A Novel Undergraduate Learning Tool For Engineering Control and Applied Rheology

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Abstract:

Meaningful engineering projects involve systems engineering which challenge students to apply knowledge they gained in studying individual subject-centered courses into a holistic product. This particularly applies to engineering students who are traditionally applications oriented.
Engineering controls is a course most students find challenging to master in the limited time at their disposal within traditionally crowded engineering syllabus. However, presenting them with a singular and palpable task which requires application of this basic knowledge – and even more, lends itself to learning through self-discovery. This is particularly the case in mechatronics, robotics and automation in general – a backbone to most of devices in use today, where the control theory plays a crucial part.
Engineering rheology is a specialist branch of Fluid Mechanics encountered by only a few students – usually at the postgraduate level. It deals with the behaviour of fluids often outside their every-day experience, and which is often contrary to the expectations. It is therefore a special challenge to undergraduate students who are only used to the behaviour of Newtonian fluids they had studied (and experienced) hitherto, to at least obtain a working knowledge of the esoteric subject in order to own up to the posed problem they chose to tackle. It too requires learning through self-discovery.
The aim of this paper is to describe one such project undertaken by final year students under the authors' supervision and guidance. It involved application of control algorithms to a fluid whose rheological properties varied with the applied load through a specialised feedback loop controlling the magnetic field strength to which the fluid was exposed. The fluid viscosity varied with the strength of the applied magnetic field. – which imparted to it the non-Newtonian characteristics. Such fluids are called magneto-rheological fluids or more commonly, just MRFs. The mechanical component using an MRF was a damper such as used in automobiles. However, rather than the commonly used "passive" variety, an MRF damper is an "active" one – damping varied with the frequency of the applied load.

1. Introduction

At the University of Western Sydney, one of the Engineering Courses on offer is Robotics and Mechatronics Engineering at the undergraduate level – in the first instance. The course is particularly challenging in that it offers ample scope to learning in systems operation, involving not only Mechanical Engineering Design, but tangible applications of Control Theory – one of the majors in the course. A particularly attractive application is the semiactive control that lends itself to autonomous vehicular performance. Of particular interest to the students is any design aspect with transportation bias: electric and solar powered vehicles, scooters, boats and the like.

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2. Theoretical Background

The basic element often used in the study of vibration control in automobiles, is the "quarter car" model comprising one wheel equipped with the suspension and assumed to carry a quarter of the full load of the car. Of interest is the amount of comfort in the ride a passenger experiences. In its simplest form, for studies in one dimensional vertical motion, [1] one such model is shown in Figure 1. As shown in Figure 1, m_2 represents the sprung mass (passenger) and m_1 the unsprung mass (wheel), with corresponding stiffness k_S and k_W. The input r represents excitation due to the road surface. Gravity effects are neglected. The shock absorber or damper is shown with coefficient b. The magnitude of the force from the shock absorber is taken to be proportional to the rate of change of the relative displacements of the two masses. That is a force of $b(\dot{y}-\dot{x})$. In like manner, the force from the car suspension acts on both masses in proportion to their relative displacement. Applying Newton's law leads to the following system of equations:

$$\begin{aligned} m_1\ddot{x} &= b(\dot{y}-\dot{x}) + k_S(y-x) - k_W(x-r) \\ m_2\ddot{y} &= -k_S(y-x) - b(\dot{y}-\dot{x}) \end{aligned} \tag{1}$$

Figure 1 indicates the basic elements of the passive vibration control system comprising the vehicle chassis supported by a spring and viscous damper and the tyres, with the stiffness component only.

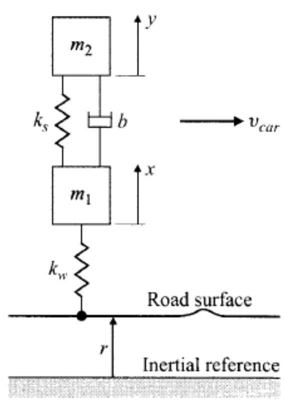

Figure 1: Quarter Car Model [1]

Using this model as the basis for further analysis and refinement, together with typical quantitative data (sprung and unsprung mass, suspension and tyre stiffness and the viscous damping coefficients) enables formulation of a two mass vibration isolation system. Using the standard second order equation, $s^2 + 2\zeta\omega_n s + \omega_n^2$ facilitates evaluation of the damping ratios

$$\zeta_1 = \frac{b}{2\sqrt{((k_W + k_S)m_1)}} \quad \text{and} \quad \zeta_2 = \frac{b}{2\sqrt{(k_W m_1)}} \tag{2}$$

Figure 2 indicates displacement of the sprung mass with respect to the input amplitude.

