# STRUCTURAL MAGNETIC INDUCTION DAMPERS IN BUILDINGS

by

Laurent J. Auge

Diplôme d'ingénieur
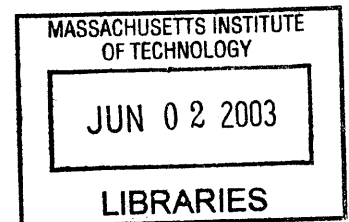École Centrale de Lyon, France
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Submitted to the Department of Civil and Environmental Engineering
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**BARKER**

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## ABSTRACT

This thesis discusses the feasibility of structural magnetic induction dampers for dampening mechanical vibrations in buildings subjected to strong dynamic excitations. The concept of energy harvesting in various fields of engineering is first examined. Then it is applied to the design of magnetic induction dampers in buildings. Various implementations of these dampers are proposed and the related expected performances are estimated. Simulations on buildings modeled as discrete multiple-degree-of-freedom shear beams subjected to earthquakes quantify the results and allow for a comparison of the performances with non-isolated and base-isolated buildings. This study demonstrates the potential efficiency of such dampers for harvesting mechanical energy in buildings and encourages further developments on this topic.

Thesis Supervisor: Jerome J. Connor

Title: Professor of Civil and Environmental Engineering

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# CHAPTER 1: INTRODUCTION

Civil engineering structures are designed according to various limit states, and are based on static or dynamic analysis. From a static analysis point of view, the design parameters are strength and stiffness: the structure should resist the prescribed static load while deflecting less than a given maximum value. From a dynamic analysis point of view, damping is an additional key parameter, especially around resonance, where the structure may otherwise blow up. Thus, structural damping is a critical parameter for all structures that are or may be subjected to dynamic loadings. Dynamic loadings can consist of wind loadings or earthquakes, which produce an excitation via ground motion.

Many structural dampers have been implemented in buildings to deal with dynamic excitation. Traditional structural dampers are linear viscous dampers, which comprise a piston moving back and forth in a compressible fluid chamber, friction dampers, Coulomb dampers or hysteretic dampers. Theses dampers are efficient in the sense that they dampen the energy input due to the dynamic loading by dissipating it through various mechanisms. The energy can be dissipated into heat or deformation of a material according to the mechanism. In each of these cases, damping takes the energy input out of the structure and dissipate it.

The idea that led us to the study of structural magnetic induction dampers is the possibility of harvesting the energy from a dynamic loading by converting it into electrical energy. Unlike traditional structural dampers, such dampers would be capable of both dampening the mechanical energy and retrieving it under another form, electrical energy.

Structural motion control has recently been a subject of growing importance for research in structural engineering. Control systems include passive and active devices. Passive devices, such as traditional viscous dampers, do not require any external energy supply. In contrast, active devices require external energy supply, for example to make an actuator work. How to provide this external energy is often a serious issue that prevents civil engineers from choosing the active control solution. Factors such as costs or maintenance issues make active motion control still a concept that is implemented very seldom by civil engineers. That is why the idea of harvesting the energy from dynamic loading could be of great interest for further developments of active control devices. In the case of structural magnetic induction dampers, the harvested electrical energy could be used to supply other active devices.

The idea of harvesting natural mechanical energy is not new but it has been only little implemented in buildings. This study will therefore strive to implement energy harvesting in buildings subjected to dynamic loading through the use of structural magnetic induction dampers. We will first examine a few methods that have been used in various fields to harvest mechanical energy and produce electrical energy. Then, we will more specifically focus on applying this concept to structural damping in buildings. We will propose designs of magnetic induction dampers, study their possible integration in buildings, and scale them for use in dampening motion due to earthquakes or strong winds. Simulations will help us assess the applicability and the potential benefits of structural magnetic induction dampers.

# CHAPTER 2: THE CONCEPT OF ENERGY HARVESTING

The idea in integrating structural magnetic induction dampers in buildings is to harvest the mechanical energy due to dynamic loadings. More specifically, the mechanical energy in buildings subjected to such conditions primarily consists of shear deformation, which consists of translational inter-story displacements. Our goal is here to transform this translational mechanical energy into electrical energy. Consequently, we will have to use a translational linear generator. This is one of the main problems of our study because most of electrical generators are alternators, which produce electrical energy from rotational mechanical energy. Therefore, the first step of this investigation is to look into what has been used so far in various fields for producing electrical energy from translational motion.

The mass production of electricity is worldwide based on alternators, which may be hydraulic alternators, nuclear alternators or pneumatic alternators. This is because rotational electrical generators are more efficient that translational electrical generators. However, in many cases, when it comes to harvest mechanical energy from a natural phenomenon, the mechanical energy turns out to consist of translational motion. We will therefore focus on mechanisms that have been used to produce electrical energy from translational motion through magnetic induction. That will help us for the design of structural magnetic induction dampers in buildings.

## 2.1 Ocean wave energy converters

*Small ocean wave energy converters*

Linear translational generators have many times been implemented so far to harvest energy from ocean waves. Some small devices, generating a power of 1-2 Watts, have been used to supply power to oceanographic monitoring sensors. The basic principle of such a device is explained below in figure 1.
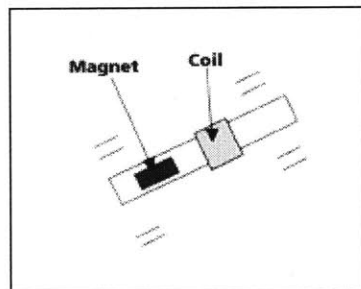
External motion causes the magnet, under very low friction, to move back and forth, through the coil, producing electrical energy.
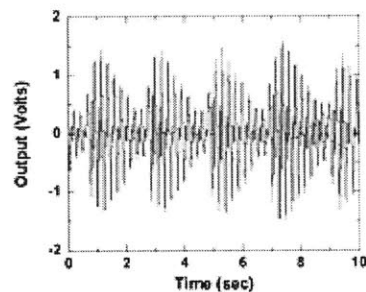
Sample electrical output obtained from generator.

