AC 2009-439: TIME-KEEPING EXPERIMENTS FOR A MECHANICAL ENGINEERING EDUCATION LABORATORY SEQUENCE

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Time Keeping Experiments for a Mechanical Engineering Education Laboratory Sequence

Abstract

The evolution of science and technology throughout history parallels the development of time keeping devices which assist mankind in measuring and coordinating their daily schedules. The earliest clocks used the natural behavior of the sun, sand, and water to approximate fixed time intervals. In the medieval period, mechanical clocks were introduced that were driven by weights and springs which offered greater time accuracy due to improved design and materials. In the last century, electric motor driven clocks and digital circuits have allowed for widespread distribution of clock devices to many homes and individuals. In this paper, a series of eight laboratory experiments have been created which use a time keeping theme to introduce basic mechanical and electrical engineering concepts, while offering the opportunity to weave societal implications into the discussions. These bench top and numerical studies include clock movements, pendulums, vibration and acoustic analysis, material properties, circuit breadboards, microprocessor programming, computer simulation, and artistic water clocks. For each experiment, the learning objectives, equipment and materials, and laboratory procedures are listed. To determine the learning effectiveness of each experiment, an assessment tool will be used to gather student feedback for laboratory improvement. Finally, these experiments can also be integrated into academic programs that emphasize science, technology, engineering and mathematical concepts within a societal context.

1.0 Introduction

The common clock, whether mechanical, electric or electronic, represents a dynamic system whose precision and sophistication has evolved with society as well as the interpretation of time. A clock generally contains a host of scientific and engineering principles which make them an ideal system for study by students since they represent practical real world applications. The span of clock technology includes physics (pendulums), fluids (water, sand), metallurgy (springs, cases), mechanisms (gear trains, levers), thermodynamics (air or Atmos clock), feedback control (escapement), mathematics (harmonic motion), electric motors, electronics (clock chip), computer programming (digital clock), and radioactive decay (atomic clock). Time keeping devices fulfill an important societal by allowing the coordination of personal, commerce, and transportation activities. It has been suggested by Mumford[1] that "the clock, not the steam engine, is the key machine of the modern industrial age". Given the familiarity and general knowledge of clocks by students and people of all ages, these time keeping devices represent an ideal medium for engineering discovery and creativity through focused laboratory experiments.

A short review of selected mechanical engineering education laboratories and clock learning materials will be presented. Knight and McDonald[2] discussed the senior level mechanical engineering laboratory at the University of Tennessee which seeks to balance mechanical and thermal system experiments. The identification of learning objectives within the mechanical engineering laboratory sequence at Rose-Hulman Institute of Technology has been addressed by Layton *et al.*[3]. Yoder *et al.*[4] discussed a revised senior control systems engineering laboratory with student assessment at Ohio Northern University. A required University of Texas at Arlington mechanical and aerospace engineering laboratory course offers an experience which focuses on data acquisition techniques and uncertainity analysis while reinforcing theory introduced in the classroom[5]. Chastain *et al.*[6] introduce and assess a senior undergraduate laboratory at Clemson University that features open ended dynamic systems, thermal/fluid, and material based experiments to observe and analyze theory in action.

An interesting article was written by Bernstein[7] which discusses the presence of feedback control in history with examples such as the clock escapement, centrifugal governor, aircraft aileron, gyroscope, and feedback amplifier. Wagner *et al.*[8] reviewed the operational behavior of an eight day mechanical clock through mathematical models, numerical simulation, and computer animation for dynamic system studies. A series of five laboratory and simulation experiments were report by Burchett *et al.*[9] which emphasize fundamental concepts in dynamic systems including a swinging pendulum whose bob is located to offer maximum angular velocity. Delson[10] discussed the use of a model clock project for students to analyze and fabricate a pendulum and escapement wheel with integration into a clock[11]. In terms of K-12 audiences, the National Science Resources Center developed the measuring time (life & earth sciences) curriculum model (grade 6) within the science and technology for children program. A series of sixteen lessons were available including “Keeping Time with the Sun and Moon” and “Investigating Invented Clocks” with three laboratory experiments (sinking water clock, pendulums, escapement)[12]. Finally, Kolberg *et al.*[13] developed a high school mechatronic course to improve perceptions of technology, design skills, and basic science (mathematics, physics, and chemistry) capabilities. Clearly, an opportunity exists to structure a learning sequence about time keeping systems which have evolved with technical achievements.

A series of eight experiments are presented within the paper that can serve as the basis for a sequence of horology inspired laboratory investigations that may be matched with societal issues to reinforce the bridge between technology and humanity. The laboratory studies can be broadly classified into three segments – physics/mechanics concepts, material and fluid properties, and electronics with computer programming with accompanying bench top instrumentation (except for the numerical study) and general laboratory skills. In the first segment, three introductory mechanical inspired experiments are proposed. The operation and mechanical analysis of a key wound mechanical clock (LAB I) establishes a foundation for time keeping study and clearly displays the use of gears to convert spring driven rotational motion into pendulum oscillation. The second laboratory (LAB II) investigates classical swinging and Coulomb torsional pendulums to allow demonstrate periodic motion and the relationship of fundamental mathematical descriptions to physical motion that occurs in nature. The vibration modes of a chime rod (LAB III) allow the study of vibration concepts which encourages the consideration of the relationship between harmonic vibrations and musical notes.

The second segment introduces three experiments regarding the mechanical properties of clock spring steel and operation of water clocks. The heat treatment of steel contained in spring barrels (LAB IV) allows material properties such as surface hardness and stiffness to be modified and directly measured. A numerical study of fluid flow in cascaded water reservoirs, in a manner similar to ancient water clocks, establishes the basis for computer simulator activities (LAB V). Next, a Gitton water clock (LAB VI) provides an example of fundamental fluid mechanics principles with the opportunity for laboratory validation and computer study as well as the realization that art inspired clocks can be created using engineering principles. The third and final segment contains two electronic experiments. A voltage controlled oscillator electric circuit (LAB VII) is created on a breadboard to demonstrate that oscillatory behavior can also be realized using electronics with similar governing equations. Finally, LAB VIII develops a microprocessor (BASIC Stamp) computerized clock system with solenoid operated chime rods that can sound a user-programmed melody for mechatronic system integration studies.

The paper is organized as follows. In Section 2, the intertwining of time keeping technology and society will be reviewed with an emphasis on human innovation. The eight laboratory exercises are discussed in Section 3 in terms of pedagogy and assignment details. In Section 4, laboratory assessment activities will be reviewed. Finally, the summary is contained in Section 5.