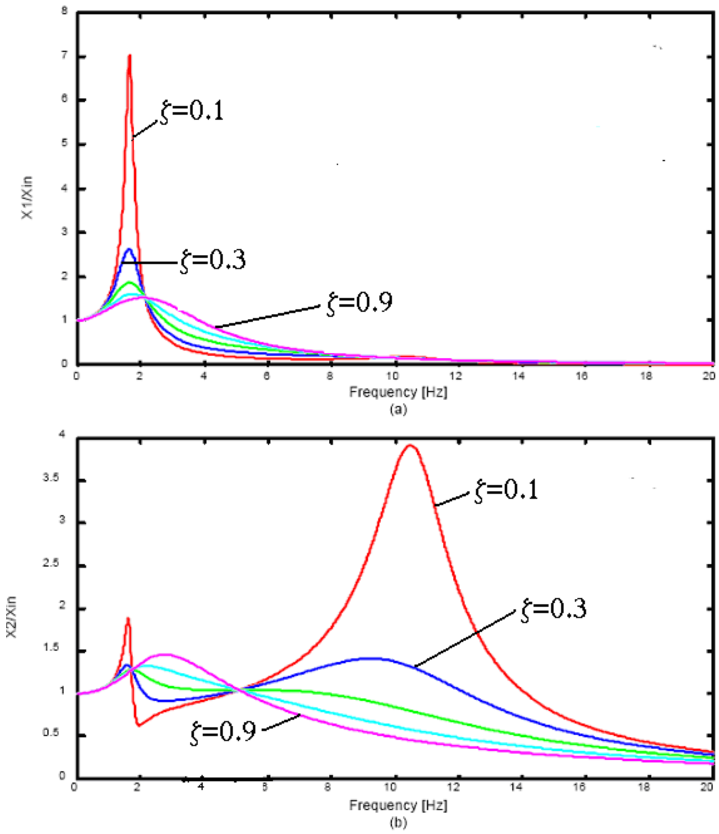

Figure 2: Transmissibility: (a) sprung (b) unsprung

When compared with the unsprung system, it can readily be seen that the effect of damping is considerable, though variable with the amplitude of the input disturbance.

A substantial amount of control over the magnitude of the transmitted vibration has been achieved with semiactive dampers mimicking the performance of the “skyhook controller”. They key element in the controlled damping system is the fluid damper with variable viscosity – depending on the strength of the surrounding magnetic field. The field strength is controlled in an adaptive mode so as to achieve considerable and the desired reduction in the amplitude of the transmitted mechanical vibration. Fluids whose viscosity can be controlled in this manner are called Magneto-rheological Fluids – or MRFs.

3. Description of the Basic Control Mechanism

In automotive aplications the ultimate shock absorber might be attached to the car body over each wheel on one end and connected up to imaginary hooks in the sky that moved along with the vehicle. The sky hooks would thrust down as the wheels bounced up on hitting bumps; the sky hooks would keep the car body on a level position! A conventional shock absorber might be expected to do the same, but not so unfortunately. Figure 3 is an ideal representation of the skyhook damper. In practice a more down to earth version is needed. At best the skyhook would need to turn off shock absorption and then turn on gardually. This leads to the concept of active or semiactive damper controls. Figure 4 is an example of a practical implementation of the ideal skyhook damper.

