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A FAST ROTATING BENDING FATIGUE TEST MACHINE

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Abstract. *This paper presents the design and development of a fast rotating bending test machine for high-cycle fatigue tests, which can rotate up to 18,000 rpm, generating cyclic stresses at 300 Hz. The bending force is applied by an electric actuator, connected in series with a load cell. An Arduino board with a DC motor controller shield receives the force feedback from the load cell, commanding the actuator to create the desired bending moment through proportional-integral (PI) controller logic. It also commands the desired rotation speed for the main motor via a PWM signal to the brushless motor speed controller. Another Arduino board is connected to a Hall-effect sensor, to count the revolutions and to control the speed of the main motor. All data can be captured by a computer, via a USB connection. Pairing the bending stress and number of cycles for failure creates a point for traditional stress-life plots, but due to its active feedback, the machine can also apply load blocks needed for Gassner curves and even to simulate variable amplitude loads. The design is versatile, can apply stresses up to 3000 MPa, is lightweight and portable, and costs a fraction of standard commercial models.*

Keywords: *fatigue, testing machine, S-N method, variable amplitude loads, instrumentation, machine design*

1. INTRODUCTION

Fatigue is a mechanical failure mechanism caused by the repeated application of variable loads, and characterized by the initiation and growth of a crack that may eventually lead the structural component to fail. Fatigue failures are localized, progressive and cumulative. They depend on a number of features, such as the material and shape of the critical point of the component, and on the applied load history. Fatigue failure costs are significant, estimated as about 3% of the US GDP (Norton, 2007). Since the gradual initiation and growth of a crack usually does not alter the behavior of the structural component, it can pass unnoticed until sudden failure, causing loss of human lives, equipment and structures. That is why fatigue prediction methods are so important in practice. Among them, the most used is the traditional S-N method, which correlates the elastic stress history (S) at a critical point of a component with the high number of cycles (N) needed to initiate a macrocrack there. S-N design methods intend to avoid crack initiation, and they need fatigue properties that are usually measured in rotating bending machines, such as the one schematized in Figure 1.

High-cycle fatigue tests are widely used by industries and research laboratories, as well as for educational purposes. They are particularly important to properly measure real or practical fatigue limits. Even though such limits may be associated with relatively short lives of 10^6-10^7 cycles in steels and other ferrous alloys, they may be associated to much longer lives, up to $5 \cdot 10^8$ cycles, in Al and some other non-ferrous alloys. Such long tests are only practical in fast and energy-efficient machines. Servo-hydraulic testing machines are versatile, relatively easy to control, and may apply very large forces, but they are very expensive, consume a lot of energy, and are not so fast. They are almost indispensable in any serious fatigue lab, but they are not a good choice to collect a large amount of S-N data, in particular in the case of non-ferrous alloys. Servo-controlled resonant electromechanical testing machines are faster and more energy-efficient, so they may be a better choice for measuring S-N data, but they are even more expensive and cannot apply high loads. Traditional dead-load rotating-bending fatigue testing machines, on the other hand, are energy-efficient and less expensive than servo-hydraulic or servo-electromechanical machines, but since they are not servo-assisted, they can only deal with constant amplitude fatigue tests with zero mean loads.

The machine presented in this work has been conceived and designed to eliminate the main disadvantage of the dead-load rotating-bending machines, their lack of servo-control. Moreover, it has been designed to be very fast, capable of rotating at up to 300Hz, or to generate almost $26 \cdot 10^6$ cycles per day, using special bearings and a small electrical motor. Its details are described next.

