Baldor Basics: Understanding Torque

Edward Cowern, P.E.

In the process of applying industrial drive products, we occasionally are misled into believing that we are applying horsepower. The real driving force is not horsepower — it is torque. This paper is developed to impart a deeper understanding of torque, its relationship to horsepower, and the types of loads we most frequently encounter.

Introduction

Torque is the twisting force supplied by a drive to the load. In most applications a substantial amount of torque must be applied to the driven shaft before it will even start to turn. In the English system the standard units of torque as used in the power transmission industry are pound inches (lb. in.) or pound feet (lb. ft.) and, in some cases for very low levels of torque, you will encounter ounce inches (oz. in.).

Torque Basics

At some time we all have had difficulty in removing the lid from a jar. The reason we have this trouble is simply that we are unable to supply adequate torque to the lid to break it loose. The solution to our dilemma may be to: 1) grit our teeth and try harder; 2) use a rubber pad or cloth to increase the ability to transmit torque without slippage; or 3) use a mechanical device to help multiply your torque producing capability. Failing on all of the above, we may pass the jar to someone stronger who can produce more torque.

If we were to wrap a cord around the lid and supply a force to the end of the cord through a scale (Fig. 1), we could get the exact measurement of the torque required to loosen the lid.

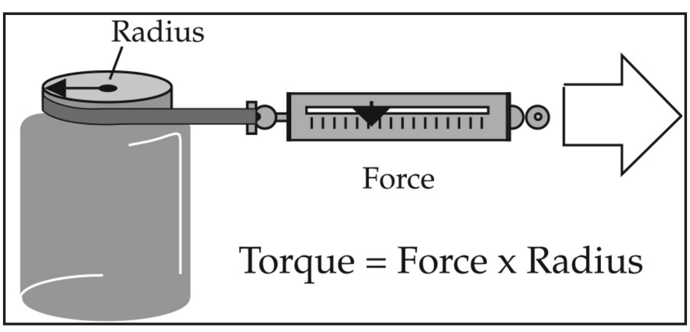


Figure 1 If we were to wrap a cord around the lid and supply a force to the end of the cord through a scale, we could get the exact measurement of the torque required to loosen the lid.

The torque required would be the force as indicated on the scale, multiplied by the radius of the lid.

For example, if the indicated force on the scale at the time of "breakaway" was 25 lbs., and the lid radius was 1.5 inches, the torque required would have been:

$$T = 25 \text{ lbs.} \times 1.5 \text{ in.} = 37.5 \text{ lb. inches}$$

Although this example does give a reasonable illustration of torque, it does not represent a very common example of requirements on industrial equipment.

There is, however, one additional, important point that can be derived from the jar and the lid example, namely — "sticksion." Sticksion is a term generated to indicate the amount of torque required to break a load loose on its way to making the first revolution.

In general the break-away torque requirement to start a machine will be substantially greater than that required to keep it running once it has started. The amount of sticksion present in a machine will be dependent on the characteristics of the machine, as well as the type of bearings that are used on the moving parts (Table 1).

Table 1 Typical values of breakaway torque for various general classifications of machinery.

Torque	% of Running Torque	Types of Machines
Breakaway Torque	120% to 130%	General machines with ball or roller bearings
Breakaway Torque	130% to 160%	General machines with sleeve bearings
Breakaway Torque	160% to 250%	Conveyors and machines with excessive sliding friction
Breakaway Torque	250% to 600%	Machines that have "high" load spots in their cycle, such as some printing and punch presses, and machines with "cam" or "crank" operated mechanisms.

Table 1 indicates typical values of break-away torque for various general classifications of machinery.

Assuming that the sticksion, or break-away torque, has been overcome and the load has started, a continuing amount of torque must be supplied to handle the running torque requirements of the machine.

In a high percentage of industrial applications the torque requirement of the load is independent of the speed at which the machine is driven. This type of load is generally called a "constant torque load."

Constant torque loads will be used to introduce the basic concepts of horsepower; additional load types will then be introduced.

Horsepower

Many years ago the invention of the steam engine made it necessary to establish a unit of measurement that could be used as a basis for comparison for how much work could be done by an engine. The unit that was chosen was related to the animal that was to be replaced by the new sources of power — the horse.