2.0 Technology and Societal Perspectives on Horology

The history of clock technology is intertwined with society's need for continual improvements in timekeeping[14]. The word clock itself is derived from the word *clocca* or bell, relating to a strike mechanism that would announce an interval of time. In 1400 BC, water clocks (clepsydras) were created to improve time keeping without the sun by using a known amount of water flow[15] as shown in Figure 1. Early water clocks involved simple containers that dripped water at a constant rate. Later versions were more advanced, using an upper reservoir and allowing only a slow flow of water into a tall and thin lower metered reservoir for accurate measurement. Around 725 BC a Chinese polymath, Su Sung, built a mechanical clock tower which used a water driven escapement to power the clock[16].

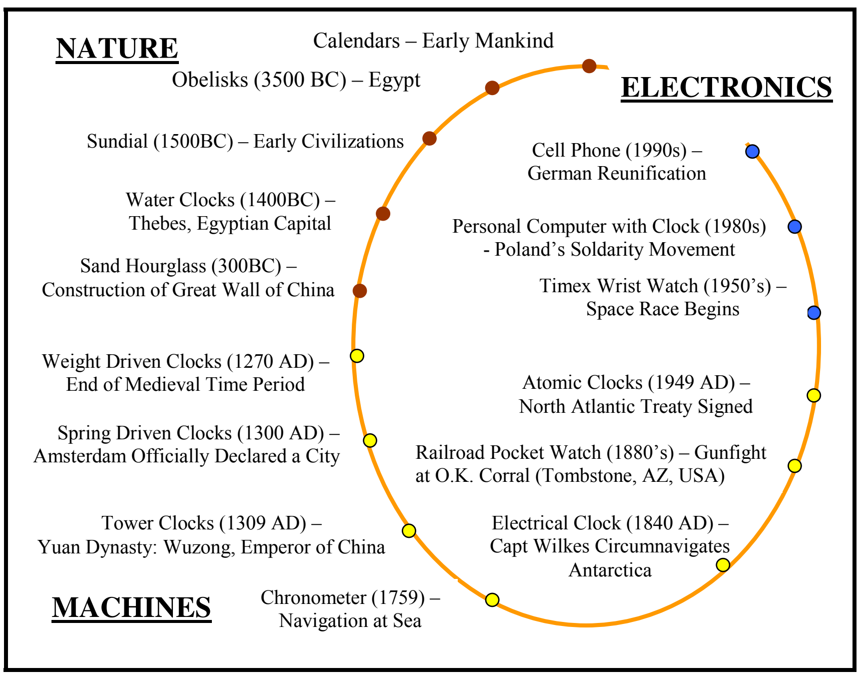

Figure 1: Evolution of clock systems with significant historical events

A significant advancement in clock evolution occurred in the 1300s with the introduction of large weight powered mechanical clocks[15]. These public clocks did not display time but rather rang a bell every hour and used gears controlled by an escapement to govern the speed. These clocks used a verge-and foliot escapement, which was used for more than 300 years, however, had many problems associated with the period of oscillation dependent on the driving force and friction, making these types of clock difficult to regulate[15]. In the early 1500s, Peter Henlein of

Nuremberg, Germany developed coiled springs that enabled clockmakers to shrink the size and weight of the clocks. In 1656, Christian Huygens created the first pendulum clock. The addition of a pendulum to regulate the escapement speed improved clock accuracy to within seconds a day versus minutes in earlier types. Through the early 1800s, clocks had remained expensive due to the limitations of custom manufacturing. However, Eli Terry created machines that could mass produce identical clock components which lowered the cost of a clock and made it affordable for more people to own[17]. The introduction of electricity near the turn of the last century allowed the replacement of mechanical drives with electric motors to move the clock hands. This major technology leap occurred in 1929 when the vibration of a quartz crystal was used for time measurement[18]. When a small electric current is applied to quartz, the crystal vibrates at a constant frequency which can be monitored. The last technological development of clocks was the development of the atomic clock in the 1950s using cesium atoms. The cesium atom's natural frequency was accurate enough to be incorporated into the National Institute of Standards and Technology's official timekeeping system and recognized as the new international unit of time in 1967, replacing the old second which was based on the Earth's motion.

Much of modern life has come to depend on precise time (Cipolla, 1967). The day is long past when society could function with a timepiece accurate to the nearest quarter-hour. For instance, transportation, communication, financial transactions, manufacturing, electric power and many other technologies have become dependent on accurate clocks[18]. With this necessitated precision timekeeping have come societal controversies with timekeeping. Several social debates are highlighted below that can accompany the laboratory investigations.

Time Measurement Attitudes: As mechanical clocks became more numerous in Europe in the fourteenth century, they brought about with them a change in attitude towards the measurement of time[14]. Villagers had been used to hearing bells toll to signify events from celebrations to call to arms to pray time, but when the mechanical clock was added now people knew the hour as well. Since public clocks were very expensive to build and maintain, the decision to build a clock was of great debate for townspeople. Once the decision to build a clock was reached, the design and size of the clock created further debate as towns rivaled others for having the right to claim their town's clock the best and the biggest clock.

Factory Work Hours: With the industrial revolution in America, a strict time schedule came for factory workers. This is the first time the clock was used to signal the start and end of the workday[15]. To maximize work time, mangers of factories were known to tamper with the clocks to get more work than agreed upon out of the workers. There were several instances throughout New England and in New York City, where workers rose up against their employers to fight against management corruption of time[18].

Sunday Work Protests: In early 1800 in America, a group of activists known as Sabbatarians started a movement to protest Sunday work. As Sunday had always been held as a day of rest, the Sabbatarians felt that commerce and industry were threatening God's authority over time and creating their own time. They protested against the United States Postal Service's transportation of mail on Sunday, the railroad industry running trains, and libraries/museums being open to the public. They even protested against whalemen working on Sundays. This protest was the first in America to demonstrate the efficiency of volunteer organizations for activism[18].

Standard Time: Before the railroad industry's development of standard time, each community on the railroad in the late 1800s was the driving force for the country to accept a uniform standard time, so that the trains could operate on time and avoid collisions because of differences in local times. The switch however, to a standard time did not come without opposition. People living along boundary zones noticed that the sun and their clocks were widely different and did not like living by an artificial time. Also, the railroad industry was one of the most powerful industries of the time and many saw the standard time as an abuse of their power and corruption of political officials to accept railroad time[18].

Daylight Saving Time: Daylight Saving Time (DST) was adopted in the United States during WWI. As soon as the war ended, numerous protests, mostly from farmers, caused Congress to repel the act. DST was again enacted during WWII. From 1945 to 1966, there was no federal law regarding DST, so states and localities were free to choose whether or not to observe DST and could choose when it began and ended. This understandably caused confusion, especially for the broadcasting industry, as well as for railways, airlines, and bus companies. President Nixon signed into law the Emergency Daylight Saving Time Energy Conservation Act of 1973, returning the concept of daylight saving time on a national level. There has always been opposition to daylight saving time, with some states or parts of states refusing to observe it. Those working in the agricultural industry have always been the most vehement opposers of it and there has always been debate as to whether or not it saves energy[18].

