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ACQUIRING TORQUE AND ROTATIONAL SPEED DATA FROM A STATIONARY BICYCLE FOR UNDERGRADUATE TEACHING

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ABSTRACT

A laboratory module was recently developed for an introductory experimental course for sophomore mechanical and aerospace engineering students. The goal of this laboratory is to provide the students with an understanding of digital data acquisition systems for measuring torque and angular velocity in real time. The laboratory comprises of a stationary exercise bicycle, adapted to house a torquemeter on its front axle, an optical tachometer, the data acquisition system and software which converts a computer into a virtual instrument. A group of two or three students is rotated through the laboratory as part of a larger number of laboratory modules. The students access the experiment via the virtual instrument. The experiment requires a student to ride the bicycle. The data acquired are then subsequently analyzed by the students who are required to write individual laboratory reports.

INTRODUCTION

Although not explicitly stated, ABET requires students to be exposed to hands-on engineering experiences [1]. Typically, the requirement is spread over a number of pre-engineering laboratory courses in chemistry and physics, followed by engineering experimentation that can extend from the freshman to the senior year. For example, at the University of Texas at Arlington (UTA), freshmen engineering students take an introductory course that provides some basic experiments that are partly common experiences and partly specialized depending on the student's intended major.

Mechanical and aerospace students at UTA are formally introduced to experimental methods at the sophomore level in a course entitled Engineering Methods and Measurements. An overview of this course is described in [2]. Briefly, the course comprises of two semester hours of lectures and one semester hour of laboratory. The lessons in the classroom are reinforced with homework and project assignments. These assignments are also relevant to the laboratory experience. There are nine laboratory modules for the students to execute; which is quite intensive compared to similar offerings at other universities. The existing laboratory modules cover the following topics:

1. Metrology
2. Basic Digital Measurements 1
3. Basic Digital Measurements 2
4. Structural Dynamics Analysis
5. Flow Rate Measurement
6. Heat Transfer 1 (Free/Forced Convection)
7. Heat Transfer 2 (Forced Convection)
8. Heat Transfer 3 (Conduction)
9. Introduction to LabVIEW™

Except for metrology, which teaches the students to use calipers and micrometers, all the other modules are computer-based, exposing the students to modern digital data acquisition techniques utilizing LabVIEW™ as the software platform. Emphasis is placed on understanding the capability and limitations of the hardware and software, as well as on the vast potential capabilities that are provided. Thus, students realize the nuances of digital systems, including sampling, aliasing, resolution and so forth. Students are also exposed to more traditional requirements such as uncertainty and statistical analysis. The laboratory offerings are continually being upgraded or replaced with new hardware and procedures. Since most of the laboratory modules operate with the students changing one parameter and observing the result, it was thought that a different experience, whereby field signals are acquired, may pose a different

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and interesting experience. Towards this goal, it was decided that an exercise bicycle can be used for students to gather the appropriate field signals, namely, torque and rotational speed.

Using LabVIEW™, virtual circuits connecting simulated electronic components can be assembled using a unique graphical-user-interface (GUI). A LabVIEW™ virtual instrument can emulate logic and analog circuits, perform mathematical operations on the signal in the time, frequency and phase domains, and display and store data sets all in real time as the experiment is being performed. Using LabVIEW™ eliminates much of the time and expense involved in setting up an experiment. Also, LabVIEW™'s GUI gives the students participating in the laboratory a more detailed view of the experiment than they would receive using hard circuits and instruments. Using LabVIEW also eliminates some of the clutter at the work place associated with electronic equipment and also makes for a more robust system, with fewer exposed electronics that may be interfered with.

PROBLEM STATEMENT AND SPECIFICATIONS

The laboratory experience intends to cover a gap in the existing offerings by exposing students to digital counting and timing, and shows how a digital system uses such information to calculate speed. The choice of the exercise bicycle was somewhat arbitrary but, as pointed out above, has the benefit of allowing students to acquire field signals and thus understand the difficulties with interpreting such signals.

The learning goals for this laboratory module are to demonstrate:

- Torque and rotational velocity measurement
- Digital counting and timing
- Using computer to produce a virtual instrument front end
- AC signal conditioning techniques
- Data reduction, including uncertainty analysis

LABORATORY DEVELOPMENT

The laboratory elements are comprised of hardware and software. The hardware includes the test article, sensors, signal conditioners, data acquisition system and host computer. The software platform is LabVIEW™, which has been standardized throughout the course. Important considerations in hardware selection include robustness, reparability and, when necessary, ease of replacement.