After a great deal of testing it was found that the average workhorse could accomplish work at a rate equal to 33,000 ft. lbs. in one minute — the equivalent to lifting 1 ton (2,000 lbs.) 16.5 feet, or 1,000 lbs., 33 feet in one minute.

This unit, once established, became the Western Hemi-

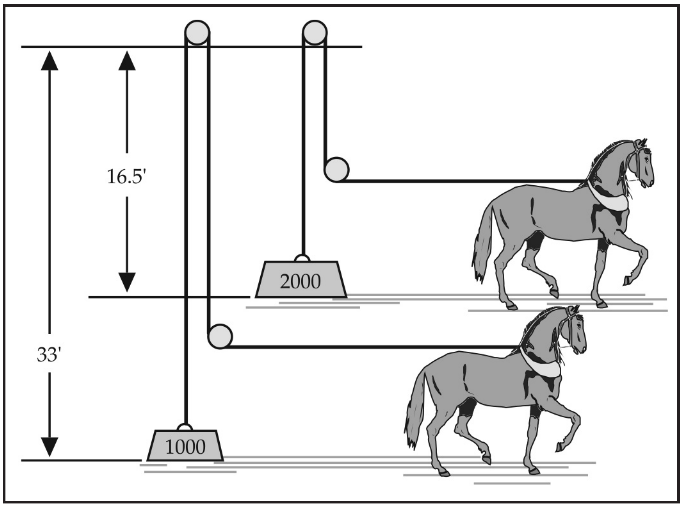


Figure 2 The average work-horse accomplishes work at a rate equal to 33,000 ft. lbs. in one minute; or equal to lifting 1 ton (2,000 lbs.) 16.5 feet, or 1,000 lbs., 33 feet in one minute.

sphere's standard for measuring the rate at which motors and other drives can produce work. For example, a 1 H.P. motor can produce 33,000 ft. lbs. of work in one minute.

Torque and horsepower are related to each other by a basic formula which states that:

$$\text{Horsepower} = \frac{\text{Torque} \times \text{Speed}}{\text{Constant}}$$

The value of the constant changes depending upon the units that are used for torque; the most frequently used combinations are:

$$HP = \frac{T \times S}{5252} \qquad T = \text{Torque in lb. ft.} \quad S = \text{Speed in RPM}$$

OR

$$HP = \frac{T \times S}{63{,}025} \qquad T = \text{Torque in lb. in.} \quad S = \text{Speed in RPM}$$

OR

$$HP = \frac{T \times S}{1{,}000{,}000} \qquad T = \text{Torque in in. ounces} \quad S = \text{Speed in RPM}$$

Rearranging these formulas to obtain torque, we can arrive at the equations:

$$T = \frac{HP \times 5252}{S} \qquad T = \text{Torque in lb. ft.} \quad S = \text{Speed in RPM}$$

OR

$$T = \frac{HP \times 63{,}025}{S} \qquad T = \text{Torque in lb. in.} \quad S = \text{Speed in RPM}$$

OR

$$T = \frac{HP \times 1{,}000{,}000}{S} \qquad T = \text{Torque in in. ounces} \quad S = \text{Speed in RPM}$$

In order to save time, graphs and tables are frequently used to show values of torque, speed and horsepower.

The previous discussion applies to calculations for *all* single-speed loads where the required torque and speed for a given operating condition are known.

Adjustable Speed Drives

When adjustable speed drives, such as DC SCR units, magnetic couplings, or variable frequency drives are to be utilized, a determination of *load type* must be made.

As previously mentioned, the most common type of load is the "constant torque" load. The relationships of torque and horsepower to speed for a "constant" torque load are shown (Fig. 3).

