

# Real time tuned mass damper simulation system

by

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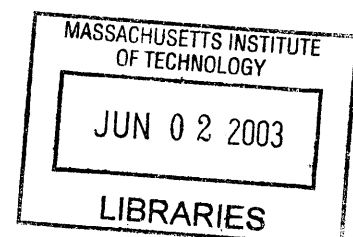
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**BARKER**



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Submitted to the Department of Civil and Environmental Engineering on May 9, 2003, in partial fulfillment of the requirements for the degree of Master of Engineering in Civil and Environmental Engineering

## **Abstract**

The major concern in the construction industry in constructing tall structures is vibration due to wind and earthquake. Tuned mass dampers are an effective and practical ways to reduce the effect of vibration in structures.

This thesis presents a tool, which simulates the effect of tuned mass dampers on the structure. This tool has been proposed to form a part of the website, [moment.mit.edu](http://moment.mit.edu). Java applets have been used to represent the working of the tuned mass damper, graphically.

This would provide a better understanding for the students, so that they can design tuned mass damper effectively and use it appropriately. Strong dynamic figurers and graphs are used to convey the concept and the idea.

**Thesis Supervisor: Prof. Jerome J. Connor**  
**Title: Professor, Civil and Environmental Engineering**

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*I would like to thanks my parents, brother and my friend, Sakshi, for their never ending love, patience and support. Without you, I would not be the woman I am today*

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## **Chapter 1: Introduction**

The major concern in the construction industry in constructing tall structures is vibration due to wind and earthquake. Wide span structures like bridges; observer stands; stairway; stadium roofs and slender tall structures tend to be easily excited to high amplitudes in one of their basic mode shapes. [10]

The natural frequency is low for such buildings due to their dimensions. In any kind of similar construction, the major concern is the amount of lateral displacement. In many cases, lateral motion may interfere with normal services and communication facilities in the buildings. With Tuned Mass Dampers (TMD), these vibrations can be reduced very effectively. [10]

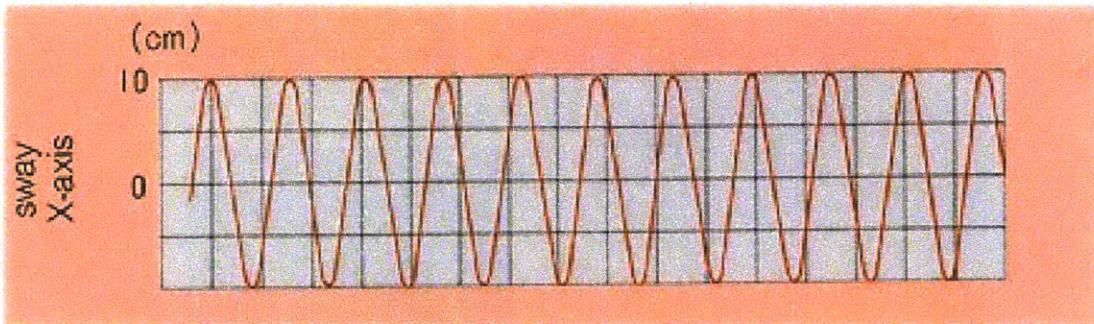


Figure 1: Without Damper [11]

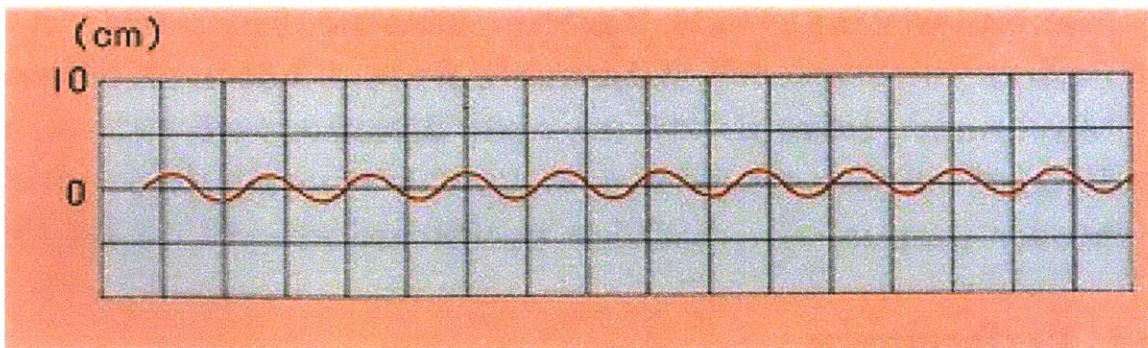
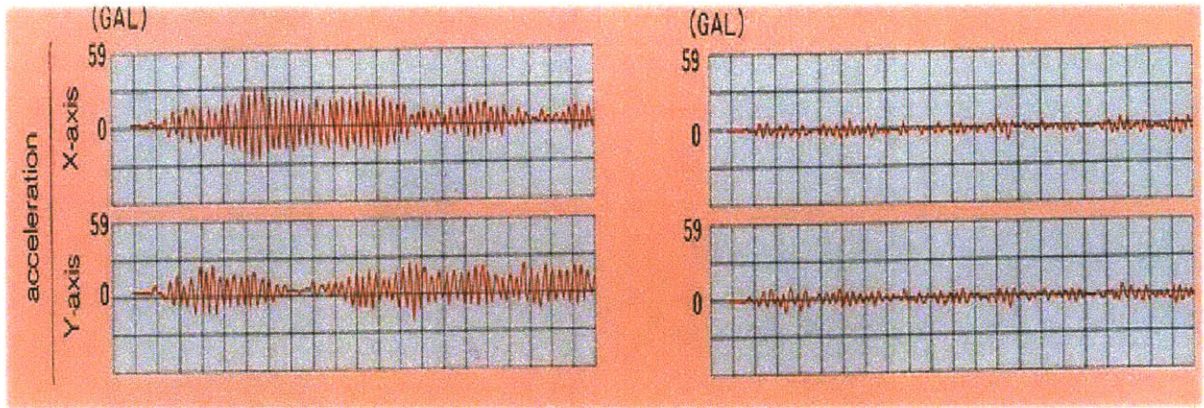


Figure 2: With Damper [11]



Without Damper

With Damper

Figure 3: Effect of TMD [11]

Tuned mass dampers are effective and practical ways to reduce the effect of vibration in structures. TMD is composed of a spring, mass, and dashpot. A TMD is a single degree-of-freedom system, which adds a mode of vibration to the base structure. [12]

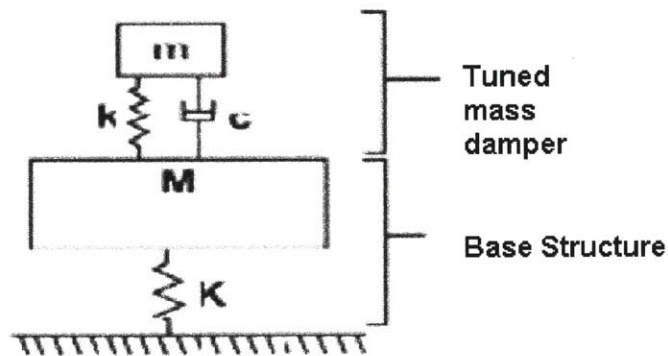


Figure 4: Tuned Mass [12]

The stiffness  $k$  and mass  $m$  [Figure 4] of the TMD are chosen such that it puts the TMD natural frequency just below the required frequency of the base structure. The target mode, which is the required frequency is replaced by two modes, one slightly

above and one slightly below the original frequency. Both of these modes are damped by the dashpot of the TMD. As a result, when the building sways the damper moves in the opposite direction and absorbs the motion. [12] In addition, it has sensors, which detect the sway of the building and computers, which controls the positioning of the dampers in order to make the best utilization of the TMDs natural tendency to absorb motion. [11]

The primary limitation of a TMD is that it is a narrow-band device. It will add high damping only to modes with frequencies close to its own. This means that multiple TMDs may be needed to obtain high damping of modes. Thus, it is very important to understand the working of the TMD. It is more important to understand the behavior of the TMD under different condition of mass ratio, frequency ratio and damping rather than analysis of the TMD. [12]

In order to provide a better understanding for the students, so that they can design a TMD effectively and use it appropriately, a new paradigm has emerged in engineering education, which emphasizes in teaching behavior and synthesis rather than teaching analysis. It encourages learning by discovery and provides real world application to these learning. [8]

As part of this new paradigm, this thesis offers a better approach for building effective environments to improve learning of concepts of tuned mass dampers. This thesis is organized as follows: Chapter 2 discusses the Tuned mass dampers in detail. It elaborates on the working as well as types of TMD. In addition, it also provides some



case studies and existing examples of buildings using TMD. Chapter 3, provides an overview of the website ([moment.mit.edu](http://moment.mit.edu)), which contains an interactive environments to improve learning of concepts of structural engineering. Chapter 4 describes in detail the existing interactive environment for TMD, its limitations, and the new improved methodology used to provide better understanding of the TMD. Chapter 5 contains the conclusion.

Modified java applets have been adapted as the tool to enhance the learning experience. An interactive model and graphs are used to convey the concept and the idea effectively. This thesis proposes a better solution to encourage conceptual understanding through effective and interactive computer aided learning tools.

## **Chapter 2:Tuned mass damper**

### **2.1 Introduction to Tuned Mass Dampers:**

TMD is a modular device composed of a spring, mass, and damper [Figure 4]. This assembly is attached to the structure to reduce the dynamic response of the structure. Tuned mass dampers are an effective means of reducing vibration in structures. The frequency of the damper is tuned to the frequency of the structure to which it is attached, so that when that frequency is excited, the damper will resonate out of phase with the structural motion. [9]

*“Frahm first applied the TMD concept in 1909 (Frahm, 1909) to reduce the rolling motion of ships as well as ship hull vibrations. Ormondroyd and Den Hartog (1928) later presented a theory for TMD. This were followed by a detailed discussion on optimal tuning and damping parameters in Den Hartog’s book on mechanical vibrations (1940). The initial theory was applicable for an undamped SDOF system subjected to a sinusoidal force excitation. Extension of the theory to damped SDOF system has been investigated by numerous researchers. Significant contributions were made by Randall et al. (1981), Warburton (1981,1982), Warburton and Ayorinde (1980), and Tsai and Lin (1993)”.* [9]

A TMD is a single degree-of-freedom system. It adds a mode of vibration to the base structure. The stiffness  $k$  and mass  $m$  of the TMD [Figure 4] are used such that the

natural frequency of the TMD is just below the frequency of the structure to which it is attached. This causes a strong dynamic interaction between the TMD and the structure. The structural mode is replaced by two modes, one slightly above and one slightly below the original frequency. The damper of the TMD will damp both of the modes. [12]

Advantages of using the TMDs are [12] and [11]:

- They are compact, space saving, modular devices that can have a simple connection to the base structure.
- Its natural period can be easily adjusted.
- They can be added to a structure that is already designed or built.
- A well-designed TMD can add high damping with minimum weight.
- Weight of damper is not on the system so there is little resistance and friction.
- The TMD does not affect the static strength or stiffness of the base structure.
- For designing the TMD, it is often possible to test the structure by inexpensive test or analysis.
- It is totally fire proof.

### ***2.1.1 Working:***

When the building sways the damper moves in the opposite direction and absorbs the motion. In addition, it has sensors, which detect the sway of the building and computers, which controls the positioning of the dampers in order to make the best utilization of the TMDs natural tendency to absorb motion. [11]

### ***2.1.2 Performance [11]:***

- It is capable of damping twist motions also.
- Its control system facilitates by reducing 50% of the weight of damper with improvement in performance.
- It is economical in terms of energy consumption

### ***2.1.3 Safety issues [11]:***

- A built-in sensor quickly detects any malfunction and prevents any motion, which would increase the sway.
- Failure of the system results in the cut-off of power from the motors.
- Abnormal displacement of the damper results in power cut-off or the application of a brake.



