

Dennis' Design Den
Build Your Own Dynamometer: System Design And Mechanical Construction
by Dennis L Feucht

This month, the original "baby dyno" project will be continued at the next level of detail: the project design and construction overview. This will give you some idea of the size of such a project and the technical competencies required to succeed at it. You will need at least some experience with: analog circuits, very simple digital circuits, basic power circuits, embedded μ Cs and their programming, and some basic machine-shop mechanics for the fixturing. You will also need to have some electronics project experience building gadgetry that goes in an enclosure. You'll have a nontrivial enclosure construction task, especially in mounting a fan-cooled bank of power resistors, no less circuit boards, open-frame power supply, etc.

Background

A few years ago, Jim, a motor-drive friend of mine from Portland, OR, who now works for Emerson Electric in St. Louis, MO, and I both wanted a dyno but not at commercial prices. While Magtrol and Vibrac build attractive products, the one unattractive feature to us was the high price. We were not prepared to spend \$10,000 US out of our own pockets just to have our own dyno. Magtrol's line of dynos, for instance, is based on a magnetic hysteresis brake. A relatively small current in its coil produces dissipative load torque on the motor under test.

This led to some thinking about how we could build our own dyno. We could do analog, digital, power, and μ C-based hardware and software design. We both have product design experience. Why shouldn't we just design and build our own dynos? The hysteresis brake itself is a somewhat specialized item that Magtrol builds. We wanted to use more commonly-available parts. Why not use another motor as a generator, and apply a controlled electrical load to it to vary torque? This led to the baby dyno project that is described in this series of articles.

As time went by, Jim worked out the mechanical design and we embarked on the construction of two prototypes. I had the machining done to build two sets of fixturing where I lived at the time, near Meadville, PA, the tool and die capital of the USA (where the zipper was invented). This "fixturing," as it is called, is shown below.



On a solid metal base is mounted two pairs of side-mounted guide rails: a pair for the test-motor fixture and a pair for sliding the bracket holding the load-torque motor, which will be used as a generator. The generator is mounted on the metal box, to the lower left, while the motor under test is mounted on the upright L-bracket



with triangular stiffeners on the sides. On the vertical face of the bracket is a large hole and 6 threaded mounting holes, for mounting a plate customized to fit the motor to be tested. The smaller concentric circular hole, as seen in the picture, is on that motor mounting plate. The same test bracket can then be used for various motors, each with their own mounting plate that screws to the one universal bracket. The mounting plates are simple: a square plate of metal with six holes for passing bolts through and a hole for the motor shaft. One is shown above, with a step-motor mounted to it.

The test-motor shaft reaches through the test bracket and is joined to the generator shaft using a shaft coupler. Some couplers are shown (next page). They range in size and type. Some study of the commercially-available couplers can be helpful. The two couplers to the left are Helical brand and are both high in quality and costly. The two on the right (one disassembled) we obtained from a surplus mechanical sales outlet for about \$2 US each. One difference between a good coupler and one of lower quality is that the good one has low torsional compliance and high axial compliance. In other words, you cannot twist it but you can stretch it. The two dimensions do not couple.



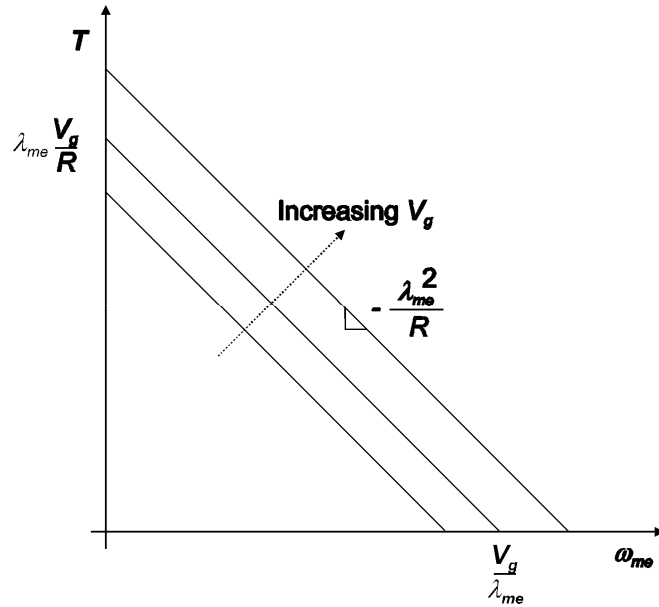
The detailed set of mechanical drawings for this particular fixturing is part of a dyno designware package I sell <http://www.innovatia.com> giving more design detail than will be given here (but not as much construction detail nor schematics). However, there is nothing too mysterious about the mechanical design, and your engineering imagination might well refine or go beyond our design. I recommend that you understand how our fixturing functions, as shown above, and then use the ideas for your own design. Perhaps you will be testing only small motors (<20 W) and need not resort to steel plates and bolts. Perhaps you have woodworking tools and prefer to work in wood. The possibilities for fixturing should be driven by what is needed to hold your intended motors to be tested

