# A Variable-Speed Turntable for Accelerometer Performance Testing

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## Abstract

To test the static performance of MEMS accelerometers in an academic laboratory environment, a means of producing a constant acceleration is required. One method of producing a constant acceleration is with a horizontally rotating turntable with a constant rotational speed. With the device-under-test (DUT) mounted in a fixed orientation and radius from the center of the turntable, the centripetal acceleration experienced by the DUT can be established. The acceleration can then be adjusted by controlling the turntable's speed of rotation. Wireless techniques are used to transmit the measured data from the rotating surface to a stationary data acquisition system. This paper presents the design and application of a custom variable-speed turntable for use in an academic laboratory for the testing and demonstration of various types of accelerometers. The design of a custom battery-powered wireless data acquisition system to interface with the DUT is also presented. The turntable design includes many safety features that are necessary for this type of rotating apparatus. LabVIEW software to format and display the data received from the rotating data acquisition system is also presented and discussed. Accelerometer application examples and testing results are also included.

## Introduction and Motivation

Solid-state microelectromechanical system (MEMS) accelerometers are ubiquitous in modern consumer products. Among their many applications, they control the orientation of cell phone displays, monitor the vibration of home appliances, and deploy vehicle airbags in the event of a collision (Weinberg, 2009; Doebelin, 2004). In an engineering academic environment, the study of accelerometers is essential to understanding the operation of many modern systems. The concepts employed in the measurement of acceleration are well covered in engineering mechanics courses but to demonstrate their operation, a suitable testing apparatus is required.

As part of a junior-level instrumentation and measurement course in a BSME program, accelerometers are studied. Laboratory exercises involve the use very low-g MEMS accelerometers (typically less than 3g) as inclinometers (tilt sensors). This type of static application allows the accelerometers to be tested with +1g and -1g accelerations simply by changing their orientation with respect to the earth's gravitational field. This method allows for calibration of very low-g accelerometers to determine the zero-g offset and the static sensitivity of a particular device in one to three dimensions (Freescale, 2015).

To explore the static performance of higher-g accelerometers, a means for producing higher levels of constant acceleration is required. A platform rotating in the horizontal plane at a constant rotational speed, $\omega$, can be used to produce the desired constant acceleration, a, when the DUT is located at a fixed radius, R, from the center of rotation as shown in Equation 1(Halliday & Resnick, 1981). The acceleration produced by the rotating platform is the centripetal acceleration and is directed radially.

$$a = R\omega^2 \tag{1}$$

To transfer power and measurement signals to and from the DUT, a means of crossing the stationary to rotating parts must be used. Historically, slip rings were used for this purpose (Levy, McPherson, & Hobbs, 1948). Modern systems typically employ batteries on the rotating part to power the measurement system and DUT. Wireless methods, such as infrared/visible light and radio signals, are used to transmit the measurement data from the rotating to stationary equipment.

The turntable system described here was originally constructed in a rather crude manner using a thin aluminum disc bolted to the shaft of a small 3-phase induction motor. The motor was fastened to a plywood base and driven by a variable frequency drive (VFD) unit to allow the motor's speed to be varied. The motor and VFD were part of a vendor demonstration setup that was donated to the college. Figure 1 shows a photograph of the original system.

*Figure 1*. Photographs of original turntable and portable VFD.

Despite its simplistic design, the original turntable was effective for testing MEMS accelerometers in an engineering laboratory setting. A 9V battery and 5V regulator mounted near the center of the disc was used to power a PIC microcontroller and the DUT. The DUT was mounted at a carefully measured radius near the edge of the turntable. The microcontroller averaged several samples and transmitted the result via its serial port and an infrared LED. A phototransistor circuit connected to the serial port on a bench PC received the transmitted signal. LabVIEW software converted and displayed the serial data.

The rotational speed of the spinning disc was controlled with the VFD and measured with a strobe light tachometer. The centripetal acceleration experienced by the DUT could be determined using the measured mounting radius and rotational speed together with Equation 1. To obtain data for negative accelerations, the disc was stopped, the DUT was rotated 180° and remounted, and the disc was spun-up again to the desired speeds.

Although the crude system was effective for making measurements, it sorely lacked any kind of safety provisions that would make it useful except for carefully controlled demonstration purposes. The thin disc was susceptible to being bent if not carefully handled and stored. It was also not capable of carrying heavier DUT loads without flexing. Therefore, a safer, more robust design was needed. Figure 2 shows photographs of the redesigned turntable.

