AC 2009-297: INCORPORATING A TEACHER'S RESEARCH PROJECT INTO AN UNDERGRADUATE LEVEL COURSE

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Incorporating a Teacher's Research Project into an Undergraduate Level Course

1. Introduction

This paper describes the integrating of a research topic into an undergraduate "System Dynamics and Vibration" course. The process helped the students to capture the essential aspects of the problems in a mechanical model, make reasonable simplifying assumptions, and reduce this model into solvable problems, such as, single degree of freedom and multiple degrees of freedom vibrations. It provided the missing link between the theoretical concepts and the real engineering world.

The research topic used was related to a study on reliability of electronic products subjected to drop impact. Drop reliability is a great concern to semiconductor and electronic product manufacturers, especially for portable devices such as mobile phones and PDAs. It is not uncommon for those portable electronic products to be accidentally dropped onto the ground. Vulnerable elements inside such products may experience very high accelerations and dynamic stresses. This ultimately causes failures in solder joints, intermetallic layers at solder-pad interfaces, or boards via cracking. The impacts and shocks can lead to the failure and malfunction of the products. Manufacturers usually determine the fragility of such products by three levels research on the drop reliability – component level, board level, and system level [1-8]. Vibration analysis can be used in both board level and system level analysis.

Board level drop tests can be simplified and analyzed as one degree of freedom dynamic systems, and system level product analysis can be simplified and analyzed as a two degree of freedom system. Two projects of finding analytical and numerical solutions for both board level drop tests and system level product analysis were assigned in different stages of the students' learning experience.

In the paper, the description, implementation and assessment of the teaching process are presented and discussed. Section 2 presents the description and implementation of the single degree of freedom model and analysis for the simplified board level drop tests. Section 3 describes the multiple degrees of freedom analysis for the system level products subjected to the drop impacts. Finally, assessment and conclusion are given at the end of the paper.

2. Project 1 - Single Degree of Freedom Model and Analysis

A board level drop test can be simulated with a one degree of freedom (1DOF) dynamic system. The students are assigned the project when they are learning 1DOF systems. Both theoretical and numerical solutions are required to find the displacement and acceleration of the drop test board.

Specifically, the students are required to:

1. Model the standard board level drop test system as a 1DOF system, and derive the simplified system's equations of motion.

2. Derive the time response of the system with piecewise half-sine excitation.
3. Develop a MATLAB/SIMULINK model to numerically simulate the displacement response and acceleration response of the test board.

2.1 Board Level Drop Impact Test Method

The board level drop tests are standardized by the JEDEC standard for manufacturers [9]. It recommends mounting 15 package components on the test board in three rows of five components each. The test board is mounted inverted on a base plate by four screws at the corners. This base plate is then mounted on a drop table. The drop table, controlled by guide rods, is allowed to strike a rigid base from a specified height. In the experimental set-up, the prescribed acceleration pulse is achieved by manipulating the fall height and the stiffness of the strike base. Figure 1 is the typical drop apparatus and mounting scheme [9]. An understanding of the mechanics of this event will be useful for the conduct of the experiment. The base structure and standoff connectors are typically made of metal whose longitudinal stiffness is much higher than the flexural stiffness of the test board. Thus, the test board in the drop test can be simplified as a 1DOF spring-mass-damper system.

