2006-916: HIGH CYCLE FATIGUE TESTER

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High Cycle Fatigue Tester

Abstract

Metal fatigue is the fracture and failure of structural parts subject to cyclic loads that are much less than loads necessary to cause yielding or tensile fractures. High cycle fatigue failures (millions of cycles) can occur with surprisingly low loads. In many industries, equipment is subject to hundreds of millions or billions of cycles and fatigue failures are a constant problem. Demonstrating high cycle fatigue in the limits of the classroom is very difficult since the test of a single specimen can take hours. Demonstrating the fatigue limit requires a large sample size (lots of tests) and statistical analysis – nearly impossible to do in the classroom with current fatigue testers.

Faculty at Purdue University – College of Technology at New Albany (PUNA) developed a classroom fatigue tester to improve student learning of fatigue concepts. Their objective was to develop a table top, high cycle fatigue tester capable of demonstrating high cycle fatigue in a time period compatible with classroom instruction. The resulting prototype includes a fatigue tester that operates at around 30,000 cycles per minute, capable of achieving a million cycles in a little over 30 minutes, as well as the sensors and electronic circuits to count the cycles until the specimen breaks. The prototype was then tested in the classroom to show that it is capable of performing high cycle fatigue tests.

This paper describes the development and construction of a classroom ready fatigue tester and its associated electronics for a sophomore level mechanical engineering technology strength of materials course. It includes a discussion of the performance of the fatigue tester, and the assessment, evaluation and improvement planned for the project. Lastly, it describes the broader impact of this project to better educate engineering technology students in the implications of fatigue failures.

Introduction

In the limits of the classroom, both time and space, it is difficult for students to experience fatigue failures. Particularly difficult to demonstrate is high cycle fatigue failures. Loads in the millions of cycles take a considerable amount of time to complete, thus making it hard to complete within the time constraints of a class or lab period. Common fatigue testers operating at 1800 rpm would take over 9 hours to just to reach a million cycles with a single test specimen. Repeated tests (to get a large sample size) and statistical analysis are required in order to demonstrate the fatigue characteristics of a particular metal. Thus it is extremely difficult to fatigue test a metal in the classroom and students must rely on published test data to predict the fatigue properties of a metal.

In addition to the difficulty in demonstrating fatigue in the classroom, data on the fatigue characteristics of metals for more than million cycles is not widely available. Students are presented with the concept of a fatigue limit in carbon and low alloy steel – a level of stress below which the metal would not be expected to fail due to fatigue. For carbon steel, the fatigue limit transition occurs around a million cycles.[1] Demonstrating this fatigue limit in the classroom is nearly impossible with a tester operating at 1800 rpm.

Lastly, temperature, particularly high temperature, is not a variable controlled during many fatigue tests. Most fatigue tests are performed at room temperature and the possible difference in fatigue performance at high temperatures is not usually tested.[2]

For these reasons, Purdue University – New Albany (PUNA) has started the development of a new high cycle, high temperature fatigue tester, as well as, the associated classroom lab exercises that will result in curriculum improvement and improved undergraduate learning of fatigue failures in metals.

The goals of this project are to improve the quality of teaching high cycle and high temperature fatigue to engineering and technology students by:

1. Developing a table top fatigue tester capable of demonstrating high cycle fatigue as well as creating and controlling high temperatures in the fatigue specimen to demonstrate the effects of temperature.
2. Testing the prototype in the classroom to show it is capable of performing high cycle fatigue tests in a time period compatible with classroom instruction as well as creating and controlling high temperatures in the test specimen.
3. Assessing the improvement in student learning by using the new device and curriculum.
4. Reporting the results of the prototype testing.
5. Sharing the fatigue results and tester design with other educational institutions as well as interested commercial institutions.

The intellectual merit of the project is to expand knowledge of the fatigue performance of metals subject to high cycles and high temperatures. The broader impact will be to better educate students in implications of fatigue failures and potentially increase the amount of available data on high cycle fatigue and the effects of temperature on fatigue.

This project will consist of two stages in order to address the problems with fatigue testing and student learning as stated above. The first stage will be to develop a classroom laboratory fatigue tester and demonstrate its use in classroom lab exercises. The second will be to develop and assess associated classroom activities into a product that enhances student learning.

