Backlash vs. Lost Motion

Understanding backlash, lost motion, repeatability and precision allows the designer to choose the best servo gearhead for his application

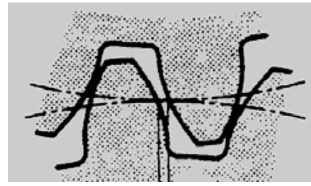
The continuing demand for improved industrial productivity has fueled the development of high performance servomechanisms capable of dynamic precision movement. Precision planetary servo gearheads are often an essential component of a servo system, providing a mechanical advantage plus the ability to control large loads quickly in an economical fashion. Servo gearheads provide speed reduction, torque manipulation and reduced inertia.

In choosing the correct servo gearhead, a designer must consider backlash, lost motion, repeatability and precision. Unfortunately, because of differences in semantics and methods of measurement, there is confusion in the marketplace regarding these factors. This is especially true for backlash and lost motion, which are often erroneously believed to be synonymous in describing the relative motion of the gearhead output position in relation to the input movement. This article clarifies the difference between these performance factors and provides guidance in understanding their relative importance.

Simply stated, all mechanical devices, even a bar of solid steel, have some elasticity. Thus, a small torque can be applied to the input of a device (or one end of the bar) and be absorbed in the windup of the device or bar, with no movement at the output (or other end of the bar). This is the *lost motion.* Backlash of a gearbox is a component of lost motion.

Backlash
Backlash is the amount by which the width of a gear's tooth space exceeds the thickness of an engaging tooth measured at the pitch circle of the gears. Backlash, sometimes termed *slop*, *lash, free-play*, or simply *play,* is an angular quantity due to the gear's circular geometry. This can be termed *clearance backlash*.

Backlash is necessary for clearance to accommodate manufacturing errors, provide space for lubrication and allow for thermal expansion of components. The most critical aspect of backlash is allowance for manufacturing errors. Second is that it provides the clearance for a lubricating film between the meshing teeth. The combination of manufacturing errors and/or incorrect lubrication is detrimental to the value of backlash in operation. Poor manufacturing quality results in smaller contact areas of the meshing teeth, resulting in high contact pressure on the components. This pressure may exceed the allowable pressure of the lubrication, which leads to metal-to-metal contact, resulting in high wear.



Proper lubrication minimizes backlash
Designs with gear teeth of proper hardness, surface finish, and quality level allow the lubrication film to be maintained which eliminates metal to metal contact and wear.
Lubricants are essential to minimizing backlash and the appropriate choice of lubricant is application specific. Oil is superior to grease in its allowable contact stress capacity, heat dissipation and film forming characteristics, which permit it to penetrate tight clearances between precision gears.

Measuring backlash
In servo-mechanical transmissions, backlash is measured at the output shaft of the gearhead while holding the input shaft rigid. The ambiguity in published values for backlash from various manufacturers is due to the fact that there is no standard process for measuring backlash. Is the specified value the maximum value or average? Is it a plus or minus value or the total? Is any force used to rotate the output in order to insure full-face contact on the gears and the bearing rollers?

Quality manufacturers will apply some amount of torque when measuring backlash and call the result *Torsional Backlash*. This is where the terminology gets confusing. Because a force is applied, some manufacturers will call torsional backlash *lost motion* because it involves rotating the output with no rotation at the input. The lost motion includes the deflection of the gear teeth for full-face contact, motion as a result of bearing clearances, as well as friction and *clearance backlash*. Torsional backlash is synonymous with lost motion and common sense tells us that the amount of force applied will greatly affect the values of lost motion or torsional backlash.

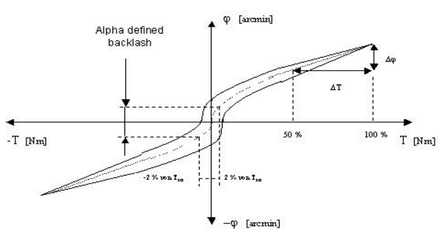
The manufacturing quality of the gearhead and the shape of the teeth are the major determinants of torsional backlash. Manufacturing irregularities result in unequal tooth load distribution and skewed tooth engagements, resulting in deflections that affect the torsional backlash or lost motion values.