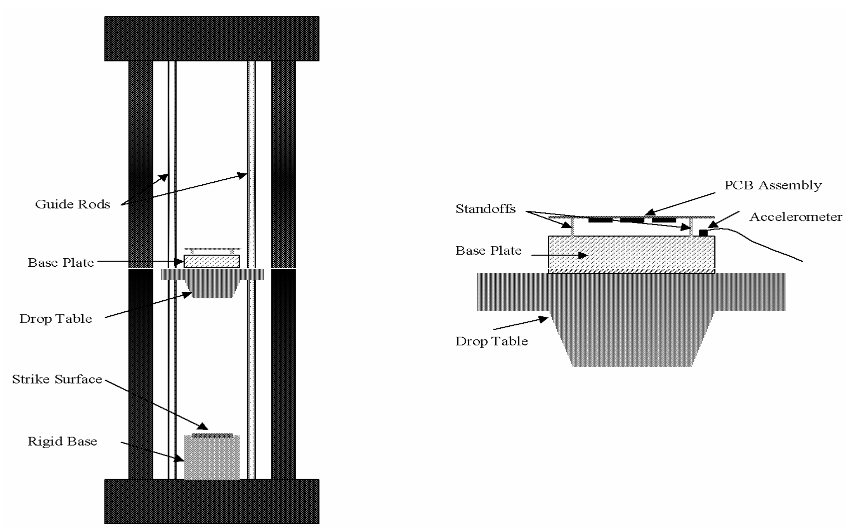


Figure 1. Typical drop apparatus and mounting scheme [9]

2.2 Simplified Model

The test board supported by four screws in the drop test can be simplified a 1DOF mass-spring-damper system. The equation of motion is

$$M\ddot{x}(t) + B\dot{x}(t) + Kx(t) = f(t) \quad (1)$$

where M is the mass, B is the damping coefficient, and K is the spring constant of the test board, $x(t)$ is the displacement of the test board of the system, and $f(t)$ is the applied impact impulse.

The JEDEC standard suggests that the test board be subjected to the half-sine pulse acceleration as shown in Figure 2.

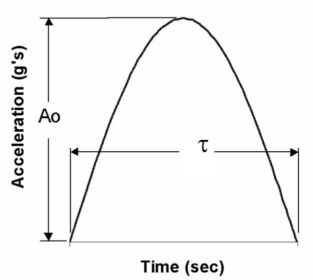


Figure 2. Typical drop test half-sine pulse

The mathematical expression is

$$A(t) = A_0 \sin(\frac{\pi t}{\tau}), \tag{2}$$

where, A_0 is the peak acceleration and τ is time duration of the pulse. Thus, the impact pulse $f(t)$ in Eq. (1), when t is between 0 and τ, is

$$f(t) = MA_0 \sin(\frac{\pi t}{\tau}) = G_P \sin(\frac{\pi t}{\tau}), \tag{3}$$

or, the excitation can be expressed piecewise as,

$$f(t) = \begin{cases} G_p \sin(\frac{\pi t}{\tau}), & 0 \le t \le \tau \\ 0, & t > \tau \end{cases}, \tag{4}$$

with the initial conditions equal to zeros.

2.3 Theoretical Solution

Piecewise excitation expression in Eq. (4) increases the difficulties of solving the 1DOF problems in Eq. (1). The solution when $0 \le t \le \tau$ can be used as the initial condition of the equation when $t > \tau$. The problem becomes solving two sets of ordinary differential equations, as follows.

$$\begin{cases} m\ddot{x} + kx = G_p \sin(\pi t / \tau) \\ x(0) = \dot{x}(0) = 0 \end{cases} \quad \text{when } t \le \tau, \tag{5}$$

and

$$\begin{cases} m\ddot{x} + kx = 0 \\ \text{I.C.s are } x(\tau), \dot{x}(\tau) \text{ obtained from Eq (5)} \end{cases} \quad \text{when } t > \tau. \tag{6}$$

Thus, the displacement response of the test board subjected to a half-sine pulse can be expressed by,

$$x(t) = \frac{G_p}{m}\frac{1}{\omega_n^2 - (\pi/\tau)^2}\left[\sin\left(\frac{\pi t}{\tau}\right) - \frac{\pi}{\tau\omega_n}\sin(\omega_n t)\right], \text{ when } t \le \tau \qquad (7)$$

and

$$x(t-\tau) = -\frac{G_p \pi}{m\tau\omega_n\left(\omega_n^2 - (\pi/\tau)^2\right)}\{\sin(\omega_n t) + \sin[\omega_n(t-\tau)]\}, \text{ when } t > \tau \qquad (8)$$

2.4 Numerical Solution

The students are required to develop a MATLAB/SIMULINK model to determine a system's dynamic response. A SIMULINK model can facilitate the parameter study. Using such a tool, the relationship between input and output can be obtained and visualized easily and quickly with selected system parameters. The block diagram and the corresponding SIMULINK models are shown in Fig. 3. The input half-sine pulse is generated in the MATLAB workspace before the execution of the SIMULINK model. Both displacement and acceleration can be displayed simultaneously.

