Using mechanical speed reduction to get the best performance from electric motors

Once you have selected an appropriate motor, choosing the best reduction ratio is the single most important factor in determining how well the motor will work in a particular application. There are several methods that can be used to implement mechanical speed reduction. Here are some examples along with some pros and cons.

- Gears. Work well if properly designed but can be difficult because of the tight tolerances required
- Gearbox. A compact and convenient solution but often costs more than the motor itself
- Belts and pulleys. Toothed timing belts are quiet and easy to use, but they can take up too much space if multiple stages are needed. They normally require a tensioning mechanism.
- Sprockets and chains. Can handle high torque and are easy to use because of the loose tolerances required, but they can be noisy. They can sometimes be used without a tensioning device.

If there is too much speed reduction, the motor may have plenty of torque but the RPM will be too slow. If there is insufficient speed reduction, the motor will need to draw much more current than would otherwise be necessary to produce the required torque.

The amount of current drawn by the motor is an important consideration because the heat generated by the motor is proportional to the current squared. In the first case, (too much reduction), the motor is normally safe because it will be drawing reduced current. But if the speed reduction is insufficient, the motor can easily draw currents high enough to cause overheating. And if the reduction is insufficient, the motor may be forced to work in an RPM range that is far from the speed at which it has high efficiency. This can cause overheating at relatively low levels of torque. The benefits of proper speed reduction include:

- Reduced motor heating
- Increased acceleration
- Increased torque
- Longer battery life
- Increased durability for motors and motor controllers.

It is good practice to use the most mechanical speed reduction possible. Even a small change in the ratio can make a significant change in the performance of the system. We always recommend erring a little on the side of over-reduction when designing a new application.

Example 1:

Consider the AmpFlow A28-400-G motor with the AmpFlow speed reducer with a reduction ratio of 1:8.3. When operating at 550 RPM at 41 Amps of current, the motor has an efficiency of 82.6%, (not counting some small friction loss in the speed reducer). And the torque output would be around 2000 oz-in. This is a very efficient motor but there is still about 170 watts of waste heat generated at this operating point.

If we try to operate the same motor at 2000 oz-in without a speed reducer, the current required would be about 310A and the waste heat would be over 4000W. This is a tremendous overload condition and the motor would quickly overheat.

The reduction ratio is optimal when the RPM of the output from the speed reducer matches the required top speed when the motor is running at an RPM that is at or above the efficiency peak for that motor. If the motor can not develop the torque required for the application with this reduction ratio, or if the waste heat is too high at this level of output, then the motor may be too small for the application. Charts showing the efficiency, power output, and current draw at various speeds are available at www.AmpFlow.com

Example 2:

A mobile robot requires a top speed of 10 MPH using the A28-400-G motors. We want to achieve this speed when the motor is running at a speed a little higher than its RPM of peak efficiency, (which is 4500 RPM for this motor). So we choose 4700 RPM as the motor speed. The reduction ratio of the AmpFlow speed reducer is 1:8.3 making our wheel speed about 570 RPM. So we need to choose the proper wheel diameter to get close to the optimal overall reduction ratio. To get 10 MPH with a wheel revolving at 570 RPM, the wheel would need to be about six inches in diameter.

Example 3:

The same robot requires the same top speed of 10 MPH but the wheel diameter is 13 inches. A 13-inch wheel revolves at about 260 RPM when traveling at 10 MPH. With the motor running at 4700 RPM, we need a reduction ratio of 1:18 to get 260 RPM at the wheel. If the AmpFlow speed reducer is used in this application, then an additional reduction ratio of about 1:2.2 is required. (18 / 8.3 = ~2.2). This might be done by using a chain-and-sprocket reduction with a 15-tooth sprocket on the output of the gearmotor and a 33-tooth sprocket on the wheel. If the AmpFlow speed reducer is not used, then the entire 1:18 reduction must be achieved using one of the speed reduction methods listed above.