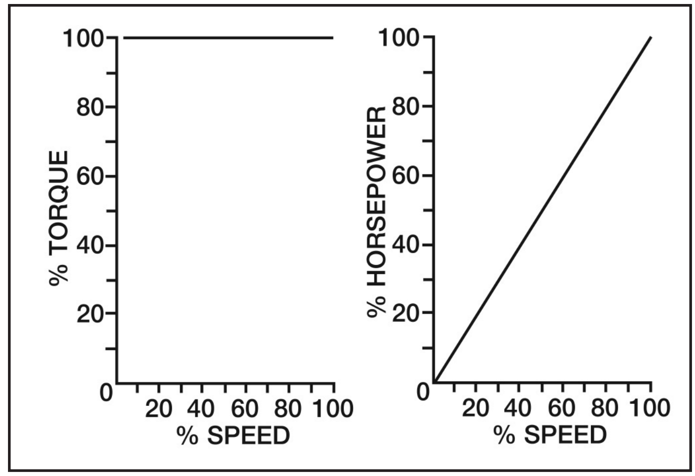


Figure 3 Constant Torque Speed-Torque Relationship

In the case of "constant torque" loads the drive must be sized to handle the following:

1. Torque required to break-away the load
2. Torque required to run load
3. Output *speed* required to operate machine at maximum required speed

Please note that only after the load has 1) been started, and 2) adequate torque is available to run it, does speed become a factor.

Only after these three items have been determined is it possible to calculate the required horsepower for the application.

Most adjustable speed drives are inherently "constant torque" devices; therefore no special considerations are involved in handling "constant torque" loads.

Constant Horsepower

A load type that occurs most frequently in metal working applications is the constant horsepower load.

On applications requiring constant horsepower the torque requirement is greatest at the lowest speed and diminishes at higher speeds. In order to visualize this requirement consider

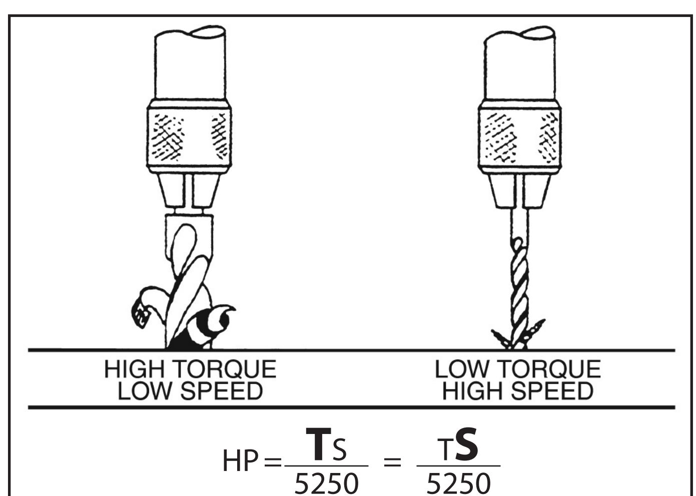


Figure 4 Constant HP Speed-Torque Relationships

the torque requirements of a drill press (Fig. 4).

When a *large hole* is being drilled, the drill is operated at a *low speed*; but it requires a very *high torque* to turn the large drill in the material.

When a *small hole* is being drilled, the drill is operated at a *high speed*, but it requires a very *low torque* to turn the small drill in the material.

A mathematical approach to this type of requirement would indicate that the HP requirement would be nearly constant, regardless of machine speed. Figure 5 shows the relationships of torque and horsepower to speed on constant horsepower loads.

As previously mentioned, this load type occurs most frequently on metalworking applications such as: drilling or boring; tapping; turning (lathes); planing; milling; grinding; wire drawing, etc. Center driven winders winding materials under constant tension also require constant horsepower. Constant horsepower can also be a requirement on some types of mixers.

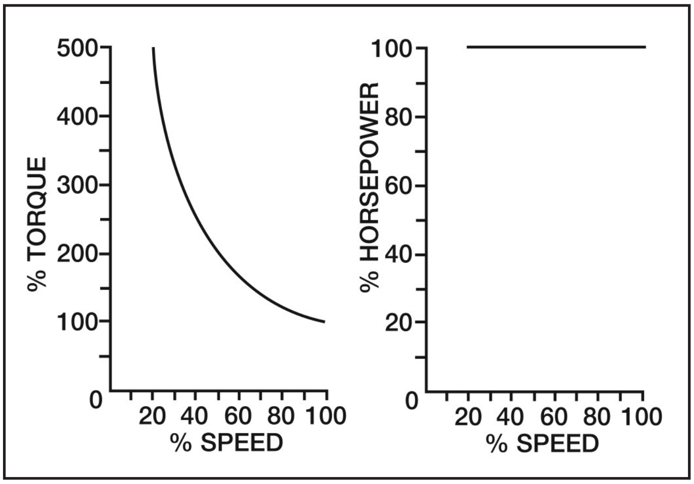


Figure 5 Constant HP speed /torque relationships.

