Heavy Movable Structures, Inc.

SIXTH BIENNIAL SYMPOSIUM

October 30 - November 1, 1996

Doubletree Resort Surfside
Clearwater Beach, Florida

Torque Characteristics of Wound-Rotor Motors, Revisited

by

Lance V. Borden, P.E.,
Modjeski and Masters, Inc.

TORQUE CHARACTERISTICS OF WOUND-ROTOR MOTORS REVISITED

by

Lance V. Borden, P. E., Senior Associate
Modjeski and Masters, Inc.

This paper was originally given at the 1985 Movable Bridge Symposium, under the title "Torque Characteristics of Wound-Rotor Motors Used in Bridge Drive Systems." It is re-presented here with minor revisions, and a validating recent case-in-point to underscore: 1) the information presented, 2) remind all of us involved with movable bridges of the need to properly coordinate the machinery design with the actual performance characteristics of the electric motor/drive combination used, and 3) insist on the revision of AREA and AASHTO to recognize and account for the actual performance characteristics of AC electric motors.

MOTOR CHARACTERISTICS

Probably the most common type of electric motor used as the prime mover in movable bridge drives has been the AC wound-rotor induction motor. Its most notable characteristics from the bridge drive designer's viewpoint are its high starting torque, and the variety of speed/torque curves realizable, both of which can be easily altered for any given motor.

Modern wound-rotor motors commonly used on movable bridges are of the crane and hoist type, and are generally assumed to follow a typical wound-rotor induction motor speed/torque curve. Figure 1 is one such speed/torque curve often presented in motor textbooks. Of particular interest, especially to machinery designers, is the peak or maximum torque, in this case termed the breakdown torque. Notice that this "typical" curve implies a maximum available torque of only 200 percent.

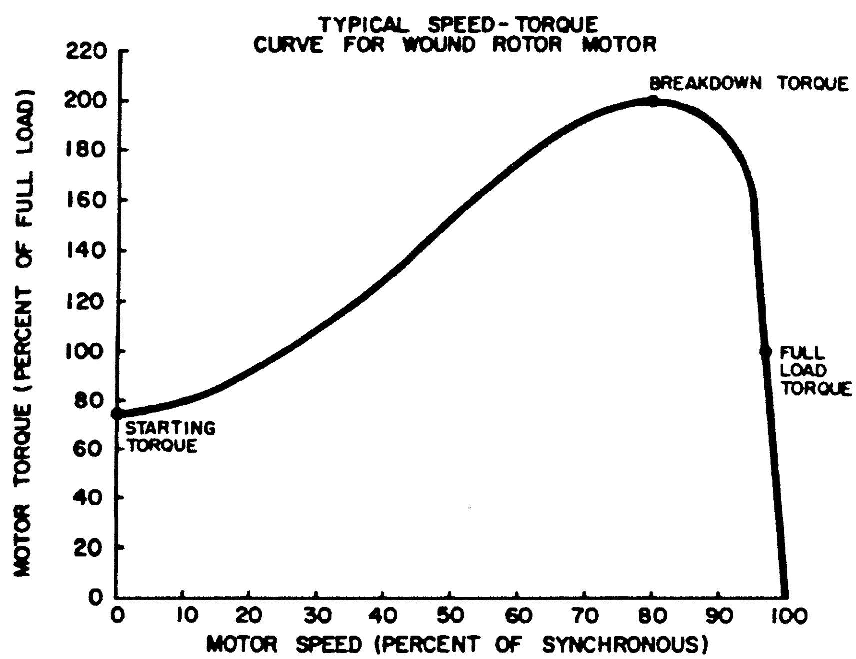


FIGURE 1

A wound-rotor motor built according to the current standards of the National Electrical Manufacturers Association (NEMA) may well surprise anyone who assumes that Figure 1 is an accurate quantitative representation of his prospective motor. Modern wound-rotor motors are capable of far higher breakdown torque. NEMA MG 1-1978 specifies:

"The breakdown torque for alternating current wound-rotor crane motors, with rated voltage and frequency applied, shall be not less than 275 percent of full-load torque."

Notice that while a minimum breakdown torque of 275 percent of full-load torque is required, *no maximum torque is established*. However, that same NEMA requirement offers some guidance by advising machinery designers that:

"For the selection of gearing and other mechanical design features of the crane, 375 percent of rated full-load torque shall be used as the maximum value of breakdown torque for an alternating current wound-rotor crane motor."

Although this paragraph still does not explicitly establish a maximum torque constraint for motor manufacturing, it does imply that motor users should assume that the motors will not deliver more than 375 percent of their rated full-load torque at the breakdown point.