Some manufacturers claim zero backlash in their gearboxes due to the negative connotation associated with backlash. It is important to point out that this zero backlash claim is in regard to the actual free-play and much different than the torsional backlash. However, one may ask, "Can any mechanical device be manufactured with zero clearance or free play?"

Lost Motion

Lost Motion describes the condition in which an input to a mechanism yields no corresponding displacement at the output. Lost motion is one of the principal causes of positional uncertainty in a motion system. Lost Motion is not typically specified as such, since it is a function of the torque applied in a particular application. However, a useful alternative is the *stiffness* of the gear-head sometimes termed *torsional rigidity* or *torsional stiffness.* This characteristic, in units of torque over an angle (Nm/arcmin or in-lb/ degree), denotes a gearhead's "spring effect" or stiffness.

Stiffness of the gearhead is determined by rigidly mounting the unit, locking the input, applying a series of unidirectional torque loads to the output and, for each value, measuring the angular displacement at a number of positions about the circumference of the output shaft. The resulting data series is linear when the torque load nears the capacity of the gearhead. The slope of the line in this area defines the torsional stiffness in units of force per angle increment. When this test is performed with bi-directional rotation and torque application, backlash contributes to the results. The difference between the data upon reversal indicates the lost motion or torsional backlash as a function of the applied torque.



Backlash Compensation

Backlash, or lost motion, is not an issue in the case of continuous single direction motion. Here, the resistance of the load forces the meshing gear teeth into contact that is maintained by constant unidirectional gear rotation. However, any reversal of motion (and some cyclical horizontal motion with high inertia) requires that the teeth first dis-engage then re-engage on the opposite tooth surfaces. Unless programming of the servo control system compensates for backlash (and the values for backlash are correct), this will give rise to positioning errors in many applications. If you know what the backlash value is, and more importantly what it will be after many hours of operation under load, you can easily compensate for it in your servo system.

Backlash can be negated by obtaining position data for control feedback at the critical point-of-motion rather than at the end of the driving motor shaft. While a motor shaft-mounted sensor may be needed for control of the motor itself, locating an additional transducer for positioning control at the critical motion point bypasses the train of components along with their lost motion characteristics. Another method of compensating for backlash is in the drive manufacturer's software. The system will overshoot or undershoot the calculated position based on the amount of backlash entered as a software parameter.

For single direction motion systems, where backlash has been shown to be inconsequential, adequate torsional stiffness is critical to achieving duty cycle objectives. Consider a uni-directional rotary mechanism for cut-off applications. The intermittent cutting forces result in instantaneous high torque demands. These torque "spikes" through the gearhead input cause the gear teeth to deflect or move, the output shaft to twist, etc., which may produce erroneous cuts.

The inertia of the knife is very important here as well, because the higher the inertia, the greater the effect the stiffness will be in the control of the system. In these dynamic applications, a gearhead is used because the gearhead ratio has an exponential effect on the control of the system. This allows a motor to use its energy to move the load quickly as opposed to using its energy to rotate the stator.

A controlled motion profile for this cut-off system entails accelerating and decelerating the knife. If the torsional rigidity of the drivetrain is not rigid enough to resist deflections due to the dynamic loads, the output shaft will lag the motor shaft and its feedback transducer (resolver or encoder). Duty cycles must be limited to allow the system time to reach stability, which compromises throughput capacity; otherwise unacceptably large position uncertainty will result due to the torsional rigidity.

Unlike backlash, no servo controller programming or adjustment can fully compensate for insufficient stiffness. The stiffness / rigidity characteristics of the motion components fundamentally limit the dynamic response capability of a system. Attempts to increase performance in this case will be frustrated by servo instability (position hunting) or unacceptable settling time. The types of couplings and line-shafting also have a large impact on the system stiffness and dynamic response.

For a gearhead, maximum stiffness and torque capacity are achieved when the ring gear is manufactured integral to the housing rather than fastened into it. This allows for the largest torque capacity and internal component size for a given envelope size. The higher the stiffness, the easier it is to control a system's accuracy of movement.

It is equally important to consider the torsional rigidity of all components between the output shaft of the gearhead and the load to get a true measurement of the lost motion in a system. Even if the compromised throughput is tolerable, the lack of stiffness and the resulting oscillations may result in premature failure of the system due to fatigue of some component - gears, shafts, couplings, etc.