An example of this might be a food mixer used to mix a variety of batters and dough. In this case dough would require *low speed* and *high torque*. Thin batters would require *high speed* and *low torque*; this is constant horsepower.

Spring coilers, four-slide machines, punch presses and eye-letting presses will frequently have torque requirements falling somewhere between the characteristics of constant horsepower and constant torque.

A general test for deciding if a machine might require constant horsepower would be to study the machine output. When a machine is designed to produce a fixed number of pounds-per-hour — regardless of whether it is making small parts at high speed, or large parts at a lower speed — the drive requirement is apt to be constant horsepower.

Although details of selecting drives for constant horsepower loads are beyond the scope of this presentation, some possibilities are cited.

For example, "constant horsepower" loads can be handled by oversizing drives such as standard SCR units or slip couplings. This is done by matching the drive's output torque with the machine's requirement at low speed. Depending upon the speed range that is required, this can result in gross oversizing at the high speed. More practical approaches involve using stepped pulleys, gearshift transmissions and metallic or rubber belt adjustable pitch pulley drives. Some additional and more sophisticated approaches are DC (SCR) drives operating with a combination of armature control at full field power up to base speed and field weakening above base speed. Some variable frequency drives can also be used at frequencies above 60 Hz, with voltage held constant to achieve a moderate amount of constant horsepower speed range.

Variable Torque

The final load type that is often encountered is the "variable torque" load. In general, variable torque loads are found only in centrifugal pumps, fans and blowers.

A cross-section of a centrifugal pump is shown (Fig. 6). The torque requirement for this load type can be thought of as being nearly opposite that of the constant horsepower load. For a variable torque load the torque required at *low speed* is very low, but the torque required at *high speed* is very high. Mathematically, the *torque* requirement is a function of the *speed squared*, and the *horsepower* is a function of the *speed cubed*.

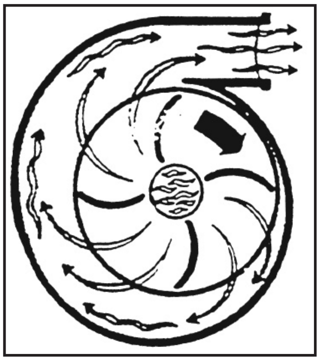


Figure 6 Centrifugal pump — variable torque load.

The relationships of torque and horsepower to speed on variable torque loads are shown (Fig. 7).

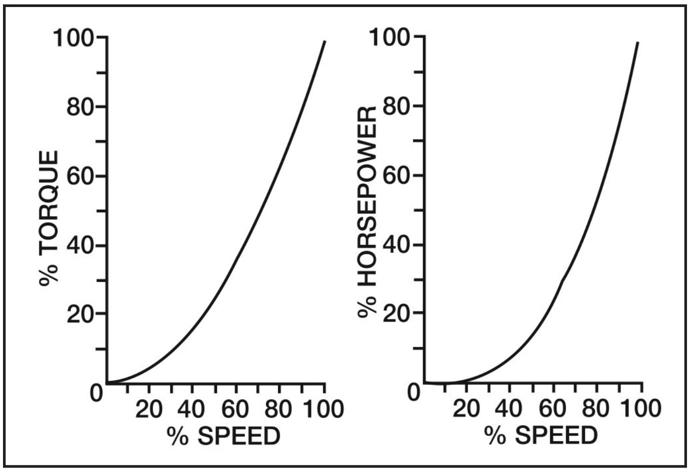


Figure 7 Variable torque — speed-torque relationships.