The Exercise Bicycle

The Lemond Revmaster Stationary Cycle was selected for use because of its durable construction and because its design includes features which could be easily modified to include the torquemeter and tachometer. Figures 1 and 2 show the Revmaster used in this laboratory. Most of the cycle's components, including the frame, are made of heavy stainless steel, which allowed for the retrofitting of instrumentation onto the chassis, while at the same time providing a solid structure that does not tip over or shake unlike lighter portable cycles.

Figure 1. Lemond Revmaster, torquemeter side.

Figure 2. Lemond Revmaster, tachometer side.

The Torquemeter

A Himmelstein MCRT® 3120T(2-2), precision, non-contact pulley/sprocket torquemeter has been incorporated into the bicycle's pulley system [4], Fig. 3. The torquemeter is bulky compared to the cycle and mounting it to the cycle

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without interfering with the bicycle's function and that of the speed measurement system required detailed consideration.

Figure 4 shows the configuration of the properly installed torquemeter, per the manufacturer. The figure shows that the torquemeter must be installed at *the end* of the load shaft. The power output pulley is connected to the torquemeter and completely independent of the load shaft. This configuration is necessary because the power generated by the cyclist has to be transferred *through* the torquemeter to the source of resistance at some point in the drive-train. In other words, the continuity of the power transfer from the cyclist to the flywheel must be severed at some point and rejoined indirectly through the torquemeter. The above design peculiarity gives the torquemeter its ability to measure torque independently of velocity or acceleration.

The MCRT also has several signal conditioning requirements. According to the manufacturer [5], the signal conditioner must provide:

- 3 to 6 Vrms of 3 kHz sinusoidal drive
- the ability to null any cabling unbalance
- adjustable span capable of producing the desired signal output
- phase sensitive demodulation
- removal of the carrier frequency and its harmonics from the torque signal

The original output pulley of the bicycle was removed and replaced by an adapter which fitted into the mounting hole of the torquemeter. A new output pulley was created and mounted to the face of the torquemeter. Figures 5 and 6respectively show the modified pulley system and the torquemeter in place of the original output pulley.

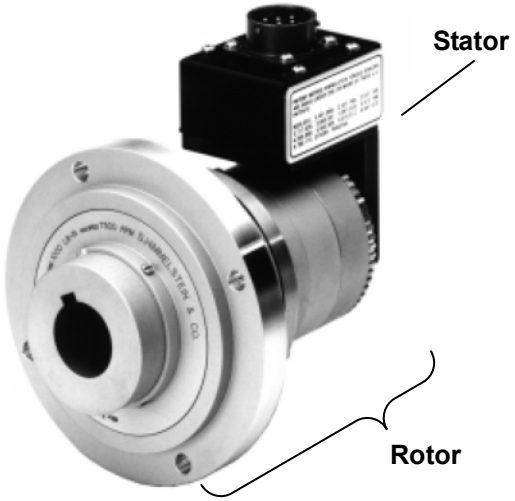

Figure 3. The MCRT® 3120T(2-2) NNN torquemeter [4].

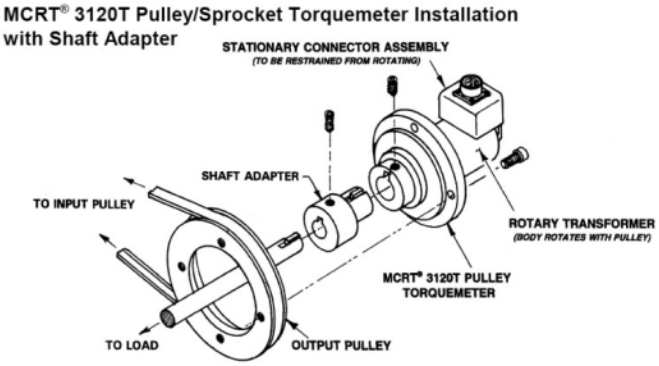

Figure 4. Proper configuration of MCRT® 3120T [4].