The proposed project will be completed over a two year period. Development of the fatigue tester and the building of a classroom ready prototype will occur during the first year. The second year will be for developing classroom activities and testing the device in the classroom as part of materials and strength of materials courses. Most of the development work will be done in the summer months, while, obviously, the classroom activities will occur during the fall and spring school semesters.

Mechanical Design of the Prototype Fatigue Tester

In order to address the limitations of demonstrating fatigue failure in the classroom, a new fatigue tester will be developed. It will be similar to a common fatigue testing device often called a R.R. Moore fatigue tester. This type of fatigue tester has a cylindrical specimen that rotates while a load is applied in one direction. While this and other devices for testing fatigue exist, none have the capability for achieving high cycles in classroom time periods or the ability to test metals at high temperatures. This fatigue tester will test metals at temperatures from room temperature to hundreds of degrees F and also achieve millions of cycles within a single lab class.

The test specimen is fatigued by applying a bending load to it and then spinning it at a high speed. As the specimen rotates, a particular point is subject to alternating tensile and compressive forces. This fatigues the metal and eventually causes the specimen to break. The addition of the heater and temperature control allow the user to investigate and compare fatigue at elevated temperatures to the fatigue that occurs at room temperature.

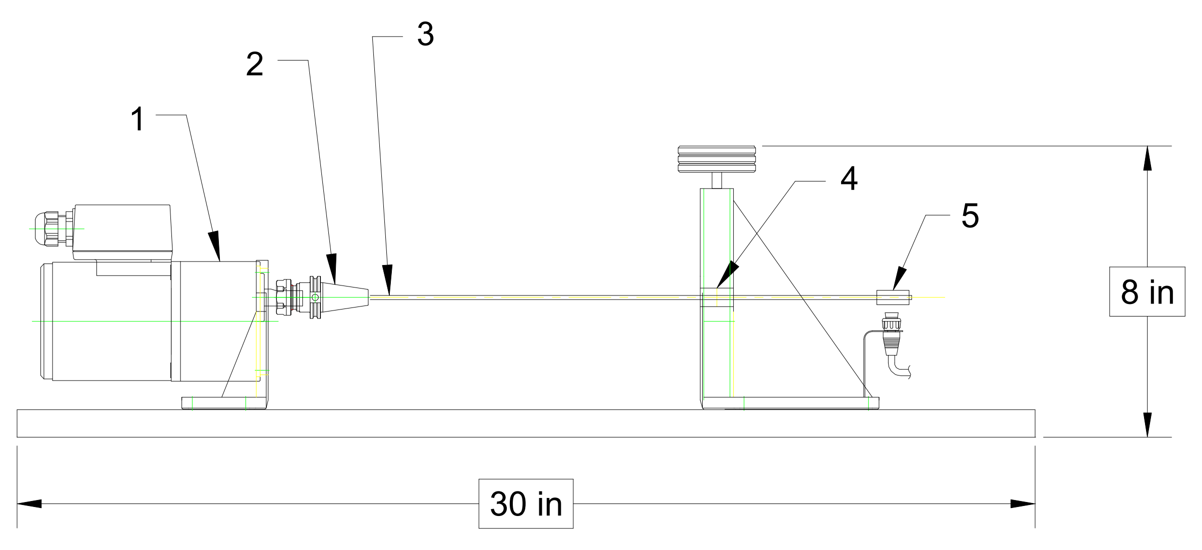

Figure 1. Prototype Fatigue Tester.

A simple model of the proposed fatigue tester was built in order to show the feasibility of constructing a high cycle fatigue tester before pursuing additional funding. By using available motors, bearings, etc. and mounting these to a frame, this prototype device shows that high cycle fatigue can be demonstrated in a reasonable amount of class time. The model device does not have the capability of heating the test specimen and has only a cycle counter, not a data acquisition system. This preliminary work shows that the proposed project has significant potential to enhance student learning. The prototype consists of the following components:

1. Electric motor and drive components capable of rotating a test specimen at speeds of 5,000, 10,000, 15,000, 20,000, 25,000 and 30,000 rpm.

2. Collets to hold a cylindrical test specimen.
3. 3/16” cylindrical, mild steel test specimen with grooves to cause stress concentrations at every inch along the specimen.
4. Apparatus to create a bending load on the specimen. The apparatus has a bearing to connect to the test specimen and slides vertically along a track. Adding weights to the top of the slide allows the load to be varied.
5. Sensor and electronic circuit with digital display to count the number of rotations of the test specimen as described below.