*Figure 1: Basic translational linear generator [1]*

This device is based on magnetic induction. It is very small and produces only little power. To make it work properly, the friction between the magnet and the coil has to be very low. This is made possible by applying a surface treatment on both materials, which reduce the friction to negligible levels. With theses precautions, such a translational linear generator is operational.

Larger ocean wave energy converters have also recently been a topic of research. Figure 2 shows such devices.
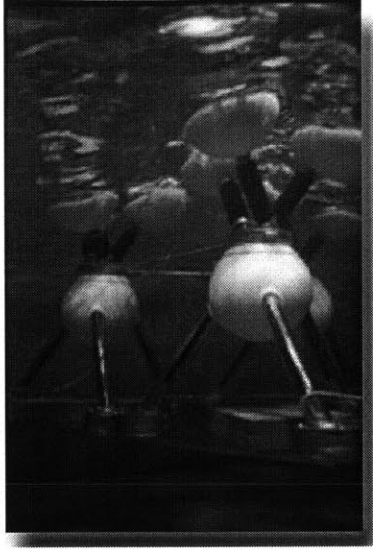
*Figure 2: Ocean wave energy converters [2]*

The upper part of the device consists of buoys floating on the water surface whereas the lower part is composed of large horizontal plates. The buoys are prone to undergo the vertical motion due to ocean waves. In contrast, the horizontal plates can be considered as fixed because their geometry strongly opposes the vertical motion and also because at such a depth water particle movement from waves is essentially attenuated. Consequently, ocean waves produce a translational motion between the lower and the upper part of the device. A possible translational electrical generator to be located between these two parts is shown in figure 3.



*Figure 3: Linear generator used in ocean wave energy converters [2]*

This linear generator comprises a 23'' aluminum rod, ring spacers, permanent magnets and coil sets.

## Larger scale wave energy converters

More powerful wave energy converters have been implemented, which convert linear motion to rotational motion. The created rotational motion then powers an alternator. This concept of converting translational motion to rotational motion before transforming mechanical energy into electrical energy is interesting and may also be applied to motion control in buildings. This relates to the better performance of rotational generators with respect to translational generators. The study of such a device may consequently be useful. The most famous is the Wells turbine, shown in figure 4, which can convert air linear motion into unidirectional rotation.
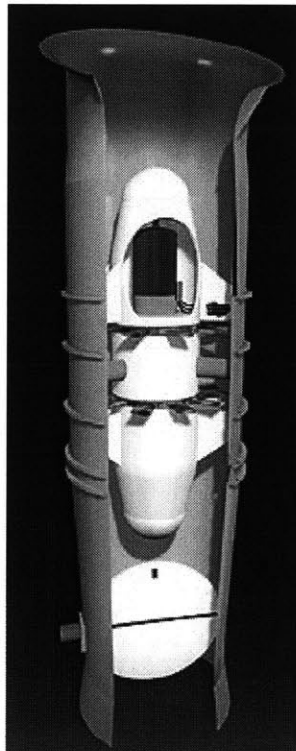


*Figure 4: Wells Turbine [3]*

Wells turbines are pneumatic turbines: an air steam flows across the turbine blades and produces rotational motion. In case of wave energy converters, an oscillating water column, as illustrated by figure 5, provides the air stream.
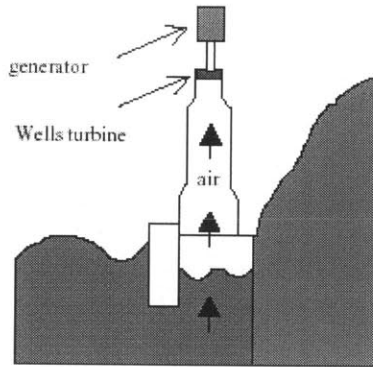


*Figure 5: Wave energy converters based on Wells turbine [4]*

A column of air, contained above the water level, is alternately compressed and decompressed by wave movement to generate an alternating stream of high velocity air in an exit blowhole.

To sum up, the electrical power is in this case produced by an alternator driven through the use of a pneumatic turbine, itself powered by ocean wave translational motion. We can retain from this device that a possible design for magnetic induction dampers in buildings would be to first convert translational motion through rotational motion, then use a rotational induction generator.

## 2.2 Harvesting energy in civil engineering structures

The concept of harvesting dynamic excitation energy in civil engineering structures has become increasingly attractive because it could permit to power active control devices. The main issue in active structural motion control is to make energy available at all times to the active devices that otherwise cannot work. Many research projects have been carried out to study the way of harvesting mechanical energy from dynamically excited structures and convert it into electrical energy. However, the amount of electrical energy harvested in current systems is small. It goes typically from 1 µW to a few Watts. Such systems are composed of piezoelectric materials or embedded transducers. Piezoelectric materials are capable of producing an internal voltage when subjected to mechanical strains. Transducers are devices that can convert mechanical energy through electrical energy. They may be composed of permanent magnets and coil windings, relying on the phenomenon of induction. For example, studies have shown that acceleration sensors in a bridge could be powered by the energy harvested from bridge vibrations due to car traffic. Such a bridge would implement some induction-based transducers.

However, neither buildings nor other civil engineering structures have so far implemented structural magnetic induction dampers. Some contains induction-based devices capable of producing little amount of electrical energy but these cannot be considered as dampers, because the power generated being so little, the energy extracted from the structure is negligible. Therefore, one of the most significant tasks of this work consists in the study of the feasibility of large scale structural magnetic induction dampers in buildings, capable for example of extracting a significant amount of the energy of an earthquake. This work primarily involves proposals of possible designs and the assessment of their capabilities.