## 2.2 Case Studies: Example of existing tuned mass damper system

Two kinds of tuned mass dampers are used in practice. They are:

- Translational tuned mass damper
- Pendulum tuned mass damper

### ***2.2.1. Translational Tuned Mass Damper:***

The figure below shows the typical design of a Translational tuned mass damper. It is unidirectional. The mass rests on the bearings, which works as rollers. This allows the mass to translate sideways in relation to the floor. The mass and the adjacent vertical support members flank springs and dampers. This transmits the lateral force, in the opposite direction, to floor level and then into the structural frame. [9]

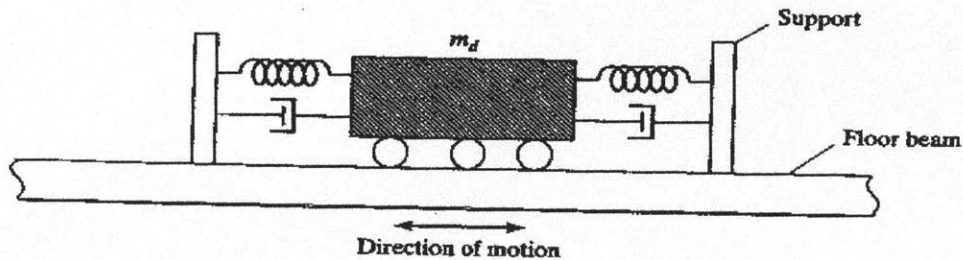


Figure 5: Translational tuned mass damper [9]

### ***John Hancock Tower: (Engineering news Record, Oct, 1975)***

Two dampers were added to the 60 stories John Hancock Tower in Boston to reduce the response to wind gust loading. The Dampers are added to the opposite ends of the 48<sup>th</sup> storey, 67 m apart, and move to work against sway as well as twisting due to the sway of the structure. Both dampers weigh 2700 KN. It consist of a lead filled steel box

about 5.2 m square, 1 m deep and 9 meter long steel plate. The lead filled plate is laterally controlled by stiff strings and anchored to the interior columns of the building. Servo hydraulic cylinders also control it, which slides back and forth on a hydrostatic bearing consisting of a thin layer of oil forced through the holes in the steel plate. Whenever the horizontal acceleration exceeds 0.003g for two consecutive cycles, the system without human involvement is activated. [9]

***Citicorp Center*** (*Engineering News Record, Aug.1975, McNamara 1977,Petersen1980*)

The Citicorp (Manhattan) building is 279 m high and has a fundamental period of around 6.5 s with an inbuilt damping ratio of 1% along each axis. The Citicorp TMD located at the 63<sup>rd</sup> floor of the structure has a mass of 366vMg,about 2% of the effective modal mass of the first mode and was 250 times larger than any existing tuned mass damper at the time of installation. Intended to be biaxial resonant on the structure with a variable operating period of 6.25 s +/- 20%, adjustable linear damping from 8 to 14%. And a peak relative displacement of +/-1.4 m, the damper is expected to reduce the building sway amplitude by 50%. The drop corresponds to increasing the basic structural damping by 4%. During operation, the bearings supplied oil from a separate hydraulic pump, which is capable of raising its mass block by 2 cm to its operating position in 3 minutes. The damper system is activated automatically shut itself down when the building acceleration does not exceed 0.00075g. [9]

***Canadian National Tower: 9 Engineering News Record, 1976)***

The 102 m steel antenna mast on top of the Canadian National Tower in Toronto (553 m high including the antenna) required two lead dampers to prevent the antenna from deflecting excessively when subjected to wind excitation. The damper system consist of two doughnut-shaped steel rings, 35 cm wide, 30 cm deep and 2.4 m and 3 m in diameter. Both ring holds about 9 metric tons of lead and is supported by three steel beams attached to the sides of the antenna mast. Four bearing universal joints that pivot in all directions connect the rings of the beams. In addition four separate hydraulically activated fluid dampers mounted on the side of the mast and attached to the center of each universal joint dissipate energy. As the lead weighted rings move back and forth, the hydraulic damper system dissipates the input energy and reduces the towers response. The damper are tuned to the second and fourth modes of vibration in order to minimize antenna bending loads; the first and third modes have the same characteristics as the prestressed concrete structure supporting the antenna and did not require additional damping. [9]

***Chiba port Tower (kitamura et al., 1988)***

Chiba port Tower (completed in 1986) was the first tower in Japan to be outfitted with TMD. Chiba Port Tower is a steel structure 125 m high weighing 1950 metric tons and having a parallelogram shape plan with a side length of 15 m. The first and second mode periods are 2.25 s and 0.51 s, respectively for the x direction and 2.7 s and 0.57 s for the y direction. Damping for the fundamental mode is estimated at 0.5%. Damping ratio proportional to frequencies was assumed for the higher modes of analysis. The reason of the TMD is to increase the damping of the first mode for both x and y

directions. The damper has mass ratio with respect to the modal mass of the first mass of about  $1/120$  in the x direction and  $1/180$  in the y direction; periods in the x and the y directions of 2.24 s and 2.72 s respectively; and a damping damper ratio of 15%. The maximum relative displacement of the damper with respect to the tower is about  $\pm 1$  m in each direction. Reduction of around of 30 to 40% in the displacement of the top floor and 30% in the peak bending moments are expected. [9]

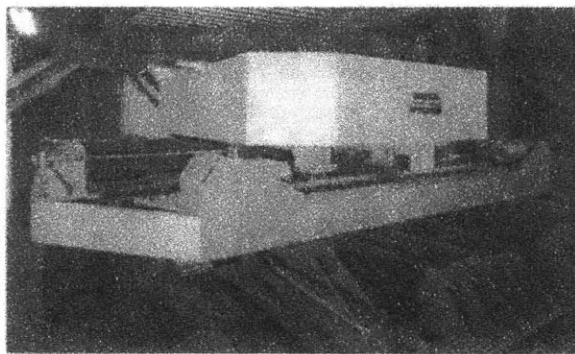


Figure 6: Tuned mass damper for Chiba-Port Tower [9]

The former version of the TMDs use complex mechanisms for the bearing and damping elements, have comparatively large masses, occupy significant space, and are pretty costly. Current versions have been intended to minimize these restrictions. It employs a multiassemblage of elastomeric rubber bearing which function as shear springs, and bitumen rubber compound (BRC) elements, which provide viscoelastic-damping capacity. The device is compact in size, requires simple controls, is multidirectional and is easily assembled and modified. [9]

The efficiency of the tuned mass damper can be increased by auxiliary mass and an actuator to the tuned mass and driving the auxiliary mass with the actuator such that its response is in the opposite direction with the response to the tuned mass. The effect of driving the auxiliary mass is to produce an added force that complements the force

generated by the tuned mass and therefore increases the equivalent damping of the TMD. Since the actuator requires an external energy source, this system is referred to as an active tuned mass damper. [9]

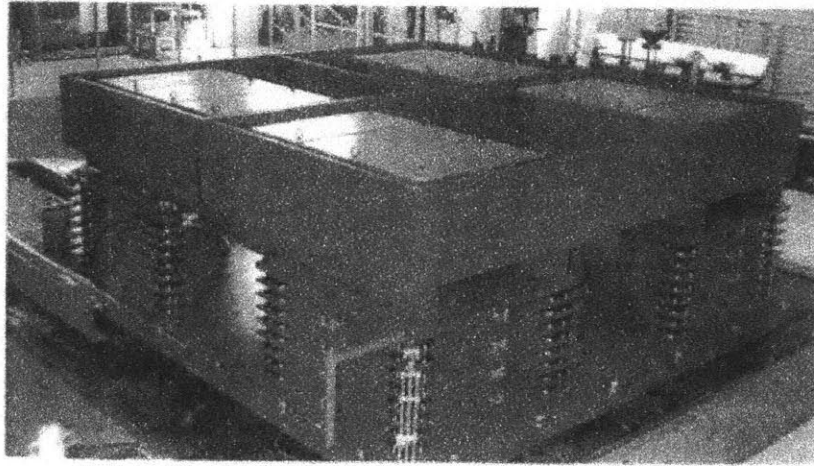


Figure 7: TMD-Huis Ten Bosch Tower, Nagasaki [9]

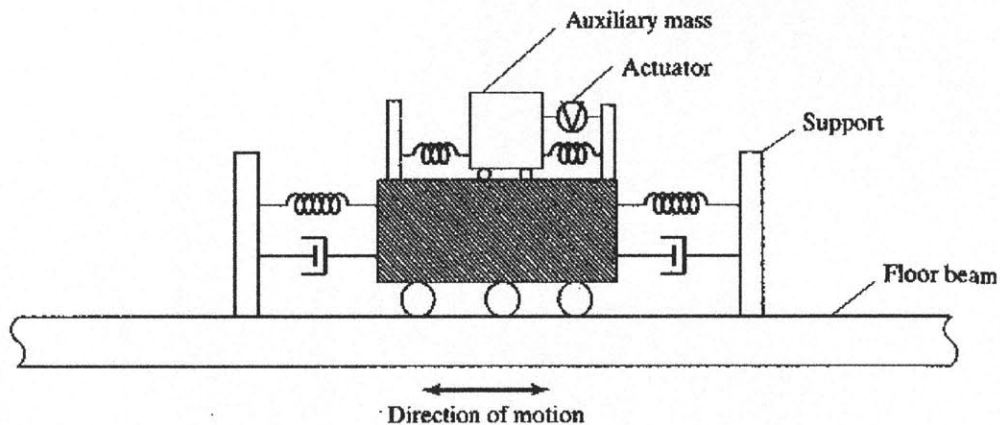


Figure 8: An active tuned mass damper configuration [9]

### **2.2.2 Pendulum Tuned Mass Damper:**

Supporting the mass with cables, which allow the system to behave as a pendulum, can eliminate the problem associated with the bearings. The movement of the

floor excites the pendulum. As a result, this causes a horizontal force that opposes the floor motion.

The simple pendulum tuned mass damper has a limitation. Since the time period depends on the length of the pendulum, the required length for large natural period of the pendulum may be greater than the typical height of the building. Resorting to the scheme shown in the figure can eliminate this limitation. The interior rigid link magnifies the support motion for the pendulum. The rigid links moves in phase with the damper and has the same displacement amplitude. Each additional link increases the effective length by a length  $L$ . [9]

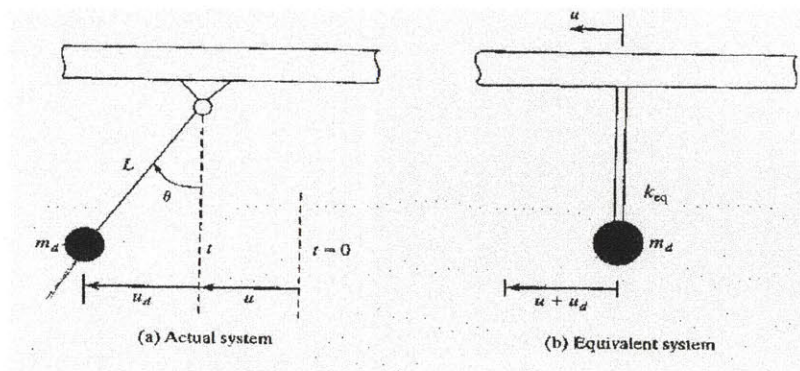


Figure 9: A simple pendulum tuned mass damper [9]

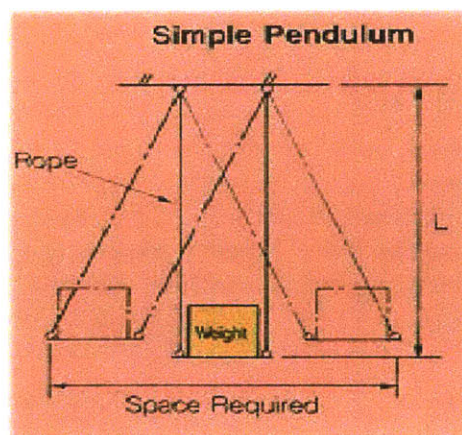


Figure 10: Simple Pendulum [11]

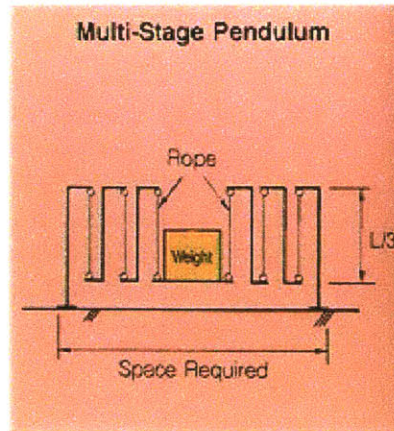


Figure 11: Multi-Stage Pendulum [11]

***Crystal Tower*** (Nagase and Hisatoku, 1990)

The tower is located in Osaka, Japan. It is 157 m high and 28 m by 67 m in plan. It weighs 44000 metric tons and has a fundamental period of 4s (in the north-south direction) and 3s (in the east-west direction). The pendulum tuned mass damper is used to reduce the motion in the tower due to wind. It reduced to wind induced motion by 50%. Six of the nine air cooling and heating ice thermal storage tank (each weighing 90 tons) are hung from the top of the roof girders and used as the pendulum mass. Four of the tanks are 4m long and slide in the north-south direction whereas two of the tanks are 3m long and slides in the east-west direction. Oil dampers attached to the pendulums dissipate the pendulum energy. The cost of the tuned mass damper was around \$350,000, which is less than 0.2% of the construction cost. [11]

### 2.3 Types of tuned mass dampers

***Tuned mass damper theory for SDOF system.***

There are various cases varying from fully undamped to fully damped condition.

