Device for Mechanical Plotting of Power/Speed Curves For a D.C. Motor

by

Jace Cali Warner

Submitted to the
Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of
Bachelors of Science in Mechanical Engineering

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2017

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Accepted by Dr. Rohit Karnik
Associate Professor of Mechanical Engineering
Undergraduate Officer
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Submitted to the Department of Mechanical Engineering
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Abstract

The relationships between power, speed, and torque in a direct current motor are often not intuitive to students based on functionality of modern dynamometers. Previous work in a 1998 master’s thesis by Peter T. Lee built a device to mechanically demonstrate the torque/speed relationship for engineering students. This thesis expands that work to prototype a modified device to show the power/speed relationship utilizing a mechanical multiplier. Speed and torque output are converted into linear motions along perpendicular axes, and power is output as their product. This thesis summarizes the design and construction of a first prototype of such a mechanical dynamometer device that can be used in teaching demonstrations.

Thesis Supervisor: Dr. Daniel Braunstein
Title: Senior Lecturer, Director of Pappalardo Undergraduate Teaching Laboratories
Acknowledgments

Enormous gratitude to Danny and the Pappalardo staff; this was an enormous learning process for me, and as with any case, when there is learning, someone was doing the teaching. Thanks for your unending patience. And, of course, TK, Margo, for your support and love.
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1 Introduction

1.1 Prior Work

Peter T. Lee, under Professor Woodie Flowers, built a fully mechanical dynamometer to measure torque and speed of a D.C. motor.[1] The piece, shown in Figure 1-1, has been retained by the MIT Museum archives and was designed to provide a clear visual tool for undergraduate students to use in understanding motor characteristics. This thesis is building off Lee’s work, designing a new device to visualize power as the product of torque and speed.

Figure 1-1: Peter T. Lee’s original dynamometer[1] as currently stored in the museum archive (#2010.029002) showing relevant parts.

1.2 Background

Direct current (DC) motors have characteristic relationships between torque, speed, and power. Motors are often characterized by their no-load speed and their maximum (stall) torque; however a trade-off exists between these two such that higher torques result in decreasing speed and vice versa, forming a negative linear relationship. Power is the product of the torque and speed, hence the power curve is an inverted parabola with maximum
value at one half of the no-load speed (and one-half of the stall torque). The devices used to measure torque, speed, and power of motors are called dynamometers. Modern dynamometers are characteristically electromechanical and rely on digital displays to output the results.

Mechanical multipliers were utilized during the early twentieth century for military weaponry. The declassified 1944 *Basic Fire Control Mechanisms* from the US Navy provided the basis for designing a mechanism to multiply inputs, shown in Figure 1-2, utilizing rack and pinion in order to mechanically move inputs and outputs.[2] By multiplying the speed and the torque axes and mechanically plotting this product as a function of motor speed, the power of the motor can be drawn.

2 Mechanical Design

2.1 Description

The device built in this thesis is a mechanical dynamometer, converting speed and torque into linear motions, utilizing a mechanical multiplier to plot their product, power, as a function of speed. It is comprised of three subsystems – the speed axis, the torque axis, and the drawing system. The first two draw heavily on mechanisms worked out in Lee’s previous thesis. As Lee determined, the rotational speed of the motor shaft can be converted into a linear motion through the use of a spring and flyball governors. This same basic mechanism was utilized, though it was redesigned to allow for the accommodation of the drawing system. Likewise, torque can be elucidated by mounting the motor on bearings, giving an extremely compliant mount that will rotate with the back torque of an applied load. Using a wire and an extension spring, this is converted into a linear motion perpendicular to the speed motion. The final subsystem consists of a number of slotted sliding parts to plot out the motion of the two axes and their product.

The chosen multiplication mechanism was ultimately a modification of the screw type multiplier, shown Figure 1-2. In this system, there are two perpendicular linear inputs. In the first input, the speed axis, the slotted slider bar moves directly with the input. The other axis has the slotted slider bar pinned to the input and horizontally constrained at the
other end at a zero point. The output is the intersection of the two slots as the vertical height, parallel to the pinned input (the torque axis). The output is a scalar multiple of the product by similar triangles geometries, as shown in Figure 2-3.