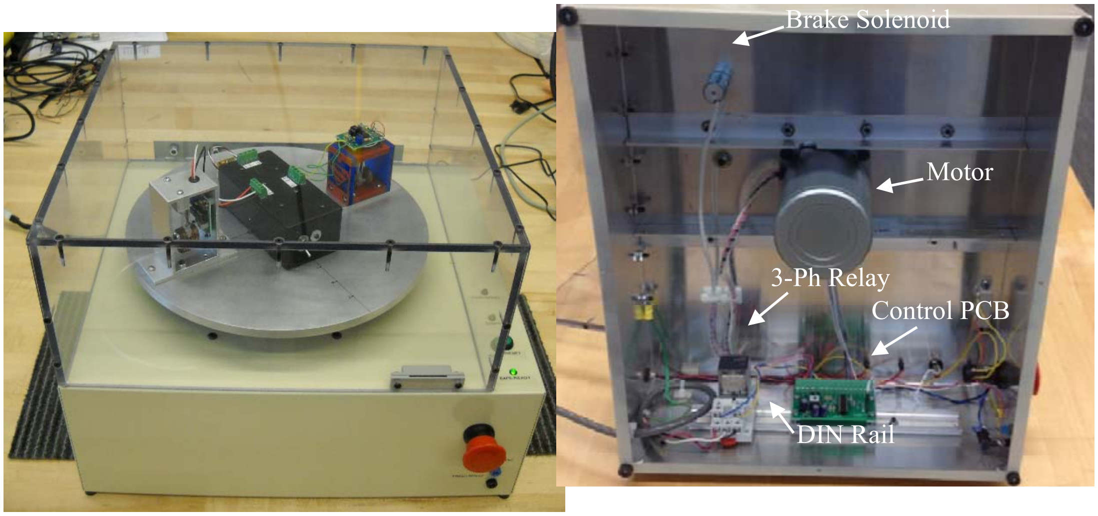


*Figure 2*. Photographs of redesigned turntable, top and bottom.

## System Design

### *Turntable and Control Electronics*

Figure 3 shows a block diagram of the new turntable control and drive system. Based on the experience with the original design, a new turntable was designed and built with several improvements:

- Thicker aluminum platter to resist bending (a heavier disc would also serve as a better flywheel to help maintain a more constant rotational speed)
- Clear, shatter-resistant safety cover with interlocks to remove motor power when the cover is lifted
- Sturdy motor mounting enclosure

- Emergency stop button
- Braking system to quickly stop the turntable
- Battery-powered measurement system with a wireless radio data link
- Over-speed shutdown
- Optical encoder for turntable speed measurement
- Reference accelerometer for comparison measurements
- Operational status controls and indictors

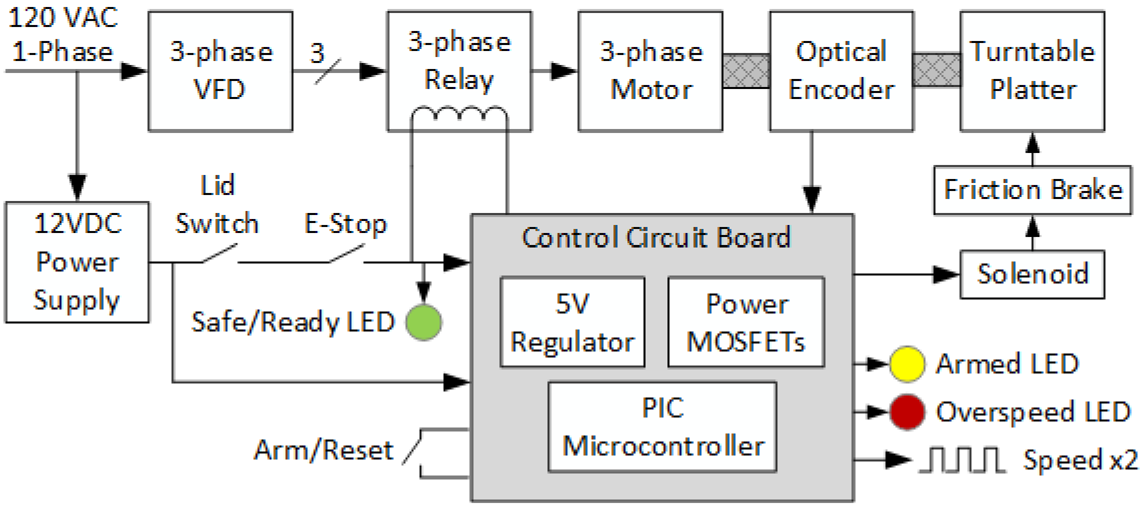


*Figure 3*. Turntable control and drive system block diagram

A turntable diameter of 12 inches and was chosen this application. Small DUTs could be mounted at a radius of five inches, which allowed accelerations of 40g to be produced at about 530 RPM. This speed is easily obtained with a small 3-phase motor and VFD. The turntable was machined from 0.375" thick aluminum in the campus machine shop. This thickness allowed tapped holes to be included for mounting the DUTs and measurement system components. A standard flange was used to mount the platter to the motor shaft. Figure 4 shows a partial assembly drawing of the turntable motor shaft apparatus.