The key to drive sizing on variable torque loads is *strictly* related to providing adequate torque and horsepower at the *maximum* speed that will be required. *Maximum* must be emphasized, since a 9% increase in speed over the normal maximum will produce a 30% increase in the horsepower requirement.

It is impossible to speculate on the number of motors that have been burned out because people have unknowingly changed pulley ratios to obtain "more output" from their centrifugal pumps or blowers.

Table 2 illustrates the very dramatic changes in horsepower requirements for relatively small changes in speeds that occur with variable torque loads.

Table 2

% Speed Change	% Torque Change	% of Original HP	% HP Change
–20	–36	51	–49
–15	–28	61	–39
–10	–19	73	–27
– 5	–10	86	–14
0	0	100	0
+5	+10	116	+16
+10	+21	133	+33
+15	+32	152	+52
+20	+44	173	+73

Most variable speed drives are inherently capable of handling variable torque loads, provided that they are adequately sized to handle the horsepower requirement at *maximum* speed.

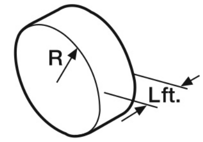
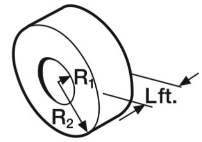
PART	RADIUS OF GYRATION (IN FEET)	SIZE OF LOAD WR^2 = POUNDS X $FEET^2$
CIRCULAR CYLINDER 	.71R	1.58 W LR^4 (R^4 = RxRxRxR) W = weight in pounds of one cubic foot of the material
HOLLOW CIRCULAR CYLINDER 	$.71\sqrt{R_2^2+R_1^2}$	1.58w L (R_2^4-R_1^4) W = weight in pounds of one cubic foot of the material

Figure 8 Formulas for determining radius of gyration and *WR*^{2} of two frequently occurring cylindrical shapes: wt.: steel = 490; cast iron = 450; aluminum = 165.

High-Inertia Loads*

A discussion of load types would not be complete without including information on "high-inertia loads." **A load is generally considered to be "high inertia" when the reflected inertia at the motor shaft is greater than five times the motor rotor inertia.*

Inertia is the tendency of an object that is at rest to stay at rest, or an object that is moving to keep moving.

In the industrial drive business we tend to think immediately of flywheels as having high inertia; but, many other types of motor-driven equipment such as large fans, centrifuges, extractors, hammer mills, and some types of machine tools have inertias that have to be identified and analyzed in order to produce satisfactory applications.

The High-Inertia Problem

The high-inertia aspect of a load normally has to be considered only during acceleration and deceleration. For example, if a standard motor is applied to a large high-inertia blower, there is a possibility that the motor could be damaged or fail completely on its first attempt to start. This failure could occur even though the motor might have more than adequate torque and horsepower capacity to drive the load *after* it reaches the required running speed.

A good example of high inertia that most of us are familiar with is a jet plane taking off. In this case the maximum output of the engines is required to accelerate the weight of the plane and contents. Only when it has reached take-off speed and is nearly ready to leave the ground do the engines start doing the useful work of moving the plane to the final destination.

Similarly, when the plane lands the reversed thrust of the engines and brakes are used to slow down and stop the inertia of the plane.

In the motor and drive industry the inertia of a rotating body is referred to as the "WR^2" or "WK^2." In the English system "W" is the weight in pounds and "R" or "K" is the *radius of gyration* in feet. It is usually easy to obtain the weight of the body, but determining the radius of gyration can be a little more difficult. Figure 8 provides the formulas for determining the radius of gyration and WR^2 of two frequently occurring cylindrical shapes.

In most cases the WR^2 of flywheels can be determined by utilizing one or both of these normal shapes. In the case of flywheels having spokes, the contribution made by the spokes can generally be ignored and the inertia calculation based only on the formula for a hollow circular cylinder (Fig. 8); weight of the spokes should be included. If exact calculations are required, formulas are available to enable the calculation of WR^2 values of nearly any shape.

Similarly, equipment manufacturers will be able to provide the exact inertia values for a given application.

Motor manufacturers can be asked to supply the maximum WK^2 limits for any specific application requirement. (Please note WK^2 and WR^2 are used interchangeably and are the same).