Repeatability
The objective for many motion systems is accuracy in indexing or moving and the desire for positioning to a location to be repeated consistently. This term is called *repeatability.* Designers want parts to rotate and to locate them in relation to the theoretical values. Backlash and lost motion play a minor role in this. The largest impact on repeatability is the accuracy of your gear teeth or cam profile, as well as the accuracy of the positional feedback device on your servomotor.

Precision
Precision relates to repeatability, speed and the ability to cycle at peak loads in opposite directions. If the inaccuracies of the gear teeth, backlash in the system or manufacturing tolerances are great, the gearhead will overheat, mis-index or fatigue to failure. A torsionally rigid gearbox with minimal torsional backlash will allow the greatest precision.

Limitations of Various Gearbox Designs
Manufacturers of planetary gearheads generally specify backlash, sometimes offering a specification for torsional backlash, which is the same as lost motion. Cycloidal or harmonic gearhead designs use cams and rollers or flexible splines that are pre-loaded together and roll in relation to one another. These designs often claim zero backlash, but state values of lost motion in the 1-3 arcmin range. Therefore the semantics give the impression that these designs are more accurate than a planetary gearhead. This is untrue, because many planetary gearhead suppliers apply a higher torque when measuring the backlash than cycloidal or harmonic gearbox manufacturers. The previous figure illustrates the difference in torsional backlash for measurements at 2% and 4% of rated torque. One can easily see that the amount of force applied during measurement has a large effect on the resulting values. Thus, the values for torsional backlash measured at a higher rated torque for the planetary gearbox appear to be greater than the values of torsional backlash of other types of gearboxes, which are often measured to a different standard.

An important downside of the cycloidal and harmonic designs is that pre-loading extracts a significant penalty in efficiency. Frictional losses due to pre-loading can be as high as 50% compared to 10% or less for a conventional gear mechanism of similar size & construction. This lack of efficiency causes problems in small incremental moves because the torque required to overcome the friction is greater than the overall torque requirement of the load, resulting in overshoot and jerky motion. This inefficiency also produces heat, which limits the speeds in cyclical motion and the allowable operating time at continuous motion.

A further limitation of many anti-backlash designs is that the elastic pre-loading causes variable friction at the output as the gearbox input shaft is rotated. This can lead to a velocity-dependent torque ripple, which may pose significant control problems at constant speeds associated with the natural frequency of the pre-loaded elements. These designs are not suitable for those applications requiring smooth rotation (i.e., laser-cutting, painting, gluing or contouring applications).

How Much Backlash Is Too Much?
It is essential to keep in mind the objectives of the motion system and the gearhead's significant influence in determining system performance. While many people may think they need zero backlash, the reality may be that backlash readings not exceeding 2 arcmins may be acceptable. This amount of angular error in a gearhead that is rotating an 8" diameter roll equates to a maximum of 0.001" of movement at the roll surface. The equation to calculate this is: (2 x Π x radius / 360 / 60 x backlash in arcmin = positional error in the same units as the radius).

Consider All The Design Elements
Considering the uncertainty regarding stiffness and position, why use a gearhead at all? The reasons are for the mechanical advantage plus the ability to control large loads quickly in an economical fashion. Motor torque requirements and the resulting cables, drive, amplifier and energy costs for a direct-drive system are very large compared to a system with a gearhead. Gearheads increase resolution at the motor and let the motor run at a higher speed, which provides more kinetic energy to overcome load disturbances. For speeds below 500 rpm and for high precision, high load applications, a servo gearhead is the most economical method of achieving the greatest precision in the smallest amount of time.
Designers must realize what is important -- precision, position, repeatability or reliability. The combination of these factors will determine the most suitable gearbox for the application. We could have entered the cost of the gearhead into this equation, but the price differences between gearhead suppliers is miniscule compared to the costs of a replacement in the field and the impact a faulty design or failure has on your customers.

Remember, gearhead catalogs are sales tools. Ask your vendor to supply test or inspectional data if precision and reliability are important. Make sure to compare equivalent specs – compare one manufacturer's torsional backlash to another's lost motion, because they are different names for the same thing. And remember that zero backlash does not result in exact positional location. The rigidity, lost motion and dynamics of the control system as a whole will determine how close the system can come to perfect positioning.