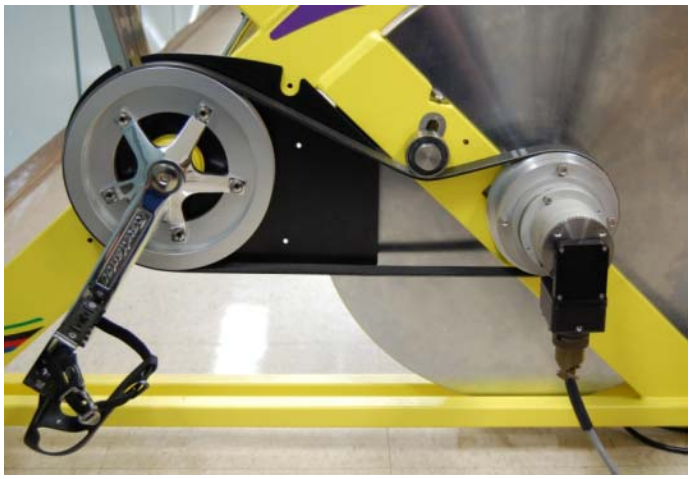

Figure 5. Modified pulley system.

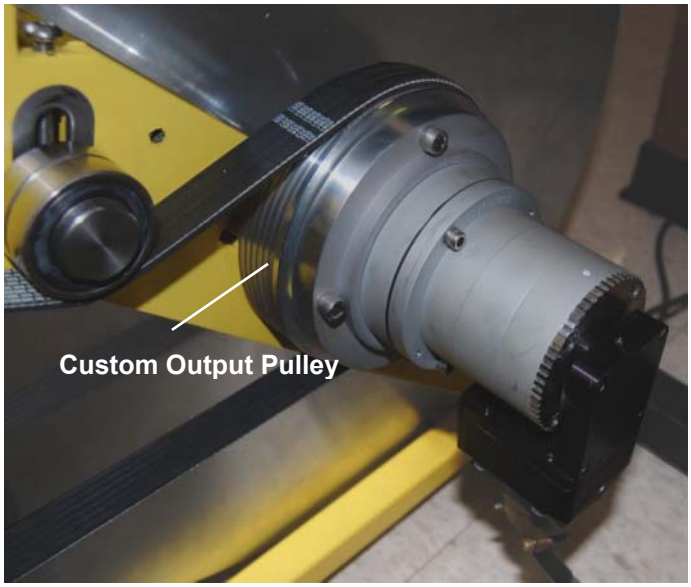

Figure 6. Torquemeter in place of small output pulley.

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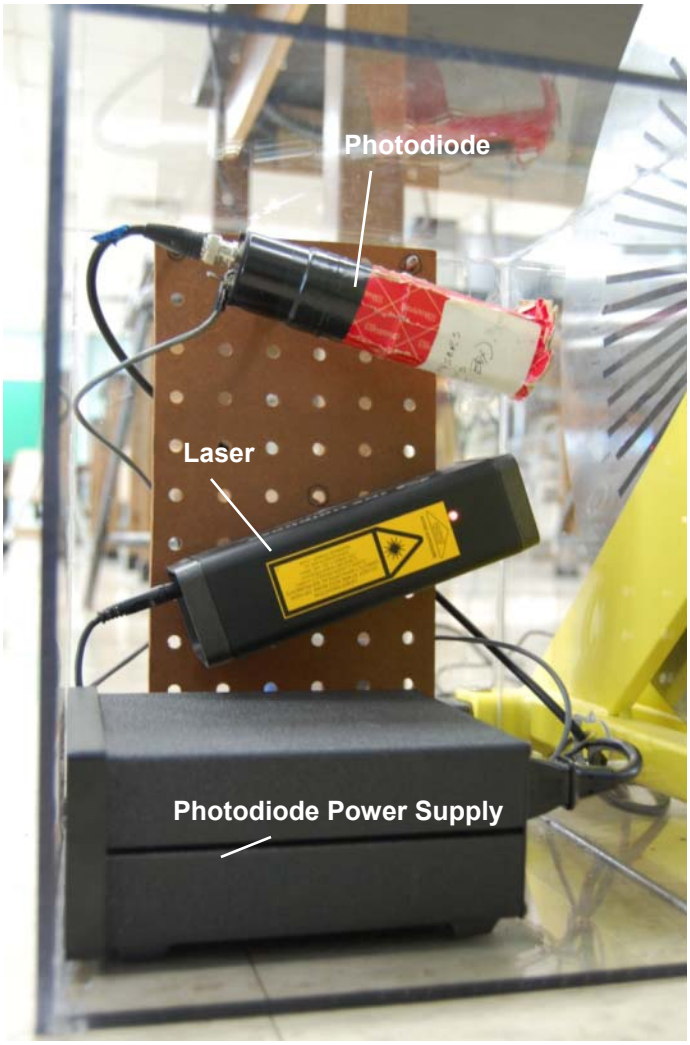

Figure 7. Tachometer.