Although the original turntable motor was adequate for the application, a new motor was purchased that had a slightly thicker shaft and provided mounting holes at the end rather than on the side of the motor. This allowed the motor to be simply mounted vertically in a sturdy 17"x 15"x 6" aluminum chassis as shown in Figure 2. A 1/8 horsepower, 3-phase, 220/230 VAC induction motor manufactured by Oriental Motor was used. The original, vendor-donated, Allen-Bradley VFD was repurposed to drive the new motor. It is housed in a rugged tote case as shown in Figure 1.

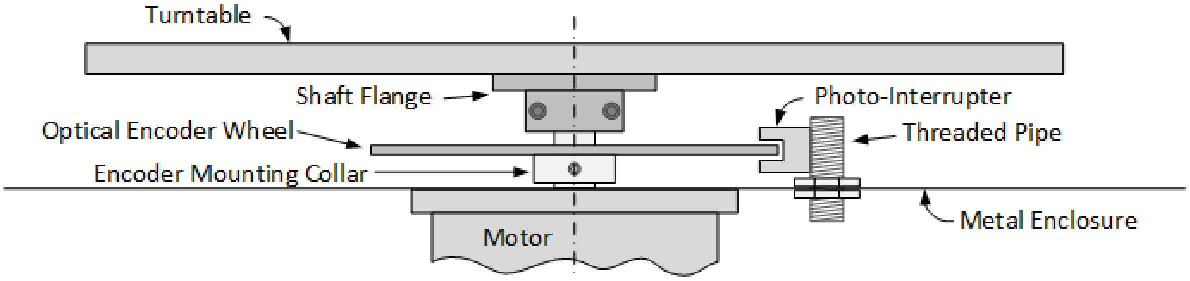


*Figure 4.* Assembly drawing detail showing shaft-mounted optical encoder.

A 0.25" thick clear polycarbonate lid provides protection from any flying objects but still allows full visibility of the turntable area. The lid is hinged at the back edge and is equipped with a magnetic reed switch at the front edge to indicate when the lid is open (open switch) or closed (closed switch). An emergency-stop (E-stop) "mushroom" switch is also mounted on the front of the system enclosure as shown in Figure 2. The E-stop is set (open switch) by simply pressing the mushroom and is reset (closed switch) by twisting the mushroom. The reed switch and E-stop are wired in series such that the lid *must* be closed and the E-stop switch *must* be reset to allow power to be applied to the 3-phase contactor coil, which controls the turntable drive motor *regardless of any other control signals from the system's microcontroller.*

A microcontroller is used to provide additional safety functions. The 3-phase relay coil is energized via a power MOSFET device controlled by the microcontroller. Another power MOSFET is used to drive a solenoid, which applies the friction brake to quickly stop the turntable. The 3-phase relay and the control circuit board are mounted to a DIN rail within the chassis as previously shown in Figure 2. The control system microcontroller software is easily up updated via the programming header provided on the PCB.

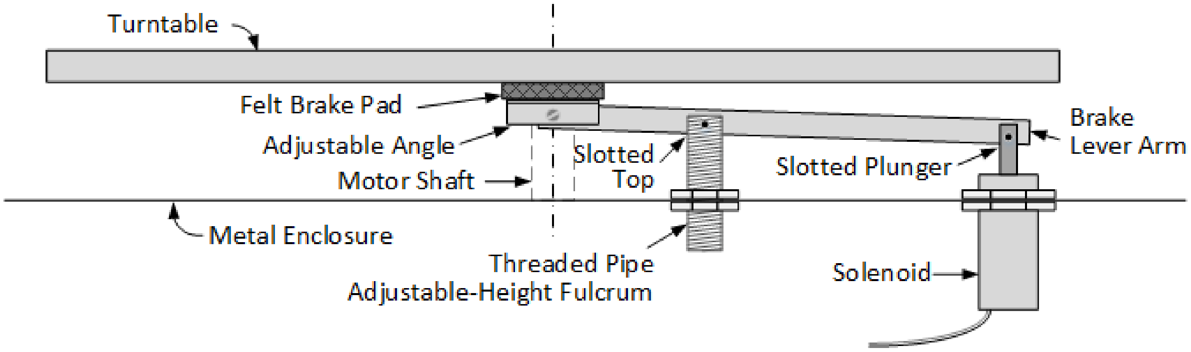


*Figure 5.* Assembly drawing detail showing friction brake mechanism.