***1. Undamped structure: Undamped TMD***



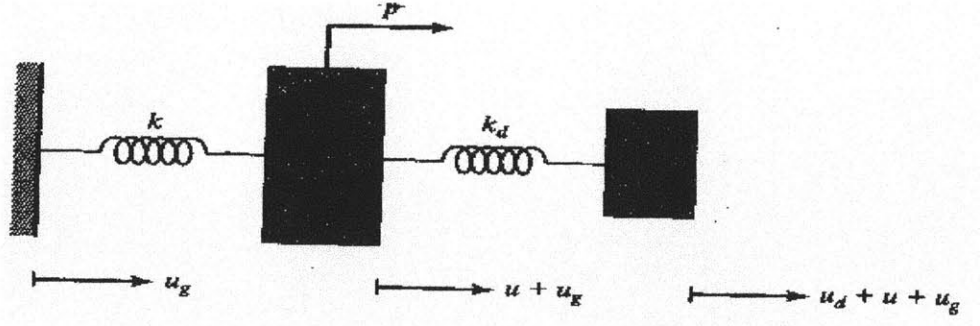


Figure 12: Undamped structure: Undamped TMD [9]

The figure shows a SDOF system having primary mass  $m$  and stiffness  $k$ , subjected to external force and ground motion. A tuned mass damper of mass  $m_d$  and stiffness  $k_d$  is attached to the primary mass. The various displacement measures are  $u_g$ , the absolute ground motion; and  $u$ , the relative motion between the primary mass and the ground; and  $u_d$ , the relative displacement between the damper and the primary mass. The governing equations are [9]:

$$m_d [\ddot{u}_d + \ddot{u}] + k_d u_d = -m_d a_g$$

$$m\ddot{u} + ku - k_d u_d = -ma_g + p$$

Where:

$a_g$  = Absolute ground acceleration;

$p$  = Loading applied to the primary mass.

Once the mass damper property is defined, we can determine the response for different forcing frequencies. The primary mass would move under ground motion excitation in this case. [9]

## 2. Undamped Structure: Damped TMD



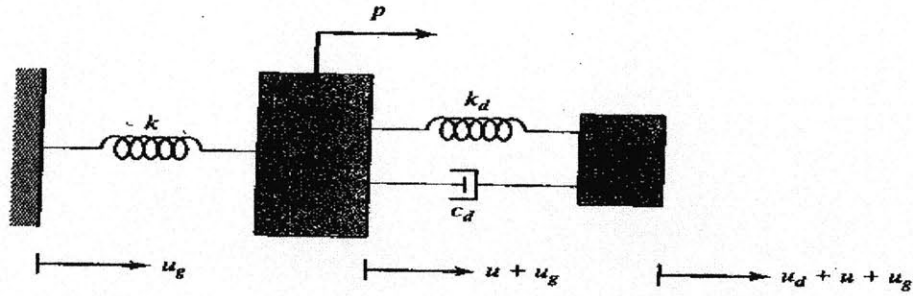


Figure 13: Undamped Structure: Damped TMD[9]

In this case damping is included in the mass damper, as shown in the figure. The equations for this case are:

$$m_d \ddot{u}_d + c_d \dot{u}_d + k_d u_d + m_d \ddot{u} = -m_d a_g$$

$$m \ddot{u} + k u - c_d \dot{u}_d - k_d u_d = -m a_g + p$$

The inclusion of the damping in the system produces a phase shift between the periodic excitation and the response. [9]

### 3. Damped Structure: Damped TMD

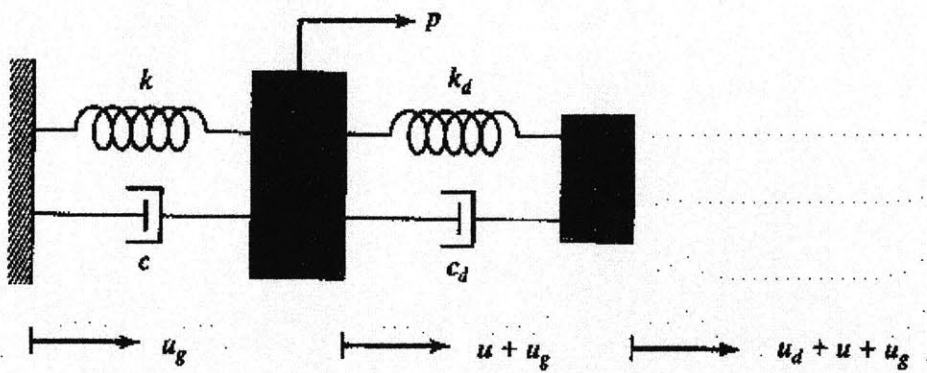


Figure 14: Damped Structure: Damped TMD [9]

All real systems contain some damping. An absorber is attached only to a lightly damped structure. The main system in the figure consists of a mass  $m$ , stiffness  $k_d$  and a

viscous damper  $c_d$ . Subjecting the system to both external and internal forcing and ground excitation, the equations of motion are [9]:

$$m_d \ddot{u}_d + c_d \dot{u}_d + k_d u_d + m_d \ddot{u} = -m_d a_g$$

$$m \ddot{u} + c \dot{u} + k u - c_d \dot{u}_d - k_d u_d = -m a_g + p$$

***Tuned mass damper for MDOF system.***

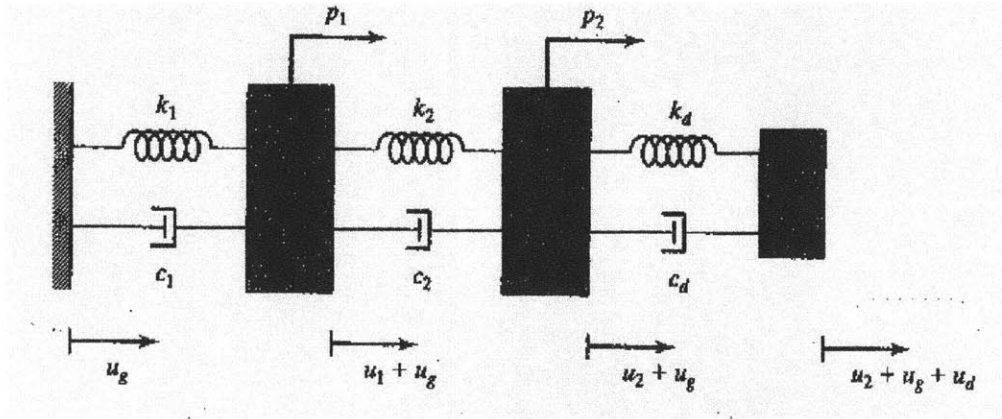


Figure 15: Tuned mass damper for MDOF system [9]

The theory of the SDOF system discussed earlier is extended to deal with a MDOF system having a number of tuned mass dampers located throughout the structure. The governing equations of the system are [9]:

$$m_1 \ddot{u}_1 + c_1 \dot{u}_1 + k_1 u_1 - k_2 (u_2 - u_1) - c_2 (\dot{u}_2 - \dot{u}_1) = p_1 - m_1 \ddot{u}_g$$

$$m_2 \ddot{u}_2 + c_2 (\dot{u}_2 - \dot{u}_1) + k_2 (u_2 - u_1) - k_d u_d - c_d \dot{u}_d = p_2 - m_2 \ddot{u}_g$$

## **Chapter 3: Moment.mit.edu:**

### **3.1 Introduction**

Moment.mit.edu is a new archetype, which provides an effective and interactive learning of structural behaviors. Structural analyses are the most important tool of a structural engineer. Moment.mit.edu is an excellent computer aided learning tool for structures. It is a well-structured conceptual design for active learning of structural analysis.

The purpose of this tool is to develop a fully integrated and interactive learning environment for Structural Behavior and Engineering. It allows students to view the bigger picture and obtain a deeper conceptual understanding. It has been designed such that it motivates, interests and helps in faster learning of the analytical aspects. This helps to understand more complex concepts such as Dynamics and Earthquake engineering. Some of its advantages are [8]:

- Student can learn on his/her own without the need of a tutor.
- It ensures proper progress of the student as well as provides room for experimentation.
- Provides practical applications to the problems.
- Provides appropriate feedback for better understanding of the student.
- Students can closely relate it to the classroom material for better understanding.

There are various similar tools available but they lack a well-annotated and guided context and correct emphasis on behavior. This provides a better tool as it contains images, text and examples for better understanding of the concept. Unlike others

interactive tools, it provides an interactive environment, which allows information and ideas to be exchanged between the computer and the user. It also provides an environment for active learning by forcing the students to engage in conversation. In addition, it is an adaptive learning. It adapts to the level of understanding the student demonstrates. [8]

### 3.2 Interactive learning module:

A range of Learning Modules and Simulators using Java applets have been developed to simulate Structural Engineering and Dynamics concepts.

Interactive learning has been subdivided under the headings: static module, dynamic module.

#### ***Static Module:***

- 1) *Interactive Learning Module on stability of a Single Body.* This has been developed as a part of Emma Shepherdson's thesis. This module provides an engaging experience on stabilizing a single body and connection types. It uses Shockwave. [14]

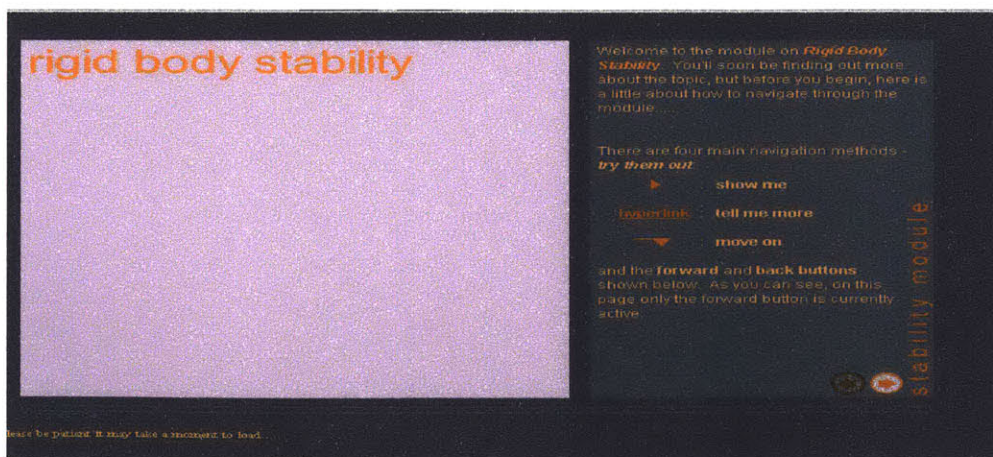


Figure 16: Interactive Learning Module on stability of a Single Body [14]

- 2) *Simply Supported Beam with 2 Point Loads*: This is a complete exercise with an excellent interface. It consist of a simply supported beam with two point loads that can have their magnitude and position adjusted with the scrollbars. By moving the scrollbars we can see how the interactive beam works. Diagrams for Shear, Moment, Rotation and Displacement are simulated for each load in their respective color. The total response due to the two loads is shown in red. It also provides lessons to go through to identify the key features of the beam's behaviors. [14]

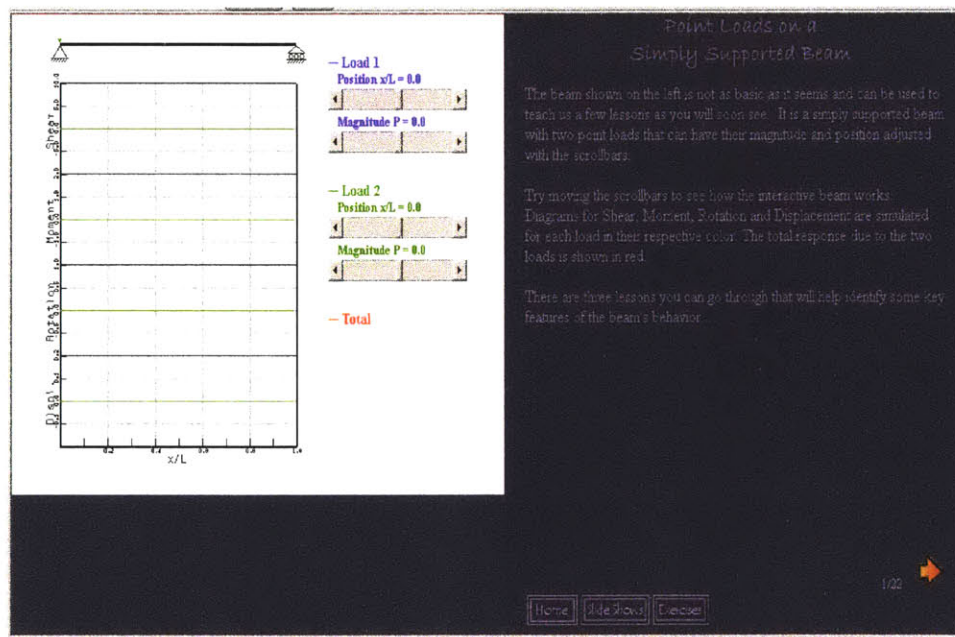


Figure 17: Simply Supported Beam with 2 Point Loads: [14]

