Session 3226

A Student Controlled Two-Degree of Freedom Vibration Laboratory

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Abstract

In recent years there has been a significant increase in the use of computers in teaching. At the same time there has been a corresponding reduction in laboratories undertaken by students, especially where large classes are involved. With increasing student/staff ratios the cost of running well staffed laboratories has become unacceptable. At the same time very few universities reward staff for producing new laboratories. All these factors have led to fewer laboratories. The need for hands-on laboratories is as great as ever, particularly to illustrate that the real world does not behave as mathematical models predict it will. This paper describes a computer controlled vibration laboratory that is inherently safe and does not need an instructor. The laboratory is controlled through the computer which protects both it and the student. Results are collected and analysed by the computer. Most importantly the laboratory has been designed to behave in a different manner from the theoretical models developed in lectures and students are expected to criticise their lecture models. Finally students may leave comments for fellow students so that the laboratory may slowly evolve in content.

1 Background

The current pressure on teaching resources often means that laboratory classes are removed from the curriculum or at least replaced by virtual laboratories involving simulations. In 1994 Stone [1] describing some computer simulations stated, "Now a warning, it is possible (inevitable?) that students will believe that the real world behaves exactly the same as depicted by the animation programs. This is a dangerous outcome and it is strongly advised that real laboratories be used in parallel with the CAL package. We are in the process of developing self-teach laboratories that have been deliberately designed to not behave as the theoretical models. It is hoped that this will make the students more critically aware of the limits of modelling." As resources for education are reduced and promotion is rarely affected by any time spent on developing laboratories there is the danger that more simulations will replace laboratories. However the need for laboratories remains the same,

- Students learn best when all their senses are involved. Laboratories use the most senses.
- Isolation from the real world is dangerous for engineering students. They need to know the limits of theory.
- There is no substitute for hands-on experience of real engineering products.

This paper describes the continuing development of a possible compromise solution to the need for laboratories and the limitations of staff time. Thus the laboratory is essentially student controlled, safe and may be done at any time. Lyons [2] concluded that "a laboratory designed with this in mind would have the following benefits:

- The control and prevention of unsafe conditions could be achieved through the application of safe limits by the computer. The student would not be able to run the experiment outside these limits.
- Large groups could be avoided as students would have the choice to do the laboratory alone and at their own pace.
- The large task of scheduling laboratory classes would be reduced or removed as students could do the laboratory at the time of their choice.
- The real apparatus as opposed to a simulation could allow open ended investigation and improved physical understanding of the topic."

Lyons developed a single degree of freedom vibration laboratory to meet these requirements. That laboratory was extended by Barrett-Leonard [3] to be a multi-degree of freedom laboratory. However it became apparent that there was a need for a purpose built two degree of freedom vibration laboratory that would illustrate major concepts. This paper describes the laboratory that was developed.

2 Design of Rig

When the vibration of systems is being taught most course cover the theory for a mass/spring system with viscous damping. This brings out the concepts of damped and undamped natural frequency, transient decaying motion and for steady state vibration resonance and vibration isolation. The lab developed by Lyons [2] was such a lab having the benefits of computer control described above.

When multi-degree of vibration is considered the important concepts to be taught are, multiple natural frequencies, mode shapes, damped and undamped absorbers etc. Barrett-Leonard [3] extended the lab of Lyons to cover multi-degree of freedom vibration. There was a disadvantage with this extended lab in that as it was an extension of the linear vibration rig of Lyons it too involved mainly translation and little rotation.

It became apparent that an old torsional two-degree of freedom rig was much my suitable for demonstrating the concepts of multiple natural frequencies, mode shapes and undamped absorbers. The large and visible low frequency vibration was much appreciated by students. It was thus decided to re-design this lab to be computer controlled.