The user interacts with the device by grabbing the shaft between the two mounted bearing plates, exerting a torque that causes the system to readjust, in the meantime drawing the power-speed curve.

![Diagram of the device](image)

Figure 2-3: The multiplier works via right triangle similarity such that for inputs $a$ and $b$ and product $ab$, the output, $x$, is a multiple of the actual product, $x = \frac{ab}{K}$. [2]

2.2 Design Choices and Limitation

This thesis was a first prototype and thus many of the design choices followed to allow for quick, precise fabrication. Views from the Solidworks assembly are seen in Figure 2-4 on the following page. The frame was constructed of 80-20 aluminum extrusion, with many of the system components purchased from McMaster-Carr. The remaining parts were designed for water-jet or easy milling and turning operations. As with many first working prototypes, the industrial design was minimally considered at this stage and instead the design was focused on bench-top mock-up and easy adjustment.

In designing this device, the conscious choice to separate the carriage shaft for the speed module from the motor shaft was made, simplifying the bearing assembly, and allowing the drawing board to be stationary, unlike that of Lee's device. This introduced a difficulty of accessing the motor shaft to apply torque, as well as opening the door to misalignment issues, both of which will be discussed later.
(a) Top view of CAD assembly of device. The multiplier arms are clearly visible in the lower right, with the speed input constrained on both ends and the torque input pinned to the slider on the left and pinned to the zero point (obscured by the frame) on the right.

(b) Other view of CAD assembly highlighting key elements of subsystems.

Figure 2-4: Basic design and explanation of parts
The design also parts from Lee's in using the torque spool, an intermediary piece to which the motor is firmly mounted, but spins freely in the bearing. The ability to mount different motors into the device would be beneficial to the applicability of the device. This helps to eliminate motor size as a design constraint, requiring only that the mounting holes for the motor face be drilled into this part. While this also obscures the clarity and simplicity of the wire wrapping, the position of the carriage along the shaft is visible and should be sufficient for understanding.

The design does not account for second order effects. Lee's device had included a damper and extensive calculation to minimize the resonances with the natural frequency of the system. In this prototype, the losses of the system are wholly uncharacterized, so the higher order effects were likewise neglected in the theoretical design.

2.3 Supporting Physics

Speed Subsystem

The free body diagram of the flying governors is seen in Figure 2-5 and Figure 2-6. Notice $r = l \sin \theta$. The spring force acts only in the negative $x$ direction, while the governor force acts at a magnitude $m_b \omega^2 r \cos \theta$ in the positive $x$-direction. Note each governor acts $m_b \omega^2 r \sin \theta$ in the positive and negative $y$-directions, canceling out for zero net $y$-force.

![Figure 2-5: Diagram for symmetrical flying governors of mass each $m_b$ on arms of length $l$, spinning at angular velocity $\omega$ at an angle $\theta$ from the horizontal.](image)

![Figure 2-6: Free body diagram to show balance of spring force and governor forces assuming governors can be modeled as point masses and the carriage is modeled as massless.](image)
From this free body diagram, the horizontal forces must balance to find speed:

\[ 2F_{gov}\cos\theta - F_{spring} = 0 \]  \hspace{1cm} (1)

\[ 2m_b\omega^2 r \cos\theta - k\Delta x = 0 \]  \hspace{1cm} (2)

\[ \omega^2 = \frac{k\Delta x}{2m_br \cos\theta} = \frac{k\Delta x}{2m_bl \sin\theta \cos\theta} = \frac{k\Delta x}{m_bl \sin 2\theta} \]  \hspace{1cm} (3)

This highlights the fact that the relationship is not mathematically linear, but is designed to be locally linear around the system parameters, as shown in Figure 2-7.

Figure 2-7: Plot of local linearization of the angular speed, \( \omega \), for the first 1.5 inches of \( \Delta x \) for the speed mechanism using system parameters, just shy of the calculated maximum speed of 170 rpm and maximum allowable displacement of 3 inches.