# CHAPTER 3: DESIGN OF STRUCTURAL MAGNETIC INDUCTION DAMPERS

A building subjected to dynamic loadings such as strong winds or earthquakes will present inter-story displacements, velocities and accelerations due essentially to shear deformation. The general concept of structural magnetic induction dampers consists of dampening this mechanical energy by converting it into electrical energy.

## 3.1 What is magnetic induction?

Magnetic induction designates the following physical phenomenon: an induced current is created in an electrical circuit when this one is subjected to variations of magnetic field. This can happen either when a fixed circuit is placed in a varying magnetic field or when the circuit moves within a constant magnetic field. Magnetic induction is in essence well adapted to damping applications because it is based on the natural principle of moderation. More specifically, Lenz's law states that the induced current will be in a direction that opposes the change that produced it. In the case of a magnetic induction damper, the induced current will produce a force that opposes the movement of the structure. That is exactly the aim of damping devices. Figure 6 shows the induction phenomenon, based on the moderation principle.
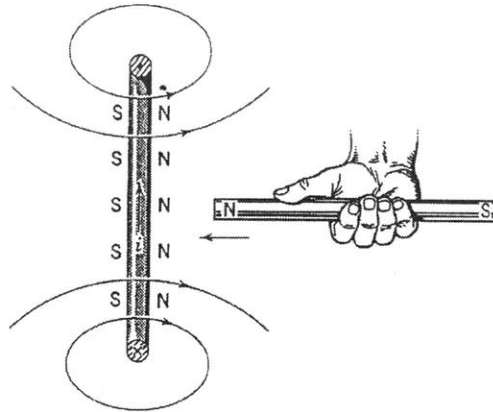
*Figure 6: The induction phenomenon (Kiameh, p. 26.12)*
*If we move the magnet toward the loop, the induced current points as shown, setting up a*
*magnetic field that opposes the motion of the magnet*

Induction phenomena are interesting for engineering applications also because they make it possible to convert mechanical energy to electrical energy or vice-versa without even any contact. It is consequently an efficient way to transform energy. That is why the production of electricity is worldwide based on magnetic induction.

## 3.2 First design of a translational linear generator

*Basic concept*

We will now propose a design of a translational linear generator that will be able to act as a magnetic induction damper in a building. The basic sketch of the generator is shown by following figure 7:
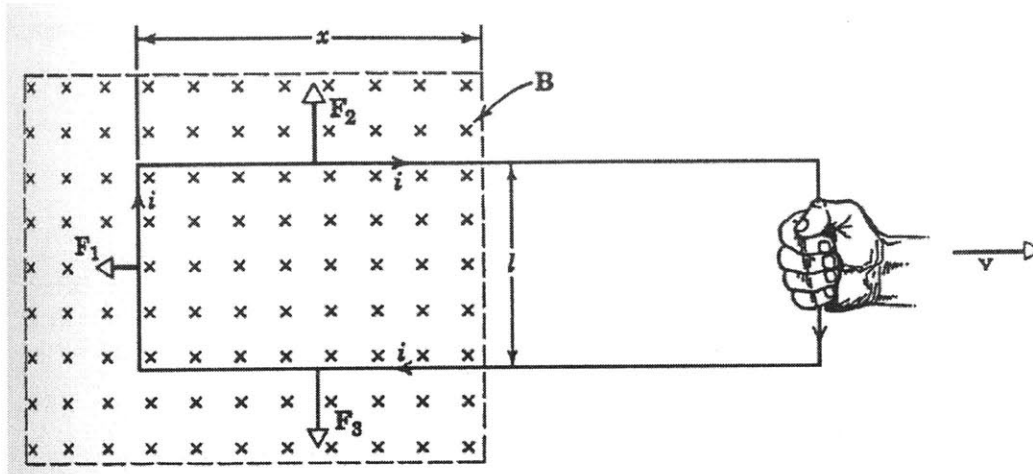
*Figure 7: Basic sketch of a translational linear generator (Kiameh, p. 26.13)*

A rectangular coil winding is moving back and forth in and out of a magnetic field. The constant magnetic field, possibly provided by strong permanent magnets, is perpendicular to the rectangular loop. The velocity v of the rectangular loop with respect to the magnets may for example represent the inter-story velocity in a building subjected to a dynamic loading. We will further develop this topic later in this study.

The translation motion of the rectangular loop with respect to the permanent magnets causes a variation in the magnetic flux through the loop and consequently, according to induction laws, a electro-motive force and so a current are induced. We also know that an electrical circuit carrying a current and located in a magnetic field is subjected to Laplace's force. This force is to be interpreted as an interaction force between the fixed permanent magnets and the coil winding. It actually stands for the damping force between those two elements. This simple translational linear generator is the basis for a possible design of structural magnetic induction dampers in buildings.