The Optical Tachometer

The tachometer design takes advantage of the Revmaster's reflective stainless steel flywheel which allowed for an optical arrangement utilizing a laser and photodetector. Figure 7 shows the tachometer placed in a custom-built lexan enclosure. A helium-neon laser (JDS Uniphase Model NT61-315) was used to illuminate a spot on the flywheel. The figure shows thin strips of black electrical tape attached to the flywheel at equal intervals in a constant radius, creating a dashed circle. The uniformity of spacing between the tape strips was found to greatly affect the cleanliness of the tachometer signal due to the method used in the LabVIEW™ Virtual Instrument to obtain the frequency of the pulses. This method and the importance of tape uniformity will be explained in detail below.

The laser light is chopped as the wheel turns, thereby producing an on-off signal in the photodetector (Electro-Optical Systems, S-050-H/EIO photodiode/receiver module). The photodiode is shielded from the ambient light by a short length of tubing to form a lens shade. Light shielding was found to be necessary to improve signal-to-noise ratio and to prevent tripping a built-in cutoff switch when the laser light was reflected into the unshielded photodetector [6].

Signal Conditioning

Signal conditioning for the torquemeter and the photodetector will now be described. The torquemeter has a dynamic rotor and a stator component which is secured to the frame of the bicycle (See Figs.. 3, 6). The rotor consists essentially of two cylinders, one inside the other. There are strain gauges in between the two cylinders and connected to each. Changes in the strain gauge resistances are converted to a voltage via a Wheatstone bridge inside the torquemeter's stator component.

When the rotor's inner and outer cylinders are both at rest or rotating with the same constant period, no displacement occurs between them. As such, the strain gauges and Wheatstone bridge will be in balance and no voltage difference will be created. These conditions are met only when not torque is being applied to the torquemeter. Torque applied via the pedals or hand-break causes one of the cylinders to accelerate while the other cylinder tries to maintain its velocity. The resulting displacement between the cylinders deforms the strain gauges, resulting in the creation of a voltage differential in the Wheatstone bridge.

Since the strain gauges are housed inside a mass that is free to rotate, induction coils are used to transfer the bridge's driving current between the stator and rotor sections of the torquemeter. Thus, the torquemeter requires a precise, sinusoidal excitation voltage. This means that the output torque signal voltage is also sinusoidal and at the same frequency as the excitation voltage [4]. AC excitation complicates signal processing. Perhaps the greatest complication is that the direction of torque is indicated not by positive or negative voltage but by the output torque signal's phase relative to the excitation signal [4,5].

The torquemeter is driven by a BK Precision Signal Generator set to deliver a 3 kHz sine wave with a RMS voltage of 3-5V. The torquemeter accepts the excitation and outputs two different signals. The first is a mV range AC signal, referred to hereafter as "Torque (mV)". The amplitude of Torque (mV) varies with the magnitude of the applied torque. The second signal is actually the excitation signal being sent back through the cable, theoretically encountering the same impedance as Torque (mV). For this reason, the second signal was named "Impedance Matched Excitation" (IME). The IME (V) signal is used as a constant to which the Torque (mV) signal is compared.

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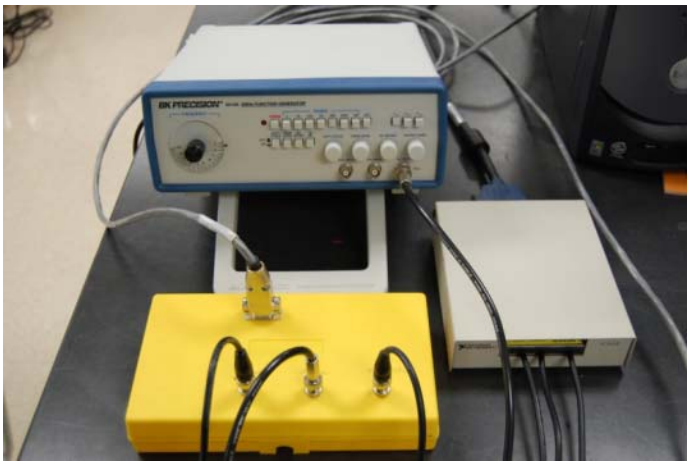

Figure 8. Signal Generator and data acquisition system

Figure 8 shows the signal generator at the top of the figure. The box to the right of the signal generator is the NI-DAQ SCB-68 connector block module. Cables carrying the IME, Torque (mV), and tachometer pulse signals are connected to the NI-DAQ Module in differential mode coupling. The yellow box at the bottom of the figure splits the category 6 shielded cable from the torquemeter into three RF cables carrying Excitation, IME, and Torque (mV) signals.