To appreciate what these minimum and maximums may mean, let's look at an actual case. The Author had an opportunity to witness the testing of a set of main and auxiliary drive motors for a new tower-drive vertical lift bridge. The motors were 50 HP and 20 HP, 600 RPM, drip proof, wound-rotor crane motors. The motors were subjected to the "complete test", on the Manufacturer's dynamometer. For a summary of the tests, see Table 1. The measured torque/speed curve of one of the motors is shown in Figure 2. The other motors displayed similar curves.

Table 1 - Test Results for Eight Wound-Rotor Motors

Test Date	H.P.	Serial No.	Full-load Torque	Breakdown Torque	Bkdwn Tq. % F.L.T.
2-6-84	20	051020	180.4	575.6	319
4-9-84	20	051020	180.5	573.3	318
2-27-84	20	051021	181.0	564.5	312
4-9 & 10	20	051021	180.8	555.5	307
2-16-84	20	051022	180.2	576.9	320
4-10-84	20	051022	180.9	582.9	322
2-22-84	50	042039	445.2	1518.0	341
4-10-84	50	042039	446.1	1514.0	339
2-9-84	50	042040	445.7	1318.3	338
4-13-84	50	042040	445.2	1312.3	295
2-21-84	50	042041	445.0	1518.5	341
4-12-84	50	042041	446.5	1514.7	339
2-21-84	50	042042	445.5	1407.1	315
4-11-84	50	042042	446.8	1383.1	309
2-28-84	50	042043	446.4	1481.2	332
4-11-84	50	042043	446.1	1492.0	334

MEASURED SPEED-TORQUE CURVE
FOR 50HP WOUND ROTOR MOTOR

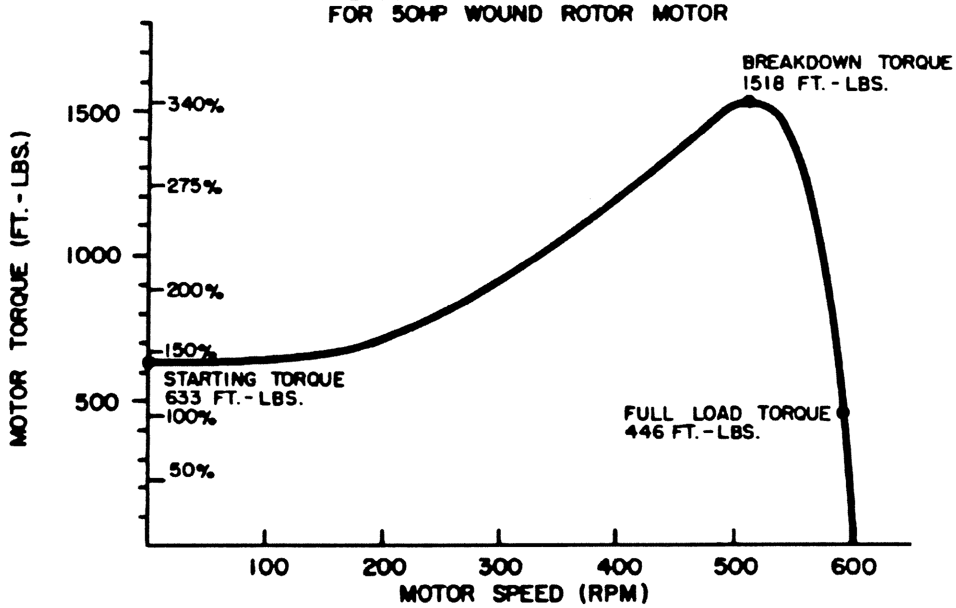


FIGURE 2

Typically, the three points on the curve of most interest would be the rated full-load torque (and speed), the starting or locked rotor torque, and the breakdown torque. From the curve of Figure 2, it is seen that this motor develops its rated horsepower at 588 RPM, or just 2 percent slip. It can also be seen that its locked rotor torque is better than some authors suggest, but the most significant point to be seen on Figure 2 is the breakdown torque, which peaks at 340 percent of rated full-load torque. This is significantly higher than the 200 percent shown in some textbooks, or the 275 percent minimum required by NEMA, but of particular importance, it is significantly higher than the 150 percent previously suggested for bridge machinery design by AASHTO. This will be discussed in more detail later in this paper.

To exploit the potentially high starting torques available with a wound-rotor motor, the user must select the appropriate speed/torque characteristics by choosing the proper external rotor circuit resistance. Figure 3 shows a family of speed/torque curves the user could experience by changing the values of rotor resistance. In general, notice that increasing the rotor resistance shifts the breakdown torque to successively lower speeds, until finally it occurs at zero speed. This is the curve producing maximum starting torque. Further increases in rotor circuit resistance then simply lower the starting torque to produce soft start characteristics. Notice also that while the breakdown point shifts towards lower speeds, the magnitude of the breakdown torque remains relatively constant.