The friction braking mechanism is mounted beneath the turntable as shown in Figure 5. When the braking solenoid is energized, it pulls the plunger down which pushes the brake pad up against the bottom of the platter at a radius of about three inches. The underside of the platter is kept clear with no obstructions at this radius. The braking friction can be changed by adjusting the height of the threaded fulcrum post.

Braking action is controlled by energizing the brake solenoid for a fixed time interval that is set in the microcontroller software. A braking interval of five seconds was found to work well for rotational speeds up to 531 PRM, which produces 40g at a radius of five inches. The main purpose of the brake is to quickly stop the turntable if the lid is lifted or the E-stop button is pressed. Another benefit of the brake is to minimize the wait-time until the DUTs and measurement system hardware can be accessed at the end of a test cycle.

The turntable speed is measured with an optical encoder wheel mounted to the motor shaft as shown in Figure 5. The encoder wheel was designed and 3D printed with the help of an undergraduate mechanical engineering student. The encoder wheel is five inches in diameter, 1/16" thick ABS plastic, and contains 120 slits near the outer edge. The wheel is mounted to the motor shaft using a standard shaft collar arrangement. With 120 slits, the frequency of output pulses of the associated photo-interrupter is numerically equal to twice the speed of the motor in revolutions per minute as described by Equation 2.

$$\left(\frac{120\,pulses}{1\,rev}\right)\left(\frac{n\,rev}{1\,min}\right)\left(\frac{1\,min}{60\,sec}\right) = 2n/sec \tag{2}$$

The embedded microcontroller's software serves as a state-machine that implements the state diagram shown in Figure 6. The primary function of the microcontroller is to ensure safe operation of the turntable. As previously described, the safety lid and E-stop switches can independently de-energize the 3-phase relay. The microcontroller, however, will not allow the relay to be re-energized until both of these switches are closed ***and*** the Go/Arm button has been pressed. A timed braking interval is also applied by the microcontroller upon either the safety lid opening or E-stop switch activation events and the system is returned to the starting point, STATE 0.

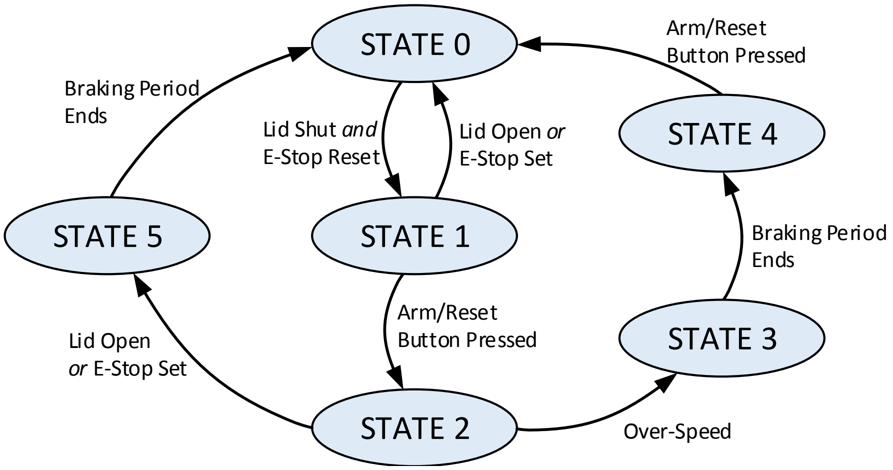


*Figure 6.* State diagram of embedded turntable control software.

The microcontroller continually measures the speed of the turntable by counting pulses from the optical encoder. If the number of pulses exceeds the programmed over-speed threshold, the 3-phase relay is de-energized and the braking interval is initiated. The system is then returned to the starting point, STATE 0. The over-speed threshold is set to an appropriate value based on the current application of the turntable.