The largest practical speed reduction using just two gears or two sprockets or two pulleys is about 1:5. Above that you run into problems with oversized gears/sprockets/pulleys and problems with insufficient chain or belt wrap around the smaller of the two items. So in the above example you might design a two-stage reducer with each stage having a ratio of 1:4.3, (4.3 x 4.3 = ~18), or a three-stage reducer with a ratio of 1:2.6 for each of the three stages.

Electronic speed controllers:

Do not rely on electronic speed reduction to do the job of a mechanical speed reducer. The purpose of electronic motor controllers is to control the speed from 0 to 100%, (and also the direction in reversible controllers). Using the controller to limit the motor speed has all the drawbacks listed above, (and in some cases, even more). The machine should be designed so that the controller is fully on at 100% throttle when the machine is operating at its top required speed.

Modern high-frequency motor controllers work by switching the power on and off thousands of times per second. To get more speed, the "on" time is increased, and to reduce speed the "on" time is decreased – reaching zero "on" time at zero RPM. The high switching speeds combined with the inductance of the motor has the effect of turning the system into a voltage controller rather than a current controller.

Measure the motor voltage in a 24V system that is throttled to about 25% and you will get a reading of 6V. Let's say the 24V battery is capable of supplying 100 amps, or a total of 2400 watts. If 2400W are going into the controller then 2400W must be coming out of the controller. If 2400W are going into the motor at 6V, then the current must be 400A, (2400W / 6V = 400A). The math has been simplified in this example by not taking into account efficiency losses and a few other considerations, but the basic idea remains the same: the electronic motor controller can push more current into the motor than the battery can actually supply!

Since the motor heating is proportional to the current squared, you can see why using an electronic speed controller to limit top speed is no substitute for the proper mechanical speed reduction ratio.

Example 4:

Let's say your power supply can produce no more than 11A output at 36V, (like the AmpFlow S-400-36). You want to use the AmpFlow E30-150 to operate a pump that is rated at 1/3 horsepower (250W), at 1800 RPM. At 36V, this motor will produce 250W of output at 8200 RPM with waste heat of about 80W. But there is a big mismatch between the pump RPM and the motor speed. Since the power supply is limited to only 11A, you might think that the motor would be protected from overheating.

The torque is proportional to the available current. This motor will have 51 oz-in of torque at 11A. Let's say the pump drags the motor speed down to 1800 RPM. The mechanical power output of a system with 51 oz-in at 1800 RPM is only about 70W (51 oz-in x 1800 RPM / 1352 = ~70W). But the motor is burning 11A of current at 36V (400W). All the electrical power that is not being turned into mechanical output ends up as heat. So the waste heat is 330W. This will overheat the motor. And at only 70W of power, that pump will not be able to even reach 1800 RPM. So the above figures actually get worse, depending on the exact characteristics of the pump.

This same motor, with the addition of a speed reducer with a reduction ratio of 1:4.5 would happily produce the 1800 RPM with only 80W of waste heat.

How to choose the best reduction ratio:

As stated above: The reduction ratio is optimal when the RPM of the output from the speed reducer matches the required top speed when the motor is running at an RPM that is at or above the efficiency peak for that motor. For a robot or a vehicle, this means choosing a wheel diameter or a reduction ratio that matches the motor's speed with the top speed that is required for the application. This rule-of-thumb also applies to designing mechanisms or machines. But usually in a machine, the required torque is known more precisely. So check the performance charts on the AmpFlow web site and make sure the motor produces sufficient torque.

AmpFlow motors can be used in an RPM range that is below the speed of peak efficiency shown on the charts, but the higher the torque, the shorter the duty cycle needs to be to allow the motor to cool down. It is best to err a little on the side of over-reduction rather than risk overheating the motor.

Engineering assistance:

If you need help selecting a motor or determining the optimal reduction ratio, give us a call or send an email. For a robot or vehicle we will need to know the weight of the vehicle, the wheel diameter, and the desired top speed. For a machine or mechanism we will need to know the RPM and the torque. In all cases we will need to know the duty cycle, (on time vs. off time), the voltage and, (if you are using a small battery or a power supply with limited output), what the available current is.

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