The DAQ

Both signals are routed to the National Instruments Data Acquisition Module, through which they are received by the NI-DAQ PCI-6024E card in the computer. Ultimately, the signals are read and interpreted by the LabVIEW™ software. The signal conditioning that LabVIEW™ performs will be discussed in conjunction with the tachometer signal.

Figure 9. NI-DAQ SCB-68 Connector Module.

The LabVIEW™ Interface

LabVIEW™ is a ubiquitous graphical programming platform that can be used for data acquisition, instrument control and automation by making use of the so-called Virtual Instruments (VI). The VIs have a front panel, which houses the displays and controls, and the block diagram where the various circuit components are laid out and wired. LabVIEW™ VIs can be interfaced to a large number of hardwares through appropriate buses and drivers. The present setup utilizes solely National Instruments devices for simplicity and convenience.

LabVIEW™ was used to perform all data acquisition, display and storage, as well as control functions. The user interacts with the experiment through the front panel of the virtual instrument that is displayed on the computer monitor.

The front panel is shown in Fig. 10. Each graph and indicator has a corresponding icon on the VI's back panel, shown in Fig. 11. Sections of the front panel have been numbered in Fig. 10. The Following is an explanation of each section in by number:

(10.1) Contains numerical inputs which control the Data Acquisition Assistant. The values in these fields control the frequency and duration of data points taken by the VI. See the previous section, *the DAQ*, for details.

(10.2) Displays the unprocessed input signals from the torquemeter and tachometer.

(10.3) Monitors the status and values of the tachometer's signal processing operations. The green light indicates whether or not the period finding function used to process the Pulse signal (see Fig. 13 and explanation) is functioning.

(10.4) Displays graphs of the intermediate signals created during the torquemeter's signal processing (see Fig. 12 and explanation).

(10.5) Contains graphs of the final torque and velocity measurements. The data displayed by these graphs is written to an Excel file for use in the student's individual reports.

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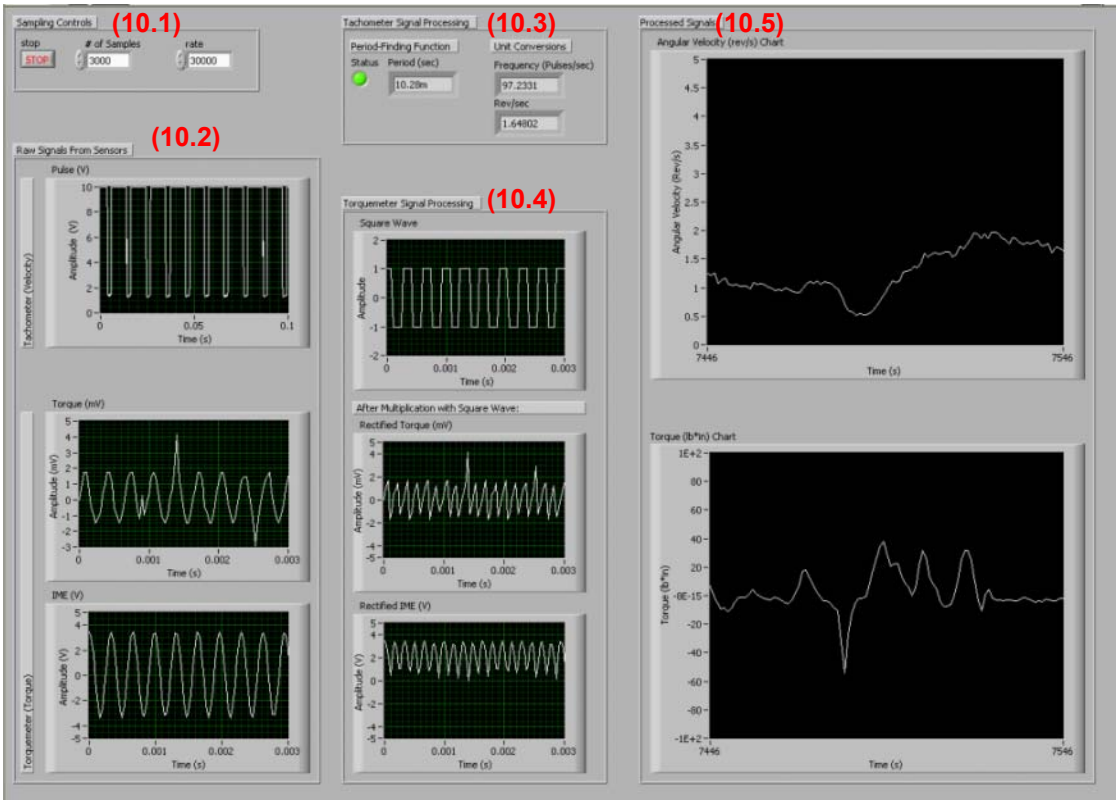

Figure 10. Front Panel of virtual instrument.