*Equations involved in the proposed translational linear generator*

Figure 8 reminds the various parameters of the problem:
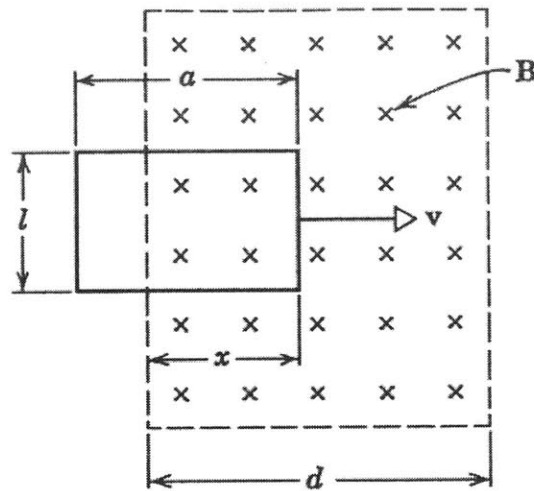
*Figure 8: Parameters involved in the translational linear generator (Kiameh, p. 26.13)*

*The position of the loop is measured by x, the distance between the effective left edge of the field **B** and the right end of the loop.*

The magnetic flux $\phi$ through the loop is given by

$$\phi = \iint B \cdot dS = B \cdot l \cdot x.$$

Then, according to Faraday's law, the induced voltage or electro-motive force (emf) is defined by

$$e = -\frac{d\phi}{dt}.$$

Consequently, the emf can be written as

$$|e| = B \cdot l \cdot \frac{dx}{dt} = B \cdot l \cdot v.$$

Then, we can deduce the current i as follows:

$$i = \frac{e}{R} = \frac{B \cdot l}{R} \cdot v,$$

where R represents the resistance of the circuit.

From Lenz's law, this current must be clockwise on Figure 7 because it is opposing the change (the decrease in $\phi$). It establishes a magnetic field in the same direction as the external magnetic field within the loop.

Laplace's law states that a circuit element **dl** with a current I in it and located in a magnetic field **B** is subjected to the following force:

$$dF = idl \times B.$$

We calculate the resultant force on the rectangular loop using the following analysis from figure 9.
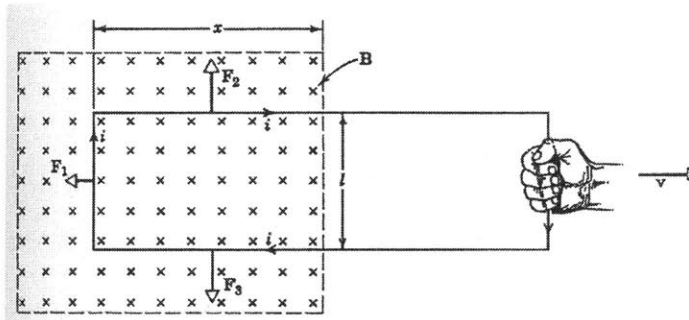


*Figure 9: Calculation of the resultant force applied on the rectangular loop (Kiameh, p. 26.13)*

Outside of the magnetic field area, Laplace's force is zero because **B** is zero. Forces **F₂** and **F₃** cancel each other because they are equal and in opposite directions. **F₁** can be expressed as

$$F_1 = i \cdot l \cdot B \cdot \sin 90° = \frac{B^2 \cdot l^2 \cdot v}{R}.$$

Consequently, the resultant force applied on the rectangular loop is

$$F = \frac{B^2 \cdot l^2}{R} \cdot v.$$

The force F opposes the velocity v so it can be considered as a damping force. The damping coefficient C in this case clearly appears as being given by

$$C = \frac{B^2 \cdot l^2}{R}.$$

If we want to increase the scale of this induction mechanism, we can replace the single rectangular loop by a coil winding composed of N coil turns.

In this latter case, the new expressions of the various physical variables are the following:

$$\phi = \iint B \cdot dS = N \cdot B \cdot l \cdot x,$$

$$|e| = N \cdot B \cdot l \cdot \frac{dx}{dt} = N \cdot B \cdot l \cdot v,$$

$$i = \frac{e}{R} = \frac{N \cdot B \cdot l}{R} \cdot v,$$

$$F = \frac{N^2 \cdot B^2 \cdot l^2}{R} \cdot v,$$

$$C = \frac{N^2 \cdot B^2 \cdot l^2}{R}. \quad (1)$$

## 3.3 Second possible design for a magnetic induction damper

*Basic concept*

In our first design, the proposed magnetic induction damper consists of a rectangular coil moving back and forth in a magnetic field created by fixed permanent magnets. Another alternative is to have a fixed electrical circuit and a variable magnetic field, for example created by a moving magnet. More specifically, the fixed electrical circuit could be a circular coil winding, similar to a solenoid, inside of which a moving magnet goes back and forth, as illustrated by figure 10.
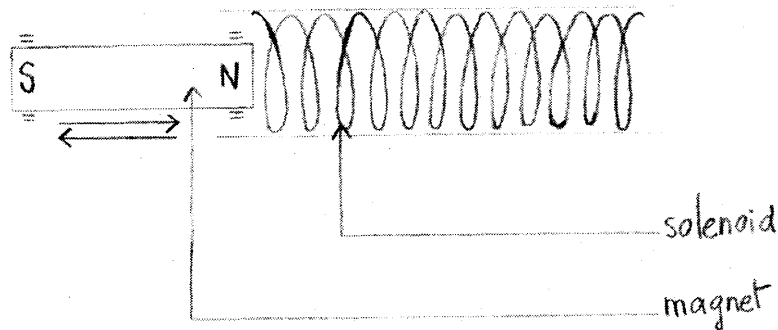


*Figure 10: Other possible design for a magnetic induction damper*
*A moving magnet induces a current in a solenoid.*

*Principle of the device*

In the following paragraph, we briefly explain how this device works and why it can be considered as damper. First of all, figure 11 below recalls what a solenoid is and how it behaves.
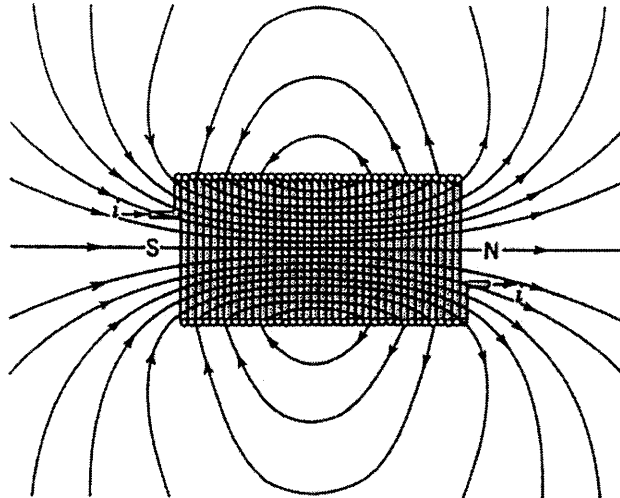
*Figure 11: Magnetic field lines created by a solenoid carrying a current (Kiameh, p. 26.11)*