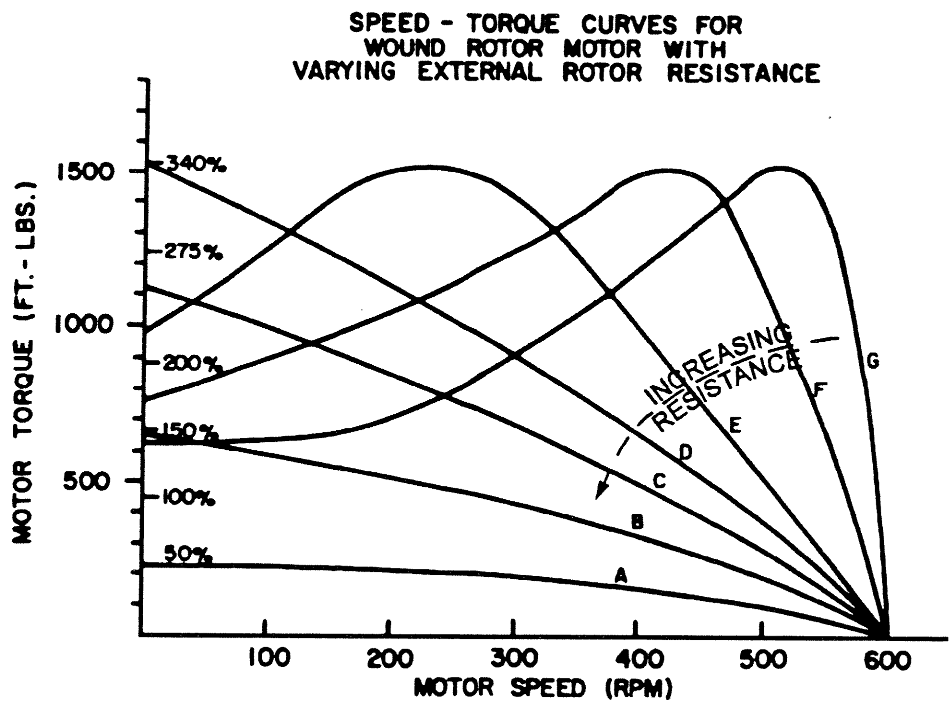


FIGURE 3

CONTROL SCHEMES

To evaluate a wound-rotor motor's behavior in a drive system, we also need to be concerned with the characteristics of the motor controller. Just how does the controller effect the available torque from the motor? Does it provide true torque limiting, or is it actual current limiting? And what's the difference?

One of the simplest, and most common controllers found on older bridges is the stepped resistance controller. In a typical installation, the rotor resistance is varied by manually operating a drum switch, much like that used in trolley cars. A bank of heavy-duty tapped resistors was provided for the rotor circuit, and the resulting family of torque curves was utilized as shown in Figure 4. By stepping through the sequence of resistance values, motor operation is switched from curve-to-curve. By making these transitions at the correct moment, the average torque can be kept high, but the torque peaks kept within reason, say below 180 percent. In practice, much was and sometimes still is left to the judgment of the bridge operator. With no accurate way for the operator to determine actual torque output from the motor, it often is simply his personal preference as to when he switches to the next lower resistance step during acceleration. *It seems very likely that the bridge machinery could at least occasionally be subject to the motor's full breakdown torque.*