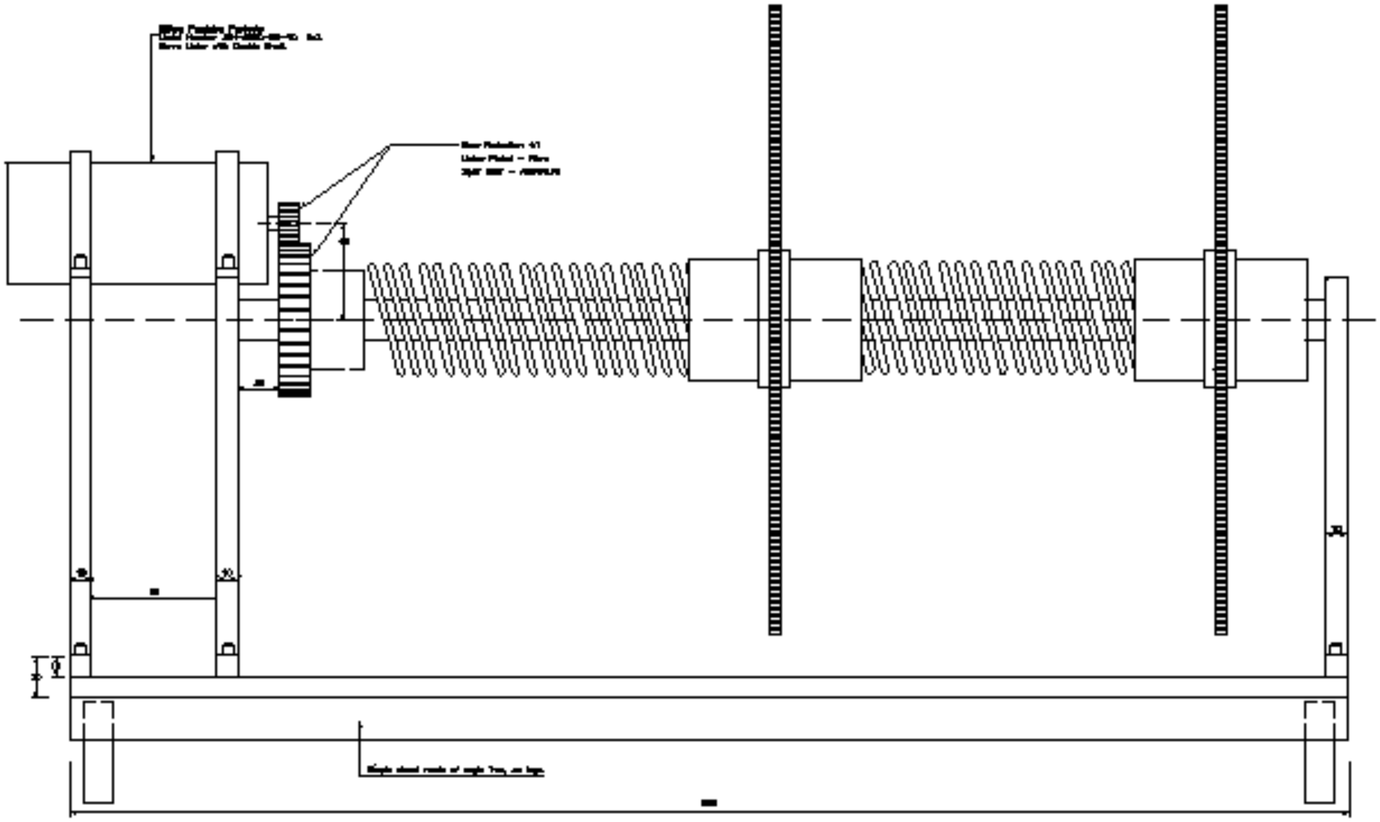

Figure 1   Design of two degree of freedom rig.

