How Green is Your Gearbox?

Todd R. Bobak, Sumitomo Drive Technologies

Introduction

Rising energy costs and concerns about global warming are at the forefront of today's news. Turn to local or national TV programming, browse the internet or read the paper and one can find numerous stories about the seemingly irreversible energy costs and the subsequent impact that these costs have on simply doing business. As a result, we as individuals are becoming increasingly aware of the cost of energy and we are being introduced to a variety of methods and/or products that will minimize the impact of these costs.

In industry, power consumption in the manufacturing environment accounts for approximately 1/3 of all energy consumed annually within the United States. In the enclosed gearing industry, questions such as "How efficient is product X?" are becoming increasingly common.

Several factors influence how efficiency is lost during operation of the gearbox system. This paper will address some of these factors, and it will further provide recommendations and ideas for obtaining a highly efficient gearbox, while still taking into consideration application constraints.

Gearbox Efficiency—Defined

As it relates to enclosed gearing, efficiency is simply the ratio of the output power (power transmitted through the gearbox as usable work) to the input power. As no mechanical device is 100% efficient, this numeric value of efficiency will always be less than 1.

If the speed reducer in Figure 1 were 100% efficient, it would be concluded that the 3,600 in-lbs of torque being applied to the input shaft would generate 540,000 in-lbs of torque at the output shaft through the 150:1 gear reduction. It can be seen in this example that the output torque is less than the "expected" value due to the internal losses. Gearbox efficiency for this example can be determined as follows:

$$\text{Efficiency} = \frac{\text{Actual Output Torque}}{\text{Theoretical Output Torque}}(100)$$

$$= \frac{463,166}{540,000}(100)$$

Given this, it is calculated that the gearbox in this example is 85.8% efficient.

Efficiency of Gearing Types

The term "speed reducer" is a general one used in describing a device that increases torque while, at the same time, reduces the rotational speed of the prime mover (which is usually an AC motor). This is achieved through the interaction of gears within the speed reducer. Different gear types can be utilized to facilitate this reduction of speed/increase of torque. Each of these gear types has distinct advantages and disadvantages associated with it and, likewise, each of these gear types has different efficiencies associated with it.

Specifically, as it relates to efficiency, two gears in mesh incur losses in efficiency due to the sliding action of one gear tooth against the corresponding gear tooth of the mating gear. This sliding action reduces the overall efficiency of the gear set since useable power is converted to heat. It is not accurate to say that a specific gear type has a definite efficiency associated with it since factors such as reduction ratio, gear-manufacturing methods and lubricant (among others) all play a role in the efficiency of a gear set. Table 1 details three common gear types, along with their associated typical efficiencies.

It is not uncommon for speed reduc-

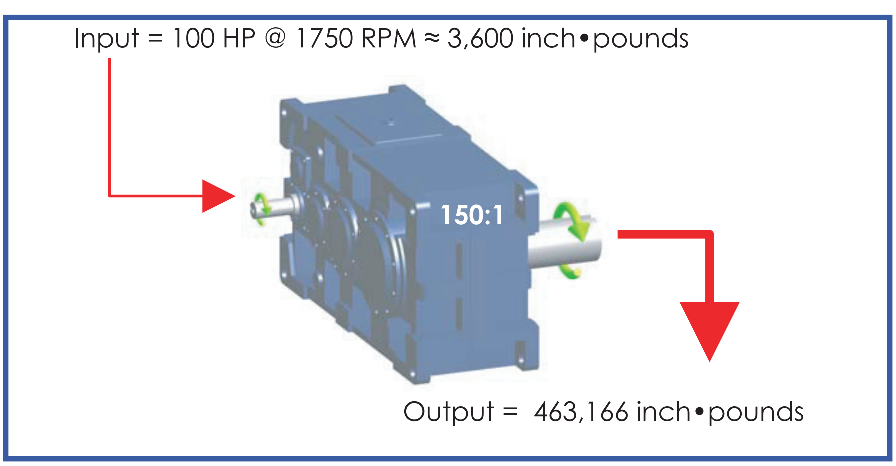

Figure 1—A gear reducer with output torque less than the expected value.

ers to incorporate more than one set of gears (or stages) to achieve the desired overall reduction ratio. In such cases, the overall efficiency of the gear train is the product of the individual efficiencies of each gear reduction stage. Say, for example, that a gearbox incorporates three stages of helical gearing. Accept as well that each stage has an efficiency of 98.5%. The overall gear train efficiency would be:

Efficiency 1st stage x Efficiency 2nd stage x Efficiency 3rd stage x 100 = Total Gear Train Efficiency

$$0.985 \times 0.985 \times 0.985 \times 100 \approx 95.6\%$$

To continue this example, it is possible that a multistage gearbox utilizes different types of gearing for each of its reduction stages. A right-angle gearbox (one where the output shaft is at a right angle to the input shaft) may utilize a spiral bevel gear set as its first reduction stage, followed by a helical gear set as its second reduction stage. Using the typical gearing efficiencies detailed previously, the efficiency of the gear train in this example can be calculated as follows:

Efficiency 1st stage x Efficiency 2nd stage

$$= 0.92 \times 0.96 \times 100 = 88.0\%$$

Oil Seals and Efficiency

Virtually all speed reducers incorporate the use of oil seals within their assemblies. These seals can be found on both the input and output shafts, as well as internally within the unit. Their primary function is to retain the lubricant within the gearbox while eliminating the ingress of dirt and water. There are a variety of different types of seals for a variety of different applications (i.e., axial shaft seals), but the most common type of seals used in industrial gearboxes are radial shaft seals.

The performance of a radial seal is dependent upon an interference fit that provides pressure of the seal lip against the shaft or collar surface. Through operation, the seal lip will gradually wear so that, in some cases, a garter spring is incorporated into the oil seal in order to maintain adequate seal lip pressure against the shaft. Additionally, a secondary seal lip may be utilized on the seal to prevent the ingress of contaminants into the system. (See Figure 2 for a view of a speed reducer with details of an oil seal for clarification.)

Since these seal lip(s) are riding against a rotating shaft (or collar), friction at this interface is developed and an energy loss (albeit small) is realized. The amount of this energy loss due to friction is dependent upon many factors that include shaft speed, shaft diameter and the surface finish/roughness against which the seal lip(s) are in contact. As an example, published data indicates that an oil seal riding on a 100 mm shaft (≈ 4") that is rotating at 500 rpm will generate frictional losses at a magnitude of 20 watts. While it is true that this is a seemingly minuscule value, it is common for some gearbox manufacturers to incorporate more than a single seal on a given shaft as an added feature to minimize or

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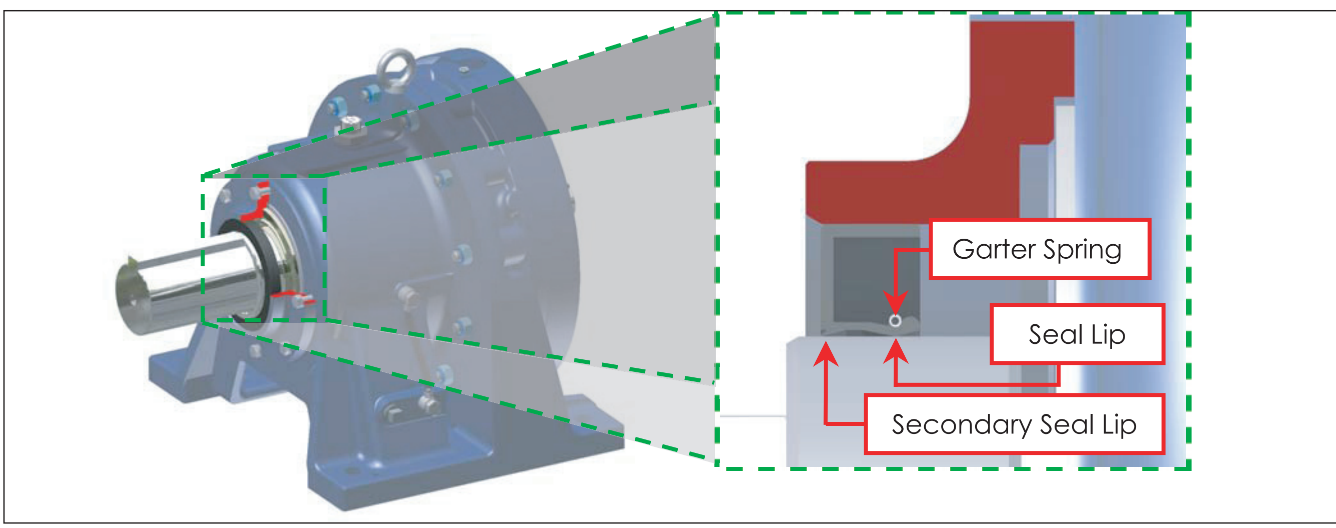

Figure 2—Speed reducer with oil seal cutaway showing additional ("secondary") seal lip.

Table 1—Three common gear types and their associated typical efficiencies.