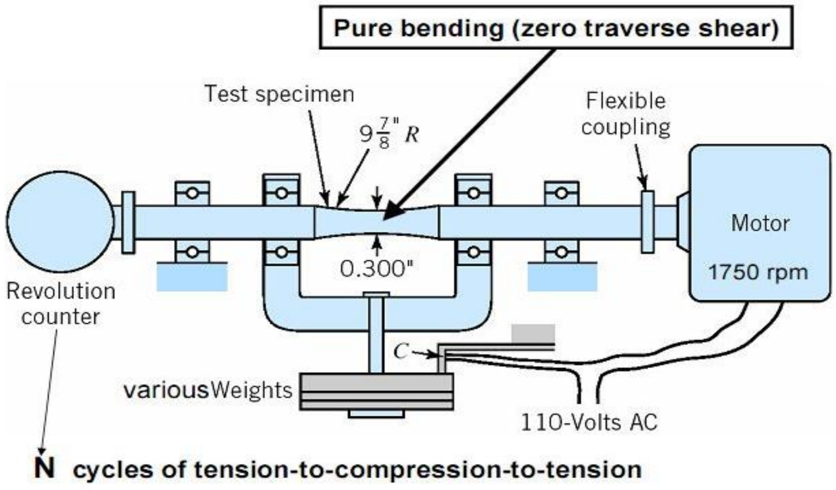

Figure 1 - R.R. Moore rotating-beam fatigue testing machine

2. MACHINE DESIGN

2.1 CAD Design

The design process started using a CAD software to model the structure and commercial components, to make a good estimate of fittings, weight and assembly procedure (see Figure 2). Commercial rotating-bending fatigue test machines usually come with a heavy workbench, necessary for the dead weights to pass through the tabletop. This new design, which uses an electric actuator, allows the machine to be much lighter (16 kg), and to be installed on any work surface.

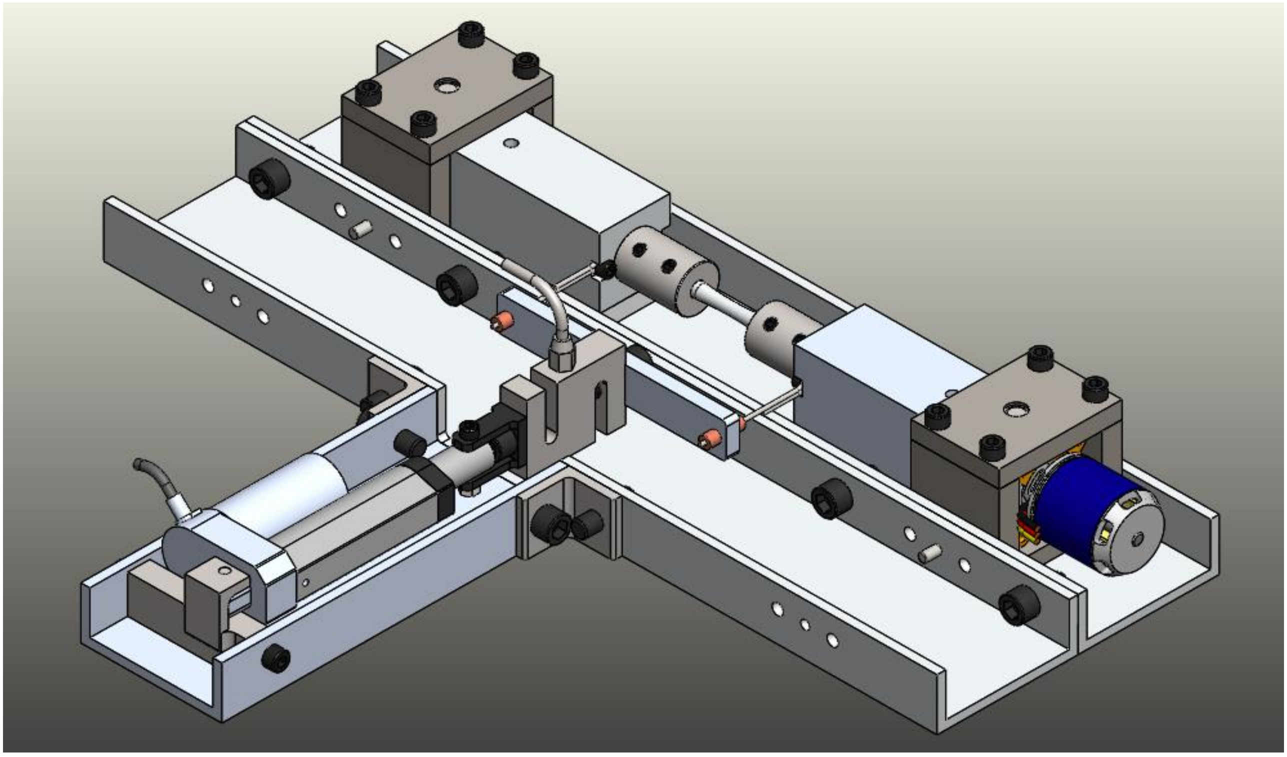

Figure 2 – Machine design on CAD software.

There are two pivoted bearing blocks that support the main rotation shaft. This allows the actuator to apply a force of up to 50 kgf at two symmetrical points in those bearing blocks, generating the desired constant bending stress on the main shaft section where the test specimen is clamped (see Figure 3). Since the main shaft is able to slide through the bearings, this cancels out undesired parasitic forces that would arise from the turning of the bearing blocks, such as axial tension.