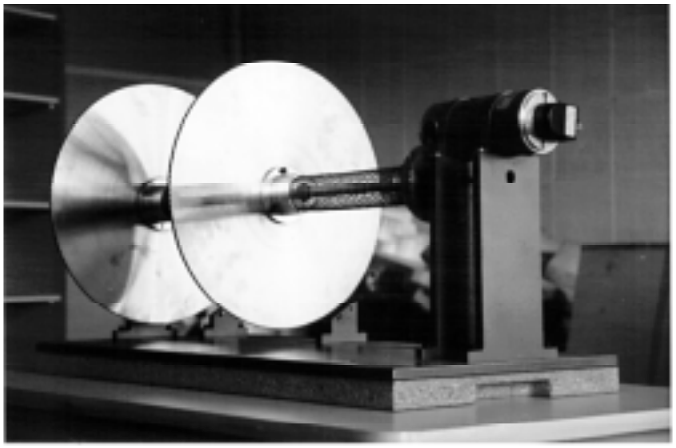

Figure 1   Photograph of rig.

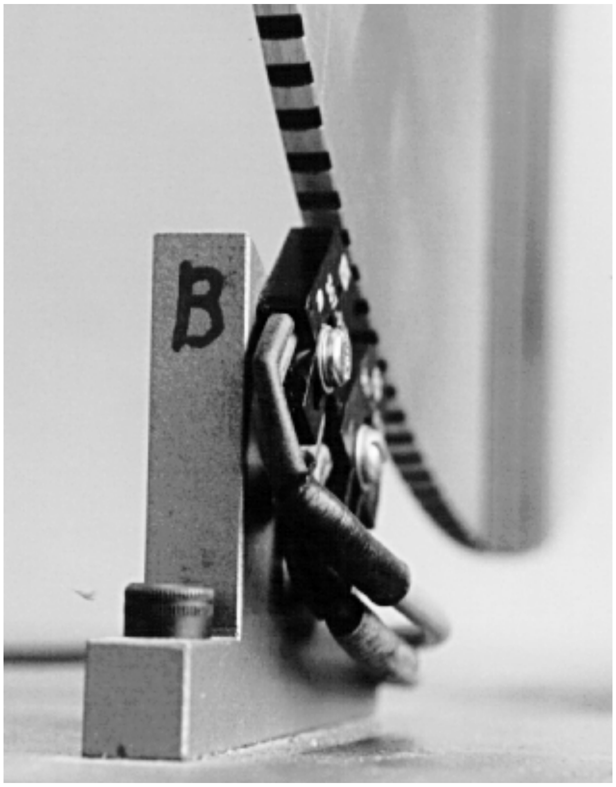

Figure 3 Optical sensors used to measure rotation

The design is shown in Figure 1 and a photograph is shown in Figure 2. The two inertias were large discs and the supporting bearings were mounted on an internal shaft that was the length of the rig. This allowed free access to the discs. The springs were chosen to give low natural frequencies and were attached to the central hubs of the discs. These hubs had spiral grooves machined to receive the springs and an external sleeve was fixed over the springs to provide a rigid and slip free connection, thus minimising energy dissipation.

Figure 3 shows the arrangement of reflective optical sensors near an inertia. Each inertia has 180 grooves machined into its rim. The channels were painted matt black while the remaining parts of the rim was still shiny aluminium. Each reflective optical sensor sends an infra -red beam from one of its lenses. If this beam hits a groove it is absorbed and not reflected due to the matt black colour. Conversely, if it hits shiny aluminium, it is reflected back to the other lenses of the sensor. Thus, each of the two sensors shown receives a digital step signal. It should be noted that each inertia has two sensors mounted near it. The reflective optical sensors are positioned such that when one sensor's infra-red beam is hitting a matt black groove, the other sensor's beam is reflecting off the bare aluminium. Thus the signals from any one sensor will be out of phase with its partner sensor. This allows the sensors, working in tandem, to measure motion and the sense of the motion.