Design of Electronic Counter and Sensor for Prototype

In order to count the number of revolutions the specimen has made before breaking, an IR pair is used to detect the number of revolutions before it fails . A black mark of about one inch is placed along the length of the test specimen. As the specimen turns, an IR pair detects this mark as in Figure 2 below.

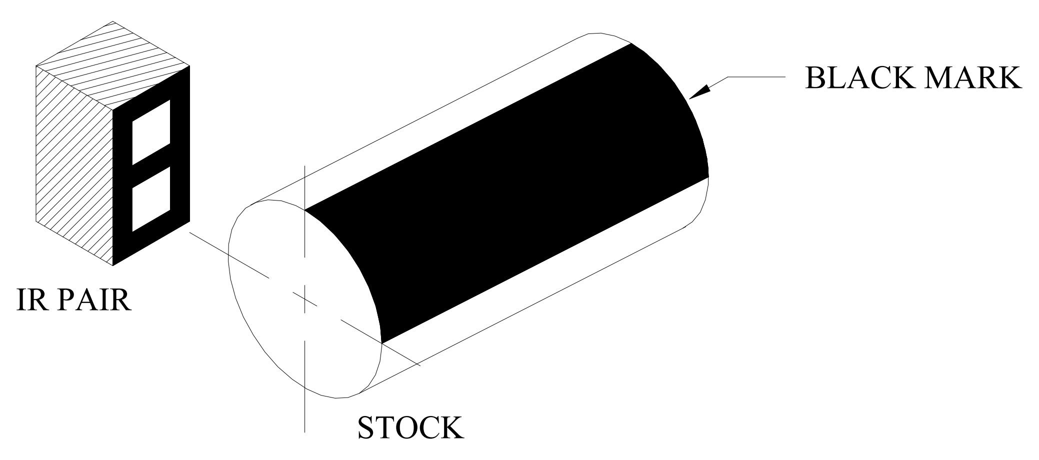

Figure 2 – The Set Up to Count the Revolutions of the Test Stock.

Every time the black mark appears in front of the IR pair, a nine-digit counter produces an increment of one count.

In the electronic part, the first section of the design is a ±15VDC power supply. The schematic diagram of the DC power supply is in Figure 3 below.

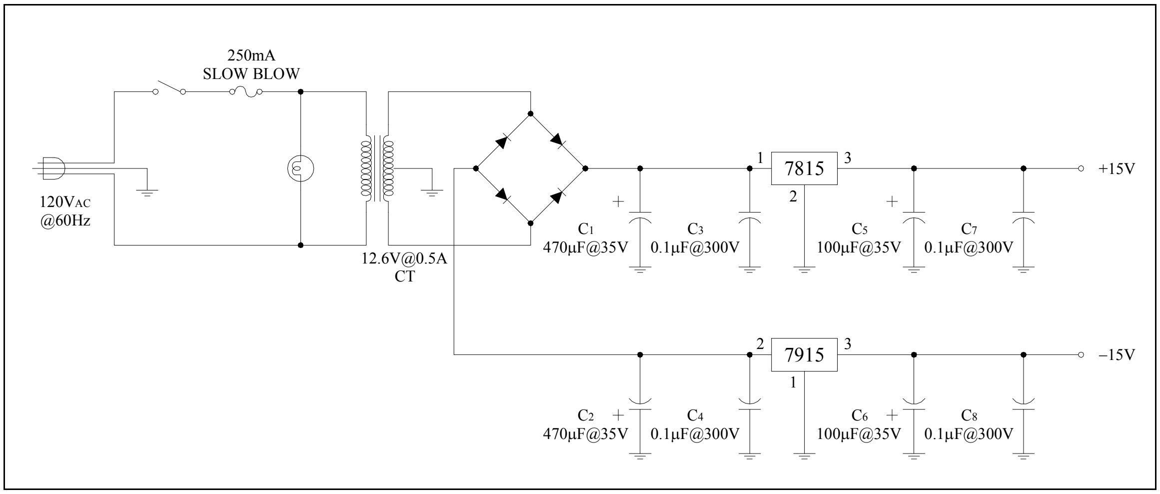

Figure 3 – The DC Power Supply

The main detection circuit is in Figure 4 below.

