

High-Response Motors on Automotive Test Stands

(Simulating Engine Torque Pulses to Test Engine Components)

Abstract: Actual on-engine testing of accessory and internal components is expensive and time consuming and many times altogether impractical, certainly on a production basis. There is an increasing need for high performance electric motors that can produce high frequency torque/velocity variations while running at a steady base speed to simulate the engine characteristics. Testing superchargers, pumps, shafts, counter balancers on a production basis with an electric motor requires rpm up to 6000 or higher and plus minus 5% to 10% velocity variation up to 100 times per second to duplicate this stress. Modern motor systems can accomplish this using Brushless technology.

The Problem: Certain parts and accessories used with internal combustion engines must have considered in their design the pulsating nature of the rotation of such engines. This pulsation creates both primary and harmonic torsional stress on any component driven by the crankshaft. Common examples of these components would be superchargers, pumps, alternators, counter balancers, shafts, etc. These components need to have both design verification as well as production testing to confirm the product performance and quality. An easily adjustable test machine capable of varying velocity and varying velocity modulation is necessary for such testing. Hydraulic systems have been used and off-balance devices as well, but such systems are difficult to use, expensive to make and require a high level of

maintenance. Electric motors would be ideal for such testing, but the challenge of producing rotational speeds of 500 to 6000 rpm (or higher), while at the same time, varying those speeds by as much as +/-10% at repetition rates of up to 100 times per second or more is impossible for most electric motors due to inertia and other factors. More specifically, for the motor, it is impossible due to the ratio of torque to inertia. In fact, this ratio is a measure of the performance limits of a motor.

Addressing the Issues: In order to move an inertia of say... 1 lb-ft² above and below a target speed of say...2000 rpm, first 5% above and then 5% below at 100Hz a certain torque must be applied to accelerate the inertia of the part first to the higher speed, then to decelerate it to the lower speed, then repeat this cycle in the time available. If we assume a uniform acceleration rate, the torque is given by the formula:

$$T=(I \times \Delta \text{RPM})/(308 \times t)$$

(Where T= torque in lb-ft, I= inertia in lb-ft², and t= time in seconds)

For our example situation where the change in RPM is 200 rpm, I=1 lb-ft² and t=0.01 seconds, the torque required is 65 lb-ft. Of course, the part must be coupled in some fashion to a motor and the motor itself must also have some inertia as well. It is reasonable to assume that a motor inertia would be required which would be equal to the part under test. This would mean the total torque required would be 130 lb-ft. A motor capable of this torque continuously would be rated about 50 hp. A typical 50 hp NEMA standard induction vector motor would have a rotor inertia of 5.5 lb-ft² and therefore would not come close to our assumed match of 1 lb-ft². The problem then becomes evident. If the motor inertia required to produce the torque to accelerate the 1 lb-ft² inertia part is much more than the part itself, then the job becomes impossible, because the motor's own inertia means it would take a motor that would produce even more torque, which means an even higher motor inertia,

etc. etc. The point is that if a motor cannot be found that will produce the torque required without having an inertia value very nearly equal to the load inertia, the job cannot be done at these proposed rates of change.

Brushless machines can achieve these very low inertias. More precisely, and more to the point, Brushless machines have significantly higher torque-to-inertia ratios than do AC induction machines or brush DC machines. This becomes a performance factor in choosing motors for cyclic applications. Table 1 below shows typical AC induction vector motors (data for vector motors from Baldor® catalogs, which are typical of most manufacturers) and Brushless motors (data from Powertec® catalog) comparing their weight, frame size, and inertia characteristics.