The history and controversies of time keeping can be integrated into the laboratory experiments. Mumford[1] stated that "… the clock was the most influential of machines, mechanically as well as socially" which invites an accompanying societal perspective to the planned exercises. The bench top experiments to be discussed in Section 3 can be integrated with the above societal issues to encourage both technology exploration as well as social awareness of how time and timekeeping has impacted our societal structure. As an example, students in the laboratory might explore the vibrations and acoustics of chime rods in clocks and then be able to explore societal aspects of the use of bells and gongs in public clocks during the Middle Ages and American industrial revolution in an accompanying study/paper for a companion history or English course.

3.0 Time Keeping Experiments

A series of eight bench top experiments and simulation studies have been created based on a horology (time keeping) theme. Although not exhaustive, these laboratory and analytical investigations range from elementary to technically challenging to accommodate a wide student audience. As shown in Table 1, the laboratory assignments have been summarized in tabular format to highlight some of the pedagogical opportunities in terms of measurement techniques, data acquisition, computer programming, modeling, design of experiments, and other. These assignments can be modified as needed to emphasize different pedagogical aspects and selected to offer comprehensive coverage of key learning criteria. The eight laboratory experiments will now be briefly discussed to provide insight into the general background, learning objectives, equipment, and class room procedures.

3.1 Operation and Gear Train Analysis of a Key Wound Mechanical Clock (Lab I)

A spring driven mechanical clock mechanism (springs removed for safety) will be disassembled/assembled to analyze the time and strike gear trains, study the train ratio, and measure the output torque and speed with comparison to calculated results.

Background: Clocks are used throughout the world to measure and keep track of time. Mechanical clocks (refer to Figure 2) rely on four principles to make them functional. First, every clock has to be powered and the most common ways for powering mechanical clocks are coiled (key wound) springs and falling weights. Coiled springs have an advantage over weights because they don't require a lot of space and therefore, they make possible portable clocks and watches. In most of these designs, the spring is wound up on one of the wheels in the clock that is meshed with the rest, thus driving the whole mechanism. As the spring is unwound, it releases power that is transmitted through the gears to the escapement. Second, an escapement mechanism[19] must be present in every clock design since its function is to create periodic motions or equal intervals of power burst that are delivered to the gear train to keep time. Third, the gear train consisting of set of gears controls and reduces the speed of rotations between the power transferred to the clock and the output indicators. Finally, the last operating principle of the clock deals with displaying the output of the clock's function. The dial usually consists of 12 hours, 60 minutes, and 60 seconds that are equally spaced within 360° of rotation.

No	Title and General Concepts	Meas Tech	Data Acq	Computer Program	Modeling /Analysis	DoE
1	Clock Operation - gears, torque, force	X			X	
2	Pendulum - inertia, period, integration	X	X		X	X
3	Chimes – freq response, acoustics	X	X	X	X	
4	Steel Material – hardness, heating	X				X
5	Fluid Simulation – modeling, response			X	X	
6	Water Clock – manometer, siphon	X			X	X
7	Electric circuits - response, debugging	X			X	
8	Mechatronic Clock – programming		X	X		

Table 1: Summary of learning concepts and pedagogy (measurement techniques, data acquisition, computer programming, modeling, design of experiment) for each experiment

Learning Objectives: The student will gain an appreciation for fundamental engineering concepts through the understanding of mechanical clock components, measurement of gear dimensions, potential and kinetic energy, and output torque and speed comparisons using various weights and accompanying numerical calculations based on simple models.

Equipment and Materials: An eight day reproduction kitchen style brass movement, clock stand, calipers, small weights, ruler, and calculator.

Laboratory Procedure: A six step sequence is suggested for students to review, disassemble, inspect, measure, and then re-assemble the clock mechanism to learn about fundamental mechanical engineering concepts.

1. Inspect clock movement and note the general position of various components; remove fasteners holding together clock plates and front plate after removing escape wheel/verge.
2. Record the location of each gear; remove and inspect the gears. Measure the necessary gear dimensions for further analytical analysis.
3. Re-assemble the gear train and front plate with fasteners; ensure proper operation.
4. Use the fabricated clock stand with the supplied identical time side gears; attached lever arms and add weights on the input and output shafts to balance the mechanism.
5. Complete necessary calculations required to determine the output torque analytically and compare results with gear teeth, lever arms, and input weights.

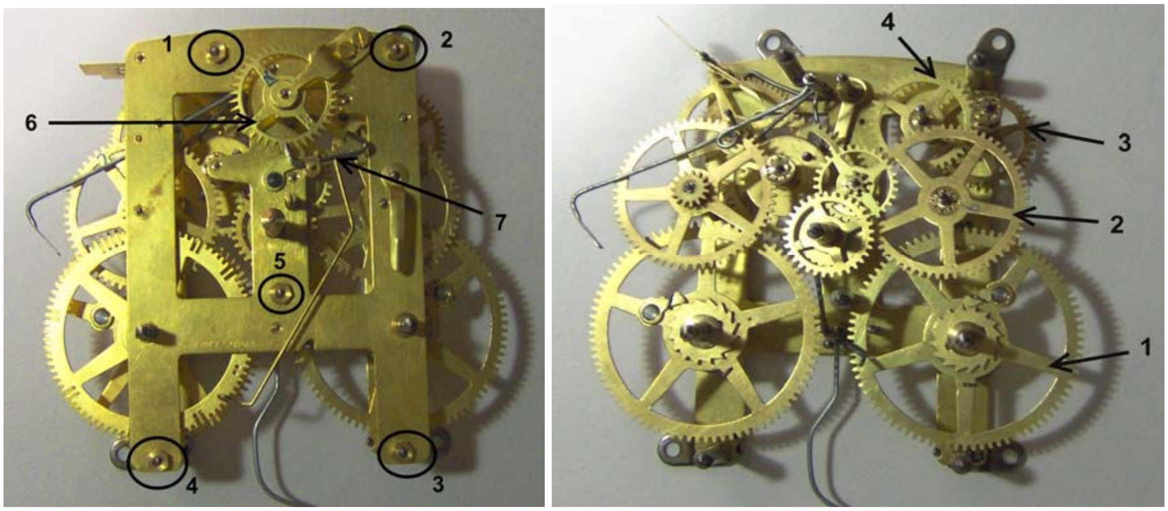

Figure 2: Assembled and internal components of a clock's mechanism – (a) front view of entire assembly, and (b) front plate removed to illustrate the meshed gear trains

3.2 Motion Analysis of Clock Pendulums (Lab II)

The mechanical properties of a clock's pendulum such as the moment of inertia and frequency will be analyzed using acceleration and Hall Effect sensors to study variations due to system parameter variations (e.g., pendulum length and weight).