OPERATING CURVE (DASHED LINE) FOR WOUND ROTOR MOTOR WITH STEPPED ROTOR RESISTANCE STARTING

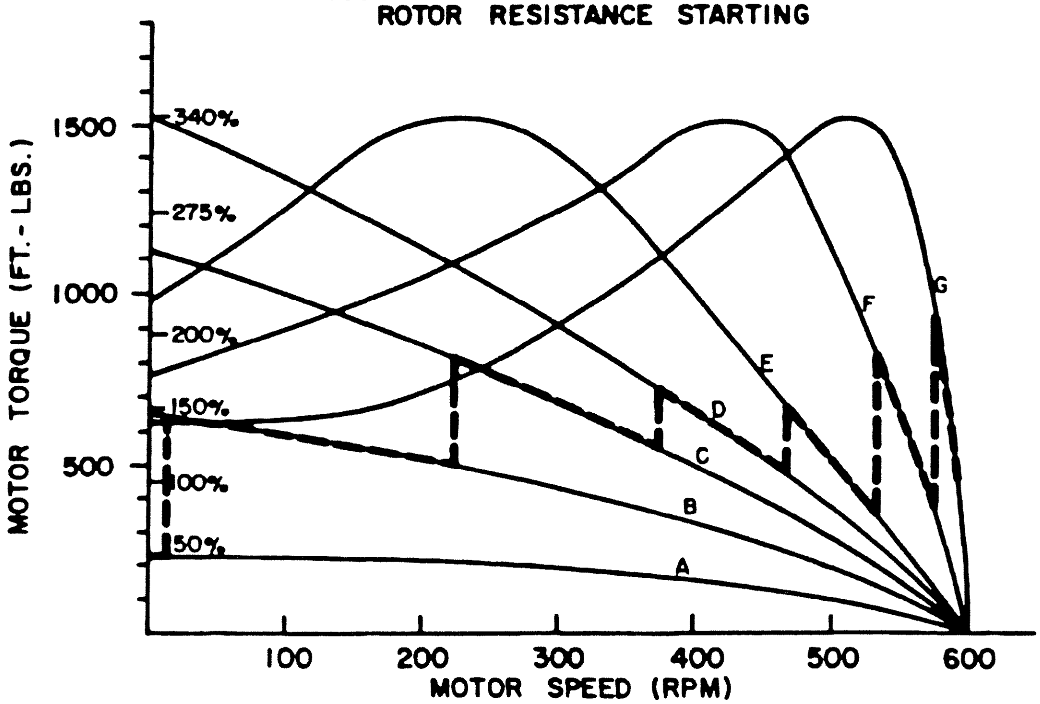
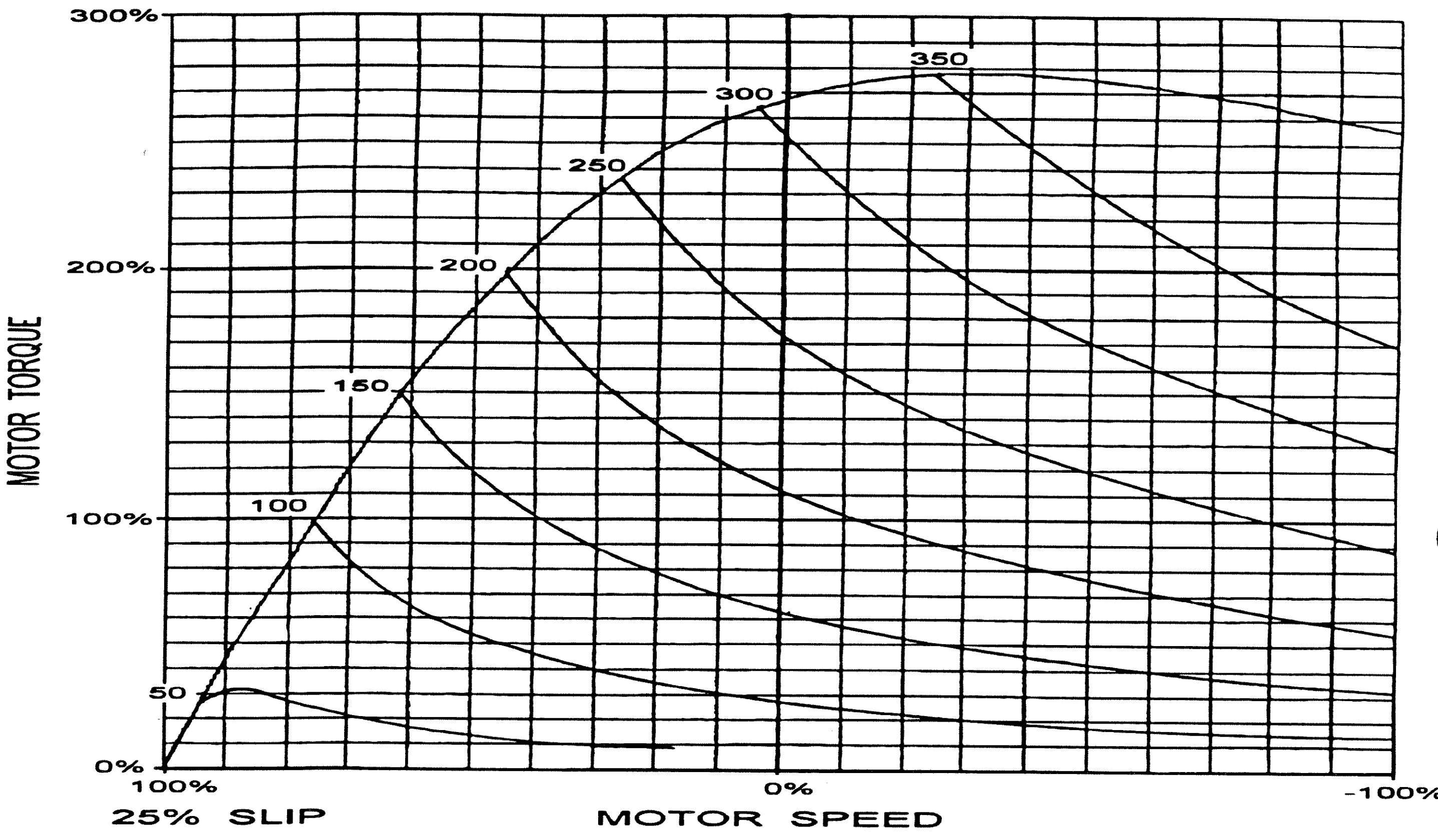