HP	Torque	Frame	Wt	Inertia	Frame	Wt	Inertia
	Rated	AC	AC	AC/ratio	BL	BL	BL/Ratio
10	30	215T	196	1.1/27	E182T	86	0.3/100
15	45	256T	309	1.8/25	ES184T	113	0.4/100
20	60	256T	321	2.3/33	E184T	129	0.5/120
25	75	284T	432	4.0/19	E213T	175	0.8/94
30	90	286T	458	4.7/19	E213T	175	0.8/112
40	120	324T	656	7.8/15	E215T	211	0.9/133
50	150	326T	679	9.7/15	E218T	261	1.1/136
60	180	364T	797	12.2/15	E254T	295	2.4/75
75	225	365T	895	15.3/15	E256T	345	2.9/78
100	300	405T	1232	27.0/11	ES259T	440	3.8/79

Table 1: (Baldor® Catalog 501 page 124 vector drive motors, inertia from catalog BR400)

Taking the example of requiring 100 Hz cyclic rate for speed variation again using our formula $T=(I \times \Delta \text{RPM})/(308 \times t)$, it takes 65 lb-ft to move the load inertia of 1 lb-ft², which takes at least a 25 hp motor based on rated torque. That induction motor, however has it's own inertia of 4 times that of the load. In other words, the motor ALONE will require 260 lbs-ft of torque to change it's own inertia at that rate. That continuous torque is not available from the motor. This is a clear example of the problem of low torque output compared to inertia. No matter how big the motor gets, it cannot provide the cyclic torque required at this rate of change of speed because it cannot even move it's own inertia at that rate with no allowance for the load itself. Looking at the formula somewhat differently, we can see that torque divided by inertia is $= \Delta \text{RPM}/308t$ so to move the load at 100 Hz (0.01 seconds) over 200 rpm, will take a total torque to inertia ratio of at least 65. Another way of considering this ratio that makes more sense is to solve the equation for RPM per second . This yields (in this case), $65 * 308 = 20,020 \text{ rpm/sec}$. This means that the motor, based on it's rated torque and it's inertia, with no other inertia attached to the shaft, could be accelerated at 20,020 rpm each second. Looking at the AC induction motor, no motors meet these criteria; therefore, no size selection can do this application. Considering the brushless motors, all sizes meet this requirement and therefore any motor can do the application from a strictly performance perspective, but of course the motor still has to meet the total power requirement of 50 hp, so the choices are limited to 50 hp or larger, otherwise, even though a smaller motor will produce the performance, it will not meet the continuous power requirement.

Actual Performance: There is more to system performance than just the torque performance of the motor and it's inverter, however. The controller used must be capable of actually controlling the motor shaft. A general rule of thumb is that a controller must have a velocity loop

bandwidth at least 5 times higher than the frequency of motor shaft variation expected to be controlled. In this case, the velocity bandwidth would need to be about 500 Hz. Additionally, using the same logic, the current loop bandwidth of the controller would need to be at least 5 kHz to achieve this performance. Such bandwidths are typically well beyond the ability of an induction motor drive running an induction machine. This a difficult subject and not well understood. The control bandwidth in a case like this is not just a function of the current loop and velocity loop bandwidths, but the feedback device used and the analog input that must respond to the command with both accuracy and speed. Many drives have 1 millisecond or longer update times for analog inputs. Clearly such long update times would prevent achieving the bandwidth required to accomplish a task as described herein. As to accuracy, the resolution of the analog to digital conversion would have to be on the order of 12 bit.

An actual example of this kind of performance on a machine was a torsional test machine testing superchargers for a well-known German manufacturer. This was a need for a production test machine, where 100% of products produced were tested at speeds up to 6000 rpm and torsional vibration tested at 2000 rpm over the range of plus/minus 5% of set speed. Production test cyclic rate was 60 hz and inertia was approximately equal to 1 lb-ft². Due to the rotational speeds required the motor had to be rated 60 hp at 6000 rpm. Performance was verified to meet specifications by computer controlled measuring equipment and accelerometers and printed actual results of the torsional tests were supplied with every supercharger shipped.

Another example of such testing is testing internal combustion engine counter-balancers. Such devices are installed to counteract primary and secondary torsional vibration resulting from piston forces. In this particular application the requirement for testing extended to 100 Hz at a basic rotation speed of 1200 rpm, with 5% variation in velocity. This

application is even more difficult because the part had to follow an input velocity command variation which was analog, so the controller not only had to be able to produce the output result, but to also accurately accept an analog input voltage varying at that rate and produce a smooth sinusoidal output with effectively no phase delay. Figure 1 shows the commanded and actual achieved motor shaft response. As can be seen, the tracking of the commanded velocity variation is very close, both in amplitude and in phase. Such an application cannot be accomplished with motors having a torque to inertia ratio of less than 60 or more. Considering that the load itself has some inertia and that this inertia must be considered as part of the total inertia, the motor's inertia needs to be as small as possible (to a point). It is still necessary, for other reasons that are beyond the scope of this paper that the motor inertia be not much smaller than 25% of the load inertia. The most beneficial "arrangement" is for the motor's inertia to be the same as the load inertia. This combination ensures the lowest power requirement and the best tracking performance (highest system bandwidth).