Background: Fundamentally, the function of a clock is to transform a predictable signal into some standard unit of time. In pendulum clocks, a free swinging or torsional configuration may exist as shown in Figure 3. The characteristics of pendulum motion are affected by the pendulum's geometry. A simple pendulum can be viewed as a concentrated point mass connected by a rigid massless bar attached to a pivot point. A torsional pendulum, found in the common anniversary clock, represents a mass hung by a short chord that rotates about the vertical axis. The period of the torsional pendulum is much longer than that of a swinging pendulum and can go many days without winding. In this study, the governing equations of motion will be investigated through data acquisition. The students will design an experiment to measure pendulum motion (displacement, acceleration). They will differentiate the free swing pendulum acceleration to obtain the velocity and displacement; similarly, the Hall Effect displacement will be integrated to determine the torsional pendulum velocity and acceleration.

Learning Objectives: The student will learn how to integrate system sensors for data acquisition, complete a test plan, and validate a physical model that illustrates periodic motion.

Equipment and Materials: This experiment contains two different systems which feature a swinging aluminum pendulum (L=19.8 cm, d=1.3 cm) with circular bob (D=6.4 cm, t=2.2 cm, m=0.68 kg), a steel circular torsional pendulum (D=7.9 cm, t=0.5 cm, m=0.23 kg) with piano wire (L=26.4 cm, d=0.4 mm), protractor, accelerometers (PCB piezotronics 333B30), Hall Effect sensor (MLX90217, 5.6Ω resistor, 1μF capacitor), adjustable clock stand, and data acquisition system (National Instruments LabView).

Laboratory Procedure: Two experimental procedures will be applied to the swinging and torsional pendulums to measure the system behavior.

1. Measure and record the pendulum's diameter, mass, and support length.

2. Attach accelerometers and Hall Effect sensor to pendulums and calibrate using the LabView data acquisition system.
3. Displace the pendulum (approximately 30º) and release so it swings/rotates freely. Record several oscillations using data acquisition system.
4. Calculate the frequency of oscillation and moment of inertia from experimental data; compare these values for each pendulum configuration.
5. Investigate the acceleration, velocity, and displacement for each pendulum. How do these experimental results compare to the free swinging ideal (analytical) scenarios?

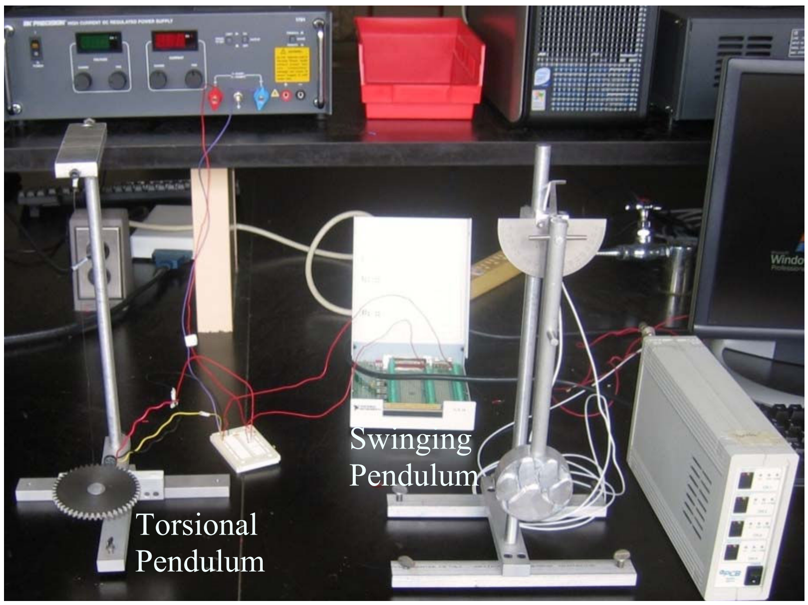

Figure 3: Experimental configuration of (a) torisonal and (b) swinging pendulum systems

3.3 Vibration Modes of a Chime Rod (Lab III)

The vibration and/or acoustic behavior of a chime rod, often struck by clocks to denote time passage, will be investigated using a microphone and accelerometer with impact hammer to determine the operating frequencies. For a greater challenge, a spiral gong with multiple modes may be studied[20].

Background: Chime rods (refer to Figure 4) and spiral gongs are used inside mechanical clocks to sound the passage of time. The striking hammer hits the chime rod or gong to produce vibrations as driven by the time side of the clock interacting with the strike side. The impact of the striking hammer against the rod generally produces a pleasing sound, which is dependent on the rod's inner/outer diameters and length. Chime rods offer a more precise musical note which can be used to sound a melody. In this experiment, free vibration (when an object is impacted with an initial force and then allowed to oscillate freely until the motion dampens out) will be investigated to determine the natural frequency. The vibration behavior of various rods will be measured using an impact hammer with accelerometers. To supplement this study, the rod's acoustics will be recorded using a microphone attached to a computer workstation. The recorded data will be analyzed with Fourier Transforms to identify the operating frequencies; testing will be performed in a small semi-anechoic chamber.

Learning Objectives: The student will understand general acoustic and vibration principles, relationship of sound vibration to musical notes, and Fast Fourier Transforms. They will learn how to perform sound and vibration measurements, use data acquisition systems, and evaluate simple acoustic and/or vibration relationships.

Equipment and Materials: Accelerometer (PCB 333B32), impact hammer (PCB 086C01), microphone (Sony F-V130), microphone pre-amplifier (Midiman), chime rods (5), Matlab, and SigLab (Spectral Dynamics 20-42) with Discrete Fourier Transform.

Laboratory Procedure: The Fast (Matlab) and Discrete (SigLab) Fourier Transform method in Matlab allows spectrum analysis to be conducted on the recorded wave to determine the frequency.

1. Hang the chime rod and/or gong inside the semi-anechoic chamber.
2. Install accelerometer on rod and position microphone; use impact hammer or mallet to strike rod. Use a similar technique for the spiral gong.
3. Measure vibration behavior and/or acoustic response with data acquisition system.
4. Execute "wavanal.m" file in Matlab or use SIGLAB to determine the frequencies.
5. Repeat experiment using a different chime rod; observe spectrum differences. Compare experimental data against the free vibration case. Why is there a difference between the acoustic and vibration frequencies?