The values shown in Table 3 are published in NEMA (National Electrical Manufacturers Association) standards MG 1. This table gives a listing of the normal maximum values of WK^2 that could be safely handled by standard motors. This table can be used as a guide. If the required WK^2 exceeds these values, the motor manufacturer should be consulted.

Why is High Inertia a Problem?

Prior to the time that a standard induction motor reaches operating speed, it will draw line current several times the rated nameplate value. The high current does not cause any problem if it is of short duration; but when the high currents persist for an extended period of time, the temperature within the motor can reach levels that can be damaging.

Figure 9 (a) presents typical plots of available torque from a standard motor vs. speed. Also plotted on curve (a) is the typical speed torque curve for a variable torque load. The values of A_1, A_2, A_3 and A_4 are the values of torque available to overcome the effect of the inertia and accelerate the load at different motor speeds as motor speed increases.

Table 3 Copyright NEMA MG 1							
	Speed, RPM						
	3600	1800	1200	900	720	600	514
HP	Load WK^2 (Exclusive of Motor WK^2), Lb-Ft^2						
1		5.8	15	31	53	82	118
1½	1.8	8.6	23	45	77	120	174
2	2.4	11	30	60	102	158	228
3	3.5	17	44	87	149	231	335
5	5.7	27	71	142	242	375	544
7½	8.3	39	104	208	355	551	799
10	11	51	137	273	467	723	1050
15	16	75	200	400	684	1060	1540
20	21	99	262	525	898	1390	2020
25	26	122	324	647	1110	1720	2490
30	31	144	384	769	1320	2040	2960
40	40	189	503	1010	1720	2680	3890
50	49	232	620	1240	2130	3300	4790
60	58	275	735	1470	2520	3820	5690
75	71	338	904	1810	3110	4830	7020
100	92	441	1180	2370	4070	6320	9190
125	113	542	1450	2920	5010	7790	11300
150	133	640	1720	3460	5940	9230	—
200	172	831	2240	4510	7750	—	—
250	210	1020	2740	5540	—	—	—
300	246	1200	3240	—	—	—	—
350	281	1370	3720	—	—	—	—
400	315	1550	—	—	—	—	—
450	349	1710	—	—	—	—	—
500	381	1880	—	—	—	—	—

Load WK^2 for Integral horsepower polyphase squirrel-cage induction motors. Table 3 lists the load WK^2 with integral-horsepower, polyphase squirrel-cage induction motors, and having performance characteristics in accordance with Part 12 (*i.e.—locked-rotor torque in accordance with 12.38.1, breakdown torque in accordance with 12.39.1, Class A or B insulation system with temperature rise in accordance with 12.43, and service factor in accordance with 12.51.2*), can accelerate without injurious heating under the following conditions:

1. Applied voltage and frequency in accordance with 12.44
2. During accelerating period a connected load torque equal to or less than a torque that varies as the square of the speed, and is equal to 100 percent of rated-load torque at rated speed.
3. Two starts in succession (coasting to rest between starts) with the motor initially at the ambient temperature, or one start with the motor initially at a temperature not exceeding its rated load operating temperature.

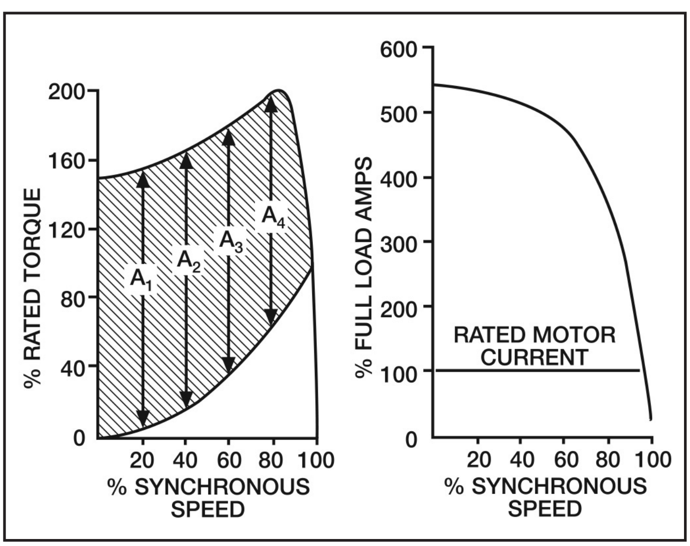


Figure 9 Acceleration period line currents (left and right).