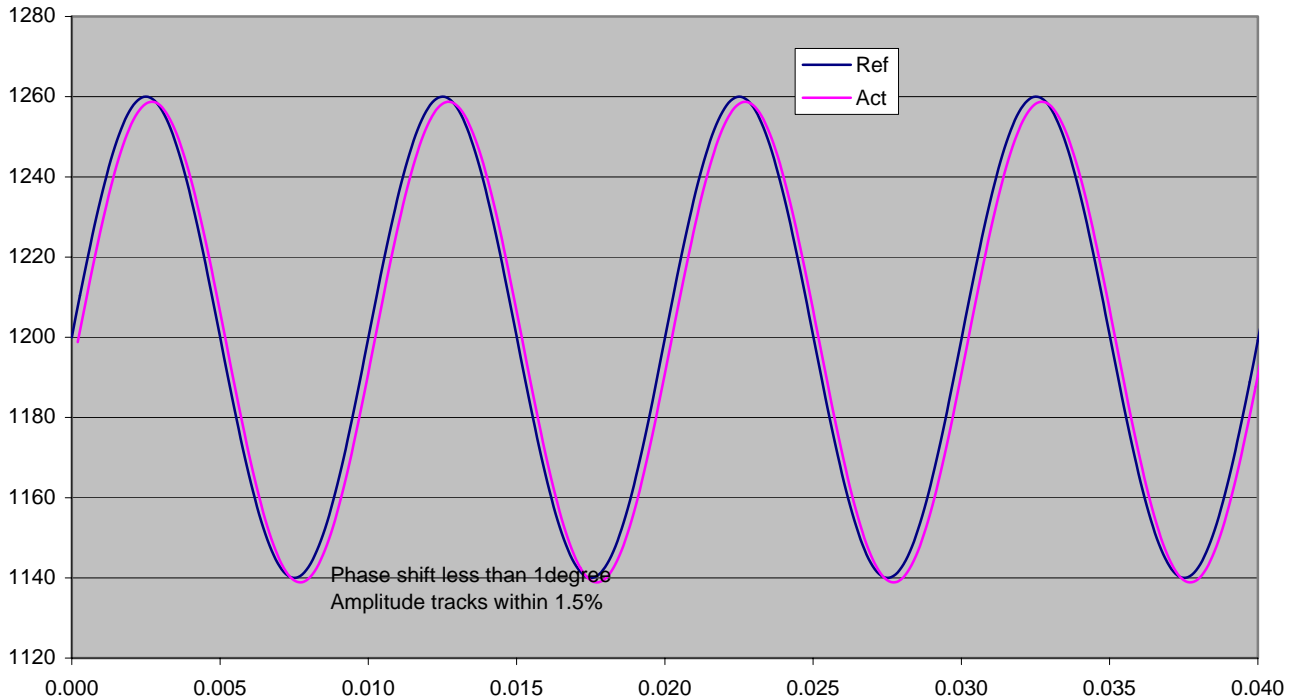


Figure 2: Plot of actual velocity command and actual motor shaft velocity

Summary and Conclusions: Critical production testing and design-proof testing of parts subjected to torsional stresses inside or outside internal combustion engines needs to simulate as closely as possible the actual stress on the part at the rotational speeds expected.

It is convenient to have motor/drive systems to drive the test stands so that running velocity as well as velocity variation be adjustable over a wide range of conditions to allow single parts to be tested over a maximum range or multiple parts having varying shapes and sizes to be tested on the same machine. Figure 2 shows a typical brushless motor construction with Neodymium permanent magnets on the shaft and a conventional three-phase stator winding, together with an internally mounted resolver for commutation and speed feedback information for the drive controller.

