Development of a Low Cost, Easily Constructed Drill Dynamometer Laboratory

Ted Hubbard, Clifton Johnston

Mechanical Engineering Department Dalhousie University,
Halifax, Nova Scotia, Canada, B3J 2X4
ted.hubbard@dal.ca

Abstract – This paper presents the development of a Drill Dynamometer laboratory using cordless drills. This particular setup was chosen as it allows students to be introduced to topics such as: motor torque and power curves, power bands, current and efficiency curves; all at a relatively low and safe power level. The setup consists of a cordless drill coupled to a hex shaft mounted friction spool. The spool and pillow block bearing mounts are Rapid Prototyped from ABS plastic. Students apply tension to a belt wrapped around the spool and brake tension is measured using a spring scale. Motor RPM is measured by means of a modified bicycle computer. The batteries on the drill are replaced with an external battery pack with voltage and current meters. Student measurements show a high degree of precision for the linear speed vs. torque curves and the parabolic power vs. torque curves. The kit is made from easily obtainable materials and supplies and was constructed quickly for less than \$200 a kit.

Keywords: dynamometer, drill, laboratory, motor torque, motor efficiency

1. INTRODUCTION

Laboratory and practical work are characteristic features of an undergraduate degree program in any engineering discipline [1,2]. The role and benefits of practical work in the engineering curriculum are to motivate students and inspire their interest a particular subject; help them to strengthen their understanding of a subject by connecting theory to practice; and to provide opportunities for students to work together on understanding and solving engineering problems.

It is often difficult to design laboratories where students can acquire numerical data without expensive and space consuming equipment. These constraints also stretch restricted funding and laboratory space, limiting the number of laboratories instructors can make available for students. Moreover, that large, expensive equipment tends to isolate the students from the actual physical phenomenon being measured and simply generates data.

Students then simply write up the results, with little conceptual connection. Despite these challenges, the application of theory in a practical setting remains an expected and beneficial part of the engineering curriculum.

In order to address these deficiencies many engineering educators developed and implemented less expensive and resource intensive laboratories. These could generally be classified as simulated or virtual laboratories and/or remote or distributed learning laboratories [3]. These types of laboratories require little space and physical resources. However, there are many instances when the learning outcomes for a laboratory are not consistent with simulated or remote delivery. Another option that has emerged is to develop smaller-scale laboratories [4]. In this delivery mode, the students learn through hands-on interaction with the physical phenomenon, but at a scale lower than would be found in industry, which often translates to lower cost. This approach allows more laboratories to be made with less space required.

The Department of Mechanical Engineering at Dalhousie University has developed a new dynamometer laboratory that utilizes a cordless drill, a spring scale, rapid prototyped (RP) parts and a bicycle computer. This lab has the advantage of introducing students to motor torque and power curves through a low power, small and inexpensive experiment.

2. IDEALIZED POWER & TORQUE CURVES

The torque capacity of an electric motor varies with speed. At no load the RPM is maximum, but no torque is produced. At stall the torque is maximum, but there is no rotation. If the Torque is varied from $0 < x < 1$ where x is the normalized torque (torque / stall torque) then the normalized output RPM is $1 - x$ (RPM / no load RPM). The power is then torque * speed:

$$Power(x) = x - x^2$$

This parabola peaks at $x = 0.5$: $\frac{1}{2}$ stall torque or $\frac{1}{2}$ no load speed.

On the electrical side as more torque is produced, more current is drawn. If the current increases linearly from a small no load value to the maximum stall current then let the current $I = r + x$ where the current ratio r = no load current/stall current. Typical r for motors is 3-10%. The efficiency is the mechanical power out divided the electrical power in: $T*\omega / I*V$. Assuming for simplicity in this idealized case that the voltage does not vary (not true in real power supplies) then

$$eff(x) = \frac{(x - x^2)}{(r + x)}$$

The peak efficiency occurs at a lower torque (higher speed). Taking the derivative of the efficiency curve, it peaks at $x = \sqrt{r^2 + r} - r$, for small r this is approximately

$$x_{peak\ eff} = \sqrt{r} - r$$

For typical r values this corresponds to peak efficiency at $x = 14-22\%$ of maximum torque. Figure 1 plots an idealized torque and power and efficiency curve for $r = 0.07$ with a peak power at 50% and a peak efficiency at 21 %.

Fig. 1. Ideal torque curves, Normalized Torque on x axis, Normalized Speed on Y axis.

3. LABORATORY SETUP

3.1. Layout

Figure 2 shows the entire layout. The Mechanical Tension is as follows ([?] indicates figure labels): An anchored turnbuckle [TB] connects to the bottom slack

side of the belt. The lower belt goes under the spool [Sp], wraps around and exits at the top of the spool. The upper tight belt connects to the yellow Spring Scale [Scale] (50N max ~10lbs). The Spool is mounted on two Rapid Prototyped (RP) pillow block bearings [B]. The Bar clamp [Clamp] trigger [Trig] moves the yellow scale to the left.