- 3) *Beam Control* - demonstrates the principle of deflection and moment control by the use of adaptive applied end moments. [14]



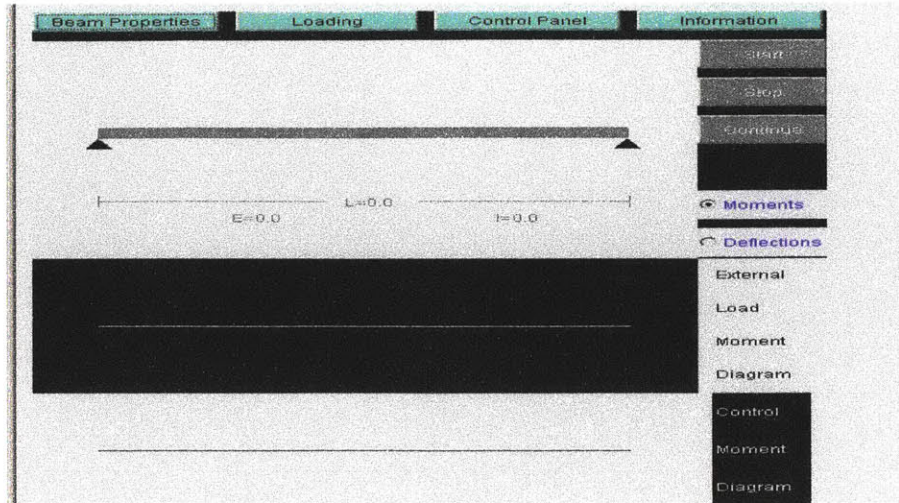


Figure 18: Beam Control [14]

- 4) *Load Paths* - this module was developed as a part of a proof of concept development of the learning environment. Email and Chat capabilities are provided and user results were collected and submitted to a database. It also uses Shockwave. [14]

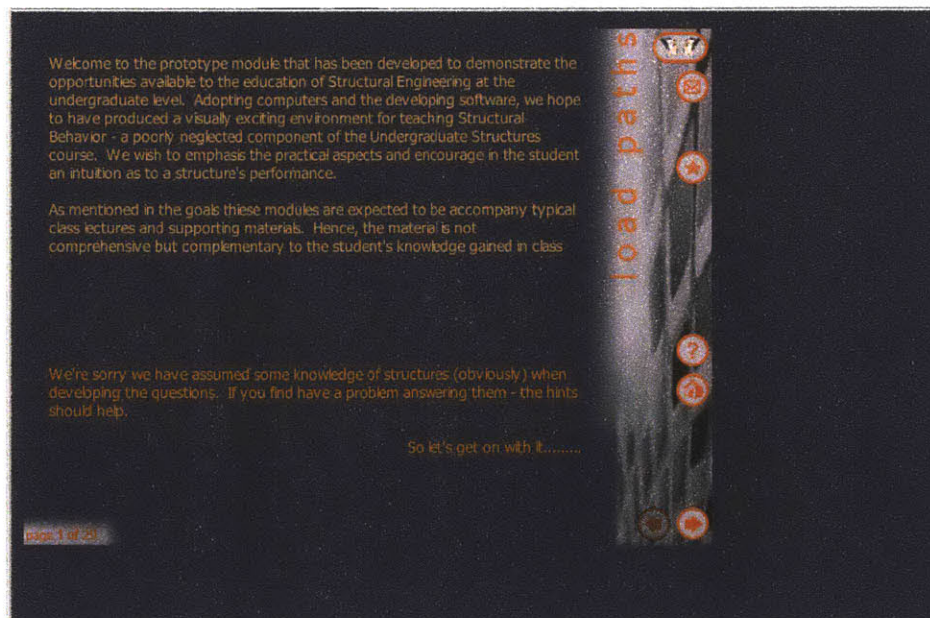


Figure 19: Load Paths [14]

### ***Dynamic Module:***

- 1) *MotionLAB: Spectra and Shearbeam*. This contains a set of GUI programs. They are used in solving problem sets in the structure courses like 1.561 (Motion Based Designed) and 1.571 (Structural Analysis and Control). In addition they are included in the textbook "Introduction of structural motion control". Both are created in MATLAB and compiled to C. [14]
- 2) *Tuned Mass Damper*: The performance of the Tuned Mass Damper (TMD) system, due to the change in mass ratio, frequency and damping ratio of the system, has been outlined and demonstrated graphically. A Java applet has been used as the tool to represent the performance of the TMD graphically. In addition it uses a model to show the practical application of the TMD. [14]

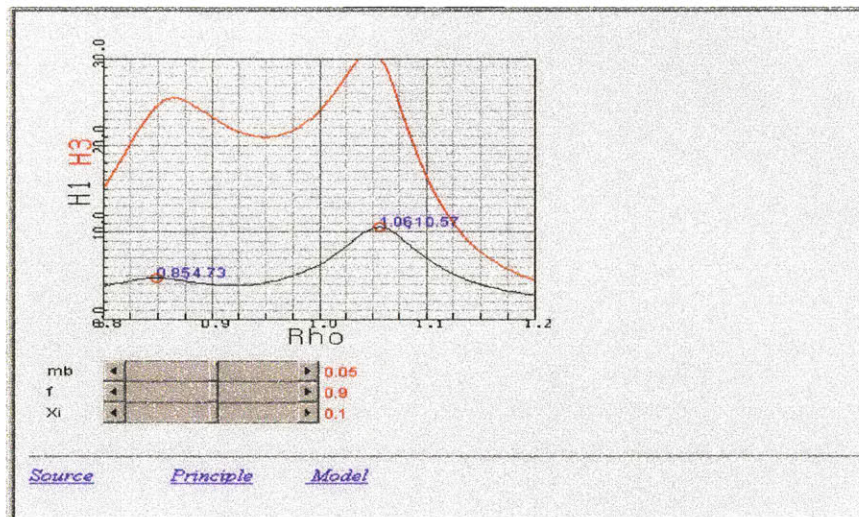


Figure 20: Tuned Mass Damper [14]

- 3) *Ground Excitation of a Single Degree of Freedom Building*: This simulation demonstrates the behavior of buildings under earthquake excitation. It shows how the building reacts as the frequency of the ground motion varies. The magnitude

and the frequency at which the ground shakes are varied using the scroll bars.

Also, a scrollbar is included to vary the building's damping ratio. [14]

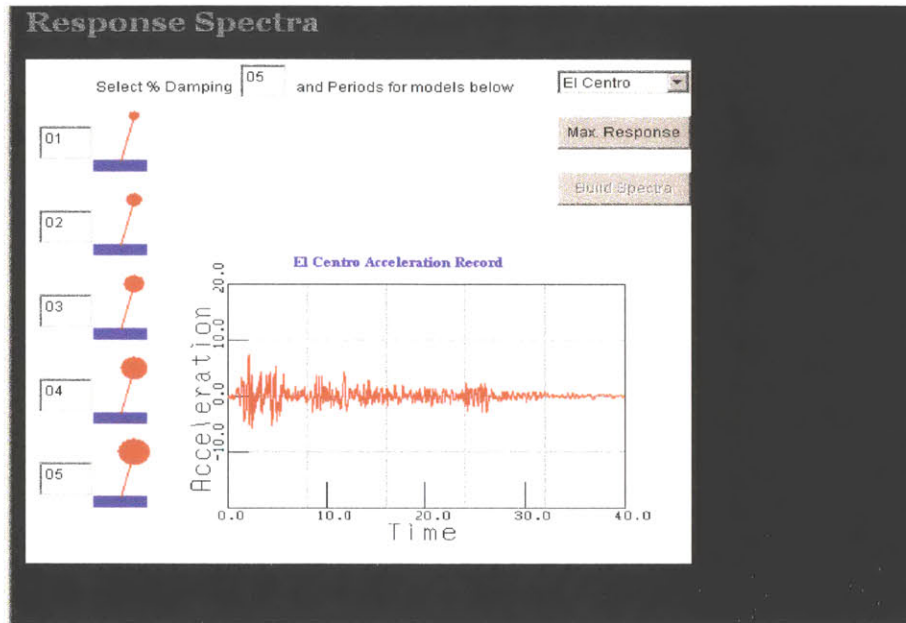


Figure 21: Ground Excitation of a Single Degree of Freedom Building [14]

- 4) *Simulation to Create Response Spectrum.*
- 5) *Mass Shaker on the Same Building:* This simulation demonstrates the behavior of a building subjected to sinusoidal loading. The forcing on the building is caused by the inertia of the vibrating mass stationed on top of the building. . It demonstrates how the building reacts as the frequency of the mass shaker varies. The magnitude and the frequency at which the mass vibrates are varied using the scroll bars. Also, a scrollbar is included to control the building's damping ratio. [14]



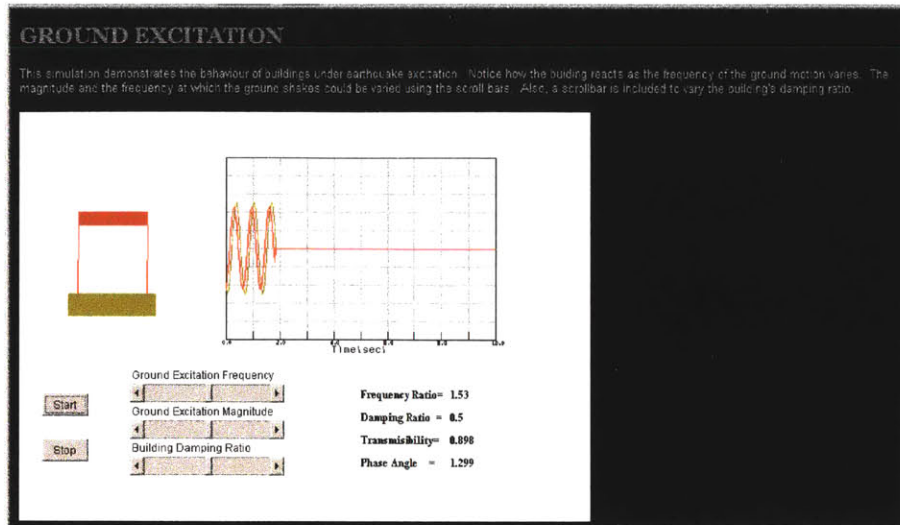


Figure 22: Mass Shaker on the Same Building [14]

- 6) *Structural Analysis tool for Trusses* -It uses finite element methods. [14]

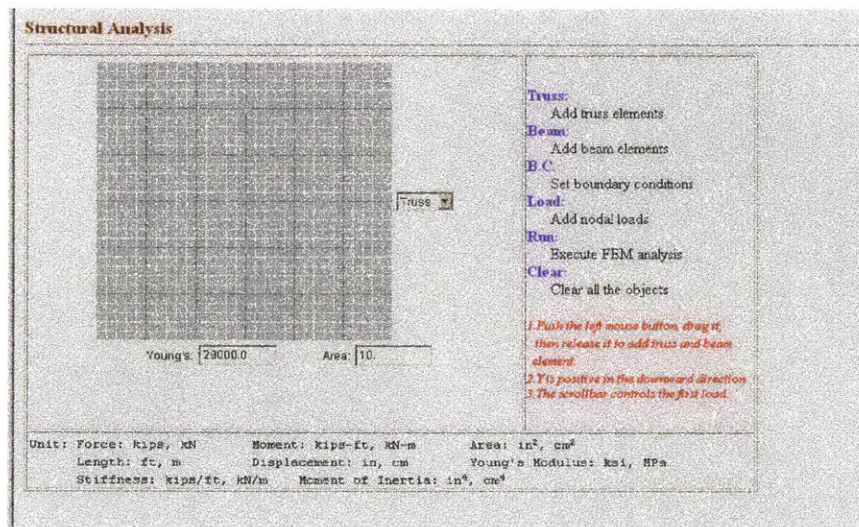


Figure 23: Structural Analysis tool for Trusses [14]

- 7) *The Motion Lab*: It is a program that allows a multiple degree of freedom system to be modeled and various loads, etc to be applied. [14]

- 8) *Motion Lab for Undergrads*: This Motion Lab simulator is simplified with a more generic, simpler interface, more appropriate for conceptual learning at the undergraduate level. [14]