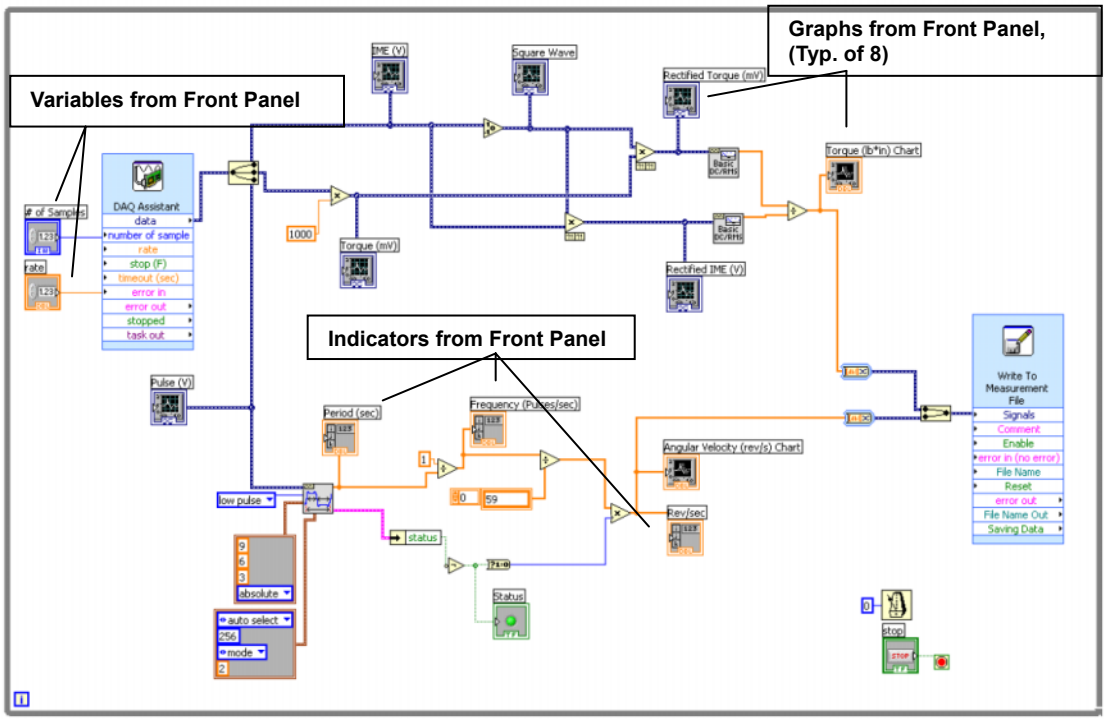

Figure 11. Back Panel of Virtual Instrument.