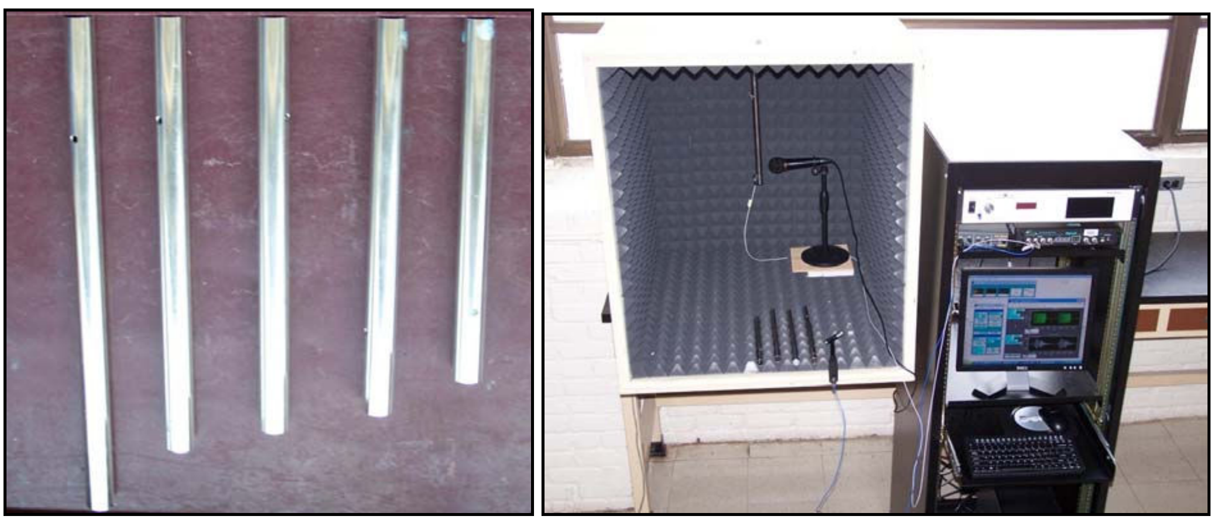

Figure 4: Vibration and acoustic study – (a) Chime rod assortment, and (b) experimental station

3.4 Mechanical Properties of a Barrel Spring After Heat Treating (Lab IV)

The mechanical torque and potential energy of coiled spring steel located in mechanical clocks will be explored to understand the effect of heat treatment and annealing of the metal. A Rockwell Hardness Tester will be applied to measure surface hardness after the steel has been prepared by following a heat treatment regiment.

Background: Spring steel (refer to Figure 5) was used in spring powered clocks beginning in the 15th century and continues to be applied today to drive internal gears. The spring steel is coiled around the arbor and enclosed inside a barrel - inner end connected to the arbor axle and outer end attached to the barrel side wall. A click located on the barrel top side prevents the spring from unwinding. The spring steel is wound by turning the arbor with a key. The clock movement is driven by external gears on the barrel's top edge. In this laboratory, the mechanical torque and stored potential energy of different specimens of spring steel due to heat treatments will be explored. The students will design an experiment to study the spring stiffness using weights hung from the apparatus for torque measurements. Further, the effects of heat treating and quenching the spring steel may be tested using a Rockwell hardness tester. Heat Treating involves heating a metal to high temperatures using an oven or a torch and then cooling by quenching in oil, water, or air. Heat treating and quenching affects the mechanical properties (stiffness and hardness) of the spring steel. The Rockwell tester measures the hardness of metal materials to evaluate the effects of heat treating and quenching. The measurements are based on the net increase in depth of the impression made by the indenter for minor and major loads applied to the test specimen.

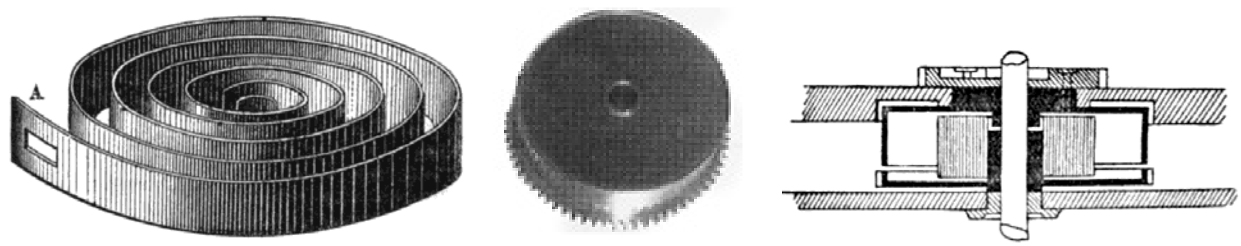

Figure 5: Spring in clock barrel – (a) coil, (b) barrel with external teeth, and (c) side cut away

Learning Objectives: Students will learn how to heat treat and quench spring steel. The test specimen's mechanical properties will be measured through surface hardness and spring elasticity. The student will explore the creation of test plans to complete the measurements.

Equipment and Materials: Spring steel (0.75"*0.0165"), propane gas torch, Rockwell hardness tester (Rams 10AR), test fixture, weights, and oil/water baths.

Laboratory Procedure:

1. Measure the spring barrel torque on the test stand by applying external weights; calculate the corresponding spring stiffness.
2. Determine initial hardness of spring steel test specimen using Rockwell hardness tester.
3. Heat the spring specimen using a torch (under supervision of technician) to a red color.
4. Quench steel in either an oil or water bath, or let air cool.
5. Repeat step 2 to determine how heat treating and quenching affect the hardness; a different spring barrel with varying steel will then be supplied to measure the stiffness.

3.5 Cascading Water Tanks for Time Keeping Numerical Study (Lab V)

A series of elevated water tanks, with different sized outlets to regulate the drainage time, may be mathematically modeled to analyze the subsequent time intervals. The governing equations and system transient behavior will be analyzed using Matlab/Simulink. A turbine flow rate sensor will be inserted to quantify the water outlet flow rate and calibrate the time period.

Background: Dating back to the 16^{th} century BC, water clocks are one of the oldest types of time keeping devices. Also known as clepsydra, these clocks were simple in design with only a storage vessel, outlet sized to regulate the fluid flow, and columns with marked intervals. The tank fluid height decreased (outflow device) at a constant rate. As the fluid level dropped, the lower portions of the graduated columns were revealed with time denoted by equidistant markings. By 200 BC, an inflow water clock, developed in China and eastern Asia, also featured a constant flow rate to measure time. In this case, the inlet water supply provided a constant fluid stream into a storage tank outfitted with a float device connected to a time indicator. Note that accurate time keeping was dependent on a constant fluid flow rate. For this laboratory, a set of cascading water tanks will be analyzed to calibrate the system for use in a time keeping application

Learning Objectives: Students will learn how to mathematically model fluid flow between water tanks and evaluate different outlet geometries using computer based Matlab algorithms.