*Magnetic field lines are the same as those created by a single magnet. A solenoid carrying a current is therefore equivalent to a magnet, having north and south poles.*

In our design, the solenoid is free from current when the magnet does not move. If we move the magnet towards the solenoid, it will according to Lenz's law induce a current in the solenoid that by its effects opposes the motion of the magnet. The direction of the current will consequently be such that the magnet pole and the solenoid pole facing each other are identical poles (both north poles or south poles). The moving magnet is subjected to a magnetic force opposing its displacement rate. Thus, the device can really be considered as a damper.

## 3.4 How to deal with the induced electrical energy?

The produced electrical energy can basically be used in two different ways: it can either be dissipated as heat through a resistance, or it can be stored in a battery. Several factors make it more effective to store the electrical energy in a battery.

First of all, formula (1) (on page 21) shows that the higher the resistance R is, the less the damping coefficient is. It is consequently impossible to dissipate a large amount of electrical energy unless the damping coefficient of the induction damper is very small. The main purpose of such a device is to dampen the maximum possible mechanical energy from a building under dynamic loading. To maximize the damping coefficient, the resistance of the electrical circuit has to be as small as possible. This is because, in this case, the induced current is more important and consequently, the resultant force applied on the electrical circuit is larger.

Storing the electrical energy in a battery is an alternative way to dissipating it as heat, which turns out to be much more interesting because it allows for the subsequent use of this energy. It may for example be used to provide power to other active devices. The issue in storing the produced electrical energy in a battery is to obtain a direct current (DC). This is because charging a battery requires having a current always in the same direction. Most of electrical generators, as the one we have just presented, produce alternating currents (AC).

However, there are various ways of obtaining a DC current. First of all, it is possible to add a mechanical system, primarily consisting of a commutator, to reverse the current when it is in the wrong direction. Figures 12a and 12b illustrate a system based on mechanical switches in the case of a rotational electrical generator.
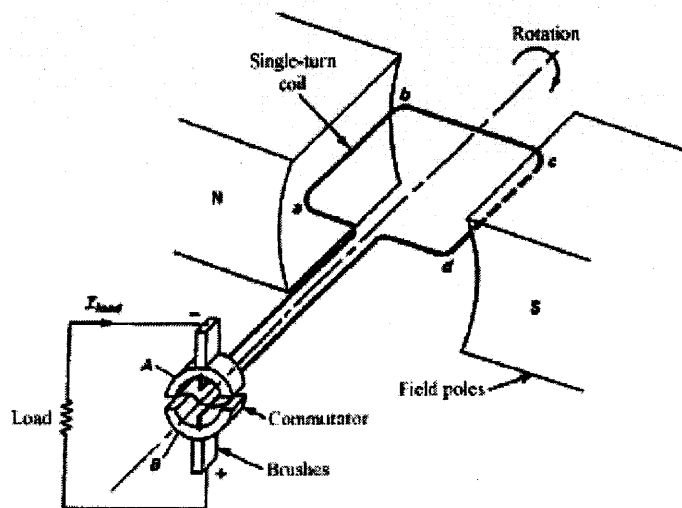


*Figure 12a: Principle of DC generator with split slip-ring [5]*
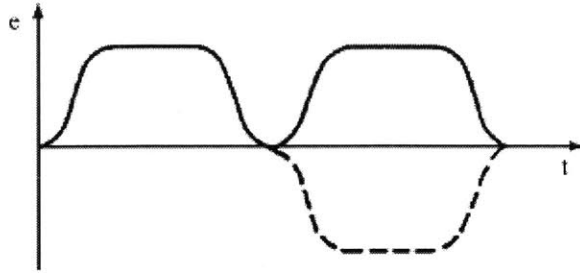
*Figure 12b: Unidirectional voltage (DC) after conversion (commutation) [5]*

Another solution is to use an electronic device, called a current rectifier, which enables to transform the AC current into a DC current, as illustrated by figure 13.
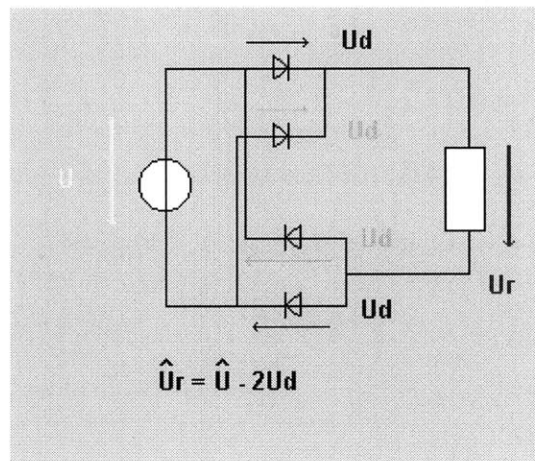


*Figure 13: Current rectifier [6]*

*Ud = 0.7 V is the conduction voltage. It causes a slight loss in the effective voltage Ur.*

However, the direct use of mechanical switches is often more efficient that the use of electronic devices. In the former case, we directly produce a DC current, whereas in the latter case, the added electronic device causes a slight voltage loss, due to its non-negligible impedance.