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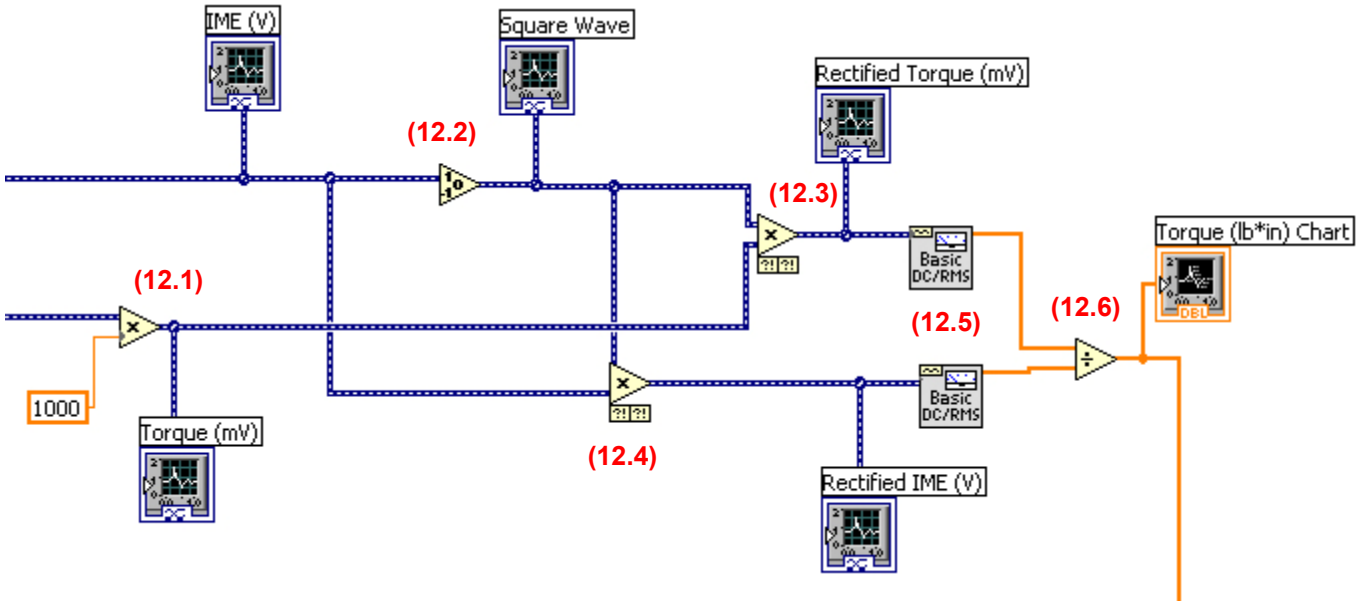

Figure 12. Torquemeter portion of VI back panel.

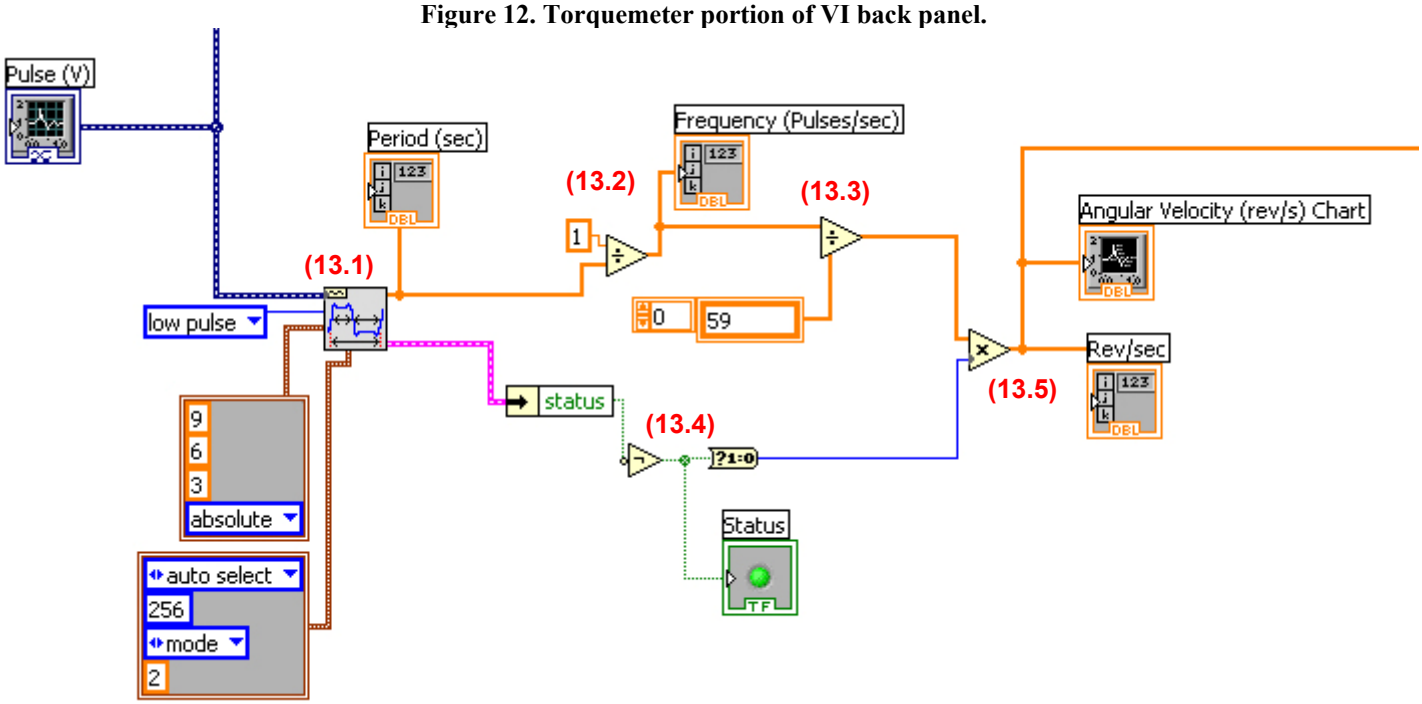

Figure 13. Tachometer portion of VI back panel.