The skyhook semi-active control policy is well known and may be summarized by

$$u = \begin{cases} u_{\max}, & if \;\; \dot{z}_2(\dot{z}_2 - \dot{z}_1) \geq 0 \\ u_{MIN}, & if \;\; \dot{z}_2(\dot{z}_2 - \dot{z}_1) < 0 \end{cases} \tag{3}$$

Modulation of damper action is designed to emulate the action of the damper in the sky. So when the two masses are moving in the positive direction but separating, the skyhook damper would apply a negative force in opposition and this corresponds to the first condition in (5). In the other case the best that can be done is to minimize the force supplied by the controlled damper. This corresponds to the second condition in (5).

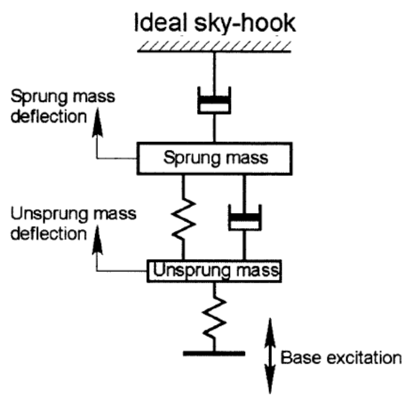

Figure 3: Idealy hooks in the sky [5].

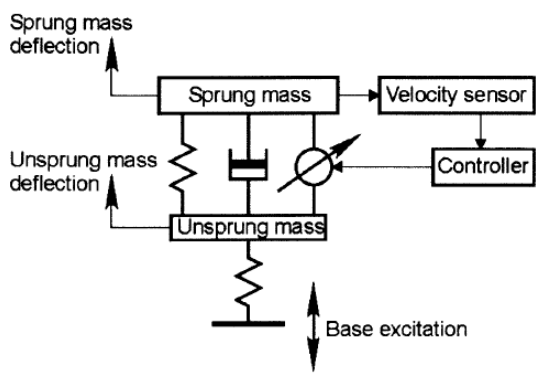

Figure 4: Down to earth version [5].

4. Mechanical Design of a Typical MRF Damper

In essence, a damper consists of a plunger confined to move along the longitudinal axis a cylinder containing it and the MR fluid. A DC current carrying coil is wound either inside the plunger or housed in its periphery. The current magnitude is adjusted according to the amplitude of the input vibration which in turn is controlled by the set limits – often dictated by the passenger comfort. The strength of the magnetic field determines the yield stress of the fluid, which is best described by a Bingham model – and it provides appropriate resistance to the plunger travel to confine it within the desired limits. A typical design is shown in Figure 3 [3].

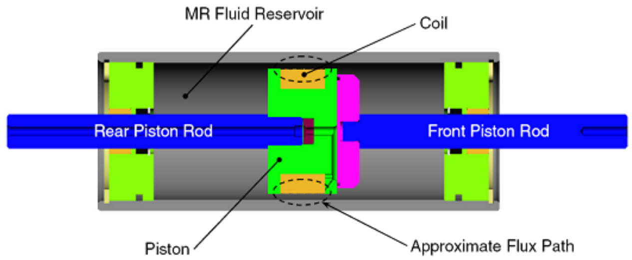

Figure 5: Typical damper design

5. System Performance Model

The whole damping system was modelled using Matlab Simulink and shown in Figure 6 below.