	Gear Type		
	Helical	Worm	Spiral Bevel
			
Typical Efficiency:	≈ 96%	≈ 79%	≈ 92%

eliminate the possibility of lubrication leakage. Having said that, multiple seals within a single-speed reducer may develop frictional losses exceeding 100 watts (once again, depending on seal sizes and rotational speeds).

Bearings and Efficiency

Bearings are another component common to all speed reducers. Roller bearings are used to secure and support shafting and gearing within the unit. These roller bearings are intended to accept external loading (radial and axial) on the input and output shafts. Additionally, these bearings accommodate the internal forces generated by the gears in mesh. To accept these forces, roller bearings rely on balls (spheres) or rollers retained between an inner and outer race. Figure 3 shows a section of a helical gearbox with details of a deep-groove ball bearing for clarification.

A bearing is a low-friction device; it is not friction-free. As one race rotates about the other race, the balls (or rollers) likewise rotate/slide within the race. The rotating/sliding action of the balls (or rollers) creates friction between these bearing components, thereby creating an additional avenue for energy loss.

Like oil seals and gearing, the amount of energy consumed by a bearing is dependent on many different factors. Mathematical formulas exist that can be used to calculate the friction torque of a given bearing. This value of friction torque is a function of the coefficient of friction between the rolling elements of the bearing, the bore diameter of the bearing itself and the load acting upon it. It is expressed as:

$$M = \frac{\mu \bullet F \bullet d}{2}$$

where: M = Friction Torque (in • lbs, N•m)
μ = Coefficient of Friction
F = Bearing Load (lbs, N)
d = Shaft Diameter (in, m)

Using this equation, the friction torque for a ball bearing of size 6211 with a 4,250 pound radial load acting upon it is approximately 5.8 inch-lbs. Whereas, for a similarly sized tapered roller bearing (32211) operating under the same loading conditions, the friction torque is calculated to be 9.8 inch-lbs. These "required" torque values may seem relatively small in comparison to the overall requirements of the system, but these values are for one bearing only. Gearboxes typically incorporate the use of four or more bearings, each one of which has a friction torque associated with it.

It should be noted that some bearings contain integrated seals or shields, the purpose of which is to maintain lubricant within the bearing and/or to prevent the ingress of foreign matter into the race. Tapered roller bearings may incorporate a Nilos ring for the same purpose. Inclusion of such sealing devices further contributes to efficiency losses since these sealing devices are in direct contact with the rotating race(s) of the bearing.

Effects of Lubricant on Efficiency

For internal gearing, the use of the appropriate lubricant is crucial to obtaining maximum service life and reliability of the gearbox. The function of the lubricant is two-fold: first, it provides a thin film between the internal rotating components, as well as the gear teeth in mesh, thereby preventing direct metal-to-metal contact; and, second, it provides a medium through which heat—developed through normal unit operation—is dissipated.

As noted previously, the type of lubrication utilized in a gearbox plays a role in the overall efficiency of the unit. As the internal gearing moves through the lubricant, the lubricant is continuously displaced by the action of the gears striking it. This is typically known as churning loss, since power that could otherwise be used for the application is absorbed (or required) by this action of the gearing striking, pumping or moving the lubricant. For example, a gearbox lubricated with grease would be less efficient than if it were to be lubricated with oil. Intuitively, this makes sense since grease is typically thicker than oil and requires a greater amount of power to move the gearing through it. Imagine, for a moment, what it would be like to swim in syrup as opposed to swimming in water. Clearly, the thicker media (syrup) would require more personal power to "swim" through.

Another avenue for loss in efficiency specifically related to gearing and lubricant is what is known as windage loss. As the gearing rotates through the lubricant, and then out of the sump, a cer-