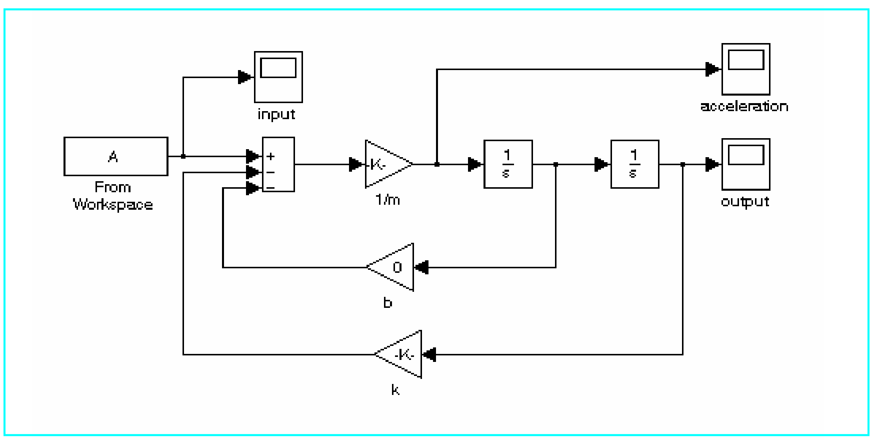


Figure 3. Block diagram and SIMULINK model for the 1DOF system

Assume the mass of a printed circuit board ("PCB") board M is 25 gram and the spring constant K is 40 N/mm. The input half-sine function is defined by the JEDEC standard as peak acceleration A_0 is 1500 Gs and time duration τ is 0.5 milliseconds. With these parameters defined in the MATLAB/SIMULINK model, the input pulse and system dynamic response for the output displacement and acceleration are obtained in Figures 4-6. The horizontal axis is time (*s*) and the vertical axis is the input excitation corresponding to *Gs*, displacement (*m*), and acceleration (*Gs*), respectively. The output displacement oscillates up and down with the same peak value.

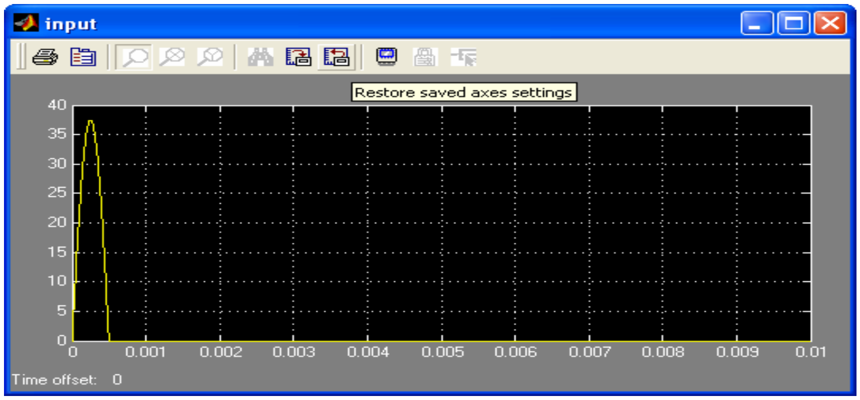


Figure 4. Input excitation to the test board with standard input.

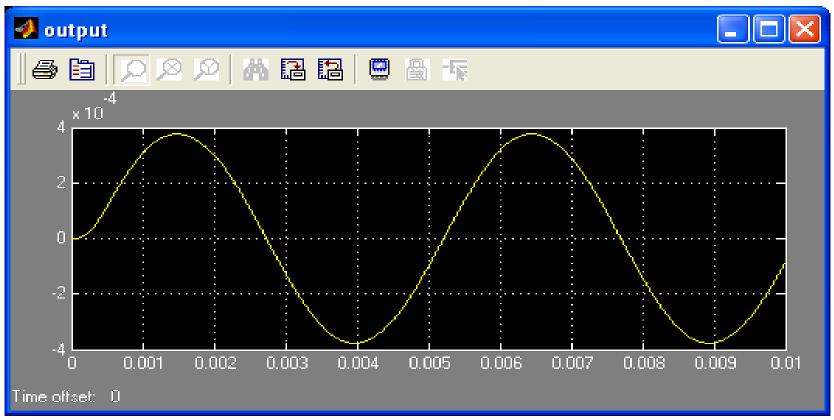


Figure 5. Output displacement of the test board with standard input.