FIGURE 4

Machinery designers should take note that essentially no explicit form of torque limiting exists with the stepped resistance scheme. Motor overload relays, if provided, generally react too slowly to be of value in terms of torque limiting.

Another type of motor controller frequently applied on movable bridges is a variable voltage (thyrister type) controller. In this scheme, the motor voltage is varied by a three-phase bank of silicon controlled rectifiers (SCR's), much the same as a solid state light dimmer. Tachometer feedback is usually employed along with an internally generated ramped reference voltage, which together provide linear acceleration and deceleration, as well as overall speed control. Adjustable current limiting is usually provided and also serves as a means of torque limiting. Although some squirrel cage motors have been used, usual practice is to use a wound-rotor motor and a fixed value of external rotor resistance to give about 20 to 25 percent slip at rated torque, producing a torque characteristic somewhat similar to a NEMA Design D squirrel cage motor. This choice of resistance may yield a starting torque nearly equal to the breakdown torque. Typical speed-torque-current operating characteristics are shown in figure 5.



MOTOR TORQUE VS. SPEED FOR DIFFERENT VALUES OF CURRENT LIMITING IN PERCENTAGE OF F.L.A.

Figure 5

There are at least two reasons why the actual value of torque provided is still a matter for concern, even though torque (current) limiting of the SCR controller is used. First, the ratio of torque per ampere varies as a function of speed for any given value of rotor resistance. So using current limiting to achieve torque limiting results in a limiting value that is not constant as the motor accelerates. Second, the chopped waveform that results from an SCR drive is a substantial distortion of the fundamental sine wave upon which motor behavior and ammeter calibrations are based. It has been established by other segments of industry that the chopped waveform results in somewhat unpredictable torque and increased heating in motors, due to the harmonic components in the three-phase voltage being applied. Concerning the ammeter, it must be recognized that as the SCR drive is adjusted for a specific value of current limiting, as measured on the ammeter, our meter indication and, therefore, the actual limiting value being set is subject to the error of measurement, the degree of which is generally significant and varies with the degree of waveform chopping at any given instant. Although the adjustable current limiting is a useful and desirable feature, it should not be relied upon as an accurate means of torque limiting in the quantitative sense.

BRIDGE MACHINERY

In review of the preceding material, it has been established that a wound-rotor motor may deliver as much as 340 percent of rated full-load torque at its breakdown point, or as its starting torque, depending on external rotor resistance. It has also been established that two of the more common controllers cannot be counted on for torque limiting in a literal or accurate sense. In reality, it can probably be generalized from these two controllers and said that no controllers of A.C. motors, wound-rotor or squirrel cage, should be assumed to provide accurate torque limiting unless reliable dynamometer test data proves otherwise. On this basis, our concern shifts to the bridge drive machinery which must handle this motor torque.

For the design of movable bridge machinery, AASHTO directs that 150 percent of an electric motor's full-load rated torque should be used at normal allowable unit stresses (AASHTO Standard Specifications for Movable Highway Bridges, 1988, Paragraph 2.5.4):

> "The machinery for moving the span shall be designed at normal allowable unit stresses for the following percentages of full-load rated torque of the prime mover for the time specified at Condition A, Article 2.5.3, speed:
>
> Electric Motors . . . . 150 percent"

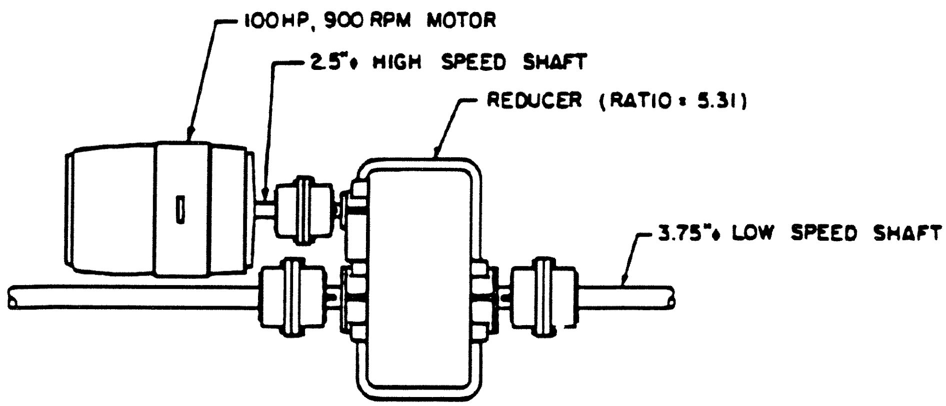
AREA also issues this directive (AREA, Chapter 15, Part 6, Paragraph 6.3.10). In their electrical sections, AASHTO and AREA require that the bridge control system should limit the torque peaks during acceleration to "...preferably not exceed 180 percent of the rated full load torque of the motor" (AASHTO, Paragraph 2.10.14; AREA, Paragraph 6.7.5.5). The practicality of actually complying with this last requirement may actually be, as previously implied, unreasonable.