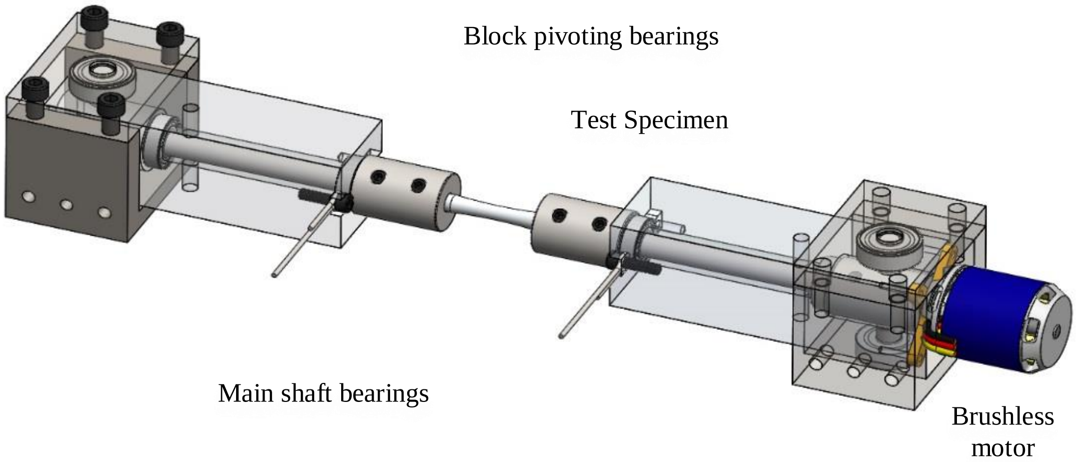

Figure 3 - Main structure components

2.2 Mechanical Solutions

Initially, the shaft couplings that hold the test specimen to the main shaft were collars, using screws on one side to clamp the shafts. Since these components have a naturally unbalanced design, the high rotational speeds led to high vibrations, causing errors in the load readings. It also damaged the brushless motor, since it has a very tight clearance between stator armature and rotor magnets. For this reason, set-screw shaft couplings were designed and machined with tight tolerances, in order to keep vibrations to a minimum (see Figure4).

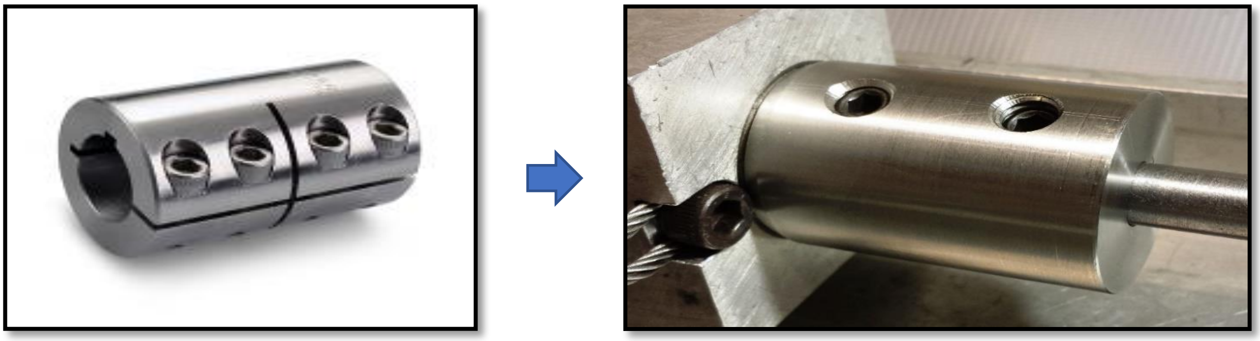

Figure 4 – Shaft couplings. To the left, a commercial shaft collar. To the right, the machined set screw precision collet.

On the initial design, the bending force was applied by a wire rope wound around a pulley, on the shaft of a high-reduction-ratio gearbox. The system proved to be powerful enough to bend the test specimen; however, it lacked precision. The gearbox backlash was large enough to reduce most of the applied load, making it impractical to control. In the final design, another structural aluminum U channel was added to support an automotive electric DC actuator, connected in series with a load cell, to apply and measure the bending load, as seen in Figure 5. This proved to be a much more reliable and precise solution, since the actuator has a self-locking mechanism.