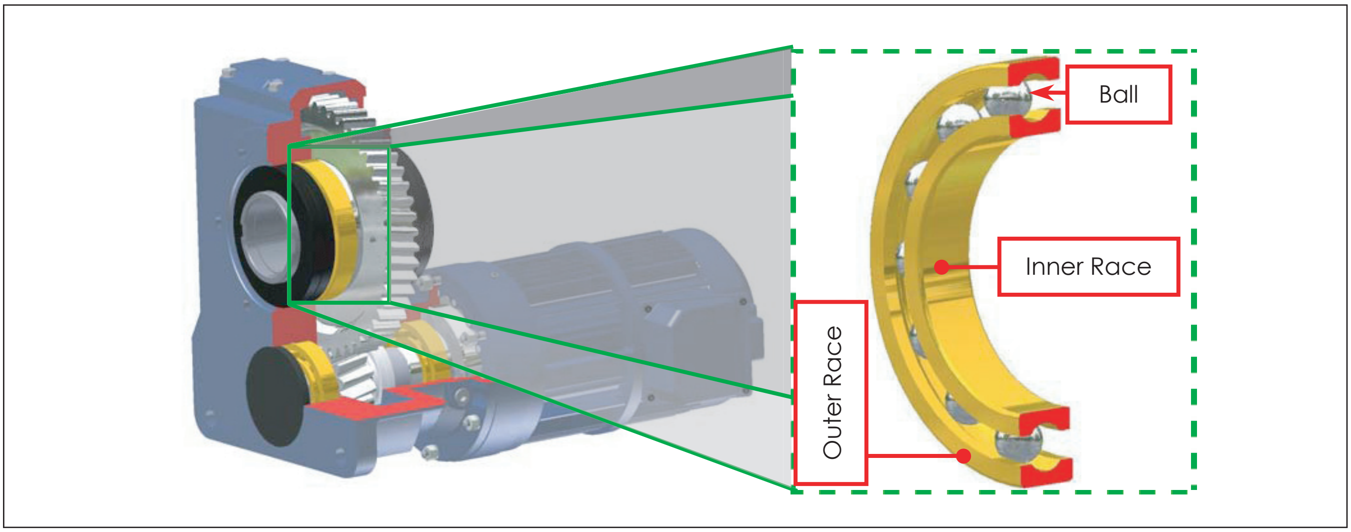

Figure 3—Speed reducer with detail of inner and outer race rings.

tain amount of lubricant adheres to the surface of the gear itself. Since the gear is rotating, centrifugal forces cast the lubricant adhering to the gearing into the enclosed atmosphere of the speed reducer casing. This action may serve to create a lubrication "mist" through which the gearing must pass. In essence, this mist is another barrier for the gear to pass through, thereby requiring (or diverting) power, which otherwise could have been utilized as usable output torque.

To quantify the effects of lubricants on speed reducer efficiency, testing has been conducted by Sumitomo Drive Technologies on a planetary gearbox of a given size and reduction ratio (4:1). This efficiency testing was conducted twice: once with the gearbox lubricated with a grease of NLGI Grade # 2 (a moderately soft grease with the approximate consistency of peanut butter), and again with a grease of NLGI Grade # 00 (a semi-fluid grease with an approximate consistency of applesauce). Other than the lubricant, no other components within the test units were changed. Post-test results revealed that the speed reducer lubricated with the NLGI # 00 grease had an efficiency of 92.1%, whereas the same unit lubricated with the NLGI # 2 grease was 90.9% efficient.

This is not to say, however, that oil lubrication for a gearbox is distinctly preferred over grease. Grease has the advantage in that it may provide for universal mounting of the gearbox (i.e., output shaft vertical up or vertical down), and its replenishment/replacement interval may be longer than a comparably sized oil lubricated unit. And last, grease is less likely to leak through the shaft seals of the unit.

Conclusions

As discussed, many components incorporated into the gearbox construction and its subsequent operation influence the overall efficiency of the speed reducer itself. While the greatest loss in efficiency is typically associated with the interaction of the gears in mesh, other factors and components also serve to influence the overall efficiency of the system.

Speed reducers can be designed to minimize efficiency losses within the product through a variety of means. Utilization of high-quality gearing with superior surface finish on the gear teeth, combined with the incorporation of low-friction seals and bearings, all serve to maximize the power efficiency of enclosed gearing products.

From the point of view of the user (or potential user), perhaps one of the most important factors in selecting a unit is to assure that its efficiency is being optimized for the application. In short, make sure that the gearbox is properly sized for the application. Prior to ordering the speed reducer from the manufacturer, it is imperative that the application power requirements and demands are clearly understood. Utilization of the appropriate service factor for the speed reducer must be taken into consideration and applied. If the gearbox is unnecessarily oversized—i.e., if the power capacity of the gearbox greatly exceeds the power of the applied motor, combined with the application service factor—much of the motor power will be used to overcome the constant losses within the gearbox, thereby leaving little additional, usable power/torque for the application itself. As such, this would be a situation where the speed reducer is yielding a very low efficiency. Conversely, however, a gearbox undersized for an application runs the risk of low life expectancy due to overload conditions, despite a seemingly high efficiency.

Also, follow the manufacturer's recommendation for the correct type of lubricant to be used within the speed reducer, along with its recommended change interval. Be it oil or grease, over time all lubricants lose their effective properties and, due to this, the overall gearbox efficiency stands to decrease over time as well.

Finally, consider the method by which the gearbox is attached to the driven shaft. Is it possible to couple the output shaft of the reducer directly to the driven shaft? This may be preferred from an efficiency point-of-view, since the use of belts and/or chains generates friction or possibly slippage at their interface, which, in turn, leads to additional efficiency losses.

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