Fig. 2. Drill dyno layout.

3.2. Cordless Drill & Electrical

Figure 3 shows the electrical layout. The cordless drill used was a Black & Decker AS6NG Cordless Screwdriver ([Drill] in Figure 3) which has an ~5W motor running at ~10,000 RPM geared down by an 81:1 planetary gearhead to 130 RPM output speed. The screw driver can also act as a small drill and comes with both screw driver and drill bits (not used). In this paper “screwdriver” and “drill” will be used interchangeably as either could be used. A brass 6” long $\frac{1}{4}$ ” hex shaft was mounted in the drill holder.

Fig. 3. Cordless Drill & Electrical

The internal battery compartment at the bottom was removed and a small hole drilled to allow passage of two 14 gauge wires that were soldered onto the battery leads. Two digital multi-meters were connected in series and parallel to measure current and voltage respectively. The no load readings for rechargeable batteries should read ~5V & ~0.6-0.8A. As the load is increased, the voltage drops to below 3 volts and the stall current rises to above 3 amps.

When turning on the drill, the upper belt should tighten and the bottom belt should slacken. If the opposite happens you are pressing the wrong button, or swap the drill leads to use that button.

3.3. Rapid Prototyping

Several parts were Rapid Prototyped (RP) out of ABS plastic (see Figure 4). The friction spool (see Figure 5) is a cylinder with 2.5 in diameter, 1 in width and a central 1/4" hex shaft. A clearance of 5 thou on each side of the hex shaft hole permitted easy insertion of the brass shaft. A 1/4" lip on each side ensures the belt will not slip off to the sides. The hex shaft is supported on both sides of the spool, this is important as cantilevering the shaft applies significant bending loads which drastically reduces the screwdriver's output. Two pillow blocks with 7/8" ID and a retaining lip were RP'ed. The 1/4" hex shaft is sleeved with a 5/16" OD & 9/32" ID bass tube. The brass tube was then slid into a 5/16" ID & 7/8 OD sealed ball bearing.

Fig. 4. Rapid Prototyped Spool & Pillow Blocks

3.4. Brake Tension

The friction spool 2.5 in diameter was chosen such that the radius (1.25") multiplied by of the maximum scale tension (50N) exceeds the maximum torque of the screwdriver. In practice the screwdriver stalled when the belt tension was 40 - 45 N. The coefficient of friction (~0.3 between ABS and the belt) does not enter into the torque calculation so long as a sufficient number of turns are made around the spool such that the slack side is slack: 2.5 turns did this in our case.

The Bar clamp trigger ([Trig] in Figure 5) moves the yellow scale to the left. The small yellow button [Rel] on the left of Bar Clamp completely releases all tension.

A few practical notes on operation: 1) Extending the clamp when the drill is off will cause the spring to jump to a higher value when the drill is turned on. Only tighten the clamp when the drill is on. 2) Do not let the yellow scale tube touch the frame holding the bar clamp, the reading will then be incorrect.

Fig. 5. Brake Tension: Top: all, Middle: Friction Spool, Bottom: Bar Clamp adjuster

3.3. RPM Measurement

RPM is measured using a modified bicycle computer (see Figure 6: computer mounted on a short piece of PVC piping). The small magnet meant to be attached to the bicycle wheel is mounted on the periphery of a RP 1 inch tach wheel. The tach wheel has a 1/4" central hex hole and

is attached to the end of the brass hex shaft after the second pillow block (see Figure 6).

Problems:

If directly setup in this way most bicycle computers have two problems for our purposes: 1) Most computers have few digits (e.g. 0-100 km/hr +/- 0.1 km/hr) and slow rotations <100 RPM correspond to low km/hr with low resolution, 2) Most have a minimum speed below which they do not function (e.g. 10 km/hr). Without adjustment for problems 1) & 2) the display might only have a small range e.g. 10-20 km/hr +/- 0.1 km/hr.

Solutions:

1) Full Range Problem: Most bicycle computers allow the user to calibrate the speed readings by entering the bicycle wheel diameter. The displayed km/hr = measured RPM * $60 * \pi * \text{wheel diameter (meters)} / 1000$. Entering an artificially large wheel diameter (~1.75m in our case) forces the computer to use a fuller range of the display. The displayed values are then divided by the used calibration factor to obtain RPM = $3 * \text{km/hr}$.

2) Minimum Speed Problem: In our case the computer stopped reading below ~10 km/hr which corresponded to 30 RPM. To correct this, two magnets were mounted opposite each other on the tach wheel, doubling the signal frequency for a given RPM, such that 10 km/hr now corresponded to 15 RPM. If this is done, the calibration wheel diameter should be adjusted down by a factor of 2. In figure 6 both modifications were made resulting in a net calibration factor of 1.5: RPM = $1.5 * \text{km/hr}$. The displayed 74 km/hr corresponds to 111 RPM.