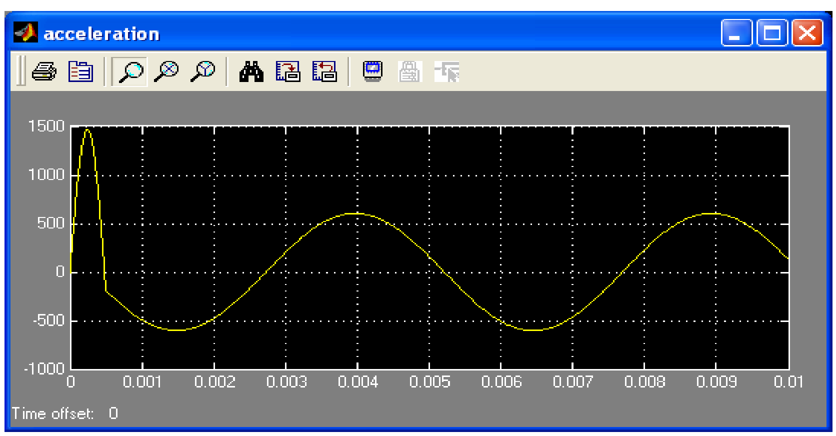


Figure 6. System response of acceleration of the JEDEC test board with standard input.

3. Project 2 – Multiple degrees of freedom Model and Analysis

3.1 System Level Drop Impact to a Portable Electronic Product

System level drop tests can be simplified as two DOF dynamic systems. The students are assigned the project when they study multiple degree of freedom system vibrations. Both theoretical and numerical solutions are required to find the displacement and acceleration of the electronic product subjected to the drop impact.

In the project, the students are required to finish the following tasks:

1. Derive the simplified system's equations of motion and initial conditions if the mobile phone drops from the height of *h*.
2. Determine the natural frequencies and vibration modes of the system, for given system parameters.
3. Simulate the displacement response and acceleration response of the PCB numerically.
4. Discuss the effects of spring constant ratio k_1/k_2 on the maximum displacement and maximum acceleration of the PCB.

3.1 System Level Drop Impact to a Portable Electronic Product

System level drop impact analysis deals with the whole electronic product analysis. The example used here is a mobile phone. Many mobile phones are composed of a PCB with electronic packages amounted on it and a plastic housing to secure the PCB. The mobile phone can be simplified as a two DOF system, as shown in Figure 7. In the model, m_1 and k_1 are the mass and spring constant of PCB; m_2 and k_2 are the mass and spring constant of the housing; x_1 and x_2 are the displacements for the PCB and housing respectively.

Because the deflection associated with PCB bending is the primary driver of solder joint failure during drop impact, the dynamic response of the PCB assembly under impact are important variables to be investigated.

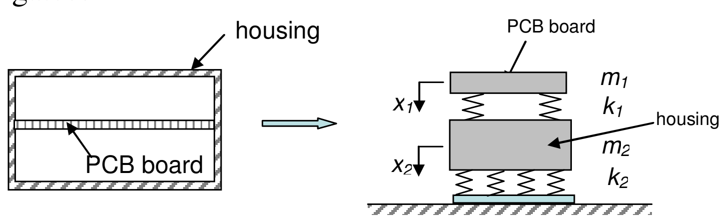


Figure 7. Simplified model of a mobile phone

3.2 Simplified Model

Based on some necessary assumptions [3,4], the equation of motion for the system in question is,

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{Bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix} \begin{Bmatrix} x_1(t) \\ x_2(t) \end{Bmatrix} = 0 . \tag{9}$$

The initial conditions are

$$\begin{Bmatrix} x_1(t) \\ x_2(t) \end{Bmatrix} = 0, \text{and} \begin{Bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{Bmatrix} = \begin{Bmatrix} \sqrt{2gh} \\ \sqrt{2gh} \end{Bmatrix} \tag{10}$$

where *h* is the drop height.