The 340 percent of full-load torque exhibited during the motor test discussed previously, is significantly greater than either the 150 percent or 180 percent suggested by AASHTO and AREA. Even NEMA's minimum breakdown torque requirement of 275 percent is significantly greater, as is NEMA's recommendation to assume 375 percent as the maximum breakdown torque when designing the crane (or in our case, bridge) machinery. To eliminate any erroneous speculation on this simple comparison of numbers, let us consider a sample machinery calculation to help put things in perspective.

EXAMPLE MACHINERY CALCULATION

Assumption

Assume that power calculations for a hypothetical movable bridge indicate the selection of a 100 Horsepower, 900 RPM motor. Assume further that we need a ratio in our primary reducer of 5.31. Looking at the manufacturer's selection tables, we find we need a Size 6, single reduction model (see Figure 6).



MACHINERY ARRANGEMENT FOR EXAMPLE CALCULATION

FIGURE 6

Motor:	100 Horsepower at 882 RPM, Wound Rotor Motor, Breakdown Torque 340% of F.L.T.
Reducer:	Rated for 204 HP (77,200 in-lbs @ 164 RPM), Ratio 5.31 High Speed Shaft Diameter: 1.75 inches Low Speed Shaft Diameter: 3.0 inches

<u>High Speed Shaft</u>

Since AASHTO, Article 2.6.7, requires a minimum shaft diameter of 2.5 inches for bridge drive machinery, we will increase the reducer high speed shaft to 2.5 inches, and then check fiber and shear stresses for the applied motor torques.

From Article 2.5.15, we use the two following equations:

$$f = \frac{16K}{\pi d^3}\left(M + \sqrt{M^2 + T^2}\right)$$

$$S = \frac{16K}{\pi d^3}\sqrt{M^2 + T^2}$$

where:

f	=	unit extreme fiber stress in tension or compression (psi)
S	=	unit shear (psi)
d	=	diameter of shaft at section considered (inches)
M	=	simple bending moment computed for the distance center-to-center of bearings (assume 168 in-lbs)
T	=	simple torsional moment (in-lbs)

K = 1.89 for the high speed shaft, as computed according to Article 2.5.11, and 1.39 for the low speed shaft.

The results for 100, 150 and 340 percent of rated motor full-load torque are tabulated in Table 2, based on forged alloy steel, AASHTO M102, Class G.

Table 2 - Stress in a 2.5-Inch Diameter Reducer Input Shaft

Motor Torque in % of Full Load Torque	Motor Torque (Inch-Lbs)	"f" Extreme Fiber Stress (psi)	* Maximum Allowable "f" (psi)	"S" Shear Stress (psi)	* Maximum Allowable "S" (psi)
100%	7,145	4,506	16,000	4,403	8,000
150%	10,718	6,707	16,000	6,604	8,000
340%	24,295	15,071	16,000	14,967	8,000

*Maximum allowable stresses for Forged Alloy Steel, AASHTO M102, Class G, and AREA, ASTM A668, Class G

Note that the maximum allowable shear stress is exceeded for 340 percent of the motors full-load torque.

Low Speed Shaft/Line Shaft

For the low speed shaft, the torques were computed assuming 2 percent loss in the reducer. To compute M, the distance between pillow blocks was arbitrarily chosen to be 8 feet, with a shaft weight of 297 pounds, and a 56-pound coupling 15 inches beyond the pillow block, resulting in 2,383 in-lbs for M.

Using the previously given equations for fiber and shear stress, it was found that the shear stress governed the shaft diameter. Various diameters were tried, using 150 percent of the motor full-load torque according to Article 2.5.4. It was found that a 3.75-inch diameter shaft was the smallest nominal diameter that would satisfy the shear stress requirement for forged alloy steel, AASHTO M102, Class G.

The fiber and shear stresses are tabulated in Table 3 for 100, 150 and 340 percent of motor full-load torque applied to the reducer high speed shaft.