Referring to Figure 9 (b), you will see that during the accelerating period this motor will draw line current that initially starts at 550% of rated current, and gradually drops off as the motor approaches rated speed. A great deal of heat is generated within the motor during this high-current interval. It is this heat build-up that is potentially damaging to the motor if the acceleration interval is overlong.

How Long Will it Take?

Calculating the time to accelerate a *direct-coupled* load can be determined quite easily by utilizing the following formula:

$$t = \frac{WR^2 \times N}{308T}$$

T = Average accelerating torque in lb. Ft.
N = Required change in speed
WR^2 = Inertia in lb. ft.^{2}
t = Time in seconds

The same formula can be rearranged to determine the average accelerating torque required to produce full speed in a given period of time.

$$T = \frac{WR^2 \times N}{308t}$$

Referring back to Figure 9(a), the accelerating torque would be the average value of the shaded area. In most cases, for standard motors through 100 HP, it is reasonable to assume that average accelerating torque available would be 150% of the motor full-load running torque and that accelerating times of 8–10 seconds, or less, would not be damaging, provided that starting is not repeated frequently. When load inertias exceed those shown in Table 4, the application should be referred to the motor supplier for complete analysis.

Reflected Inertias

Up to this point the only load inertias that have been considered have been rotating inertias *directly connected* to the motor shaft.

On many applications the load is connected to the motor by belts or a gear reducer. In these cases the "equivalent inertia" or "reflected inertia" seen at the motor shaft is the important consideration.

In the case of belted or geared loads, equivalent inertia is given by the following formula:

$$\text{Equivalent } WR^2 = WR^2_{LOAD}\left[\frac{N}{N_M}\right]^2 \times 1.1^*$$

WR^2_{LOAD} = Inertia of the rotating part
N = Speed of the rotating part
N_M = Speed of the driving motor

* Please note: the × 1.1 factor has been added as a safety factor to make an allowance for the inertia and efficiency of the pulleys (sheaves) or gears used in the speed change.

This formula will apply, regardless of whether the speed of the load is greater than, or less than, the motor speed.

Once the equivalent inertia has been calculated, the equations for accelerating time, or required torque, can be solved by substituting the equivalent WR^2 in the time or torque equation to be solved.

What Can Be Done?

When loads having high inertias are encountered, several approaches can be used. Some of the possibilities are:

1. Oversize the motor
2. Use reduced-voltage starting
3. Use special motor winding design
4. Use special slip couplings between the motor and load
5. Oversize the frame
6. Use an adjustable speed drive

Linear Motion

Occasionally applications arise where the load to be accelerated is traveling in a straight line, rather than rotating. In this case it is necessary to calculate an equivalent WR^2 for the body that is moving linearly. The equation for this conversion is as follows:

$$\text{Equilavent } WR^2 = \frac{W(V)^2}{39.5\,(S_M)^2}$$

W = Weight of load in pounds
V = Velocity of load in feet-per-minute
S_M = Speed of the motor in RPM when load moving at velocity V

Once the equivalent WR^2 has been calculated, the acceleration time, or required accelerating torque, is calculated by using the same equations for rotating loads.

Summary

- The turning force on machinery is *torque* — not horsepower.
- Horsepower blends *torque* with speed to determine the total amount of work that must be accomplished in a span of time.
- In all cases the horsepower required for single-speed application can be determined by utilizing the *torque* required at rated speed along with required speed.
- When variable speed drives are utilized, an additional determination of load type must be made. Most applications require either *constant torque* or *variable torque*. Metal cutting and metal forming applications frequently will require *constant horsepower*.
- High-inertia loads need to be approached with some caution due to high currents absorbed by the motors during the starting period. If there is any question regarding safe accelerating capabilities, the application should be referred to the motor manufacturer.

Note: An understanding of torque is essential for proper selection of any drive product. **PTE**