## 3.5 Scales and expected performances of the magnetic induction dampers

In this part, we will focus on relating the performances of the proposed magnetic induction dampers to their various parameters. We will carry out a quantitative study based on the first proposed design, that is the rectangular coil moving back and forth between two flat permanent magnets. We will estimate the capabilities of such a magnetic induction damper. Our second design will have similar capabilities.

The main properties of the damper are given by the following previously derived formulas:

$$i = \frac{e}{R} = \frac{N \cdot B \cdot l}{R} \cdot v$$

$$F = \frac{N^2 \cdot B^2 \cdot l^2}{R} \cdot v$$

$$C = \frac{N^2 \cdot B^2 \cdot l^2}{R}$$

The parameters involved in the design of this magnetic induction damper are the number of coil turn N, the magnitude of the magnetic field B, the width of the coil l and the resistance R of the electrical circuit, which includes both the coil winding and the load circuit.

Choice of N:

The damping coefficient C is proportional to $N^2$ so we should have as many coil turns as possible to increase the capabilities or the damper. However, heating of the coil may occurs if N is too large, due to the non-negligible resistance of the copper wire making up the coil. Finally, a value of **N = 150** seems to be reasonable.

Choice of B:

B also has to be large to maximize the performance of the magnetic induction damper. Magnetic fields created by permanent magnets of 0.1 Tesla are strong magnetic fields. It is

possible to reach a value of 0.2 Tesla with two flat permanent magnets. Therefore, we choose **B = 0.2 T**.

Choice of l:

l stands for the width of the coil and is limited by the physical space available in the building between two floors. We choose **l = 3 m**, which is a relatively large value, considering that the magnets must be at least that large.

Value of R:

Figure 14 shows the equivalent electrical circuit that models the actual circuit composed of the coil and the load circuit. The load circuit is mostly composed of the battery.
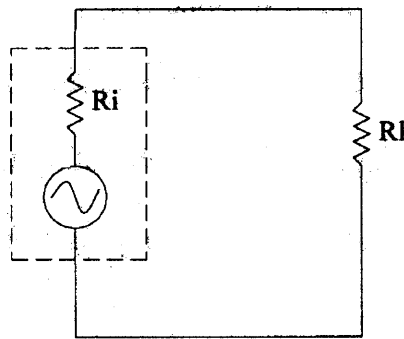


*Figure 14: Equivalent electrical circuit*

*The linear generator is modeled as an alternating voltage source plus an internal resistance Ri. The load circuit is modeled by a load resistance Rl.*

The total resistance R of the circuit is the sum of the internal resistance of the generator, Ri, and the load resistance, Rl. Rl is the internal resistance of the battery, we can take Rl = 1 Ω. Ri is the resistance of the coil winding. It is given by the following formula:

$$Ri = \rho \cdot \frac{L}{S},$$

with

Ro = 1.7 $10^{-8}$ Ω.m is the resistivity of copper

L is the total length of the coil winding.

L = 1200 m.

S is the section of the copper wire. A large section will reduce Ri so we can choose a wire diameter of 1 centimeter.

Finally Ri = 0.25 Ω,

And **R** = Ri + Rl **= 1.25 Ω**.

With those values, we finally obtain $C = \dfrac{N^2 \cdot B^2 \cdot l^2}{R} =$ **6480 kg.s$^{-1}$**.

To calculate the induced current i and the resultant force F, we have to estimate the inter-story velocity v, which produces a relative velocity between the permanent magnet and the coil. We will try in the following section to roughly estimate v. More accurate values will be obtained with MotionLAB simulations in chapter 5.

Let us take the example of a three-story building. The typical shear deformation in a building subjected to dynamic loading is given by

$$\gamma = \frac{1}{200} = \frac{\Delta u}{h},$$

where $\Delta u$ is the inter-story displacement and h is the height of a floor. h can be taken equal to 4 meters so finally the typical inter-story displacement is

$$\Delta u = \frac{4}{200} = 0.02 \, \text{m}.$$

Considering that the dynamic loading consists of a sinusoidal loading, the inter-story velocity can be expressed by

$$v = \omega \cdot \Delta u,$$

where $\omega$ is the pulsation of the loading. We can choose as a typical value the first natural pulsation of a three-story building, which can be approximated by

$$\omega = \frac{2\pi}{T} = \frac{2\pi}{0.3} = 21 \, \text{rad.s}^{-1}.$$

Hence, v = 0.42 m.s$^{-1}$. This value represents an estimate of the amplitude of the sinusoidal inter-story velocity in a three-story building.

Consequently, the time average or v$^2$ is the following:

$$\langle v^2(t) \rangle = \frac{v^2}{2} = 0.0882 \, \text{m}^2.\text{s}^{-2}.$$

Then, we can deduce the average mechanical power extracted from the building motion by the damper and converted into electrical energy:

$$\langle P \rangle = \langle F \cdot v \rangle = C \cdot \langle v^2 \rangle = 572 \ \text{W}.$$

One single damper is capable of extracting **P = 572 W**.