Table 3 - Stress in a 3.75-Inch Diameter Reducer Output Shaft

Low Speed Reducer Output Shaft Torque (3.75" Dia.)	Shaft Torque (Inch-Lbs)	"f" Extreme Fiber Stress (psi)	* Maximum Allowable "f" (psi)	"S" Shear Stress (psi)	* Maximum Allowable "S" (psi)
100%	37,181	5,322	16,000	5,002	8,000
150%	55,775	7,814	16,000	7,495	8,000
340%	126,426	17,295	16,000	16,975	8,000

*Maximum allowable stresses for Forged Alloy Steel, AASHTO M102, Class G, and AREA, ASTM A668, Class G

Output torques are based on a reducer ratio of 5.31 and losses of 2% in the reducer.

Notice that in the case of the 2.5-inch high speed input shaft, which was actually somewhat oversized to comply with AASHTO's minimum allowable shaft size of 2.5 inches, Article 2.6.7, the shear stress is 187 percent of the allowable shear stress when the motor torque goes to 340 percent. In the case of the 3.75-inch low speed output shaft, which was sized according to the 150 percent criteria, the shear and fiber stresses are 212 and 108 percent of the allowable shear and fiber stresses, respectively. Although these stresses are still far below the yield stresses, the allowable stresses given are the result of deratings for keyways, component geometry, etc. When these allowable stresses are exceeded, we are, in effect, defying the deratings. Just how far the stresses should be allowed to exceed the allowables, if at all, is a matter for serious consideration.

The 1992 Revisions to the AASHTO Movable Bridge Specification states "the machinery for moving the span shall also be designed for the stress caused by the greater of the starting torque or the breakdown torque of electric motors, using unit stresses 50 percent greater that the normal allowable stresses." If the 340% torque above is used, this results in a low speed shaft of 4.25 inch diameter, rather than the 3.75 inch diameter.

SUMMARY AND CONCLUSIONS

The modern AC-wound rotor motor (and also the NEMA Design D motor) is capable of delivering significantly more torque than may have been anticipated by AASHTO or AREA. Tables 2 and 3 illustrate that when the AASHTO and AREA criteria are followed, stresses in machinery components (shafts as the specific examples) could exceed the AASHTO and AREA allowable unit stresses.

The Author suggests a review of the AASHTO and AREA 150 percent allowance for electrical motor torque in the machinery design, with consideration given to increasing it in recognition of the higher torques anticipated with modern wound-rotor motors.

CASE IN POINT

In 1992 our firm was called out to assist with a railroad bridge on which both main drive pinion shafts in one of the towers had failed. The bridge was a tower drive vertical lift bridge, put in service in 1972. The shafts had failed in a torsional fatigue mode as a result of frequent torsional overstress.

Computations performed to check the expected loading of the shafts indicated that they had been properly designed, as far as AREA or AASHTO were concerned. The design utilized a parallel shaft gear reducer, and assumed equal loading of the two drive pinions. The pinion shafts were designed to equally divide the load for 150% of the full load torque of a 40 HP, 600 RPM, NEMA Design D motor. In other words, each pinion shaft was really only expecting to see 75% of the motor's full load torque. Assuming that the factor of safety in the shaft design for the particular steel used was between 2.5 and 3.0, then each shaft was probably designed to yield at 375% to 450% of full load motor torque if load sharing was occurring, *but only 188% to 225% if load sharing was not occurring*. An actual design analysis of the shaft itself suggests 240% as an upper limit, but with no allowance for machining imperfections.

It is worth pointing out that both AREA and AASHTO recommend *<u>no</u> load equalizing devices between opposite sides of a vertical lift bridge*. Yet no other requirement or provision is suggested to ensure equal loading of the pinions. The assumption appears to be that it just normally will occur.

In lieu of explicit load sharing devices, the load sharing is only implicit and dependent upon identical backlash in pinion/ring gear mesh, pinion indexing, flexibility/elasticity in the hoisting rope system, etc.

The drive system is a famous name brand AC thyristor drive known as an Amplistat controlling a squirrel cage NEMA D motor, which has torque characteristics somewhat similar to a wound rotor motor, but with a rated slip of usually 6-10%. The main point here is that the NEMA D motors develop very high starting torque, *"not less than 275%, expressed in percent of full-load torque"* per NEMA MG 1-1978, para. 12.37 C. Note that *no upper torque* limit is imposed.