The drive (excitation) motor was a small servo motor. The speed of the motor was controlled by the computer through variation of the voltage applied. The actual motor speed was measured using an M15 encoder providing high precision velocity signals. The encoder contains a gallium aluminium arsenide LED, collimating lens and phased array photo diode detector. The transducer aids the motor by scaling the digital signal sent from the computer, which represents the driving frequency, to the correct amplitude of digital signal that the motor can accept.

Lyons [2] had developed the software that allowed the motor to be run at any fixed speed and also by specifying a speed time graph for the input. It was necessary to extend the software to allow for sinusoidal excitation at any desired frequency.

3 Essential theory and initial measurements

The rig is close to a two degree of torsional vibration system with abutment excitation and no damping as shown schematically in figure 4.

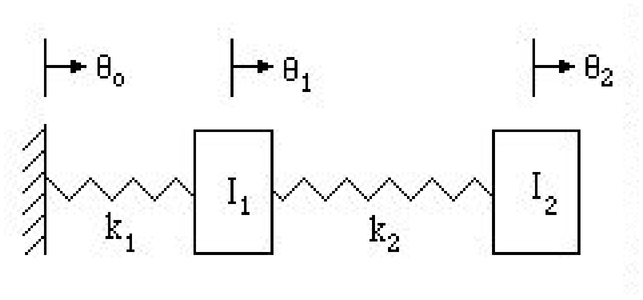

Figure 4 Schematic representation of the rig.

The natural frequency equation of this system is,

$$I_1I_2\omega^4 - (I_1k_2 + I_2k_1 + I_2k_2)\omega^2 + k_1k_2 = 0 \quad \ldots\ldots \quad (1)$$

It would be possible to give the students the values of all the parameters but it is preferable for them to be measured during the lab. However to determine each of the parameters separately would require the rig to be dismantled and re-assembled. It is possible to get round this problem in the following way.

In order to find the values of the relevant parameters it is possible to fix/hold the inertia I_1 and measure the natural free vibration of I_2 on k_2. This gives $\omega_2 = \sqrt{k_2 / I_2}$. It is also possible to fix I_2 and measure the natural free vibration of I_1 on both springs. This gives $\omega_1 = \sqrt{(k_1 + k_2) / I_1}$. Now if we divide equation (1) throughout by I_1I_2 we obtain,

$$\omega^4 - \left(\frac{k_2}{I_2} + \frac{k_1}{I_1} + \frac{k_2}{I_1}\right)\omega^2 + \frac{k_1k_2}{I_1I_2} = 0$$

$$\text{ie.} \quad \omega^4 - \left(\omega_2^2 + \omega_1^2\right)\omega^2 + (\omega_1^2 - \omega_2^2)\omega_2^2 = 0 \ldots\ldots\ldots \quad (2)$$

If we measure ω_1 and ω_2 then we may now solve equation (2) and find the two natural frequencies ω_{n1} and ω_{n2}.

We can also find the mode shapes for these frequencies from,

$$\frac{\Theta_1}{\Theta_2} = \frac{\left(k_2 - I_2\omega^2\right)}{k_2} = 1 - \frac{\omega^2}{\omega_2^2}$$ putting $\omega = \omega_{n1}$ for mode 1 and $\omega = \omega_{n2}$ for mode 2

It will then be possible to displace the rig in to each of the mode shapes in turn and measure the corresponding natural frequency. These may then be compared with the calculated values,

Finally it is possible to excite the rig via the abutment and measure the response of I_1. The theoretical steady state response may be shown to be given by,

$$\frac{\Theta_1}{\Theta_o} = \frac{k_2\left(k_2 - I_2\omega^2\right)}{I_1I_2\omega^4 - (I_1k_2 + I_2k_1 + I_2k_2)\omega^2 + k_1k_2} \quad \ldots \quad (3)$$