3.3 Theoretical Solution

The natural frequencies and vibration modes of the system can be determined based on the above equations of motion. The Laplace transformation method can be used to solve this problem. Assume $X_1(s)$ is the Laplace transform of the PCB displacement $x_1(t)$, and $\ddot{X}_1(s)$ is the Laplace transform of PCB acceleration $\ddot{x}_1(t)$. Based on Eqs. (9) and (10), $X_1(s)$ and $\ddot{X}_1(s)$ can be obtained as,

$$X_1(s) = \frac{\sqrt{2gh}\left(s^2 + \frac{k_2}{m_1} + \frac{k_1}{m_2} + \frac{k_2}{m_2}\right)}{s^4 + \left(\frac{k_1}{m_1} + \frac{k_1}{m_2} + \frac{k_2}{m_2}\right)s^2 + \left(\frac{k_1}{m_1}\frac{k_2}{m_2}\right)} \tag{11}$$

and

$$\ddot{X}_1(s) = s^2 X(s) - \sqrt{2gh}\,. \tag{12}$$

3.4 Numerical Solution

The time domain closed-form analytical solution for Eq. (9) with initial conditions is complicated. SIMULINK models can be obtained from the differential equations. The block diagram is sketched and the corresponding SIMULINK models are shown in Fig. 8.

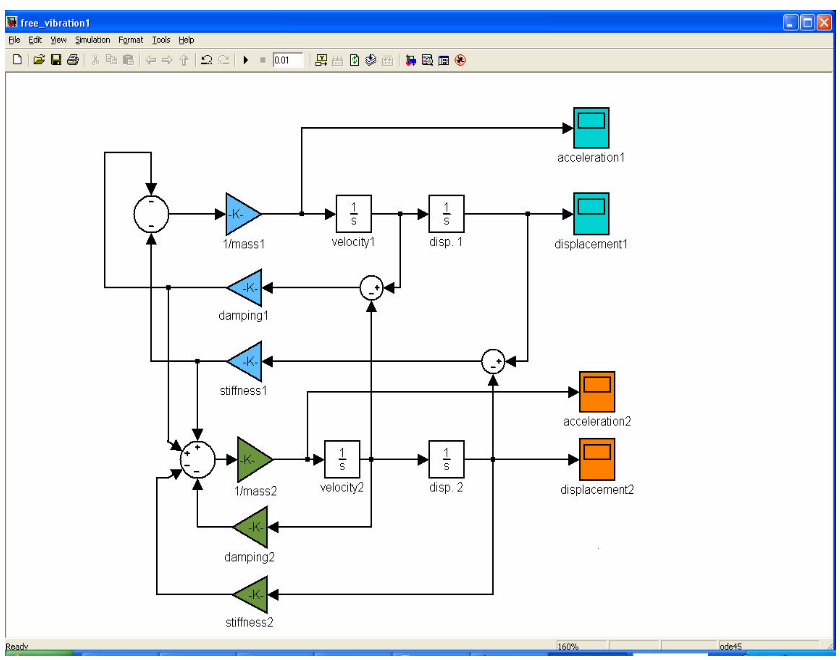
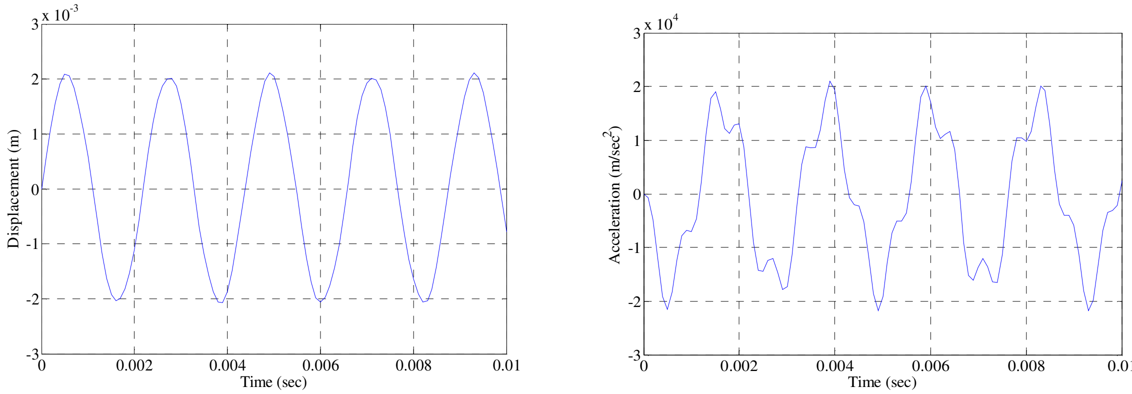