The system was designed around an estimated maximum value of \( r \) of 1.7 inches, machined governors of 0.08 lbs and maximum displacement \( \Delta x \) of 3 inches. Springs of stiffness \( k = 0.24 \) lbs/in were purchased, giving maximum angular velocity of

\[ \omega = \sqrt{\frac{2k\Delta x}{m_br}} \approx 170 \text{ rpm} \]  \hspace{1cm} (4)

This max speed is used to inform motor selection: assuming minimal losses in the transmission, this \( \omega = 170 \) rpm would be the no-load speed.

**Motor Specification Characterization**

Similarly, to help inform the motor selection, the stall torque for the system was modeled, as seen in Figure 2-8 on the following page. At equilibrium, the moments must balance such that:

\[ \tau_{stall} - F_{spring} \times r_{spool} = 0 \]  \hspace{1cm} (5)
For purchased spring constant $k = 0.46$ lbs/in, estimated 4 inches maximum displacement $\Delta x$, and spool radius 0.8 in:

$$
\tau_{\text{stall}} = k \Delta x r_{\text{spool}}
$$

(6)

Maximum power output occurs at half the stall-torque such that $P_{\text{max}} = 0.25(\tau_{\text{stall}})(\omega_{\text{max}})$, or approximately 0.75 W in this case.

$$
\tau_{\text{stall}} \approx 1.5 \text{ in-lbs}
$$

(7)

Figure 2-8: Free body diagram to show balance of forces in the torque subsystem.

Figure 2-9: Acrylic mechanical multiplier proof of concept model.

### 2.4 Design Process

#### Multiplier Proof of Concept

A simple acrylic model was laser cut to test the validity of the mechanical multiplier mechanism, shown in Figure 2-9. The mechanism was deemed feasible, with the maximum output
occurring at half of the length of the torque axis, as previously shown in Figure 2-3 on page 9.

**CAD**

The device was designed using Solidworks 2015 Student Edition, as previously shown in Figure 2-4. Engineering drawings for the parts as designed are available in the appendix.

**Machining**

A number of parts were machined using a Bridgeport Proto Trak SMX two-axis mill and Bridgeport Romi manual lathe in the Pappalardo Undergraduate Teaching Laboratory. Many of the parts were fabricated on an OMAX water-jet and post-machined as necessary.

**Assembly**

The system includes a basic frame made of one-inch aluminum 80-20 extrusion for minimal assembly time for reasonable structural integrity and ease of mounting subassemblies. The moving parts in the system all fastened into the slots of the 80-20 extrusion. The table of materials is available in Table 1 on page 16 and Table 2 on page 17. While most of the hardware used were #6-32 or 1/4-20 bolts, the list does not comprehensively cover all fasteners.

The motor was mounted to the torque spool using the face-mounting screws. The leads were soldered to a slipring and covered with heat shrink. The other end of the slipring was connected to a power source for testing.

![Fully assembled device](image)

**Figure 2-10: Fully assembled device.**
Testing

The device was tested up to using up to 12 V from the power source, assessing the functionality of the speed module, the torque module, and the drawing module. A number of different springs were tried, ultimately using a stiffer spring with a shorter compressed length than what was originally calculated to be ideal for the torque module. Adjustments to the dimensions of some machined parts were also made during the testing phase to optimize alignment.

Figure 2-11: Plots drawn in early testing fail to register significant changes in speed due to friction along the speed axis and produced less travel than expected along the torque axis for similar reasons.
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Table 2: Table of Materials (continued)

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3 Analysis and Discussion

3.1 Challenges

**Governor Arm Design**

Designing and manufacturing the governor assembly proved to be the biggest challenge in the production of a functional device, particularly the arms. The original design for the governor arms, shown in Figure 3-13b on the next page, was designed to be water-jet, with the holes reamed out such that the wall thickness around the bearing would be 0.035”. This wall-thickness proved too thin to allow for successful drilling and reaming out of the holes for the bearings to be press-fit, and additionally, the pieces became deformed when clamped into the vice of the mill. The failure modes can be seen in Figure 3-13a on the following page. While three of the nine water-jet pieces were successfully post-machined, it was decided the design was not robust enough to actually implement in a moving part in the dynamometer.