Fig. 6. Tach wheel (Top) & Bicycle computer (Bottom).

4. STUDENT RESULTS

4.1 Safety

Although the cordless screwdrivers are relatively low power and torque, proper safety precautions and procedures should be undertaken before students perform the lab. Prior to the lab, a brief safety lecture was given outlining potential hazards and how to avoid them. The primary risk of injury would come from the spool and the possibility of students getting tangled in the spool. This is of particular concern with loose or dangling clothing and/or jewelry. A secondary source of injury could be electrical but the voltage and current values are relatively low. In practice no accidents or injuries occurred over 4 lab sessions and more than 100 students.

4.2 Student Results

Figure 7 shows photos taken during the drill dyno laboratory. Students make a table with 4 columns and 9 rows. Each row corresponds to a step in belt tension. Students increase the belt tension from 0 to 40 or 45 N in 5 N steps until the drill stalls. At each step 4 measurements are recorded: tension (N), speed (km/hr) voltage & current. A simple excel program is provided to students that converts belt tension to torque km/hr to rpm and plots speed and power vs. torque as well as current and efficiency vs. torque. Figure 9 shows some typical results.

Fig. 7. Students using the drill dyno

Fig. 8. Students result for torque curves

Fig. 9. Student result for eff. curves

4.3 Resolution and Repeatability

Figure 8 illustrates the typical torque curve and Figure 9 illustrates the typical efficiency curve found by the student using the cordless drill dynamometer. Figure 8

and 9 are both characterized by an overall goodness of fit, with some variation in the individual data points. Overall, curve fits had an $R^2 > 0.99X$, with the variation only in the third decimal place. The determination of the resolution and repeatability of the students' dynamometer measurements were confounded by variations caused by the varying voltage in the AA batteries. Each set of batteries operated at a difference voltage. Both the motor efficiency and the power are dependent on the battery voltage. Therefore, each laboratory set-up would possess a unique power and efficiency curve, thereby limiting the comparison of results. However, if we compared the peak in the power curves, we should expect to find the peak at 50%. The range found in all the student results fluctuated between 49.5% and 50.5%. Combine this measure with the $R^2 > 0.99$, there is strong evidence that the measurements made in this laboratory possess good resolution and high repeatability.

5. BUDGET

The cost was approximately \$200 CDN per setup (taxes included):

ITEMS	Amount/kit
Cordless Drill	\$15
Bike Computer	\$20
Bar Clamp	\$6
Multimeters x2	\$20
9V battery for multimeter	\$3
Rechargeable AA batteries x4	\$14
Spring scale	\$3
Electrical connectors	\$10
Banana cables	\$15
Wood & MDF	\$20
Misc: Fasteners, String etc.	\$4
Turnbuckle	\$2
RP spool	\$20
RP pillow blocks x2	\$6
RP battery plug	\$4
RP tach wheel	\$3

TOTAL	\$165
15% GST	\$25
TOTAL	\$190

7. Conclusion

Space limitations and budget pressures have previously created a reduction in the number of hands-on laboratories in favour of remote or simulated laboratories. Current engineering education pedagogy is again emphasizing the benefits of active, hands-on learning. Smaller scale laboratories have begun to emerge creating a bridge between limited resources and active learning. In this paper we have described the development of a drill dynamometer laboratory for a machine design course Mechanical Engineering at Dalhousie University. The drill dynamometer uses a cordless drill as the power source and inexpensive, easy to find parts, such as a bicycle computer, spring scale, grip clamp, multimeter and simple RP parts, to complete the experiment. The cost of the entire laboratory was less than \$200, permitting the construction of 10 set-ups. The low power of the cordless drill mitigates many of the safety concerns that may arise from larger scale dynamometer laboratories and allowing the students access to all of the lab components. The students are able to measure the linear speed vs. torque curves and the parabolic power vs. torque curves to a high degree of precision.

Acknowledgements

The authors would like to thank Mr. M. Macdonald, Mr. A. Murphy & Mr. J. MacDonald for their assistance in assembling the kits. The authors would like to thank Drs. R. Bauer and J. Leon for their financial support of this project.

References

- [1] Edward Crawley, Johan Malmqvist, Sören Östlund, and Doris Brodeur, *Rethinking Engineering Education: The CDIO Approach*. New York, NY: Springer, 2010 (2nd ed.), 300 pp. {ISBN: 978-1441-94260-9}
- [2] L.D. Feisel and A.J. Rosa, "The role of the laboratory in undergraduate engineering education," *Journal of Engineering Education*, vol. 94, no. 1, pp. 121-130, 2005.
- [3] Romanas Krivickas and Jonas Krivickas, "Laboratory instruction in engineering education," *Global Journal of Engineering Education*, vol. 11, no. 2, pp. 191-196, 2007.
- [4] Anant R. Kukreti, "Teaching analysis of structures using a small-scale structural behaviour laboratory," *Journal of Engineering Education*, vol. 87, no.3, pp 215-217, 1998.