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A second look at Gearbox efficiencies

Machine Design
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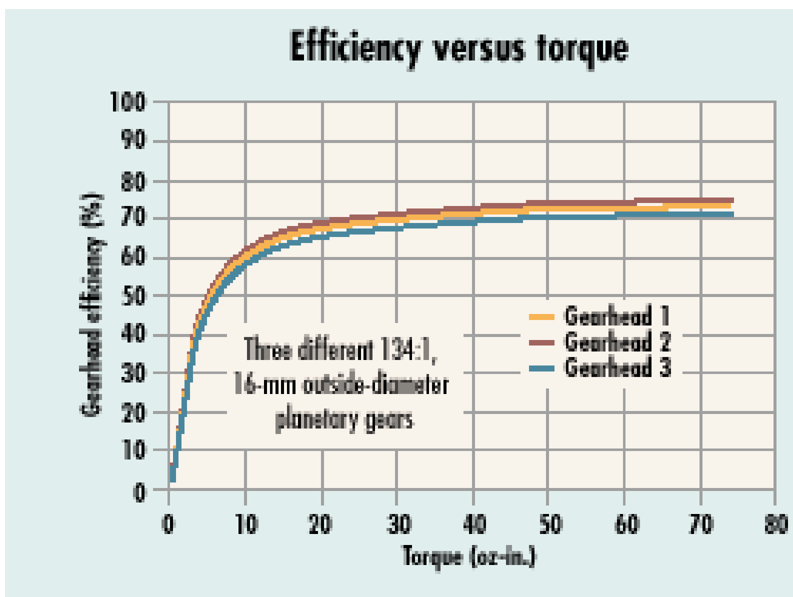
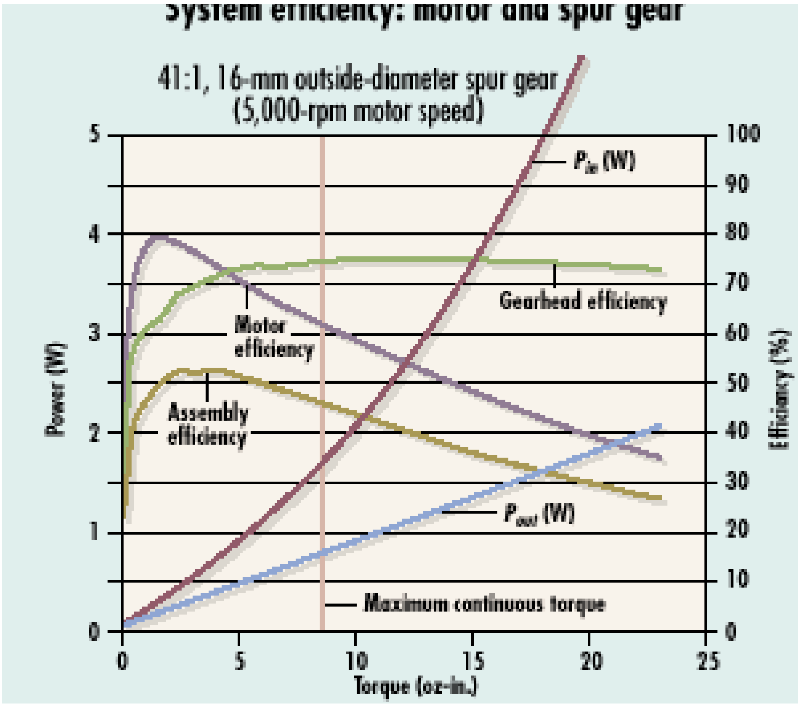


Manufacturers often specify motor efficiency. Ditto for gearbox efficiency. However, total system efficiency (motor plus gearbox) is neither clearly understood nor easily calculated. This makes gearbox efficiency specifications found in product catalogs unreliable. Catalogs typically provide only a single efficiency rating which is not entirely accurate. Efficiency depends on a number of factors, especially gearbox loading. Most manufacturers do not list efficiency tolerances, or the difference in efficiencies between a heavily-loaded gearbox and one running under normal loads.

The electrical input power to a gearbox (the product of voltage and current to the motor), multiplied by the motor efficiency is the input power to the gearbox. Output power is the gearbox speed and load torque. The ratio of output power to input power equals efficiency.

Power loss in the gearbox is mostly due to friction, which generates heat. In miniature gearboxes, heat is not much of a problem because the power losses and the absolute amounts of power involved are relatively small. However, large gearboxes use oil coolers and pumps to compensate for gearbox inefficiency.

Thus, gearbox efficiency depends on friction. This in turn depends on the quality of the gearing, the number of tooth engagements (how many times one wheel drives another) and the load torque (how much "moment" the gearbox has to deliver).



Most manufacturers will specify an intended gearbox operating point. Gearbox efficiencies in a spur gearbox at a 16-mm diameter vary from about 87% at a gear ratio of 6.3:1 to about 40% at a ratio of 10,683:1. A basic rule that designers use for spur gears is a 10% loss per engagement. One gear wheel in contact with another is defined as an engagement and the loss in that engagement is approximately 10%.

A general rule is the lighter the load and the higher the ratio, the less likely it is that the gearbox will actually reach the manufacturers' specified efficiency. Light loading and high ratios tend to produce poor gearbox efficiencies. But with heavy loading and high ratios, the gearbox will approach its theoretical efficiency.

Overall system efficiencies depend on the efficiency of the motor and gearbox together. If the efficiency of the motor and gearbox is each 50%, the two efficiencies are multiplied together to yield the system efficiency (0.5 x 0.5 or 0.25, or a system efficiency of 25%).

At low ratios, motors are more heavily loaded than the gearboxes. A low reduction ratio lets the motor "see" more of the load than at a high ratio. For example, the maximum efficiency of a 22:1 gearbox is about 76% and the maximum efficiency of the motor is about 80%. However, the two don't occur at the same time. When the motor reaches its peak efficiency, gearbox efficiency is closer to 63% instead of 74%. Therefore, when the motor is at peak efficiency the gearbox is not — in low ratios.

This is a critical issue. Assuming the gearbox has a constant efficiency leads to incorrect calculations. In this case, a 10% efficiency difference could mean a lot in the overall system efficiency. At higher gearbox ratios, motor and gearbox efficiencies follow similar curves because at that point the gearbox sees more of the load than does the motor. This leads to peak efficiencies in both gearbox and motor.

Variable motor speeds present another set of variables in the overall equation. However, at about 150:1 to 200:1, the gearbox and motor efficiencies peak at the same time. To use the least amount of power, it's critical to match the motor, gearbox, and load closely to get the best system efficiencies.

Equations used in calculating efficiency

Motor efficiency (%): $eff_{mot} = P_{out}/P_{in}$
P_{out} = Output power
P_{in} = Input power

Motor output power: $P_{out} = T \times n$
T = torque
n = speed

Motor torque: $T = (k_m \times I) - (k_m \times I_0)$
k_m = torque constant (from catalog);
I_0 = measured no-load current
I = Loaded current

Assembly efficiency: $eff_{assy} = P_{out\ assy} / P_{in\ mot}$
$P_{out\ assy}$ = Assembly output power
$P_{in\ mot}$ = Motor input power

Gearhead efficiency: $eff_{GH} = eff_{assy}/eff_{mot}$