The design was improved before assembling the governor assemblies, shown in Figure 3-13c on the next page. The walls were thickened, both along the length and around the bearing. A flat side was added to the top of the walls surrounding the bearing holes, and a fillet was added to strengthen the part and prevent bending during reaming. A 0.200” pilot hole was added to the water-jet file, additionally. The final parts were drilled, reamed, and sanded to fit successfully. In future versions, the clearances between the governor arms and the pieces to which they are mounted should be re-configured to reduce the amount of sanding necessary for appropriate fits.

**Governor Design**

The governors were initially designed for ease of manufacture from aluminum 1” square stock. However, the governors were redesigned later in the process to have a lower profile to address interference issues between the spinning governors and the torque shaft, shown in Figure 3-12. Brass was selected for its high density (0.307 lbs./cu. in., more than three times that of 6061 Aluminum) and ease of machining compared to other choices, namely steel.

![Figure 3-12: (left) Original aluminum governor as machined and (right) new brass governor as machined.](image-url)

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1McMaster-Carr specification for part #8951K51, Alloy 360
Alignment and Binding

The importance of axis alignment was not recognized until the device was assembled. In almost every part of the motor shaft did axis alignment issues need careful attention and even so, continued to present issues. This was a deviation from Peter Lee's design which carried the same shaft through the whole assembly.

Binding of the moving parts was a major concern in the construction of the device. After purchasing both lightweight aluminum shafts and carbon steel lubricated shafts, the
latter was deemed to allow for smoother motion. The device was originally designed using entirely one-degree self-aligning bearings, but they were determined to have too much shaft clearance and the bearings on the primary axes were replaced with fixed bearings. Even with this improved construction, the bearings still failed to meet performance expectations, highlighting other key design failures.

The constructed design, as labeled in Figure 3-14 also fails to adhere to Saint-Venant’s principle, in which the ratio of the length of the linear bearings, $L$, to the distance between the bearings, $D$, should be high, ideally greater than 3. Adding another bearing to each shaft extends $L$ as to make the carriage slide more easily and is recommended in future work.

![Figure 3-14: The speed carriage design as built with bearing distance $L$ and separation $D$, clearly in violation of Saint-Venant’s principle in which $L/D$ should be high.](image)

### 3.2 Next Steps

**Remaining Functional Design Issues**

The constrained motion along the speed axis needs to be addressed, through addressing the shaft misalignment, improving bearing performance, and improving geometry. As discussed earlier, this iteration used the design choice to separate the shaft for the carriage and the motor shaft, which resulted in shaft misalignment issues. Returning to the original configuration is recommended to avoid the necessity of precise alignment of each part of the shaft. Similarly, redesigning the sliding parts to obey Saint-Venant’s principle is recommended to address binding issues.
User Interface Design Issues

Peter Lee’s original device extended the motor shaft to the far opposite side, allowing a user to grab the end and apply a torque. This device moved away from that design to simplify the carriage bearing assembly for the governors; however, applying a torque is too challenging in this design for an intuitive and comfortable user experience. Looking forward, this should be prioritized as a design improvement.

Similarly, a next pass of designing in the device should better consider user experience and industrial design needs and will require user testing. Moving away from the brutalist look of 80-20 extrusion and raw water-jet parts is advisable for final product presentation. A teaching model needs to be nearly unbreakable and should instill confidence and excite interest in students with its visual appearance.

4 Conclusion

While this device is not a finished product, it has provided a solid physical basis to demonstrate the proof of physics for a future version. Much of the work remaining is in industrial and usability design, with noted improvements for improved performance of the mechanical system.
References


5 Appendix A: Engineering Drawings

Pictured on the next fourteen pages.
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SECTION B-B

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NAME: J.WARNER
DATE: 12/1/16
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6-32 TAP DRILL #36

TITLE: SPACERS

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