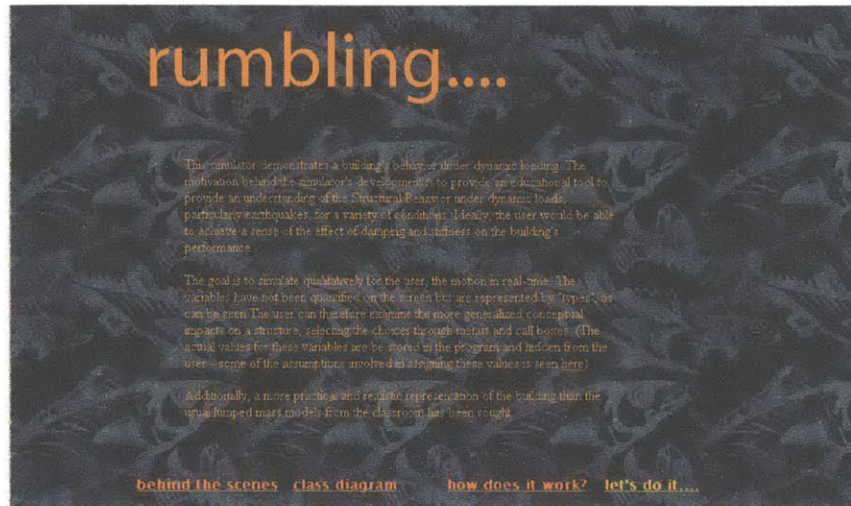


Figure 24: Motion Lab for Undergrads [14]

- 9) *Sakuta's Exercises*: This is an exercise programmed by Prof Sakuta who was a visiting professor from Japan. He began the development of the graphical and mathematical java classes. [14]

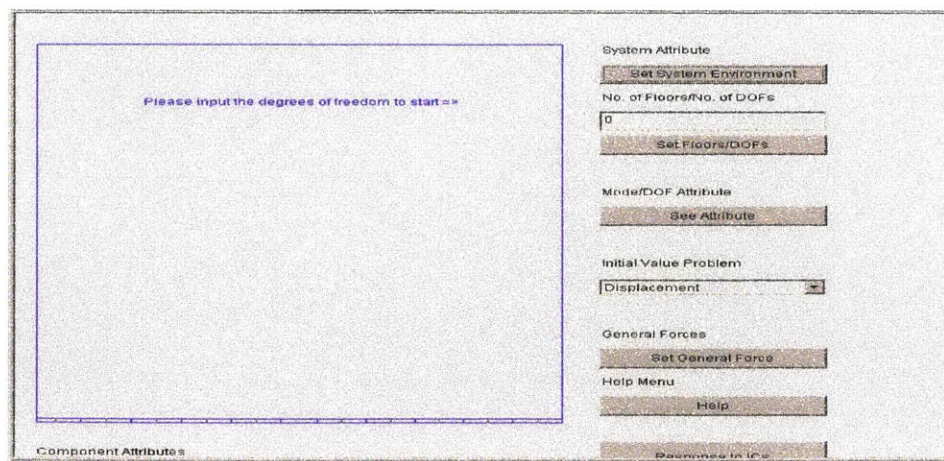


Figure 25: Sakuta's Exercises [14]

10) *Single Degree of Freedom Nonlinear Analysis Tool*: This program was developed by the Federal Emergency Management Agency. It is a very impressive and a useful tool.[14]

Basically, the emphasis is to maintain user's interest to enable learning through the best tool as well as providing proper knowledge. It is simple and easy to understand. [14]

## **Chapter 4: The problem and the proposed solution**

This chapter presents the motivation for developing a new approach for the conceptual learning for tuned mass damper.

### **4.1 Background:**

As mentioned before moment.mit.edu provides a range of learning modules and simulators using Java applets. One of them is regarding the Tuned Mass Damper (TMD). As mentioned in the second chapter, TMD is a modular device composed of a spring, mass, and damper. This assembly is attached to the structure to reduce the dynamic response of the structure.

Java applets have been used to represent the working of the TMD graphically. It represents a case where the structure is undamped and the Tuned mass damper is damped. The structure is idealized as a single degree of freedom system. The purpose of adding the mass damper is to limit the motion of the structure when it is subjected to a particular excitation. The design of the mass damper involve mass  $m_d$ , stiffness  $k_d$  and damping coefficient  $c_d$ . The near optimal approximation of the frequency of the damper

$$\omega = \omega_d$$

Where:

$\omega$  = natural frequency of the structure

$\omega_d$  = frequency of the structure

is used to design the optimal TMD [9].

Thus, for the optimal behavior of the TMD the maximum amplitude must be minimized. In order to minimize the maximum amplitude, the Rho values of the H1 or H3 must be made equal. Thus, by increasing the dampness, the peak amplitude can be reduced. This would represent the state of optimal performance of the TMD. Further increase in the value of the dampness can cause the peaks to merge. As a result, the amplitude increases beyond the optimal value. Rho values of the H1 or H3 can be made equal by the following equations [9]:

$$1 - \rho_1^2 (1 + \bar{m}) = 1 - \rho_1^2 (1 + \bar{m})$$

The effect of the damper is to limit the motion in a frequency range centered on the natural frequency of the primary mass and extending about  $0.15\omega$ . Outside this range the motion is not significantly influenced by the damper [9].

#### 4.2 The Previous Design:

The working of the TMD is graphically represented. The graph is plotted for the values of H1, H3 and Rho. Both H1 and H3 have been plotted in the same graph. The user can change the graph by changing mass ratio, frequency and  $\xi$  (Xi). Three scroll bars, for mass ratio, frequency and  $\xi$ , have been provided. The graph also shows the peak values of Rho.

Title of the scrollbar	Range of the scrollbar
Mb (mass ratio)	0 to 0.099
F (frequency ratio)	0.8 to 1.0
Xi (dampness ratio)	0 to 0.2

Table 1:Scrollbar Range for graph

Based on the value of the scrollbars, Rho is calculated and then H1 and H2 are calculated using the formulae given below [13]:

$$H_1 = \sqrt{\frac{\alpha_1^2 + 4\xi_d^2\alpha_2^2}{\alpha_3^2 + 4\xi_d^2\alpha_4^2}}$$

$$H_3 = \sqrt{\frac{\rho}{\alpha_3^2 + 4\xi_d^2\alpha_4^2}}$$

$$\frac{H_3}{H_1} = \sqrt{\frac{\rho}{\alpha_1^2 + 4\xi_d^2\alpha_2^2}}$$

$$\alpha_1 = f^2 - \rho^2$$

$$\alpha_2 = \rho f$$

$$\alpha_3 = (1 - \rho^2)(f^2 - \rho^2) - \overline{m}\rho^2 f^2$$

$$\alpha_4 = \rho f[1 - \rho^2(1 + \overline{m})]$$

Where:

a terms are function of  $\rho$ ,  $f$  and  $\overline{m}$ .

$f$ = frequency ratio=  $\omega d/\omega$

$\rho$ = Dimensionless frequency ratio

$\overline{m}$  = Mass ratio=  $m_d/m$

$\xi$ = Damping

The graphical representation of the TMD is as shown below:



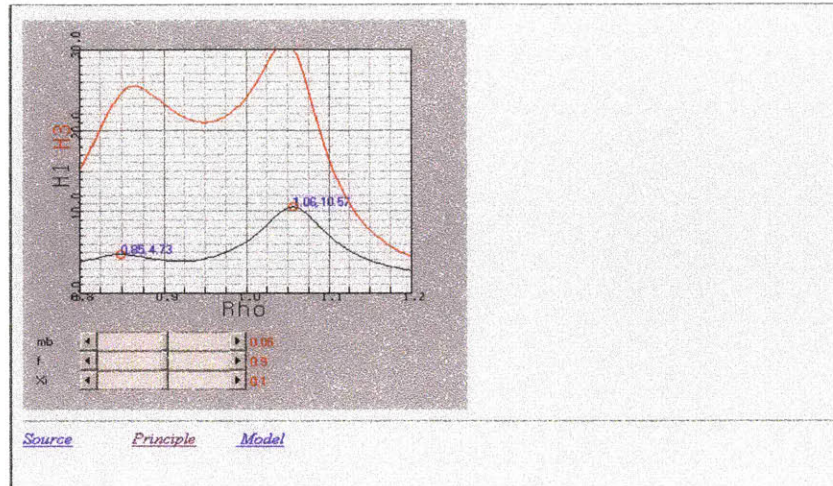


Figure 26: Previous Design [13]

The graph changes depending upon the calculation. This helps us in determining the value of mass ratio, frequency and dampness required for optimal condition of the TMD.

It also has a model, which shows the effect on the structure when a TMD is attached to it.

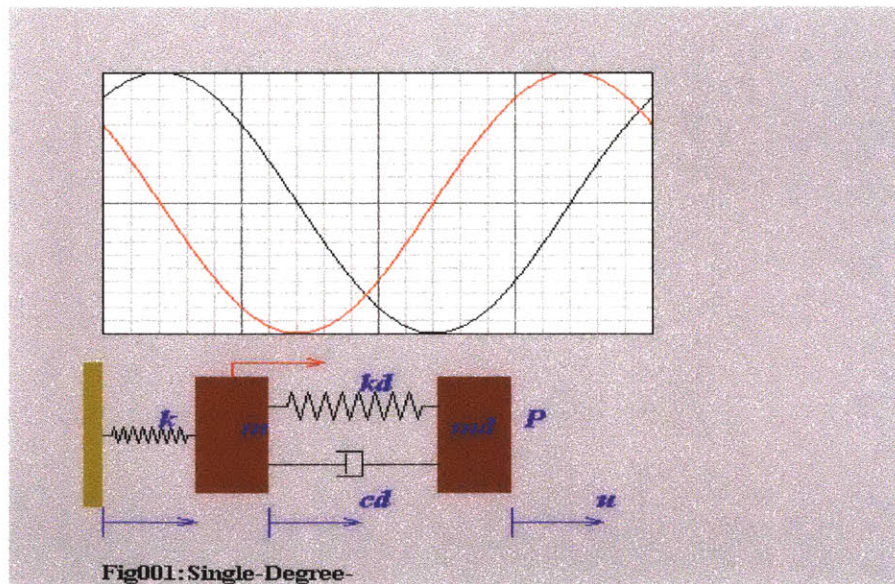


Figure 27: Original Model [13]

The value of mass ratio, frequency and dampness for the model is fixed to the values shown in the table below.

Title of the scrollbar	Fixed value of the scrollbar for the model
mb (mass ratio)	0.05
f (frequency ratio)	0.9
$\xi$ (dampness ratio)	0.1

Table 2: Scrollbar Range for the model

In addition, it also shows a corresponding graph for the model.

Although the site gives all the information, it lacks few important aspects. Some of the features that it lacks are listed below:

- 1) It lacks sensitivity.
- 2) Both H1 and H3 have been shown in the same graph. It makes it congested and it is not user friendly. If the same were shown using two graphs (side by side) it would be make it easy to understand and moreover the user would be able to compare the two cases.

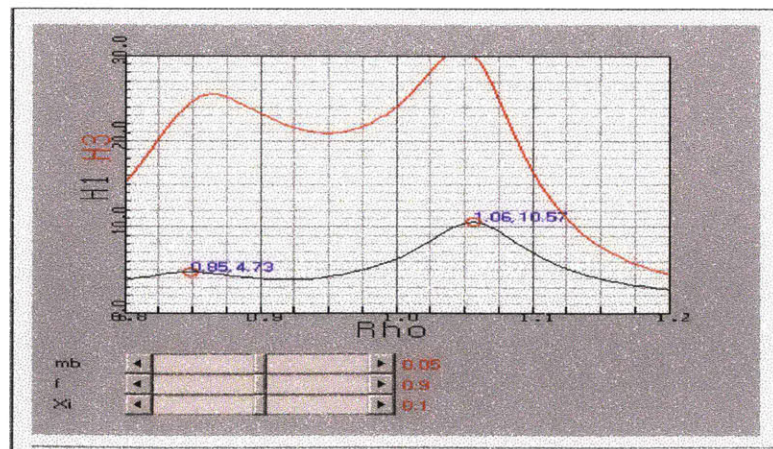


Figure 28: Previous Design [13]



- 3) The range of the graph is not large enough to show all the cases when the value of the scrollbars is changed. Thus, beyond a certain range of value the graph is unable to show the plot.