*Measurement System*

The measurement system is battery powered and mounted at the center of the rotating turntable as shown previously in Figure 2. The nominal 6V battery voltage is produced by four AA alkaline cells. A low-dropout (LDO) 5V regulator provides the voltage used by the PIC microcontroller that performs the 10-bit analog-to-digital (A2D) conversions of the DUT output signal(s). The 5V LDO also powers the DUT, as needed. A separate 3.3V regulator produces the supply voltage for the Xbee wireless transceiver, which is used to transmit the measured data from the turntable-mounted measurement system to the stationary computer. The Xbee XB24-ACI-001 device was used in the turntable system. This device is now obsolete and has been replaced by a similar device, XB24-AWI-001 (Digi, Xbee, n.d.). Figure 7 shows a block diagram of the measurement system while Figure 8 shows a photograph of the system with the lid removed and flipped. The bulk of the electronics are mounted on the underside of the lid as shown in Figure 8.

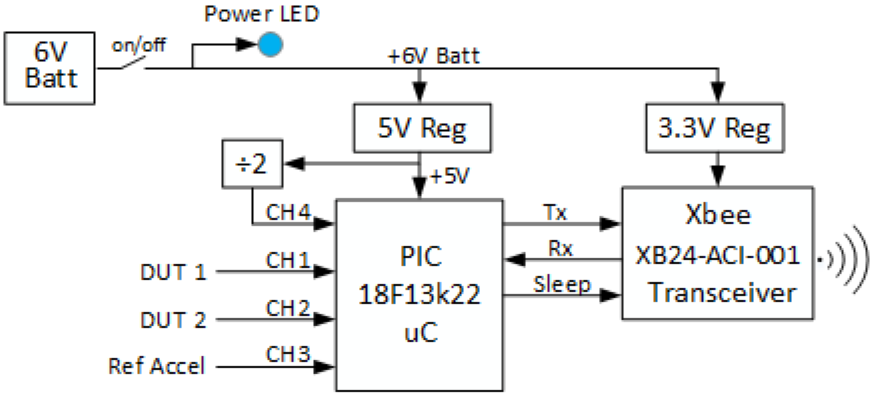


*Figure 7*. Turntable-mounted measurement system block diagram.

The measurement system microcontroller performs a 10-bit A2D conversion on each DUT output voltage, the reference accelerometer output voltage, and the 5V regulator output voltage (through a resistive voltage divider circuit). 64 equally spaced measurements are performed on each channel during a two-second interval. The average value for each set of 64 measurements is computed and the results are sent out the serial port at 9600 baud to the Xbee transceiver. To conserve battery energy, the microcontroller wakes the Xbee just long enough to transmit the measurements (about 30ms). The PIC 18F13k22 microcontroller was programmed in C using the Microchip xc8 compiler and MPLAB X IDE (Microchip, 1998-2018).

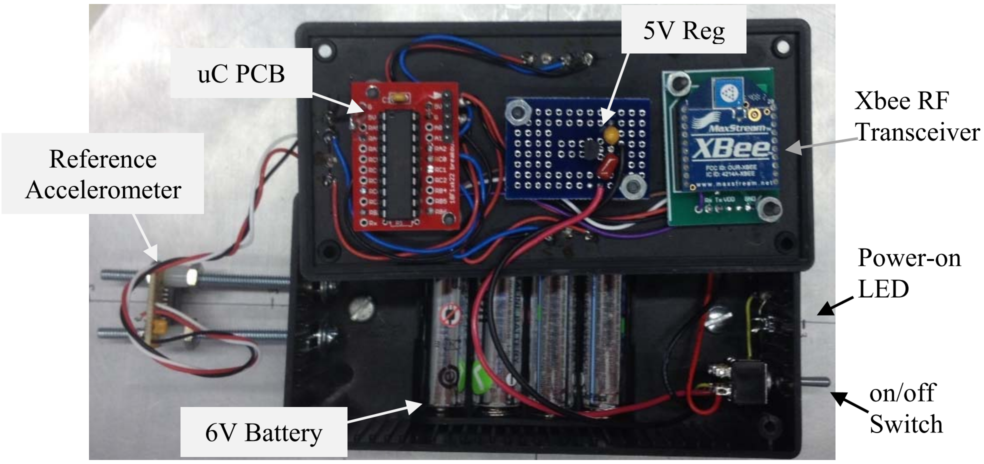
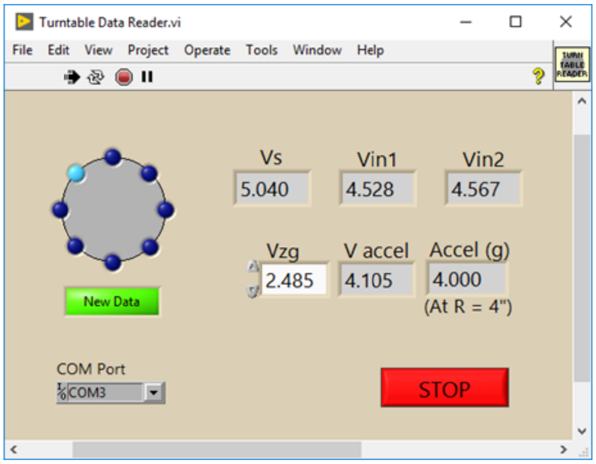


*Figure 8*. De-lidded turntable-mounted measurement system.