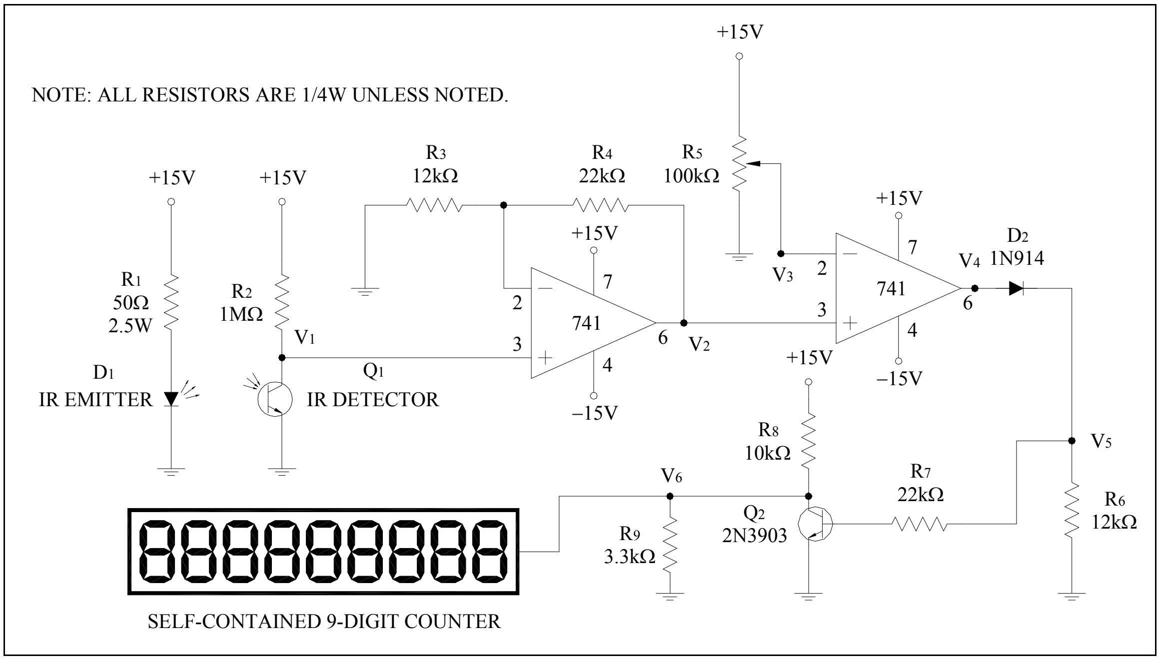

Figure 4 – The Detection Circuit

As the stock turns, when the black mark appears in front of the IR pair, the output voltage V_1 has its peak value of about 2.8V. This voltage goes through an amplifier that produces a signal V_2:

$$V_2 = V_1\left[1+\frac{R_4}{R_3}\right] = (2.8V)\left[1+\frac{22k\Omega}{12k\Omega}\right] = 7.9V$$

The waveforms of V_1 and V_2 are in Figure 5 on the next page.

The next stage of the circuit is a Voltage Comparator. The reference voltage V_3 is 5VDC. When V_2 is larger then V_3, the output voltage V_4 is in positive saturation of about +14V.When V_2 is less than V_3, the output voltage V_4 is in negative saturation of about –14V. The waveform of the voltage is in Figure 6 as shown below.