Equipment and Materials: Computer workstation with Matlab/Simulink software package.

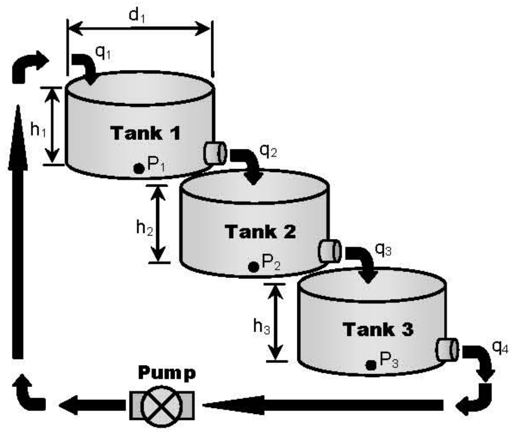

Figure 6: Three cascaded water tanks with circulation pump for numerical fluid flow study

Procedure: The system consists of three identical water tanks (refer to Figure 6) with system variables fluid inlet/outlet flows, and fluid height (pressure) as well as the system parameters of tank diameter, and paddle wheel flow sensor. If the system is left to run as is, Tank 1 will empty itself and all fluid in the system will eventually be lost. To maintain continual fluid system operation, either an infinite water source or circulation pump can be considered so that tank 1 offers an uniform pressure, P_1.

1. Derive the governing system (ordinary differential) equations for the cascading water tanks with fluid height variables.
2. Determine numerical relationship between fluid height in Tank 3 and the exit flow rate.
3. Use Matlab/Simulink to numerically solve the governing equations to study transient responses for the water tanks. What is the outlet flow rate of Tank 3 when the system has reached steady-state?
4. Adjust the outlet geometry to create a flow rate to drive a paddle wheel flow sensor that can be used for time keeping operations. What is the conversion of sensor output to time?
5. If desired, design a water pump system to circulate water from Tank 3 outlet to Tank 1 inlet to maintain continual fluid flow.

3.6 Operating Principles of the Gitton Water Clock (Lab VI)

The artistic water clocks created by Bernard Gitton can be analyzed to understand the application of fluid flow principles for time keeping systems (ignore water pump). The basic concepts to be examined include manometers, Bernoulli's principle, and siphon effect in vessels.

Background: Water clocks have been designed by Bernard Gitton (refer to Figure 7a) that demonstrate the use of fluid principles to track the passage of time as well as serve as art objects. Mr. Gitton is a French scientist who has created multiple "time-flow clocks" located throughout the world. One of the tallest clocks is located in Indianapolis at the Children's Museum[21] at 9.1 meters tall and 40 pieces of blown glass. The clock contains four subsystems - an oscillator (pendulum), a frequency divider, a minute counter, and an hour counter. The pump that moves water from the bottom tank to the top, and air bleed valves that remove unnecessary vacuums are not considered. The pendulum features a small bowl at the top that accumulates water from an elevated reservoir. The bowl empties into the first siphon as the pendulum swings (refer to Figure 7b) to provide power for clock functions.

The siphons in the clock are frequency dividers which convert the pendulum motion into a fluid volume time display. A siphon moves liquid from one container to a lower elevation container via gravity. As water is supplied by "dollops" (i.e., small fluid release) from the pendulum, the first dollop fills the siphon half way[22]. The second dollop initiates a siphon effect that continues until the container is drained. As the liquid moves through the cascaded siphons, it requires more time (increased period) to fill the subsequent siphons due to increased volume. The last siphon does not operate at atmospheric pressure. In addition, siphons may feature a connecting tube at a designated level to drain away excess fluid to reduce overflow. When the liquid arrives at the bottom tank, a vacuum signal triggers siphoning in the minute column. Similarly, a full minute column initiates a siphon effect of the column to the bottom tank which triggers a vacuum signal that siphons the hour column. In this laboratory, students will design an experiment to investigate fluid flow phenomenon through the use of a manometer, reservoir, siphon tubes, and fluid mechanics concepts to understand the water clock.

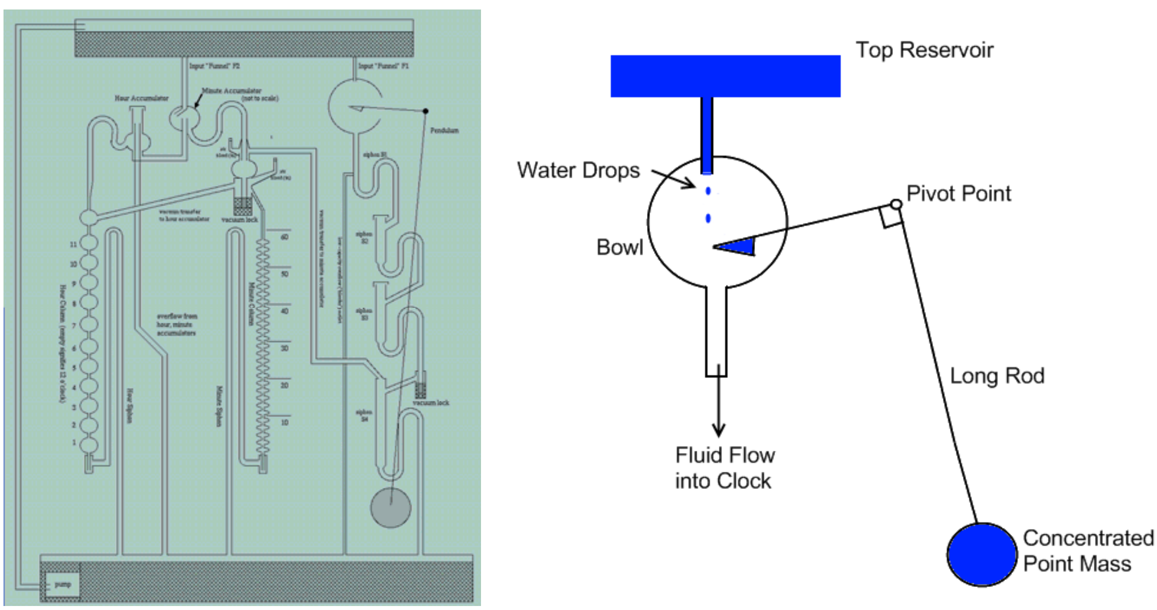

Figure 7: Water clock – (a) structure with pendulum, frequency dividing siphons, and time counter[22]; and (b) pendulum with reservoir

Learning Objectives: The students will analyze water clock operation based on fluid mechanic principles including manometers and siphons. The behavior of manometers and siphons will be measured with bench top experiments that emphasize design of experiment, followed by the mathematical modeling of the Gitton time flow clock.