The paired Xbee device receives the data burst and conveys it to a PC via USB connection. LabVIEW software on the PC is used to read the data bytes and reassemble them into the original measure values that are then displayed as shown in Figure 9. The Xbee devices were programmed using the Digi XCTU application (n.d.).



Vs 5.040
Vin1 4.528
Vin2 4.567
Vzg 2.485
V accel 4.105
Accel (g) 4.000
(At R = 4")
COM Port COM3

*Figure 9*. LabVIEW front panel for accelerometer data display.

The reference accelerometer is mounted on an adjustable threaded mechanism such that it can be precisely placed at a given radius on the turntable. The output voltage of the reference accelerometer is used to determine the acceleration experienced by the DUTs. A Freescale MMA1250 +/-5g accelerometer is used for the reference device.

## Example Applications

The initial application of the turntable was to test the performance of a student accelerometer design project. Mechanical engineering students in a third-year instrumentation and measurement course were tasked with designing and building a ±4g accelerometer using a load cell beam as the sensing element (Litwhiler, 2018). The students could calibrate their instruments over a ±1g range by simply changing the device orientation with respect to earth's gravity. However, to test the full-scale range performance of their designs, the turntable was used to produce the required 4g acceleration.

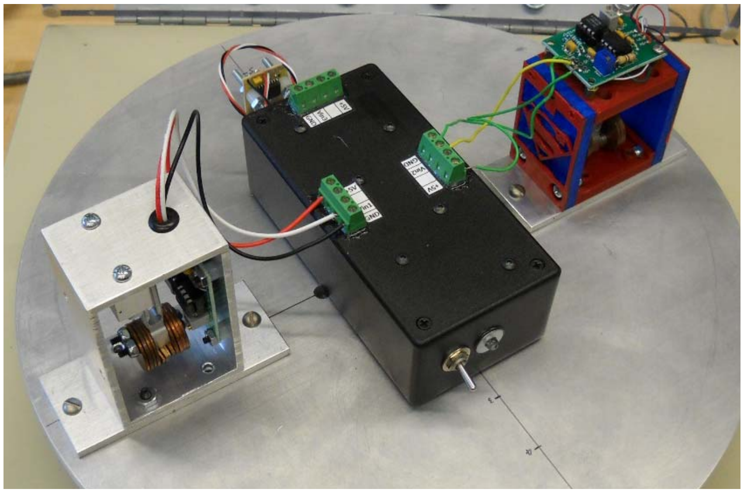


*Figure 10.* Two DUTs mounted to turntable and connected to measurement system

Two DUTs could be mounted and tested simultaneously as shown in Figure 10. Each DUT was mounted to an aluminum footplate, which was then secured to the turntable's tapped mounting holes. This "personality" footplate mounting technique avoids the need for drilling new holes in the turntable for each new application or requiring that each application conform to the existing turntable hole pattern.

The turntable rotational speed to produce 4g acceleration at a radius of 4 inches is approximately 188 RPM. The student project requirements stated that their design must tolerate an acceleration of ±6g without exceeding the limits of any component. 6g acceleration at a radius of 4 inches is achieved with a speed of approximately 230 RPM. At this speed, the optical encoder produces 460 pulses per second. The microcontroller uses an aperture time of 0.1s therefore 46 pulses are counted at 230 RPM. Thus, for this application, the over-speed threshold is set at 46 counts. If this threshold is exceeded, the 3-phase relay is de-energized, and the braking interval is commenced.

*Table 1.* Turntable and reference accelerometer example data.

| Nominal Accel. | VFD Frequency | Turntable Speed | Calculated Accel. at 4" | Ref. Accel. Output | Ref. Accel. Acceleration |
|---|---|---|---|---|---|
| 0 g | 0 Hz | 0 RPM | 0 g | 2.485 V | 0.004 g |
| 1 g | 4.07 Hz | 94 RPM | 1.004 g | 2.885 V | 1.001 g |
| 2 g | 4.90 Hz | 133 RPM | 2.009 g | 3.285 V | 1.999 g |
| 3 g | 5.72 Hz | 163 RPM | 3.018 g | 3.698 V | 3.032 g |
| 4 g | 6.51 Hz | 188 RPM | 4.014 g | 4.105 V | 4.050 g |

The DUTs were tested at rotational speeds to produce nominal accelerations of 1g, 2g, 3g, and 4g at the 4-inch radius where the DUTs were mounted. The frequency of the VFD was adjusted while monitoring the output of the calibrated reference accelerometer to determine the actual acceleration experienced by the DUTs. The turntable was then stopped to allow the DUTs to be rotated 180° about the 4-inch radius mounting point so that acceleration in the opposite direction could be tested. Table 1 and Figure 11 show examples of data from this application.