2.3 Control electronics

An Arduino development board (see Figure 6) with a DC motor controller shield receives the force sensing feedback from the load cell amplifier, ranging from zero to 5 Volts, equivalent to zero to 50 kgf. Therefore, the board is able to command the actuator to create the desired bending moment by means of a proportional-integral (PI) controller logic. It also commands the desired rotation speed for the main motor, sending a PWM control signal to a brushless motor speed controller.

Another Arduino board is connected to a Hall effect sensor, counting the magnetic pulses coming from the motor magnets. When the SS411P Hall Effect sensor detects a positive transition, from zero to maximum magnetic field, it switches digitally to "ON". The number of magnets on the motor rotor (ten) is set in the Arduino's code. Since the magnets have an alternating pole configuration, when five transitions from south to north pole are detected, one revolution is registered, counting as one stress cycle on the test specimen. This data is captured by a computer via USB connection, using a LabVIEW interface, registering the applied load, total revolutions or cycles, and current RPM.

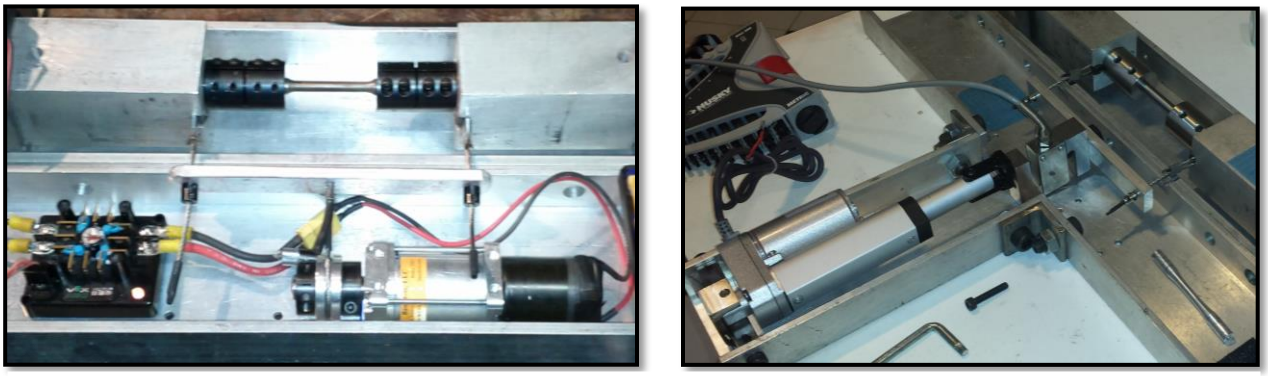

Figure 5 - To the left, the original gearbox and DC motor. To the right, the linear actuator on the final design.

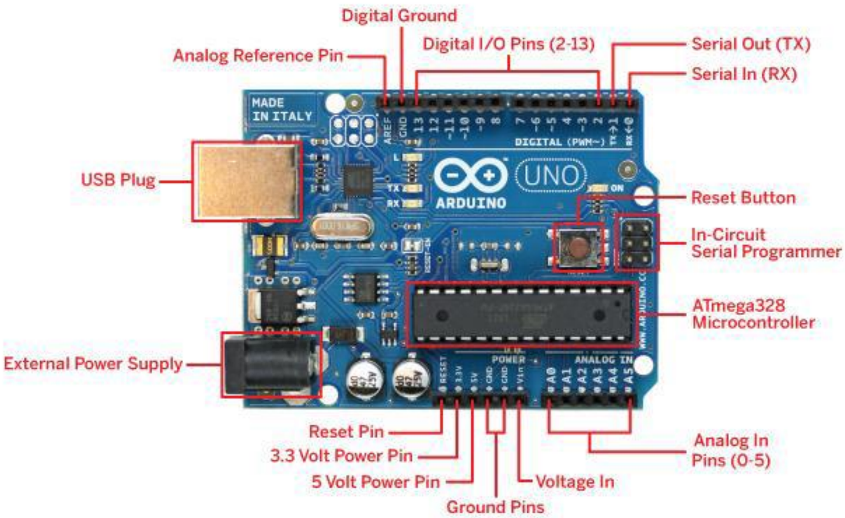

Figure 6 – ARDUINO UNO, open-source electronics development board

2.4 Fatigue Calculations

A worksheet was created to relate the force applied by the actuator in kilograms-force and the machine's dimensions to the bending stress occurring on the test specimen, as can be seen on Table 1. Several conditions can be tested using this machine, such as yield and ultimate stress, surface finish, size, load and, in the future, temperature. Pairing the applied bending moment and total number of revolutions at failure creates a point of stress and number of cycles for the stress-life plot. After multiple experiments, an S-N curve can be fitted.