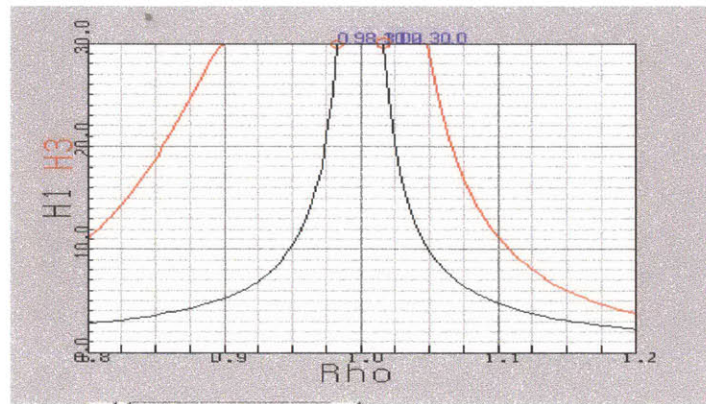


Figure 29: Previous Design [13]

- 4) The scroll bar makes more user friendly and it look better. But the range of the scroll bars for the mass ratio is insufficient .Its present range is 0 to 0.099 but it would be better to have a larger range ranging from 0 to 0.8. The range of the scrollbars for frequency and dampness is sufficient.

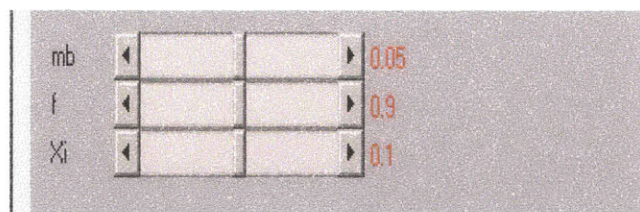


Figure 30: Previous Design [13]

- 5) It does not show the extreme cases of the  $\xi_i$ ; i.e.  $\xi_i = 0$  and  $\xi_i = 1$ . If the a graph is plotted showing the extreme cases of the  $\xi_i$  values, with dotted lines, it would make it easier for the user to compare. In addition, it would make it easy for the user to understand how the TMD works. TMD is said to have an optimal state for a specific range lying between the two extreme values of the  $\xi_i$ . So, it is important for the user to know the extreme values.
- 6) It has a nice model but it is difficult to relate it to the graph, as it is not shown next to the graph. It is shown in a different page. Thus, if the model were shown just next to the graph it would make it more users friendly.

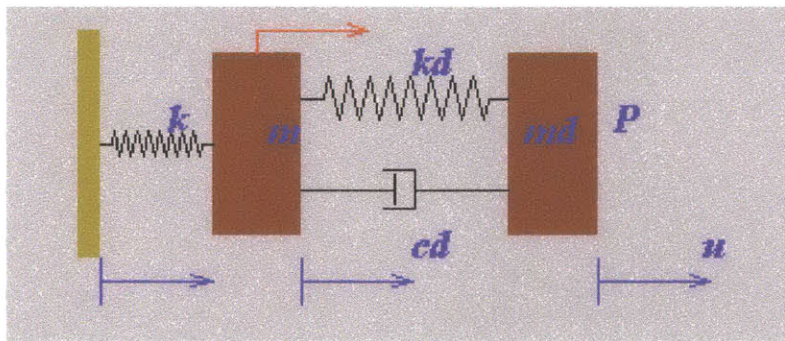


Figure 31: Previous Design [13]

- 7) Moreover, the model does not work according to the different values of the mass ratio, frequency and dampness of the scrollbar as entered by the user. It has a set value of mass ratio (0.05), frequency (0.9) and dampness (0.1). Thus, it shows the working of the TMD for a fixed value. It does not change with the change in value of the scrollbar.
- 8) It does not give any written matter, explaining the graph and the model. As a result, it makes it difficult for new students to understand.

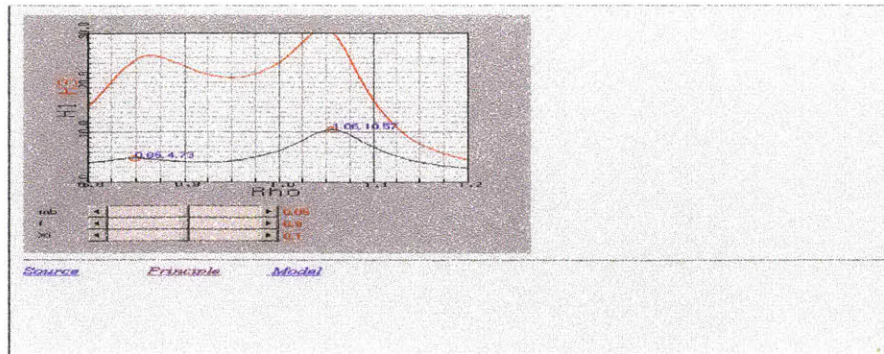


Figure 32: Previous Design [13]



### 4.3 The proposed design:

The new java code is an extension of the previous work. The similar java applets and the unchanged base classes have been used. The new, improved design is shown below.

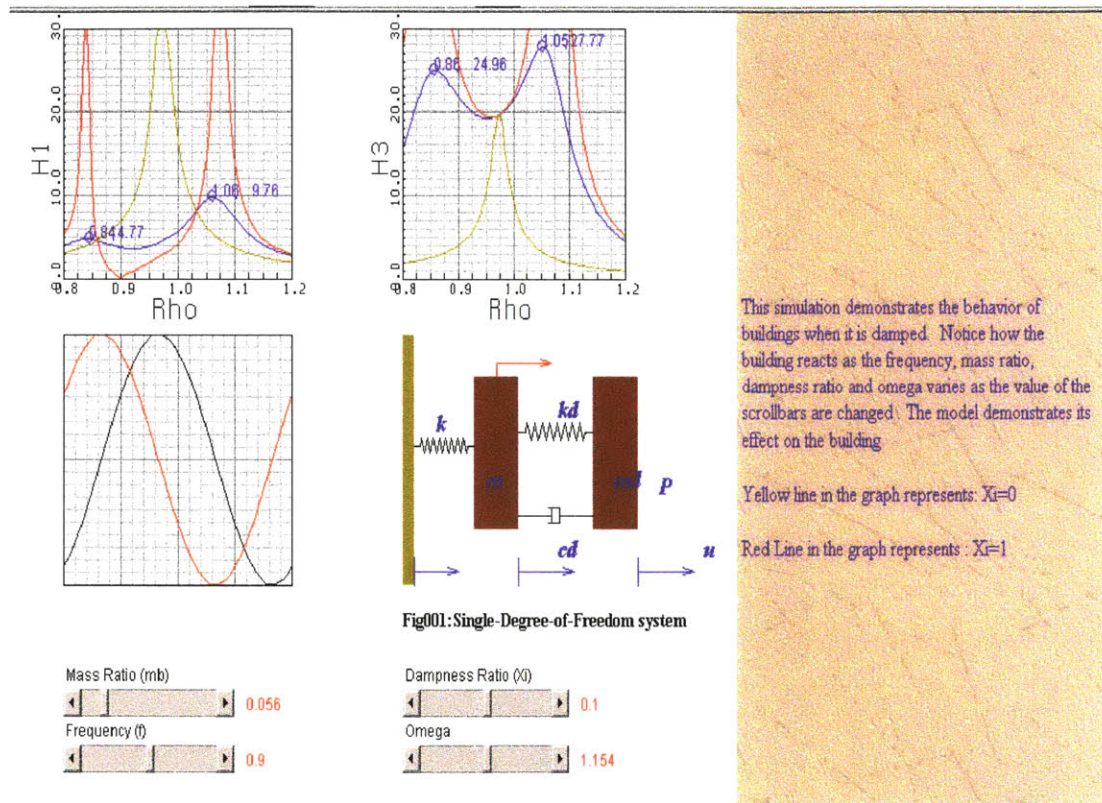


Figure 33: New Design

Features of the new design:

- 1) It has made the scrollbars, graph and the model more sensitive.
- 2) H1 and H3 have been shown as two separate graphs on the same page. This makes it easy to read and understand.

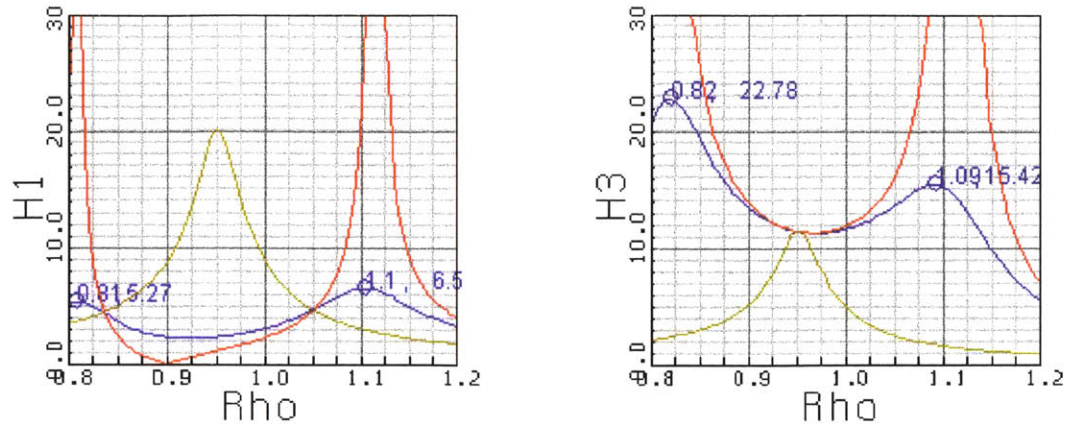


Figure 34: New Design

- 3) The range of the scrollbar for the mass ratio has been changed from the range 0 to 0.099 to the range 0 to 0.396. This gives more sensitivity to the graph.



Figure 35: New Design

- 4) The plot when the  $\xi_i = 0$  and when  $\xi_i = 1$ , has been shown in both the graph in different colors. This helps to understand the concept of TMD better.

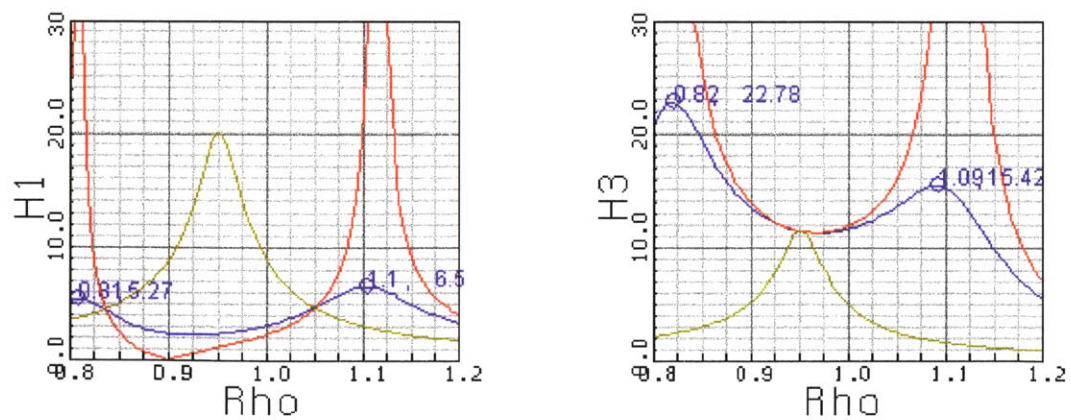


Figure 36: New Design

- 5) The model has been reinstalled beside the graph so that the user is able to see the changes in the model as the values of the scrollbar changes.

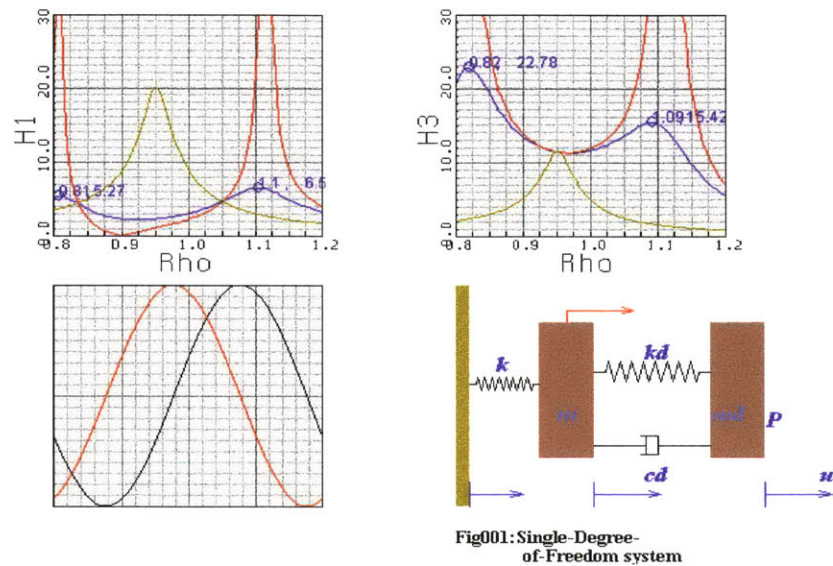


Figure 37: New Design

- 6) The model has been designed such that it would show the change in the model as the values of the scrollbar is changed. Moreover, an additional scrollbar has been provided for Omega (for the range of 0.2 to 2.0). This would help in showing the change in model due to change in Omega.