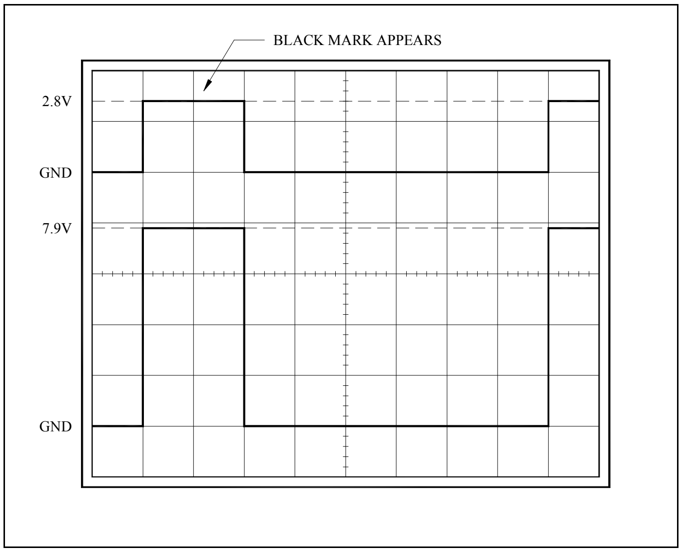

Figure 5 – The Waveforms of V_1 and V_2

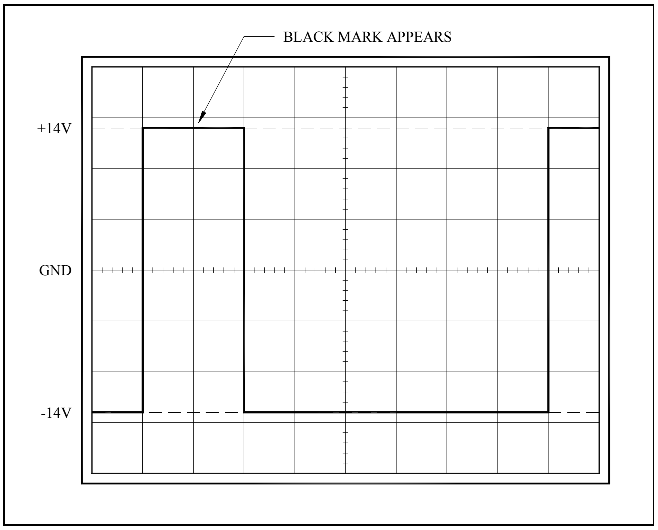

Figure 6 – The Waveform of V_4

The diode D2 eliminates the negative saturation of the voltage V_4. The signal V_5 triggers a transistor driver circuit that produces the voltage V_6 driving the counter. Figure 7 on the next page shows the waveforms of the voltages V_5 and V_6.

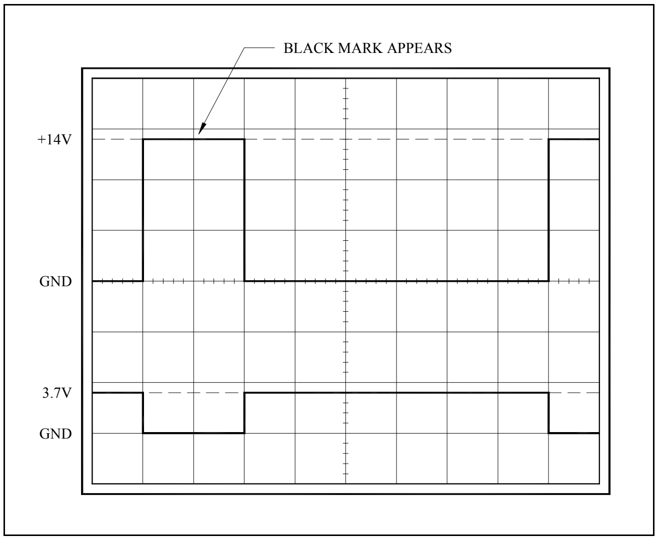

Figure 7 – The Waveforms of V_5 and V_6

The prototype fatigue tester was demonstrated using 3/6” diameter plain carbon steel test specimens. One half to two pound weights were used to created bending stress in the test specimens while the sensor and circuit described above counted the revolutions until the specimen failed. At the 30,000 rpm speed, multiple fatigue specimens were tested within the normal 2 hour lab session. Since the prototype has successfully demonstrated the concept,

