance to shock and impact loads. For V-belts, Kevlar (aramid) tensile cords increase load capacity and reduce belt stretch. For both synchronous and V-belts, Kevlar tensile cords provide excellent dimensional stability.

Both types of belts commonly used in linear positioning applications — V-belts and synchronous designs — have internal tensile cords that serve as the primary load-carrying component. Or as one engineer put it, the tensile cords are the muscle of the belt. V-belts and synchronous belts are offered with tensile cords of various materials, including polyester, fiberglass, steel, aramid (DuPont trade name Kevlar), and carbon fiber to suit a variety of application requirements.

For synchronous (toothed) belts in positioning applications — especially when used in belt-driven linear actuators — steel is typically the tensile cord material of choice. It bonds well to polyurethane belt material and provides the highest tooth shear strength. V-belts on the other hand see a more even distribution between the use of various tensile cord materials — polyester, steel, fiberglass, and Kevlar. Although belts with Kevlar tensile cords can be more expensive, they offer benefits in some applications, depending on the type of belt and the working conditions.

Referring to a belt as steel-reinforced or Kevlar-reinforced is a common way to indicate the material used for the belt's tensile cords.

One of the most notable benefits of Kevlar tensile cords is that they provide better shock and impact resistance than steel or other materials. Kevlar tensile cords also allow the belt to operate at a higher tension, which typically means higher load-carrying capability. Case in point: V-belts with Kevlar tension cords are rated for higher loads than those with other tension member materials. But Kevlar-reinforced toothed belts aren't generally rated for higher load capacities than belts with other types of tensile members. This is because other components of the belt — particularly the belt teeth — are essentially "weaker links" than the tensile members.

Kevlar also has a higher tensile modulus (lower stretch) than other tensile cord types, so Kevlar-reinforced belts experience less elongation over time. This contributes to a more consistent center-to-center distance between pulleys, minimizing the amount of belt adjustment required. Note, however, that re-tensioning intervals are typically the same for belts with Kevlar and with other tensile members, because belt tension changes more rapidly for Kevlar tensile members (even though the amount of change is smaller).

Tensile members made of Kevlar have a lower flexural modulus, or resistance to bending, than steel, giving them a noticeable advantage when it comes to resisting flex fatigue, a common cause of failure in V-belts.

Kevlar is also suitable for use with belt materials that meet food-grade requirements in applications where steel is undesirable. However, it's important to note that while Kevlar has excellent dimensional stability in dry and stable environments, wet environments, or those with fluctuating humidity levels, can be detrimental to Kevlar-reinforced belts. This is because Kevlar cords (and cords made of other aramid materials) experience a change in length as they absorb and release moisture. This length instability can affect the belt's performance — altering the engagement between belt and sprocket teeth, or affecting the tension of a V-belt, for example.

Although Kevlar is suitable for a wide range of temperatures, it has a negative thermal coefficient of expansion, meaning that it shrinks as the temperature rises and lengthens as it cools. Since this behavior is the opposite of most other machine components (especially those made of metal) — which expand as temperature increases and contract as temperature decreases — Kevlar-reinforced belts may not be suitable in environments with significant temperature fluctuations.

MORE ON BELT MATERIALS

Urethane versus neoprene in synchronous belts

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