Figure 38: New Design

- 7) The new design would include some text so that a new user can understand the working of the graph and the model.



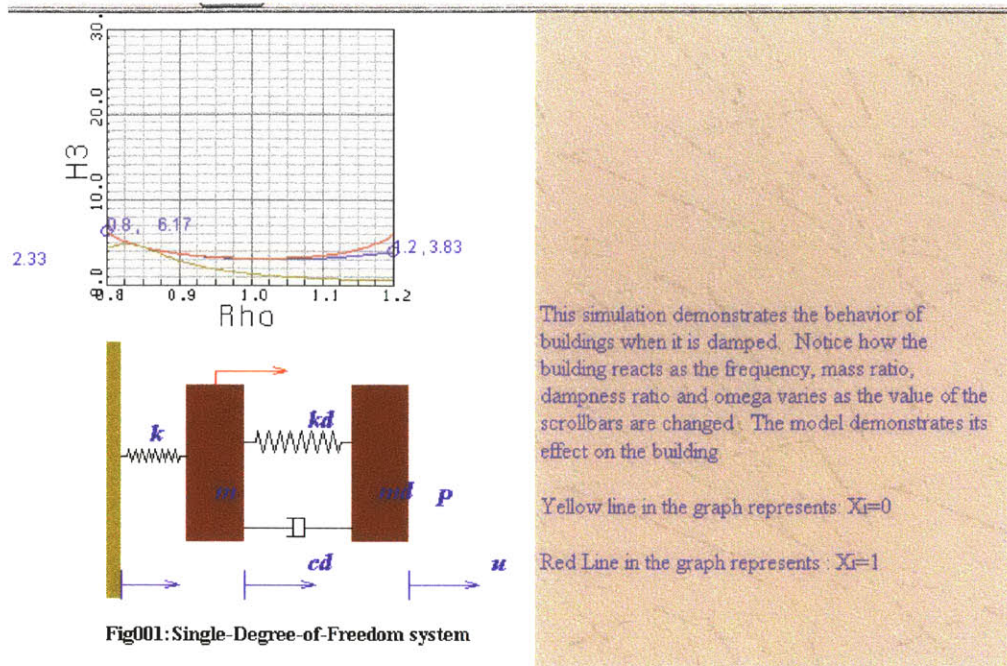


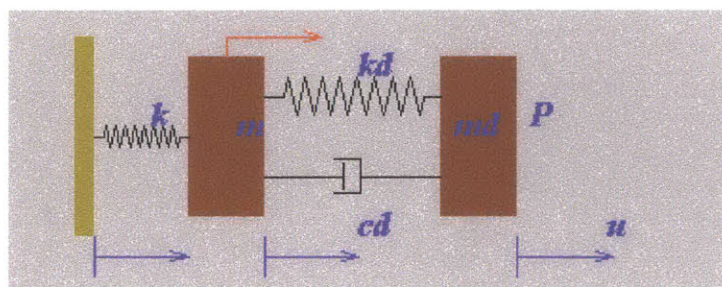
Figure 39: New Design

## **Chapter 5: Conclusion:**

The improved design of the TMD is intended to attract the civil engineering students. Structural engineer can use their creativity to design the tuned mass damper. For this creativity to become a structure that can be build, there may be a means for evaluating its performance before construction. The technical challenges involved in designing of TMD can be evaluated with the help of an evaluating tools proposed in this thesis. This simple tool might determine whether to take the design beyond the conceptual stage into actual construction or not.

The focus of this work was on achieving better conceptual learning through computer-aided interactive tutorial experience. It exploits I.T.'s possibilities to produce cutting edge learning tools. This effort led to fine-tuning of the methodology for understanding the conceptual design of the TMD.

The new design would help students in understanding the working of the tuned mass damper when the mass ratio, frequency or dampness changes. This change is graphically represented in two graphs: one H1 against Rho and second H3 against Rho. This change is also shown with the help of an interactive model. The model is as shown below



**Figure 40: New Design**

This model does not provide a clear understanding of the application the TMD in the real world. The model can be modified such that a student can easily relate it to the real world application.

The thesis indicates that the proposed conceptual design is adequate. However, greater efficiency may be achieved through further changing the model.

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- [14] "Interactive learning modules." <[http://moment.mit.edu/r\\_modules.asp](http://moment.mit.edu/r_modules.asp)>

## APPENDIX

```

1
2
3 import java.applet.*;
4 import java.awt.*;
5
6
7 //*****
8 public class Fig019 extends Engineer implements Runnable
9 //*****
10 {
11
12     Scrollbar mb_number;    Label mb_title;
13     Scrollbar f_number;    Label f_title;
14     Scrollbar Xi_number;   Label Xi_title;
15     Scrollbar n_number;    Label n_title;
16
17
18
19     Thread animator;
20     boolean please_stop;
21     Image offscreen;
22     int imagewidth,imageheight;
23     double Timestep=0.;
24     double dTimestep;
25
26 //*****
27 public void init()
28 //*****
29 {
30     setLayout( null );
31
32     mb_title = new Label( "Mass Ratio (mb)" );
33     mb_title.reshape( 50, 520, 120, 20 );
34     add( mb_title );
35     mb_number = new Scrollbar( Scrollbar.HORIZONTAL, 50, 0, 0, 100 );
36     mb_number.setPageIncrement( 2 );
37     mb_number.reshape( 50, 540, 150, 20 );
38     add( mb_number );
39
40     f_title = new Label( "Frequency (f)" );
41     f_title.reshape( 50, 560, 120, 20 );
42     add( f_title );
43     f_number = new Scrollbar( Scrollbar.HORIZONTAL, 50, 0, 0, 100 );
44     f_number.setPageIncrement( 2 );
45     f_number.reshape( 50, 580, 150, 20 );
46     add( f_number );
47
48     Xi_title = new Label( "Damping (Xi)" );
49     Xi_title.reshape( 350, 520, 120, 20 );
50     add( Xi_title );
51     Xi_number = new Scrollbar( Scrollbar.HORIZONTAL, 50, 0, 0, 100 );
52     Xi_number.setPageIncrement( 2 );
53     Xi_number.reshape( 350, 540, 150, 20 );
54     add( Xi_number );
55
56
57
58     n_title = new Label( "Omega" );
59     n_title.reshape( 350,560, 120, 20 );
60     add( n_title );
61     n_number = new Scrollbar( Scrollbar.HORIZONTAL, 50, 0, 0, 100 );
62     n_number.setPageIncrement( 2 );
63     n_number.reshape( 350, 580, 150, 20 );
64     add( n_number );
65 }
66
67 //*****
68 public Fig019()

```

```

69 //=====
70 {
71     super(500,500,30.,-5.,-5.5,0,0,300,400);
72 }
73
74
75 //=====
76 public void start()
77 //=====
78 {
79     if (animator == null)
80     {
81         animator = new Thread(this);
82         animator.start();
83     }
84 }
85
86 //=====
87 public void stop()
88 //=====
89 {
90     if (animator != null)
91     {
92         animator.stop();
93         animator = null;
94     }
95 }
96
97
98
99 //=====
100 public boolean handleEvent( Event event )
101 //=====
102 {
103     if (event.id == Event.SCROLL_ABSOLUTE ||
104         event.id == Event.SCROLL_LINE_DOWN ||
105         event.id == Event.SCROLL_LINE_UP ||
106         event.id == Event.SCROLL_PAGE_DOWN ||
107         event.id == Event.SCROLL_PAGE_UP )
108     {
109         repaint();
110         return true;
111     }
112     return super.handleEvent( event );
113 }
114 //=====
115 public void paint( Graphics g )
116 //=====
117 {
118     double
119         Rho[]=new double[110],
120         H1[]=new double[110],
121         H3[]=new double[110],
122         H1Xi0[]=new double[110],
123         H1Xi1[]=new double[110],
124         H3Xi0[]=new double[110],
125         H3Xi1[]=new double[110];
126
127     double mb      = mb_number.getValue()*0.004;
128     double f       = f_number.getValue()*0.002+.8;
129     double Xi      = XI_number.getValue()*0.002;
130
131
132     // double n      = n_number.getValue()*0.018+.2;
133     // dTimestep = n;
134     double H1peak,Rhopeak;
135     double Rhopeak1,H3peak;
136     // public static Rhopeak,

```



```

137
138     double Xaxis=20.0,Yaxis=18.;
139
140
141     double Xmax=1.2,Xmin=0.8,Ymax=30.0,Ymin=0.;
142     int Maxp=101;
143     double dx=(Xmax-Xmin)/(Maxp-1);
144
145     // Draw scale
146     g.setColor(Color.white);
147     f_rect(g,0.,10.,Xaxis,Yaxis+10);
148
149
150     f_rect(g,30.,10.,Xaxis+30,Yaxis+10);
151
152     g.setColor(Color.lightGray);
153     lattice(g,0.,10.,Xaxis,Yaxis+10,Xaxis/16.,Yaxis/30.);
154
155
156     lattice(g,30.,10.,Xaxis+30,Yaxis+10,Xaxis/16.,Yaxis/30.);
157
158     g.setColor(Color.gray);
159     lattice(g,0.,10.,Xaxis,Yaxis+10,Xaxis/4.,Yaxis/3.);
160
161
162     lattice(g,30.,10.,Xaxis+30,Yaxis+10,Xaxis/4.,Yaxis/3.);
163
164     g.setColor(Color.black);
165
166     // Calculate values
167     for(int i=0;i<Maxp;i++)
168     {
169         Rho[i]=dx*i+Xmin;
170         double RhoSQ=Rho[i]*Rho[i];
171         double a1=f*f-RhoSQ;
172         double a2=Rho[i]*f;
173         double a3=(1.-RhoSQ)*(f*f-RhoSQ)-
174             mb*RhoSQ*f*f;
175         double a4=Rho[i]*f*(1.-RhoSQ*(1.+mb));
176
177         H1[i]=Math.sqrt((a1*a1+4.*Xi*Xi*a2*a2)/
178             (a3*a3+4.*Xi*Xi*a4*a4));
179         H3[i]=Math.sqrt(Rho[i]/
180             (a3*a3+4.*Xi*Xi*a4*a4));
181
182         double X0i = 0.;
183         H1Xi0[i]=Math.sqrt((a1*a1+4.*X0i*X0i*a2*a2)/
184             (a3*a3+4.*X0i*X0i*a4*a4));
185         H3Xi0[i]=Math.sqrt(Rho[i]/
186             (a3*a3+4.*X0i*X0i*a4*a4));
187
188         double X1i = 1.;
189         H1Xi1[i]=Math.sqrt((a1*a1+4.*X1i*X1i*a2*a2)/
190             (a3*a3+4.*X1i*X1i*a4*a4));
191         H3Xi1[i]=Math.sqrt(Rho[i]/
192             (a3*a3+4.*X1i*X1i*a4*a4));
193
194         if(H1[i]>Ymax)H1[i]=Ymax;
195         if(H3[i]>Ymax)H3[i]=Ymax;
196         if(H1Xi0[i]>Ymax)H1Xi0[i]=Ymax;
197         if(H1Xi1[i]>Ymax)H1Xi1[i]=Ymax;
198         if(H3Xi0[i]>Ymax)H3Xi0[i]=Ymax;
199         if(H3Xi1[i]>Ymax)H3Xi1[i]=Ymax;
200     }
201
202     // Set user's coordinate parameters
203     Rho[Maxp+1]=Xmin;Rho[Maxp+2]=(Xmax-Xmin)/Xaxis;
204     H1[Maxp+1]=Ymin; H1[Maxp+2]=(Ymax-Ymin)/Yaxis;