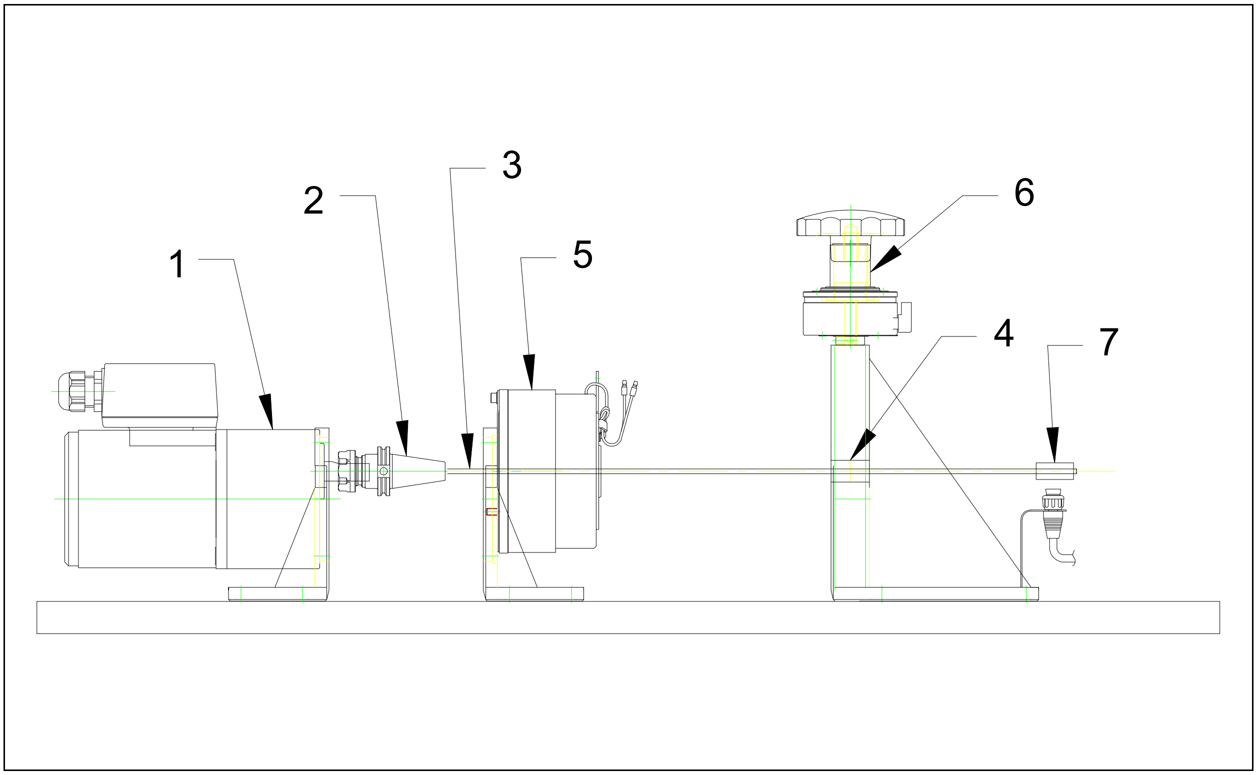

Figure 8. Planned High Cycle, High Temperature Fatigue Tester.

additional funding is being pursued in order to develop a high cycle, high temperature, fatigue tester with the following physical characteristics (See Figure 8):

1. The drive system, including an electric motor, gearing and controls, rotate the test specimen at 25,000 to 35,000 rpm.
2. Nonmetallic (ceramic) collets to hold test specimen while minimizing heat transfer to the bearings and drive system.
3. 3/16" in diameter test specimens with grooves every inch to create stress concentrations. The grooves ensure that the test specimen breaks at the desired locations. The test specimens will be metals, including plain carbon steel, stainless steel, aluminum and brass.
4. Ceramic bearings minimize heat transfer to the loading apparatus.
5. Induction heater and feedback controls maintain the temperature of specimen at hundreds or thousands of degrees F while it is being tested.
6. The specimen loading system generates a bending load in the test specimen. It includes a hand knob to adjust the load and a load cell to measure the force generated.
7. The data acquisition system records a minimum of: number of cycles before failure, temperature of the specimen, and the load on the specimen.
8. Mounting frame to support all components and instrumentation while also small enough to make the entire system portable by one person and sized to be used on any tabletop or lab bench.

The high cycle, high temperature, fatigue tester will have the following capabilities:

1. Demonstrates high cycle fatigue to students in a single class period.
2. Demonstrates the effects of temperature on fatigue.
3. Displays and records for future analysis the number of cycles, the temperature of the specimen and the load applied using a data acquisition system.

No unusual or exotic equipment is required for this project. The fatigue tester will be constructed of parts available from general purpose mechanical and electronic catalogs and parts that can be fabricated at any machine shop.

Maintenance of the fatigue tester should be minimal and well within the capabilities of lab technicians or lab assistants. Parts will be chosen taking into account availability of standard parts and ease of repair. Any customized parts can be reproduced in the university or other local machine shops.