Equipment and Materials: Manometer, siphon tubes, dual reservoirs, tape measure, and bucket.

Laboratory Procedure:

1. Analyze the operation of Bernard Gitton's Children's Museum of Indianapolis water clock[21]; identify the basic components utilized within the clock.
2. Review the theory of manometers and siphons; how do these relate devices relate to the water clock's basic design?
3. Design a manometer and siphon effect laboratory experiments to explore the water clock concepts; perform the experiments and record pertinent information.
4. Apply Bernoulli's principle to the clock's analysis; can the height and diameter of the various siphons be specified to achieve the required fluid flow behavior?
5. Integrate the pendulum's motion into the clock's fluid operation; what is the interface between the mechanical and fluid domains? What is the impact of an external water pump?

3.7 Voltage Controlled Oscillator Electronic Circuit (Lab VII)

Using a breadboard, a voltage controlled oscillator (VCO) electrical circuit will be constructed to generate an oscillatory output voltage signal. The transient behavior of the circuit should be analogous to the mechanical motion of a swinging pendulum. The output signal's frequency can be designed through electronic component selection and measured with bench instrumentation.

Background: The advent of electronics permits the introduction of circuits to demonstrate some operational behaviors similar to mechanical systems. Time keeping devices require an energy source that provides accurate input characteristics (e.g., constant flow, pendulum swinging, pulsating signal). The voltage controlled oscillator shown in Figure 8 uses a series of operational amplifiers (OP Amps), analog voltage multiplier, and analog switches to create an output similar to a pendulum's rotational behavior in a mechanical clock. This oscillatory signal may be processed to complete an electronic time keeping circuit. To validate the circuit, tests may be conducted after each step to demonstrate the system output for prescribed electrical input using an oscilloscope or handheld multimeter. The output signal transient response can be adjusted based on the selected resistor and capacitor values used in the integrating circuit.

Learning Objectives: The students will learn how to select electrical components to create a breadboard circuit, validate system operation through laboratory measurements, analyze a VCO circuit[23], and develop a mathematical model which describes analogous mechanical behavior.

Equipment and Materials: Breadboard, multimeter, oscilloscope, power supply, analog switch (ADG419), analog voltage multiplier (ADG633), op-amp (LM741), resistors (20Ω, 100 Ω, 3kΩ, 24k Ω, 100k Ω), and capacitors (0.1μF, 100μF).

Laboratory Procedure: The circuit will be constructed in segments to ensure proper assembly with oscilloscope validation. Through the circuit fabrication process, students should discuss the functionality of the assembled electrical components.

1. Construct the first inverting amplifier circuit (A). Use a multimeter between pin 6 and ground to read DC voltage by increasing V_{in} from 0 to 2V with a response of 0V to -20V.
2. Create the integrating circuit (B) below first inverting amplifier circuit (A). Use a multimeter between pin 6 and ground. Begin with V_{in}=0V, set V_{in}=12V for 10 seconds, and then V_{in}=0V. The output should rise quickly to 12V and then slowly climb; after removing the 12V input, the circuit should slowly decay to zero.

3. Construct the second inverting amplifier circuit (C) below integrating circuit (B). Use the same diagnostic process from step 1; the circuit response should also be 0V to -20V.
4. Create remaining circuit (D) with analog switches and voltage multipliers. Connect oscilloscope from pin 6 on first op-amp to ground; observe output as V_{in}= 0-10V.
5. Calculate the frequency of oscillation and corresponding period. Now design and numerically simulate a mechanical pendulum that offers the same observed behavior.

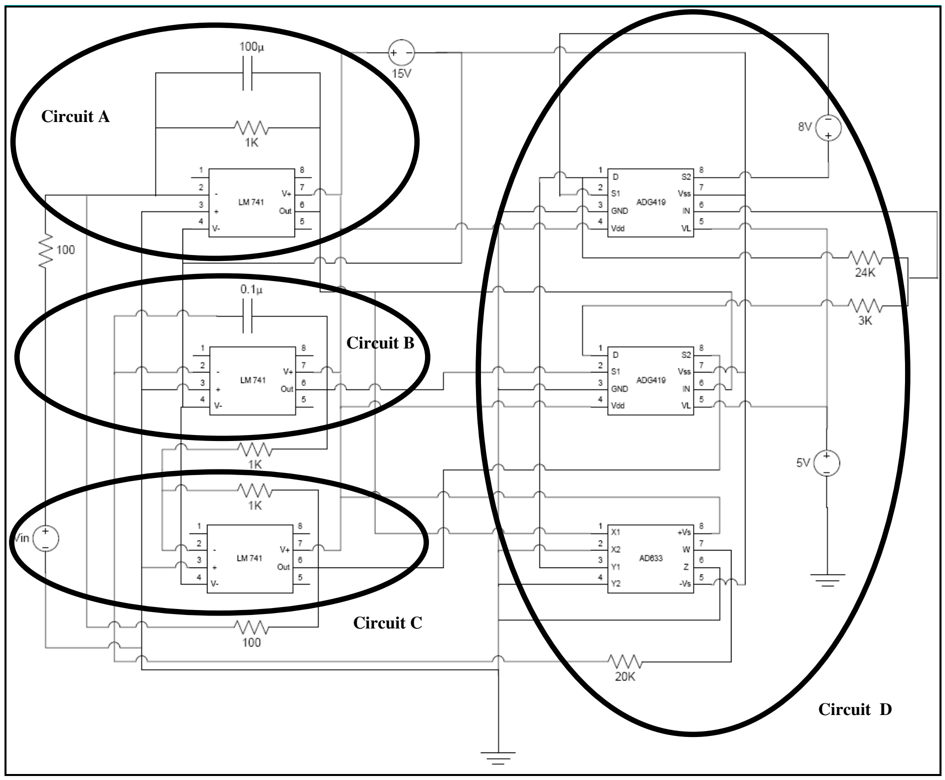

Figure 8: Voltage controlled oscillator electrical circuit with four subsystems

3.8 Microprocessor Based Clock with Solenoid Driven Chimes (Lab VIII)

A computer (BASIC Stamp™) chip will generate a time signal on a laboratory development board which will drive clock chimes. The clock output signal sounds each quarter hour and hour with integrated solenoids that strike a series of chime rods. The students will program a common melody such as Westminster through a sequence of chime rod strikes (musical notes).