3. RESULTS AND DISCUSSION

The final design (Figure 7) is easy to assemble and to maintain. It uses low-cost commercial components and structural parts that do not require CNC machining. The test specimen can be replaced in under a minute, and the main shaft can be disassembled in about 15 minutes.

During the development process, the noise and vibration generated by the machine were greatly reduced, allowing it to be operated in the same room where researchers are performing other activities (noise level below 85dB). Also, a more rigid coupling system between the actuator and bearing blocks was chosen, using a bolt as a pivot to distribute the forces evenly to both sides of the machine. Table 2 shows a comparison between the Instron® commercial machine and the S-N machine developed in this work.

Table 1 - Fatigue calculations for the S-N testing machine.

S-N METHOD FATIGUE TESTING MACHINE WORKSHEET	N(SL)	1,00E+06
	N(SL)	5,00E+08

ka	kb	kc	kθ	ke
0,9	1	1	1	1

		SI	Input		6063-T6 aluminum	Al 7075-T6 aluminum	AISI 1020 steel	4340 steel (44HRC)
Distance from center to traction point	L1 (mm)	0,076	76,0	SE	145	470	285	1372
Distance from traction point to pivot	L2 (mm)	0,129	129,0	SR	186	580	491	1469
Distance from center to pivot	L (mm)	0,205	205,0	SF (10^3)	165,5	516,2	373,2	984,2
Applied traction force	T (kgf)	117,72	**12,00**	SL	67,0	117,0	221,0	630,0
Applied bending moment	M (N.m)	7,59294	0,77	b	14,5	8,8	13,2	15,5
Test specimen's radius	y (mm)	0,00381	3,810	C	1,48E+35	9,62E+26	7,94E+36	2,20E+49
Test specimen's moment of inertia	Ixx	1,7E-10	165,5					
Test specimen's maximum stress (MPa)	σ (MPa)	1,75E+08	174,8	State	Plastic	Elastic	Elastic	Elastic
Number of cycles until failure				N (life)	4,54E+02	1,44E+07	2,19E+07	4,18E+14