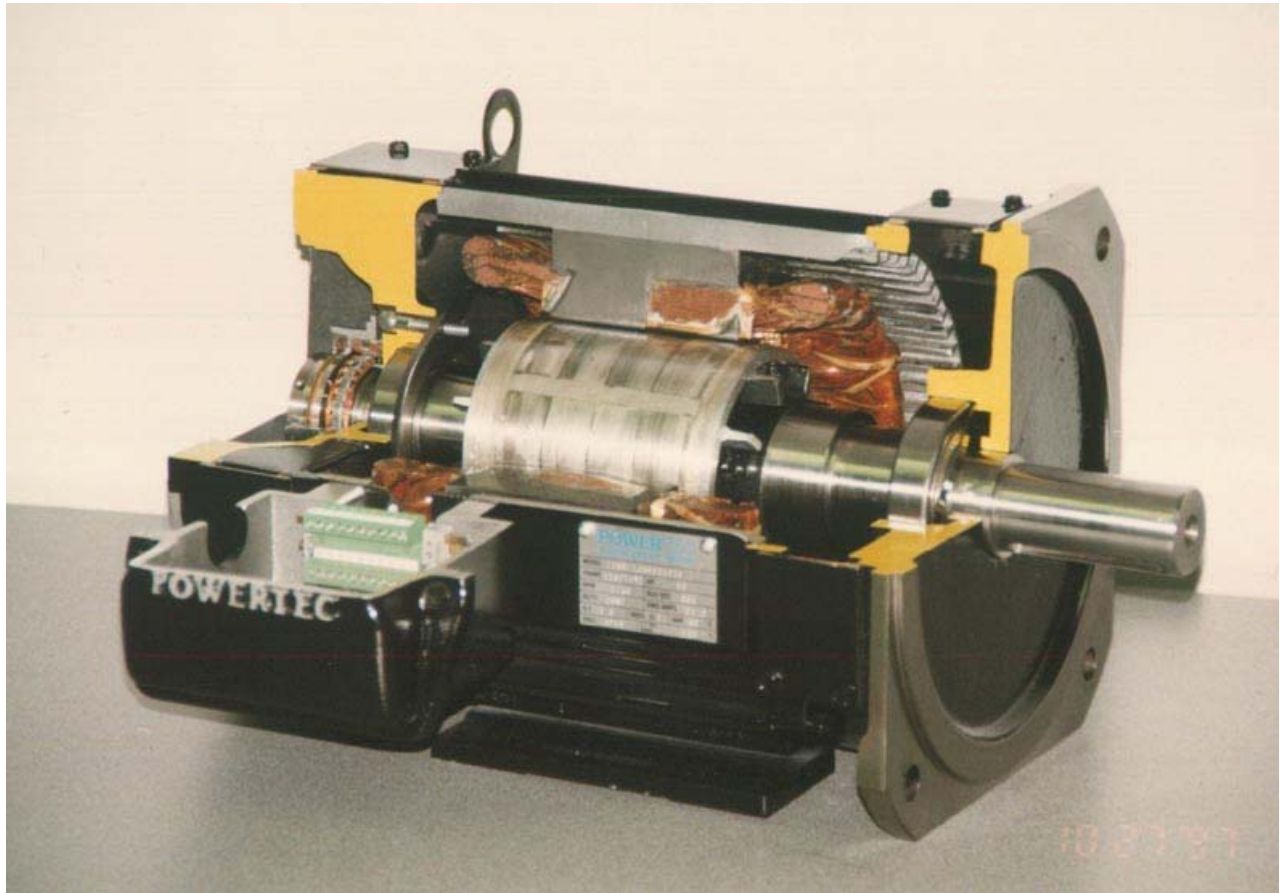


Figure 2: Brushless motor, 15 hp, E182 frame

There are significant barriers to accomplishing this with existing electric motors but modern brushless motors have sufficiently low inertia compared to their continuous and peak torque output to meet most of these requirements. As testing requirements increase both in bandwidth requirements and in size, brushless motor technology becomes one of, if not the only, choice available.

References:

Baldor® Catalog #501, Page 124

Baldor® Catalog BR400 for motor inertias

Powertec® PacTorq® Brushless Servomotors Catalog # PT-18735

Powertec® High Performance Brochure # PT-19481