```

```

205 H3[Maxp+1]=Ymin; H3[Maxp+2]=(Ymax-Ymin)/Yaxis;
206 H1Xi0[Maxp+1]=Ymin; H1Xi0[Maxp+2]=(Ymax-Ymin)/Yaxis;
207 H3Xi0[Maxp+1]=Ymin; H3Xi0[Maxp+2]=(Ymax-Ymin)/Yaxis;
208 H1Xi1[Maxp+1]=Ymin; H1Xi1[Maxp+2]=(Ymax-Ymin)/Yaxis;
209 H3Xi1[Maxp+1]=Ymin; H3Xi1[Maxp+2]=(Ymax-Ymin)/Yaxis;
210
211 // Peak point for h1
212 g.setColor(Color.blue);
213 double Xpeak,Ypeak;
214 H1peak=H1[0];Rhopeak=Rho[0];
215 for(int i=1;i<Maxp;i++)
216 {
217     if (H1[i]>H1peak)
218     {
219         Rhopeak=Rho[i];H1peak=H1[i];
220     }
221     else break;
222 }
223 Xpeak=(Rhopeak-Rho[Maxp+1])/Rho[Maxp+2]+0.;
224 Ypeak=(H1peak-H1[Maxp+1])/H1[Maxp+2]+0.;
225 number(g,Xpeak,Ypeak+10,Rhopeak,2);
226 symbol(g,Xpeak+2.,Ypeak+10,"");
227 number(g,Xpeak+2.5,Ypeak+10,H1peak,2);
228
229 marker(g,Xpeak,Ypeak+10,2);
230
231
232 H1peak=H1[Maxp];Rhopeak=Rho[Maxp];
233 for(int i=Maxp-1;i>0;i--)
234 {
235     if (H1[i]>H1peak)
236     {
237         Rhopeak=Rho[i];H1peak=H1[i];
238     }
239     else break;
240 }
241 Xpeak=(Rhopeak-Rho[Maxp+1])/Rho[Maxp+2]+0.;
242 Ypeak=(H1peak-H1[Maxp+1])/H1[Maxp+2]+0.;
243 number(g,Xpeak,Ypeak+10,Rhopeak,2);
244 symbol(g,Xpeak+2.,Ypeak+10,"");
245 number(g,Xpeak+3.5,Ypeak+10,H1peak,2);
246 marker(g,Xpeak,Ypeak+10,2);
247 double n = (n_number.getValue()*0.018+0.2);
248
249 dTimestep = n*H1peak;
250
251
252 // Peak point for h3
253 g.setColor(Color.blue);
254 double Xpeak1,Ypeak1;
255 H3peak=H3[0];Rhopeak1=Rho[0];
256 for(int i=1;i<Maxp;i++)
257 {
258     if (H3[i]>H3peak)
259     {
260         Rhopeak1=Rho[i];H3peak=H3[i];
261     }
262     else break;
263 }
264 Xpeak1=(Rhopeak1-Rho[Maxp+1])/Rho[Maxp+2]+0.;
265 Ypeak1=(H3peak-H3[Maxp+1])/H3[Maxp+2]+0.;
266 number(g,Xpeak1+30,Ypeak1+10,Rhopeak1,2);
267 symbol(g,Xpeak1+32.,Ypeak1+10,"");
268 number(g,Xpeak1+33.5,Ypeak1+10,H3peak,2);
269 marker(g,Xpeak1+30,Ypeak1+10,2);
270
271
272 H3peak=H3[Maxp];Rhopeak1=Rho[Maxp];

```

```

273     for(int i=Maxp-1;i>0;i--)
274     {
275         if (H3[i]>H3peak)
276         {
277             Rhopeak1=Rho[i];H3peak=H3[i];
278         }
279         else break;
280     }
281     Xpeak1=(Rhopeak1-Rho[Maxp+1])/Rho[Maxp+2]+0.;
282     Ypeak1=(H3peak-H3[Maxp+1])/H3[Maxp+2]+0.;
283     number(g,Xpeak1+30,Ypeak1+10,Rhopeak1,2);
284     symbol(g,Xpeak1+32.,Ypeak1+10,"");
285     number(g,Xpeak1+32.5,Ypeak1+10,H3peak,2);
286     marker(g,Xpeak1+30,Ypeak1+10,2);
287
288
289
290 //Draw line
291     g.setColor(Color.blue);
292     lline(g,0.,10.,Rho,H1,Maxp,0);
293
294     g.setColor(Color.blue);
295     lline(g,30.,10.,Rho,H3,Maxp,0);
296
297     g.setColor(Color.red);
298     lline(g,0.,10.,Rho,H1Xi0,Maxp,0);
299     lline(g,30.,10.,Rho,H3Xi0,Maxp,0);
300
301     g.setColor((Color.yellow).darker());
302     lline(g,0.,10.,Rho,H1Xi1,Maxp,0);
303     lline(g,30.,10.,Rho,H3Xi1,Maxp,0);
304 // Draw out frame
305     g.setColor(Color.black);
306     u_rect(g,0.,10.,Xaxis,Yaxis+10);
307
308     u_rect(g,30.,10.,Xaxis+30,Yaxis+10);
309
310     u_rect(g,0.,-12.,Xaxis,Yaxis-12);
311     //u_rect(g,30.,-12.,Xaxis+30,Yaxis-12);
312 // Draw Axis
313     axis(g,0.,10., Xaxis/16.,Xaxis, 0., "Rho",3,1,4,Xmin,.1);
314     axis(g,0.,10.,-Yaxis/30.,Yaxis,90., "H1" ,2,1,10,Ymin,10.);
315
316     axis(g,30.,10., Xaxis/16.,Xaxis, 0., "Rho",3,1,4,Xmin,.1);
317     axis(g,30.,10.,-Yaxis/30.,Yaxis,90., "H3" ,2,1,10,Ymin,10.);
318
319 // Draw mb,f,Xi,n
320     g.setColor(Color.red);
321     //symbol(g,-ch1*(0.5*(0.7+ch2/ch1)),Yaxis*.6,ch1,"H3",90.,2);
322     number(g,Xaxis*+0.8,-21,mb,4);
323     number(g,Xaxis*+0.8,-25,f,4);
324     number(g,Xaxis*+2.3,-21,Xi,4);
325     number(g,Xaxis*+2.3,-25,n,4);
326
327 // draw the model
328     drawFig(g);
329
330 }
331
332 //=====
333 public void run()
334 //=====
335 {
336
337     while(!please_stop)
338     {
339         Dimension d=this.size();
340         if((offscreen!=null)||

```

```

341         height)))
342     {
343         offscreen=this.createImage(d.width,d.height);
344         imagewidth=d.width;
345         imageheight=d.height;
346     }
347
348
349     Graphics g=offscreen.getGraphics();
350     paint(g);
351     g=this.getGraphics();
352     g.drawImage(offscreen,0,0,this);
353
354     try
355     {
356         Thread.sleep(00);
357     }
358
359     catch(InterruptedException e){};
360 }
361 animator=null;
362
363 }
364
365 //=====
366 public void dashpot( Graphics g ,double x0,double y0,
367     double x1,double y1)
368 //=====
369 {
370     Vector2D X0=new Vector2D(x0,y0),
371     DX=new Vector2D(x1-x0,y1-y0),
372     DY=new Vector2D(DX.Rot(90.));
373
374     u_plot(g,X0,3);
375     u_plot(g,X0.Plus(DX.Mult(.45)),2);
376     u_plot(g,(X0.Plus(DX.Mult(.45))).Plus(DY.Mult(0.075)),2);
377     u_plot(g,(X0.Plus(DX.Mult(.45))).Minus(DY.Mult(0.075)),2);
378     u_plot(g,X0.Plus(DX),3);
379     u_plot(g,X0.Plus(DX.Mult(.55)),2);
380     u_plot(g,(X0.Plus(DX.Mult(.55))).Plus(DY.Mult(0.09)),2);
381     u_plot(g,(X0.Plus(DX.Mult(.4))).Plus(DY.Mult(0.09)),2);
382
383     u_plot(g,X0.Plus(DX.Mult(.55)),3);
384     u_plot(g,(X0.Plus(DX.Mult(.55))).Minus(DY.Mult(0.09)),2);
385     u_plot(g,(X0.Plus(DX.Mult(.4))).Minus(DY.Mult(0.09)),2);
386 }
387 //=====
388 public void spring( Graphics g ,double x0,double y0,
389     double x1,double y1)
390 //=====
391 {
392     Vector2D X0=new Vector2D(x0,y0),
393     DX=new Vector2D(x1-x0,y1-y0),
394     DY=new Vector2D(DX.Rot(90.));
395     u_plot(g,X0,3);
396     u_plot(g,X0.Plus(DX.Mult(.1)),2);
397     for(double a=.1;a<.8;a+=.1)
398     {
399         u_plot(g,(X0.Plus(DX.Mult(a+.025))).Plus(DY.Mult(0.1)),
400             2);
401         u_plot(g,(X0.Plus(DX.Mult(a+.075))).Minus(DY.Mult
402             (0.1)),2);
403     }
404     u_plot(g,X0.Plus(DX.Mult(.9)),2);
405     u_plot(g,X0.Plus(DX),2);
406 }

```

```

406
407
408 //=====
409 public void drawFig( Graphics g )
410 //=====
411 {
412
413     double phase=Timestep*Math.PI/8;
414     double xm=6.+Math.cos(phase);
415     double xmd=18.+Math.sin(phase);
416     double graphx0=0.,graphy0=12.,graphx1=30.,graphy1=30.;
417     double
418         X[]=new double[110],
419         Y0[]=new double[110],
420         Y1[]=new double[110];
421
422     //double Xaxis=graphx1-graphx0,Yaxis=graphy1-graphy0;
423     double Xaxis=20,Yaxis=18;
424     double Xmax=2.*Math.PI,Xmin=0.,Ymax=1.0,Ymin=-1.;
425     int Maxp=101;
426     double dx=(Xmax-Xmin)/(Maxp-1);
427
428     // Draw scale
429     g.setColor(Color.white);
430     f_rect(g,0.,-12,Xaxis,Yaxis-12);
431     g.setColor(Color.lightGray);
432     lattice(g,0.,-12,Xaxis,Yaxis-12,Xaxis/20.,Yaxis/20.);
433     g.setColor(Color.gray);
434     lattice(g,0.,-12,Xaxis,Yaxis-12,Xaxis/4.,Yaxis/2.);
435     g.setColor(Color.black);
436
437
438     for(int i=0;i<Maxp;i++)
439     {
440         X[i]=dx*i+Xmin;
441         Y0[i]=Math.sin(X[i]+Timestep);
442         Y1[i]=Math.cos(X[i]+Timestep);
443     }
444
445     // Set user's coordinate parameters
446     X[Maxp+1]=Xmin;X[Maxp+2]=(Xmax-Xmin)/Xaxis;
447     Y0[Maxp+1]=Ymin; Y0[Maxp+2]=(Ymax-Ymin)/Yaxis;
448     Y1[Maxp+1]=Ymin; Y1[Maxp+2]=(Ymax-Ymin)/Yaxis;
449
450     //Draw line
451     g.setColor(Color.black);
452     lline(g,0.,-12,X,Y0,Maxp,0);
453     g.setColor(Color.red);
454     lline(g,0.,-12,X,Y1,Maxp,0);
455
456     // Draw out frame
457     g.setColor(Color.black);
458     u_rect(g,0.,-12,Xaxis,Yaxis-12);
459
460
461
462
463     // Base
464     g.setColor((Color.yellow).darker());
465     f_rect(g,30,-12,31,Yaxis-12);
466     // m
467     g.setColor((Color.red).darker());
468     f_rect(g,30+xm,-8.,xm+34.,Yaxis-15);
469     // md
470     f_rect(g,30+xmd,-8,xmd+34.,Yaxis-15);
471
472     // Dash pot
473     g.setColor(Color.black);

```

```

474 dashpot(g,xm+34.,-7,xmd+30,-7);
475
476 // Spring
477 spring(g,31.,Yaxis-20,30+xm,Yaxis-20);
478 spring(g,xm+34.,Yaxis-19,30+xmd,Yaxis-19);
479 // Arrows
480 g.setColor(Color.red);
481 u_plot(g,xm+32.,Yaxis-15,3);
482 u_plot(g,xm+32.,Yaxis-14,2);
483 arrow(g,xm+32.,Yaxis-14,xm+37.,Yaxis-14,2);
484
485 g.setColor(Color.blue);
486 //u_plot(g,31.,-10,3);
487 //u_plot(g,31.,-12,2);
488 //arrow(g,31.,-11.,35.,-11.,2);
489 u_plot(g,xm+34.,-10,3);
490 u_plot(g,xm+34.,-12,2);
491 arrow(g,xm+34.,-11.,xm+39.,-11.,2);
492 u_plot(g,xmd+34.,-10,3);
493 u_plot(g,xmd+34.,-12,2);
494 arrow(g,xmd+34.,-11.,xmd+39.,-11.,2);
495
496 g.setFont(new Font("TimesRoman",Font.BOLD|Font.ITALIC,18));
497
498 symbol(g,33.,-1,"k");
499 symbol(g,44.,0,"kd");
500 symbol(g,43.,-5,"cd");
501 symbol(g,42.,-10,"u");
502 symbol(g,37.5,-5,"m");
503 symbol(g,49.,-5,"md");
504 symbol(g,40.,5,"P");
505 symbol(g,53.,-10,"ud");
506 g.setFont(new Font("TimesRoman",Font.BOLD|Font.PLAIN,14));
507
508 g.setColor(Color.black);
509 symbol(g,30.,-15.,"Fig001:Single-Degree-of-Freedom system");
510 //symbol(g,30.,-16.5,"of-freedom system");
511 Timestep+=dTimestep;
512 }
513
514
515
516
517
518 //
519 }
520

```