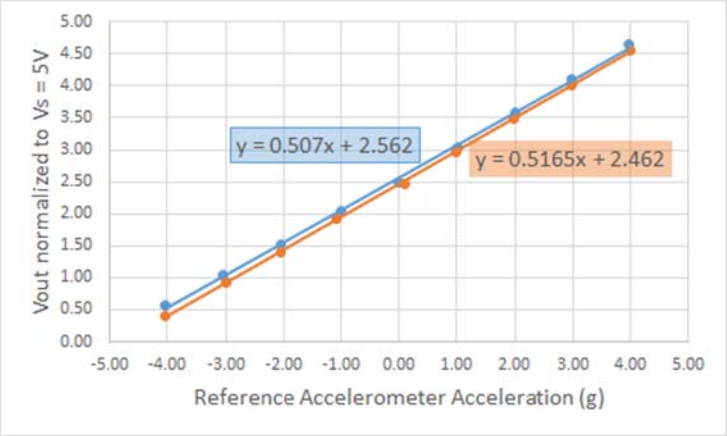


*Figure 11*. Plot of turntable test data for two student-built accelerometers.

Another application of the turntable is for demonstration of MEMS accelerometers for engineering and engineering technology students. To increase the visual impact of the test system and to help students appreciate the relationship between rotation and centripetal acceleration, a 40-g accelerometer is used. The Freescale (now NXP) MMA2201D device mounted to a PCB is used for this demonstration. Figure 12 shows two DUTs mounted to polycarbonate personality plates on the turntable at a radius of five inches. For this application, the applied acceleration is determined by rotational speed measurement without a reference accelerometer.

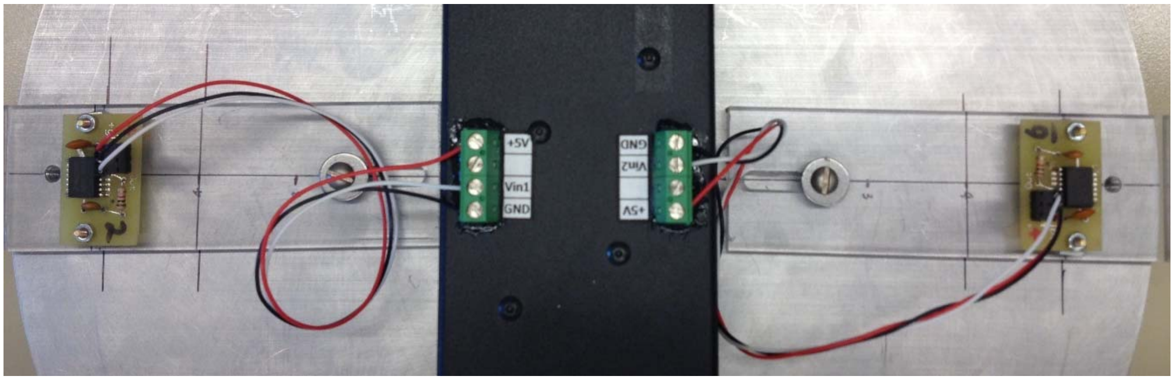


*Figure 12*. MMA2201D accelerometers mounted to turntable.

To produce a centripetal acceleration of 40g at a radius of 5 inches, a rotational speed of 531 RPM is needed. To allow this speed on the turntable, the over-speed shutdown threshold was set to 550 rpm. This was done by changing the microcontroller software such that 110 counts during the 0.1s aperture time would initiate the power disconnect and braking interval.

To measure the speed of rotation, a Fluke model 187 DMM was used to measure the frequency of the optical encoder output pulses. The rotational speed was adjusted via the VFD to obtain the desired acceleration. Table 2 shows example data from this test.