Background: One famous melody in chiming clocks is the Westminster quarters followed by striking the hour. This 16-note melody first appeared in Cambridge, England in the University Church Tower of St. Mary and has since been played worldwide including the Big Ben clock tower and grandfather clocks. The chime sequence (refer to Table 2) is a 4-note series played every 15 minutes past the hour, 8-note series played every half hour, and a 12-note series played at 15 minutes until the next hour followed by the time strike. The geometry of the chime rod (length, diameter, material) influences the resonant frequency which impacts the pitch. Through testing, the chime set produced frequencies of 2350, 3140, 3520, and 3950 Hz or pitches of 38 (D_7), 43 (G_7), 45 (A_7), and 47(B_7) which can produce the Westminster tones. This laboratory will investigate an electrical circuit, solenoid actuators, and computer programmed code to drive a set of mechanical chimes with a microprocessor (BASIC Stamp Board as shown in Figure 9a) based digital clock.

Time	Musical Note Sequence
00:15	B, A, G, D
00:30	G, B, A, D G, A, B, G
00:45	B, G, A, D D, A, B, G B, A, G, D
00:00	G, B, A, D G, A, B, G B, G, A, D D, A, B, G

Table 2: Westminster melody note sequence for quarter hour chimes using four notes

Learning Objectives: The student will learn how to integrate electro-mechanical components (actuators, electrical devices, microprocessor) to create a functional flexible mechatronic clock and develop accompanying computer algorithms. Further, the student will be able to collect operating data through computer based instrumentation to evaluate system functionality.

Equipment and Materials: BASIC Stamp™ chip, breadboard, Deltrol C6 solenoids, chime rod, host computer for program development, and oscilloscope.

Laboratory Procedure: The programming language set for the BASIC Stamp chip is similar to Matlab and/or C++. The teams will utilize a Parallax StampWorks development board (refer to Figure 9a) that hosts digital clock functions and drives external solenoids to strike the rods.

1. Establish host workstation computer to BASIC Stamp communication; review input and output functions for the clock and microprocessor chips.
2. Create a digital clock with the microprocessor real time clock circuit (use example program).
3. Demonstrate the software algorithm and clock functionality.
4. Connect the solenoids (refer to Figure 9b) to amplifier outputs 1-4 and common power; route wires from controller output ports 8-11 to amplifier input ports 1-4.
5. Develop algorithm drivers to operate the four solenoids in proper sequence based on time interval with controller output ports 8-11.
6. Demonstrate the complete system operation for time keeping and solenoid chiming.

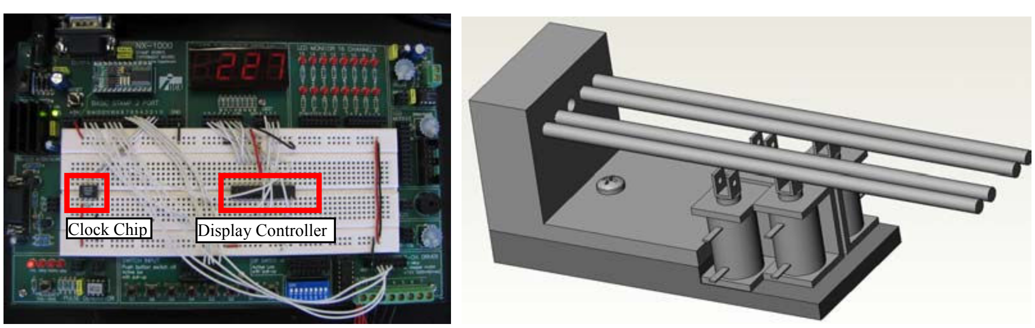

Figure 9: Mechatronic clock - (a) Development board with Stamp chip, and (b) solenoid chimes

4.0 Laboratory Assessment

To evaluate each laboratory experiment, an assessment tool will be administered at the conclusion of the given exercise to gather student feedback. The assessment document (refer to Appendix) has been divided into four areas. The first three segments seek information regarding the performance of the laboratory teaching assistants (Questions 1-2), student work load and difficulty for the laboratory (Questions 3-4), and whether the assignment reinforced engineering concepts and student skills (writing, software, statistics, design and conducting experiments) per Questions 5-10. The responses are entered on a strongly disagree (SD), disagree (D), neutral (N), agree (A), and strong agree (SA) scale which can be readily translated into numerical scores. For the fourth segment (Questions 11-13), the students can offer written comments regarding positive and negative aspects of the experiment, and other suggestions pertaining to the overall laboratory experience. It should be noted that this assessment form is actively applied in the undergraduate laboratory courses in the Department of Mechanical Engineering at Clemson University after each experiment. The collected feedback will be reviewed and combined with observations from the teaching assistants and faculty to modify the experiments as appropriate to yield an improved learning experience.

5.0 Summary

The engineering education laboratory provides students an environment to explore classical and innovative experiments that reinforce fundamental concepts and classroom theory. In many instances, the laboratory experience can be viewed as a distinguishing feature of the engineering education process. In this paper, a series of eight horology inspired experiments have been presented with accompanying background, learning objectives, equipment and materials, and test procedure. To complement the engineering investigations, an accompanying set of societal issues may be identified that allow students to examine the impact of time measurement on mankind. The availability of a set of experimental and numerical laboratory assignments with a unifying theme may fulfill the need for comprehensive and challenging student exercises.

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Appendix: Mechanical Engineering Laboratory Assessment

Directions: Please complete this questionnaire based on your recent undergraduate laboratory experiment. The student feedback will be compiled and then utilized to evaluate classroom instruction, laboratory equipment, experimental procedures, and overall assignment. Thank you for your help.

Course: ______, Laboratory Section: ____, Teaching Assistant:__________, Experiment:_____________

1. The Laboratory Teaching Assistant clearly explained what is expected of students.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

2. The Laboratory Teaching Assistant presented the laboratory materials clearly.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

3. Relative to my other courses, the work load for this particular laboratory experiment was…

Much Lighter	Lighter	About the Same	Heavy	Much Heavier
o	o	o	o	o

4. Relative to my other courses, the difficulty level of the particular laboratory materials was…

Much Easier	Easier	About the Same	Harder	Much Harder
o	o	o	o	o

5. This laboratory enhanced or exemplified a subject that was only discussed in other classes.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

6. This laboratory enhanced my understanding of engineering theory and/or practice.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

7. My report writing skills and ability to discuss results and draw conclusions have been improved.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

8. My software skills for modeling, simulation and data analysis have been improved by this lab.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

9. I have increased my knowledge of statistics with engineering applications.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

10. I have increased knowledge and experience in designing and conducting experiments.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
o	o	o	o	o

11. The best thing about this laboratory experiment is…
12. My biggest complaint about this laboratory experiment …
13. Other comments/suggestions?