The magnitude of the damping force F, the induced voltage e and the induced current i have the following values:

$$F = \frac{N^2 \cdot B^2 \cdot l^2}{R} \cdot v = 2272 \ \text{N},$$

$$e = N \cdot B \cdot l \cdot v = 38 \ \text{V},$$

$$i = \frac{e}{R} = \frac{N \cdot B \cdot l}{R} \cdot v = 30 \ \text{A}.$$

# CHAPTER 4: IMPLEMENTATION OF MAGNETIC INDUCTION DAMPERS IN BUILDINGS

## 4.1 General concept

*Overall idea*

The proposed magnetic induction dampers are composed of permanent magnets and a coil. The relative velocity of the coil with respect to the permanents magnets (or vice-versa) produces a current in the coil and consequently a resultant force, which acts as a damping force. The idea that came to us first is to obtain this relative velocity from the inter-story velocity of the building subjected to dynamic loading. This means that the permanent magnets have to be fixed on the lower floor whereas the coil winding has to be attached to the upper floor, or vice-versa. Such a device takes much space in a building but it has often been used to integrate traditional viscous dampers in buildings. Figure 15 shows viscous dampers coupled with chevron braces, in a system that provides inter-story damping in a building.
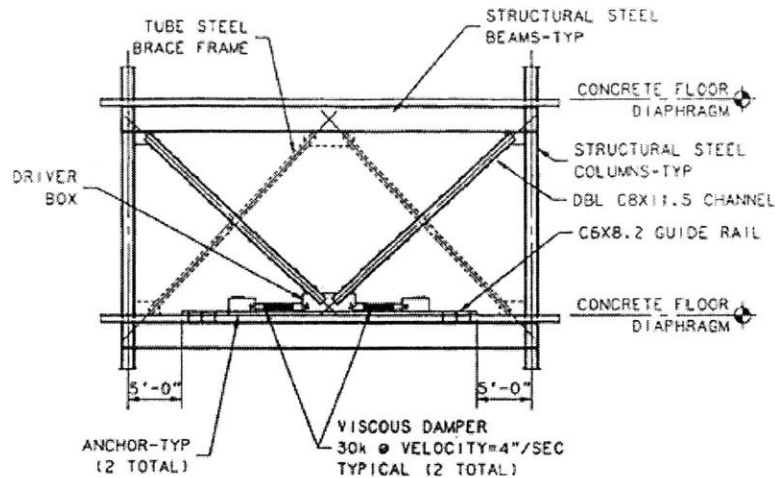
*Figure 15: Viscous dampers coupled with chevron braces [7]*

*An analogue mechanism in our proposed magnetic induction damper could relate the coil and the upper floor, establishing a relative velocity between the coil and the magnet equal to the inter-story velocity.*

Based on the same idea, we propose some basic designs showing how to make it possible to connect the coil winding to the upper floor.

## Implementation of our first design

Our first design consists of a rectangular coil moving back and forth between two flat permanent magnets. Figures 16 and 17 illustrate some possible solutions. In each case, the vertical member relating the upper floor to the coil winding is reinforced by an X-bracing system in order to gain lateral stiffness. This member has to be stiff because we want the coil winding to have the same velocity as the upper floor, and at the same time, the member to be able to withstand the damping force exerted at its end.

The coil is rolled up around a composite plate, for two primary reasons. First of all, we must not choose a conductor plate such as a metal plate because it may cause some courts-circuits in the coil. Secondly, composite materials have the advantage of being both

light and stiff, so it enables us to provide sufficient stiffness while protecting the system from unwanted inertia effects.

The simplest way of creating a uniform and constant magnetic field through the use of permanent magnets is to use a U-magnet or two flat permanent magnets with the opposing poles facing each other. The use of flat permanent magnets is more effective to obtain a strong magnetic field. Two flat permanent magnets are therefore firmly attached to the lower floor.

The difference between figure 16 and figure 17 consists in the orientation of the coil windings. They can be either set horizontally or vertically. Putting them vertically seems to be a more efficient design because it can prevent undesirable effects such as buckling of the plate supporting the coil winding. Moreover, it takes less space than the horizontal configuration.
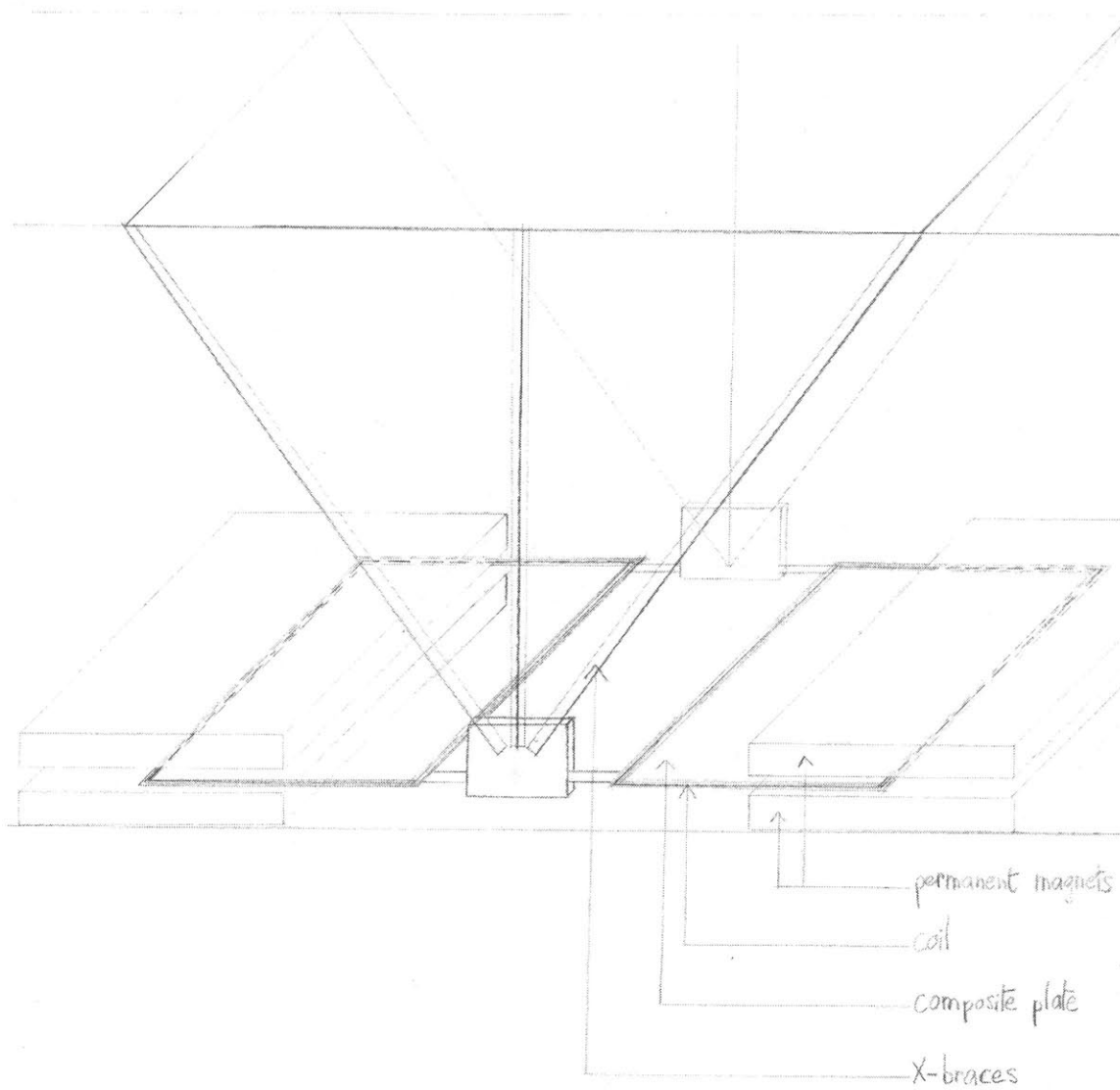
*Figure 16: First possible implementation of the proposed magnetic induction damper*