*Table 2*. Turntable data from tests to produce up to 40g acceleration.

| Nominal Acceleration | Required Nominal Speed | VFD Frequency Setting | Optical Encoder Frequency | Resulting Acceleration at 5" Radius |
|---|---|---|---|---|
| 10 g | 265.4 RPM | 9.04 Hz | 530 Hz | 9.97 g |
| 20 g | 375.3 RPM | 12.58 Hz | 750 Hz | 19.96 g |
| 30 g | 459.7 RPM | 15.29 Hz | 919 Hz | 29.98 g |
| 40 g | 530.8 RPM | 17.71 Hz | 1062 Hz | 40.03 |

## Uncertainty Analysis

The uncertainty in the acceleration experienced by a DUT on the turntable can be estimated by examining Equation 1. The propagation of uncertainty from the measured quantities (radius and rotational speed) to the result (acceleration) is determined by the sensitivity of the result to each of the parameters. The sensitivity is found by taking the partial derivative of the result with respect to each measured quantity. The uncertainty in each measured quantity ($u_r$, $u_n$) is then weighted by their respective sensitivity. The overall uncertainty in the result is then found by combining the components in an RSS manner (Figliola & Beasley, 2015). Starting with Equation 1 converted such that the radius is in inches, the rotational speed is in rpm, and the acceleration is in g:

$$a = (2.839 \times 10^{-5}) r n^2 \tag{3}$$

The uncertainty in the acceleration can then be found as follows:

$$u_a = \pm \sqrt{\left(\frac{\partial a}{\partial r} u_r\right)^2 + \left(\frac{\partial a}{\partial n} u_n\right)^2} \tag{4a}$$

$$u_a = \pm 2.839 \times 10^{-5} \sqrt{(n^2 u_r)^2 + (2rnu_n)^2} \tag{4b}$$

The uncertainty in the rotational speed of the turntable relates to the ability to accurately count pulses from the optical encoder during a fixed aperture time. Using a Fluke model 187 DMM to measure the frequency of the optical encoder output provides an accuracy of ±(0.005% of reading + 1 count) (Fluke, 2002). As shown in Equation 2, the encoder output frequency is *twice* the value of the rotational speed in rpm. Therefore, the uncertainty in the rotational speed can be estimated to be about ±1 rpm.

The uncertainty in the measured radius relates to both the ability to accurately place the DUT on the turntable and the location of the active sensing element within the DUT (IEEE, 2009). For the purpose of this analysis, it is assumed that the DUT can be placed at a known radius to within ±0.05".

For small surface-mount MEMS accelerometers, the package size is on the order of 0.15" square. Therefore, the uncertainty in the location of the sensing element within the package is less than 0.075". Combining these uncertainties in an RSS manner results in ±0.09" uncertainty in the radius or rotation.

Larger accelerometers such as the one designed by the engineering students are subject to higher uncertainty in the position of the center of the seismic mass that loads the sensing element. For this analysis, the uncertainty of the center of mass will be assumed to be on the order of ±0.1". Once again, combing this uncertainty with that of DUT placement in an RSS manner results in an uncertainty of ±0.11" in the radius of rotation.

The overall uncertainty in the applied acceleration for some example combinations of radius and rotational speed are shown in Table 3.

*Table 3.* Applied acceleration uncertainty examples.

| Radius | Rotational Speed | Nominal Acceleration | Acceleration Uncertainty, $u_a$ |
|---|---|---|---|
| 4.0 ± 0.11" | 94 ± 1 RPM | 1.004 g | ±0.035 g |
| 4.0 ± 0.11" | 188 ± 1 RPM | 4.014 g | ±0.118 g |
| 5.0 ± 0.09" | 84 ± 1 RPM | 1.002 g | ±0.030 g |
| 5.0 ± 0.09" | 531 ± 1 RPM | 40.03 g | ±0.736 g |

## Future Work and Improvements

The turntable has proven to be very useful and will continue to be modified and improved to meet the needs of the engineering courses and projects. The measurement system hardware can easily be modified to allow testing of accelerometers with digital interfaces (I2C, SPI). The measurement system software can easily be modified to include two-way communication with the PC. This will allow the user to make changes to the measurement configuration while the turntable is in motion (such as changing the measurement range of a DUT with a digital communication interface). Other faculty have also expressed interest in using the turntable to test/calibrate more complex inertial measurement units.

## Conclusion

The re-designed turntable centrifuge incorporates several improvements in safety, ease of use, and quality of construction. The safety features allow the system to be used more confidently by students and faculty. The turntable and measurement system controls are intuitive and easy to connect and use. The new turntable platter and metal chassis provide a very sturdy and robust platform on which to test accelerometer devices. The quality of materials and construction have also produced a test apparatus that allows for highly repeatable measurements.

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## Biography

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