Dyno Design Overview

The approach taken here to dynamometer design is to use a dc brush motor as a generator driven by the motor under test. Brush motors are readily available at surplus prices. For a benchtop dyno capable of testing motors up to around 400 W (about a half horsepower), a 750 W (1 hp) brush motor will suffice.

Sizing is part of the system design. The generator is chosen to have a given electromechanical flux, λ_{me} , and winding resistance, R , based on dyno torque and speed range specifications. The generator drives a full-wave diode bridge for bidirectional rotation resulting in a bipolar output voltage range. The bridge output drives the power-supply input of an H-bridge power driver with controlled duty-ratio, D . The driver output drives a bank of power resistors (R-bank) of value R_L . The power driver maximum current, I_{max} and maximum voltage, V_{max} , ratings are also specified as given design values.

Both the generator, being a dc brush motor, and brush and PMS test motors, have ideal torque-speed curves as shown below.



V_g is the voltage applied to the test motor:

$$\omega_0 = \frac{V_g}{\lambda_{me}} = \text{no-load mechanical speed}$$

and:

$$T_0 = \lambda_{me} \cdot I_0 = \lambda_{me} \cdot \left(\frac{V_g}{R} \right) = \text{stall torque}$$

In the motor manufacturer's specifications, the average motor flux linkage referred to the mechanical side of the motor, λ_{me} , is called either or both the speed constant, K_V or the torque constant, K_T . When converted to the same units, $K_V = K_T$. These generic-sounding "constants" give little insight into physical motor behavior, which is why I prefer to refer to them as a physical quantity, the electromechanical flux linkage, λ_{me} .

The other motor or generator parameter of interest is the winding resistance, R . This resistance (not reactance) varies with frequency of drive excitation (due to the skin effect in the windings), and is a factor for PWM'ed drives. It is best to use a value of R that has been measured with an RLC bridge capable of drive switching-frequency excitation. Most RLC bridges do not allow resistance measurements at, say, 20 kHz, and you might need to do some estimating of R . The lower bound will be the value as measured by a dc test instrument. Be sure to either use a 4-wire probe pair and Kelvin sensing (preferred) or short the probes, note the resistance, and subtract it after making the winding measurement.

The maximum power, P_{max} , occurs for $T(\omega)$ at $(\omega_0/2, T_0/2)$, where:

$$P_{max} = \frac{V_g \cdot I_0}{4}$$

For the generator, torque is:

$$T = \lambda_{me} \cdot I$$

and:

$$I = \frac{V_{\omega}}{R + R_g}$$

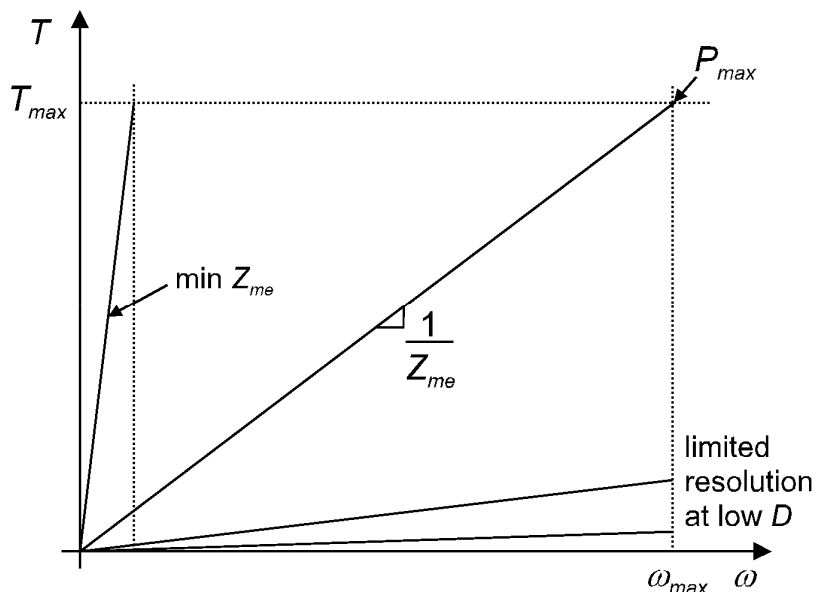
where the generator induced voltage:

$$V_{\omega} = \lambda_{me} \cdot \omega$$

and R_g is the drive source resistance. Then substituting these two equations into the torque equation:

$$T(\omega) = \frac{\lambda_{me}^2}{R + R_g} \cdot \omega$$

Unlike that of the motor, the generator $T(\omega)$ line begins at the T - ω origin and, with positive slope, increases with ω .



The generator current is controlled by varying the effective generator load resistance, R_g . For zero torque at the no-load motor speed, the current is zero and the desired R-bank load is $R_g \rightarrow \infty$. The limitation on dyno design at high speed is the resolution of the load-bank. If PWM'ing is used to provide an active electronic load for R_g then, in this region, limited resolution is encountered at low values of D .

At low speed, generator induced voltage, V_{ω} is low but motor torque is high and generator current is at maximum $I = I_{max}$, which calls for a low value of R_g . Ideally, the motor mechanical load (the generator) should have a torque-speed curve similar to that of the motor. However, the generator is mechanically driven, and its torque is low when motor torque is high at low speed. The reverse holds at high speed. The design challenge is to minimize the limitations caused by this mismatch.

The power-driver sizing affects the bounds on generator parameter λ_{me} :

$$\frac{T_{max}}{I_{max}} < \lambda_{me} < \frac{V_{max}}{\omega_{max}}$$

The generator induced-voltage source is affected by the mechanical side of the generator. Using the torque-current analogy ($T \leftrightarrow I$; $\omega \leftrightarrow V$), then the mechanical impedance presented to the motor by the generator is ω/T .

When referred to the electrical side of the generator, it is:

$$Z_{me} = \lambda_{me}^2 \cdot \frac{\omega}{T}$$

Solving for $R + R_g$ in the previous equation for $T(\omega)$, $R + R_g = Z_{me}$. In other words the total resistance in the electrical winding loop cannot exceed the mechanical impedance, referred to the electrical side of the motor. The electrical resistance is referred through λ_{me}^2 to the mechanical side of the generator as mechanical impedance, ω/T . How low $R + R_g$ can be made will determine the minimum ω , or ω_{zs} , at T_{max} , and it sets a lower speed bound on dyno operation.

This directly affects the choice of the other generator parameter, R , which must be less than $Z_{me}(\omega_{zs}, T_{max})$. Otherwise, T_{max} cannot be achieved at the zero-scale speed. The above parameters and bounds are chosen and the resulting performance analyzed. If the constraints cannot be met, one or more parameters must be changed and the analysis iterated until a satisfactory solution results.

Once P_{max} , λ_{me} , and R are determined, the search for a suitable dc brush motor for use as a generator can commence. It is possible to use a permanent-magnet synchronous (PMS) or *brushless dc* motor instead, and is preferable in avoiding brushes and commutator bars, but electronic phase control will be needed instead. In other words, if you use a PMS motor, include a motor drive to control it. The drive must be regenerative (be able to sink power), for that is the mode it will work in. Ideally, the generator power would be "inverted" into a sinewave in synch with the power line, and dumped there instead of into a bank of heat-dissipating power resistors. That refinement goes beyond this project and suggests a refining follow-on project in the future.

Next month, we'll look at the electronics hardware of the original prototype units.