The back panel is where most of the actual VI programming occurs and it is shown in Fig. 11. In this VI, the raw signals from the sensors are acquired by the DAQ Assistant on the left of the figure and processed by the circuit in the center. The top portion of this center block processes information from the torquemeter (Fig. 12) and the bottom portion processes information from the tachometer (Fig. 13), both of which will be described later. The single wire terminating into the large icon on the right side of the figure represents the processed data. The data are written to an Excel file through a function represented by the large icon.

Figure 12 shows the portion of the LabVIEW™ program which processes the torquemeter signal. The design of this portion of the virtual instrument incorporates concepts relating to phase-sensitive demodulation/rectification from [8, 9]. In the figure, the numbers in parenthesis highlight the important operations as follows:

(12.1) Converts the average DC value of the torquemeter from units of voltage to units of millivolts by multiply-

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ing it by 1,000. This is done so that the final value generated is in the same units as those used in the manufacturer's calibration of the torquemeter.

(12.2) Accepts the IME (V) signal and outputs a unit square-wave containing the sign (+1, 0, –1) of the original signal.

(12.3) Multiplies the Torque (mV) signal by the square wave, effectively performing a phase-sensitive rectification[9]. Product is positive for clockwise torque, negative for counter-clockwise torque. Thus the signal after this process corresponds to both the magnitude and direction of torque.

(12.4) Multiplies the IME (V) signal by the unit square wave, effectively rectifying the sense signal into an all-positive signal.

(12.5) Finds either the average-DC or the root-mean-squared value of a waveform. The process is performed on both signals to find their respective average-DC values, effectively removing the carrier frequency from the signal (demodulation).

(12.6) Divides the DC Torque (mV) value by the DC IME (V) value. This creates a final ratio, Torque (mV/V), that is directly proportional to the applied torque, but independent of the driver signal's voltage value. Thus, the final torque signal is insensitive to any voltage fluctuations caused by the sudden application of torque or other factors.

The algorithm described above is consistent with all the signal processing requirements identified by the torquemeter's manufacturer. Since the torquemeter's processed signal has a direct, linear relationship with the applied torque, a simple conversion constant is all that is needed to convert the mV/V value into torque units.

The tachometer signal is processed using the algorithm shown in Fig. 13. As with the torquemeter, the part of the VI devoted to the tachometer is described in terms of its major functions:

(13.1) Accepts the voltage signal ("Pulse") from the photodiode and calculates the waveform period. The boxes attached to the function with brown wires contain the variables used in the function. The pink wire represents the function's error information. Several criteria relating to the signal must be met before this function will operate properly. For instance, the function will not work when the flywheel is stationary, because then a periodic signal cannot be generated. See step 4 for further information.

(13.2) Finds the pulse frequency by calculating the reciprocal of the period.

(13.3) Divides the pulse frequency by the total number of tape strips on the flywheel. This gives the rotational velocity in revolutions per second (rev/s).

(13.4) Isolates the logic (Y/N) value from the error wire, then inverts it so that the value equals "Yes" when the function is operating . The error status value is then converted to binary (1/0).

(13.5) Multiplies the velocity (rev/s) value by the binary error value, so that if the function is not working properly, a value of zero is generated. The most common cause of error is a stationary flywheel, so a zero value is correct in most cases.

The values of torque and rotational velocity were acquired at the same sampling interval, which can be changed by the user. During testing, the setup generated paired torque and velocity data points at time intervals as short as 0.1 s.

RESULTS AND CONCLUSIONS

Currently, the setup is able to perform all of the minimum success criteria listed in the problem statement and specifications section. That is, a torque and a rotational signal can be obtained from the sensors mounted on the exercise bicycle in real time. These analog signals are conditioned, digitized and acquired for display and storage using LabVIEW. Key parameters are displayed on the VI front panel in real time. When required, the operator can activate a button to record a length of data into an EXCEL spreadsheet. A draft set of instructions is highlighted in Appendix A. This laboratory is presently being alpha tested. Feedback from the students and from the teaching assistants will be used to refine the laboratory.

ACKNOWLEDGMENTS

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