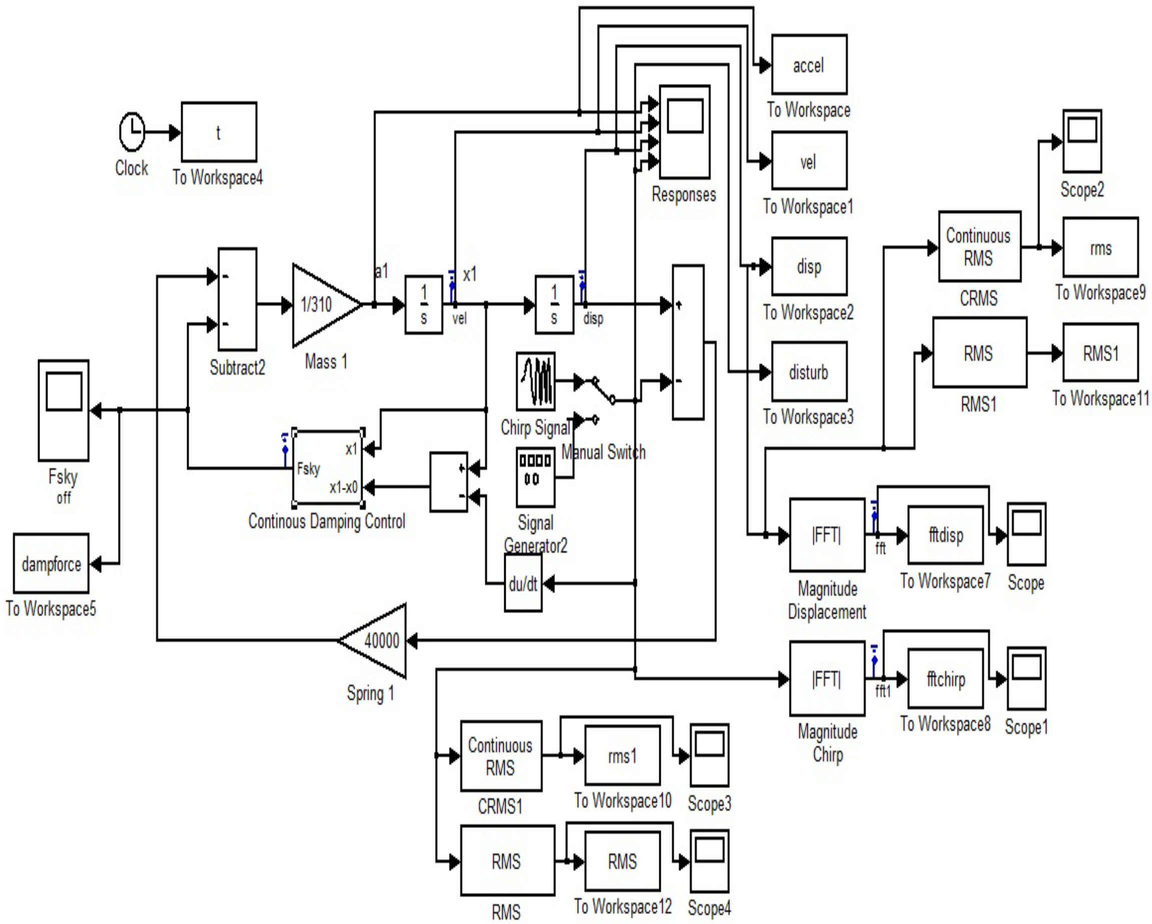

Figure 6: Single Degree of Freedom Continuous Skyhook Model

6. Discussion of System Performance

A transient response of the system described above is shown below in Figure 6. A substantial reduction in the displacement amplitude is obvious and rewarding to the designer. The magnitude of change in the amplitude is clearly dependent upon the magnitude of the electric current in the magnetising coils, which in turn affects the damping coefficient of the damper fluid via the change in the magnetic field strength,

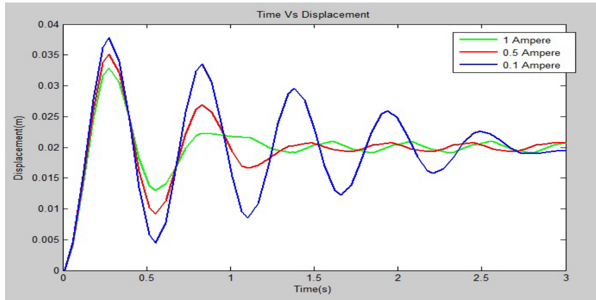

Figure 6: Transient resonses

7. A Pedagogical Sequel

A pleasing consequence of a number of such projects undertaken by our senior students in their final year of study involving active damping control with MRFs, has been continuation of their studies towards a higher degree. We believe that a major part in this was in students having to learn for themselves, with every encouragement by their supervisors, of the subject matter at an advanced level, often not covered in an undergraduate course they had been taking. This approach was also used earlier [5] as a means of introducing rheology to undergraduate students – in a similar context.

8. Conclusions

The success of their students have inspired the authors to recommend a pedagogically similar exercises for students of their colleagues. The major element of these is a considerable component of self learning inspired by intellectually challenging projects that have clear application, utility and relevance.

9. Acknowledgements

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