This should have two resonances (at the natural frequencies) and one detuned frequency at ω_2. Equation (3) may be solved if we divide by I_1I_2 so that

$$\frac{\Theta_1}{\Theta_o} = \frac{\frac{k_2}{k_1}\left(\omega_1^2 - \omega_2^2\right)\left(\omega_2^2 - \omega^2\right)}{\omega^4 - \left(\omega_2^2 + \omega_1^2\right)\omega^2 + (\omega_1^2 - \omega_2^2)\omega_2^2 = 0} \quad \ldots \quad (4)$$

We can solve this equation IF we can find k_2 / k_1. This may be done by applying a static torque T to I_2 and measuring θ_1 and θ_2. Then the same magnitude torque acts on the ends of each spring and

$$T = k_1\theta_1 = k_2(\theta_2 - \theta_1)$$

$$\text{Rearranging gives} \quad \frac{k_1}{k_2} = \frac{(\theta_2 - \theta_1)}{\theta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

4 Results

The measurement of natural free vibration frequencies can be achieved by using a stopwatch or by analysing the signal from the appropriate optical sensor. A typical set of measurements produced $\omega_1 = 1.81$ rad/s and $\omega_2 = 1.23$ rad/s. Substituting in equation (2) gave $\omega_{n1} = 0.8$ rad/s and $\omega_{n2} = 2.04$ rad/s and mode shapes of 0.57 and -1.74. On displacing into the mode shapes and releasing from rest the measured natural frequencies were found to be 0.79 rad/s and 2.1 rad/s.

As an illustration of the range of experiments that may be conducted, Figure 5 shows the measured transient response to an input speed variation that may be chosen by the student.

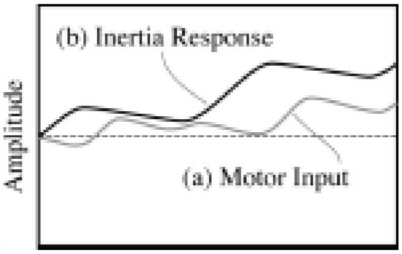

Figure 5 Typical input and response

It is also possible knowing k_2 / k_1, ω_1 and ω_2 and using equation (4) to predict the steady state response. By choosing a steady sinusoidal input the response at discrete frequencies may be checked. In particular the response of I_1 at ω_2 in theory is zero for an undamped system. The student will thus appreciate the significance of damping.

5 Conclusions

The lab described in this paper is an excellent teaching tool in that the frequencies of vibration are very low and hence the motion is easily seen by students. The calibration results are also in close agreement so that students gain confidence in the undamped theory they have been taught and in the rig. However because of the inherent damping in real world systems (even those designed to have low damping) there are differences with the theory. Also since the servo motor is not infinitely “stiff” when subjected to the torque from the vibrating system then the output from the motor is not as specified. This will prove to be an excellent means of developing critical awareness skills in students.

The computer control and the low speeds ensure that the rig is inherently safe and so it will be possible to allow students to use the rig unsupervised. It is also planned to arrange to have the rig to be accessed from more than one computer. Students may thus be queued and single rig may be used for multiple and parallel student experiments.

It is also proposed that a messaging layer be provided for students so that they may leave comments and interesting results for fellow students to follow up

7 References

1 Stone, B. J., 'A Computer Assisted Learning Package for Two-degree of Freedom Vibration.' Proceedings of ASEE '94 Conference. Edmonton, Canada. 1262-1266.

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3 Barrett-Leonard, T., Scott, N. and Stone, B. J., ‘A self teach laboratory for multi-DOF vibration.’ Abstract Proceedings of the VIII International Congress on Experimental Mechanics, Nashville Tennessee, 1996. 256-257

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B.J. Stone

Professor Brian Stone has held the Chair in Mechanical Engineering at the University of Western Australia since 1981. He obtained his doctorate from the University of Bristol in 1968. He has been writing teaching software since 1987, some of which is now used at universities throughout the world. In 1997 he was named the best Engineering teacher in Australia by a federal committee. His research interests include vibration suppression and computer simulation of dynamic systems.