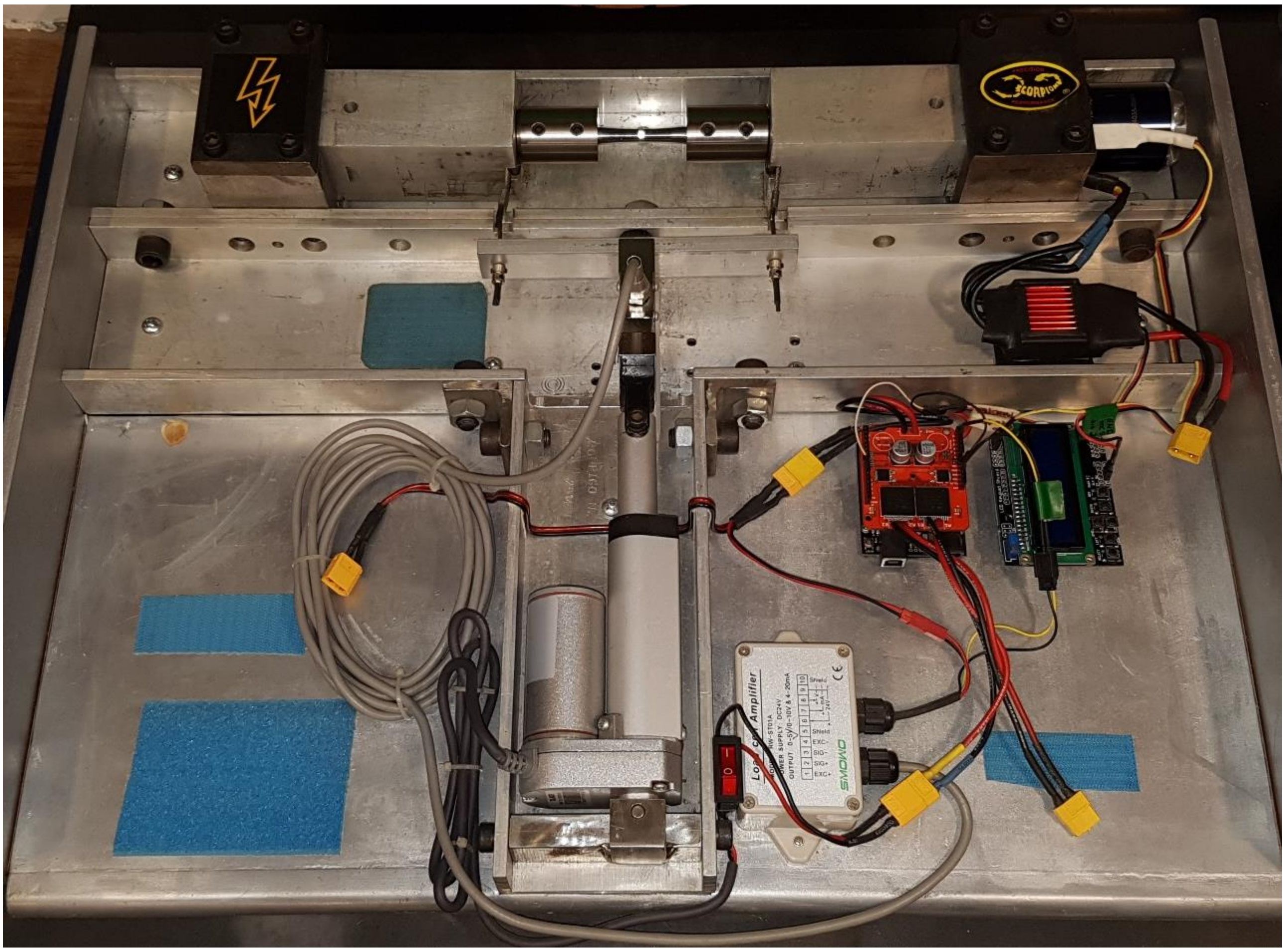

Figure 7 – Complete S-N fatigue testing machine.

Table 2 – Comparison between the developed machine and a commercial product.

Characteristics	S-N machine by PUC-Rio	Instron® R.R. Moore
Bending moment range (kg.m)	0,01 - 3,23	0,25 - 2,3
Bending moment increments (kg.m)	0,0006	0,00254
Rotation speed (RPM)	60 - 20.000	500 - 10.000
Effective minimum force (kgf)	0,1 (100g)	5
Machine weight (kg)	16	41
Dimensions (mm)	620 × 470 × 120	990 × 330 × 510
Power supply	120 V, 50/60Hz	120 V, 50/60Hz
Approximate total cost (USD)	2.500,00	24.250,00

4. CONCLUSIONS

This paper presents the design and fabrication of a new mechanical fatigue testing machine based on rotating beams, with the objective of testing high-cycle fatigue and service-life loads. The system is capable of very high speeds, up to 18,000 rpm or 300Hz, easily generating 1 million stress cycles within an hour. This makes the machine suitable for industrial material characterization, where many high-cycle tests are needed, as well as for educational use, since tests can be performed during a class. Variable bending loading can be controlled through a USB connection, allowing testing under variable amplitudes without the need for several dead-weight changes, leading to several research applications with real-life loadings. Its lightweight design and low cost, about one-tenth of the commercial machine price tag, encourage the use of multiple machines, allowing many tests to be performed at the same time.

Possible future refinements include:

- Use of a single board to control the whole process, such as an Arduino Mega board.
- An end-stop switch to stop the count and shut down motor when test specimen breaks.
- Replacing the current brushless speed controller with a sensored version, in order to have better control at low rotation speeds and more torque
- Using CNC machined ER-type collets to hold the test specimen, providing better grip, easier disassembly and a wider range of test diameters.
- Applying a low-pass filter to the force measurement to improve the proportional-integral control.
- Variable load input interface, allowing for the automatic application of real-life loading blocks.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Hendrickson, D., "Fatigue Failure Due to Variable Loading", Department of Computer Science, Physics, and Engineering - University of Michigan

Norton, R. L. *Machine Design – Integrated Approach*, 4th Edition 2007, Bookman

Meggiolaro, Marco Antonio e CASTRO, Jaime T. P. *Fadiga - Técnicas e Práticas de Dimensionamento Estrutural sob Cargas Reais de Serviço: Volume I – Iniciação de Trincas*, 2009.

Sedra, A. / Smith, K. Microeletrônica – 5 ª Edition, 2007, Prentice Hall - Br.

Shigley, J. E.; Mishke, C. R.; Budynas, R. G., 2004, *Mechanical Engineering Design*, McGraw-Hill, New York.

Dynamic mechanical testing machines - http://www.instron.us/en-us/products/testing-systems/dynamic-and-fatigue-systems

Material Property Data - http://www.matweb.com/

Material Property Data - http://aerospacemetals.com/

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