Instrumentation for the high cycle, high temperature fatigue tester will include:

- Specimen rotation sensor and counter to measure the number of load cycles applied to the specimen.
- Non contact temperature sensors to measure the temperature of the specimen without affecting the loading of the test specimen
- Load cells to measure the force applied to the test specimen.
- Data acquisition system to record test data for later analysis.
- Displays to indicate current number of cycles, load and temperature.

The data acquisition system will use standard National Instruments or equivalent computer cards and Labview software. Sensors and controls will be chosen based on standard industrial practice and will be equivalent to those found in most industries. A laptop computer will be included so that the entire system is portable and can be used in multiple classrooms.

Instructional Plan

After the building of the fatigue tester, classroom lab exercises will be developed. Then a series of evaluations will be done to determine the system's effectiveness as a teaching tool for high cycle fatigue versus existing tools. The completed fatigue tester and associated labs will be used in the materials and strength of materials classes at Purdue University – New Albany.

Educational materials accompanying the system will include the following:

1. Lab materials to investigate the performance of metals subject to a high number of load cycles.
2. Lab materials to explore the effect of high temperatures when metals are subject to a high number of load cycles.
3. An assessment of the effectiveness of the fatigue tester in teaching fatigue concepts to undergraduate students.

Assessment, Evaluation and Improvement

The evaluation plan is separated into two categories. The first category evaluates the design and performance of the completed fatigue tester against the stated capabilities. The second evaluation category measures the effectiveness of the completed system (fatigue tester + laboratory exercises) as a tool for enhanced student learning.

1. Fatigue tester design and performance.

Several progress evaluations are planned. First, as particular subassemblies are completed, each will be measured for its ability to contribute to the design outcomes listed above. Second, once all components of the system have been fabricated and tested to verify conformance, the entire functioning system will be tested to determine conformance with the system performance requirements listed in the detailed project plan. Specific evaluations include the following within the first full year of the project:

- Motor/drive subassembly can achieve more than 1 million cycles within a 2 hour class period.

- Load generating subassembly can repeatedly generate a load within 5% of the desired load.

- Induction heater and temperature control subassembly can generate and hold the temperature of the specimen from room temperature to 1000 F within plus or minus 10%

- Data acquisition system displays and records for future analysis the number of cycles, temperature of specimen and the load on the specimen.

- Entire system portable by one person and can be set up in less than 30 minutes.

2. Instructional effectiveness.

Upon completion and verification of design and performance outcomes of the completed system, a series of evaluations will be done to determine the system's effectiveness as a teaching tool for high cycle fatigue versus existing tools. The completed fatigue tester and associated labs will be tested on students in the materials and strength of materials classes. Beta testing at another location within the Purdue University - College of Technology system will then be conducted to verify initial findings with a larger number of students. The evaluation program will contain the following features:

- Before and after surveys to test the technical knowledge gained by the student in the performance of the fatigue testing lab exercise.

- Survey of student's preference for the proposed fatigue tester vs. other traditional fatigue testers and other methods of teaching (i.e. lectures) the concept of fatigue and fatigue life.

- A population size consisting of all current class sections to eliminate sampling error, with equal portions of control versus test subjects.

- Quantitative measurement using multiple-choice testing to minimize response bias.

- Criterion-referenced questions to measure specific acquired knowledge and skills.

- Analyses consisting of (at least) frequency distribution, central tendency, and correlation to objectively quantify improvements in teaching effectiveness.

Dissemination Plan

The dissemination of project outcomes will be done through publications in relevant educational journals such as the Journal of Engineering Technology, and through presentations at national conferences such as those of the American Society of Engineering Education and the American Society of Mechanical Engineers. Outcomes will also be shared within the Purdue University Colleges of Technology and Engineering, particularly to those faculty already expressing interest. Additionally, it is hoped that interest can be generated through Project Lead The Way (PLTW), a national organization dedicated to creating a dynamic partnership with our nation's schools to prepare an increasing and more diverse group of students to be successful in engineering and engineering technology programs. Lastly, there will also be exploration of commercial potential, with input from the Purdue University Office of Technology Commercialization (OTC).

Bibliography

[1] Metals Handbook: Desk Edition, J. R. Davis (Editor), 1999, ASM International

[2] High Temperature Fatigue: Properties and Prediction, R. P. Skelton, 1987, Elsevier Applied Science, London