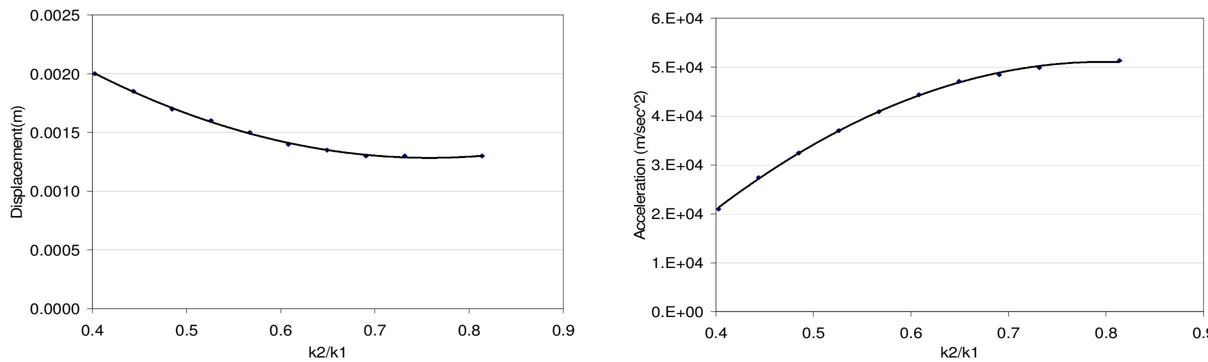
Figure 8. Block diagram and SIMULINK model for free vibration with initial conditions

Displacement response and acceleration response of the PCB for an examined mobile phone can be easily simulated, as shown in Figure 9. Representative plots are shown in Figure 10 for the effects of spring constant ratio k_1/k_2 on the maximum displacement and maximum acceleration of the PCB.



(a) (b)

Figure 9. (a) Displacement of PCB board in a mobile phone; (b) Acceleration of PCB board in a mobile phone



(a) (b)

Figure 10. (a) Maximum displacement versus stiffness ratio k_2/k_1; (b) Maximum acceleration versus stiffness ratio k_2/k_1

With the increase of stiffness ratio k_2/k_1, displacement decreases while acceleration increases. Research shows that the displacement plays a more significant role in the failure of the solder joints on PCBs [4,8]. Therefore, the housing should use the materials with relative low stiffness to ensure a low frequency ratio response.

4. Assessment

This project shows a mechanical application in the electronic industries. The project also demonstrates the direct application of mechanical vibrations and system dynamics to real world problems. This motivates and retains the students' interests in learning the subject, and inspires their recognition of the need of life-long learning.

The second project described above has been used in teaching mechanical engineering students every spring semester since spring 2005. The project discussed above was assigned for the first time in spring 2008. A student satisfaction survey on the project assignment was performed in spring 2007. Students answer questions on a Likert [10] scale of 1 (truly inadequate) to 7 (truly outstanding). The result is shown in Table 1. While there is no hard evidence yet, the results of implementation of the both projects in spring 2008 are very promising. The students indicated that they felt that doing the projects helped them better understand course concepts. The real world projects improved student satisfaction and student examination performance in the course. Full formal assessment and evaluation for both projects are planned for spring 2009.

Table 1: Student satisfaction survey in spring 2007

Number of Students	Average Rating	Standard Deviation
35	5.8	1.2

5. Conclusion

The integration of two research projects has been successfully implemented in a course in mechanical vibrations. The breadth of topics covered using the teacher's research problem includes single degree of freedom and multiple degrees of freedom system analysis taught in the course. The results of implementation of the projects were very promising.

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