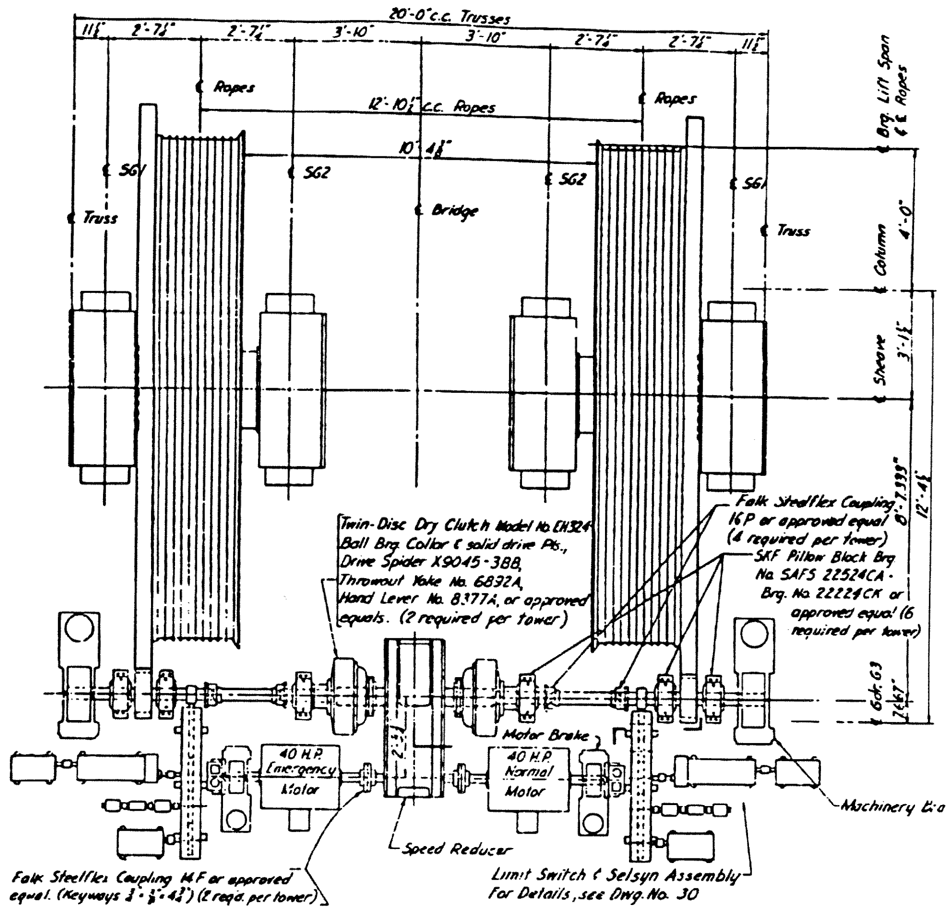


Figure 7

Bridge Machinery Layout

Our subsequent investigations, which included strain gaging the pinion shafts, showed that one pinion was worn considerably more than the other, and that load sharing was very definitely <u>not</u> occurring to any significant extent!

Table 4 - Measured Torques in Pinion Shafts

	Southwest Pinion Shaft % of AASHTO Allowables	Northwest Pinion Shaft % of AASHTO Allowables
Start Open	0%	242%
Near Full Open Slow Down	112%	9%
Start Close	216%	0%
Near Full Close Slow Down	0%	223%
Buffers	58%	8%
Seating	326%	0%

The strain gage data presented in the Table 4 above illustrates the problem. Remember, as pointed out above, only 188-225% of motor full load torque could be tolerated before shaft deformation and ultimately failure are probable. Notice that such torques did occur repeatedly.

Is this an unusual case, or is it more typical than we want to believe? A closer look at the mechanical and structural aspects of this bridge, at least in hindsight, suggest that load sharing was far less probable than the machinery designer apparently wanted to assume. For example, the bridge is tower drive - there is virtually no elasticity to count on for providing slight transverse differential displacements that would overcome differences in pinion/sheave backlash and ensure reasonable load sharing. And the relatively narrow width to height (20 ft. wide x 34 ft. high, center-to-center cords) for the lift span further added to the rigidity of the span/ropes/counterweight system, thereby offering no help there, either.

CONCLUSION

The typical assumptions still frequently being made about AC induction motor speed-torque performance, and especially torque limiting, are still too simplistic for adequate, reliable machinery and machinery support design practices. Significant revisions are badly needed to AASHTO and AREA concerning the matter of motor torques and allowable stresses in machinery and related components.

REFERENCES

ANSI/NEMA Standard Publication for Motors and Generators, MG 1-1978, NEMA, Washington, D. C.

Manual for Railway Engineering, Chapter 15, Part 6, "Movable Bridges", AREA, 1996, Washington, D. C.

Nailen, R. L., Solid State Devices Protect Motors via Soft Starts, Specifying Engineer, October, 1980

Standard Specifications for Movable Highway Bridges, 1988 Edition, AASHTO, Washington, D. C.