*The coil and the permanent magnets are horizontal and an X-bracing system relates the coil to the upper floor*

permanent magnets

coil

composite plate

X-braces

UPPER FLOOR

composite plate

coil
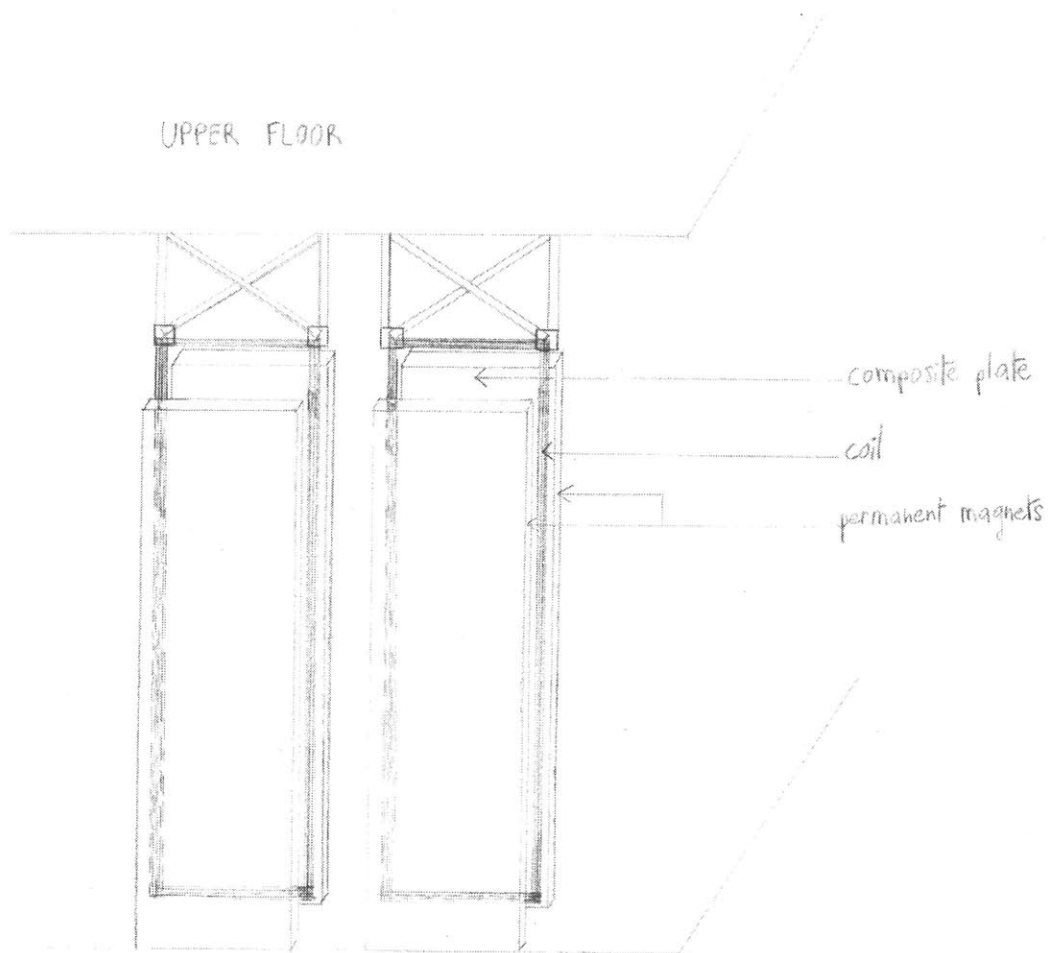
permanent magnets

*Figure 17: Second possible implementation of the proposed magnetic induction damper*

*The coil and the permanent magnets are vertical and a truss system relates the coil to the upper floor.*

## Implementation of our second design

Our second design consists of a permanent magnet moving back and forth in a coil similar to a solenoid. Integrating such a device to dampen the dynamic oscillations of a building requires like in our previous design that the two parts of the device be properly attached to adjacent floors of the building. The magnet could be attached to the upper floor, whereas the coil could be firmly fixed to the lower floor. Figure 18 shows a possible implementation of this magnetic induction damper in a building.
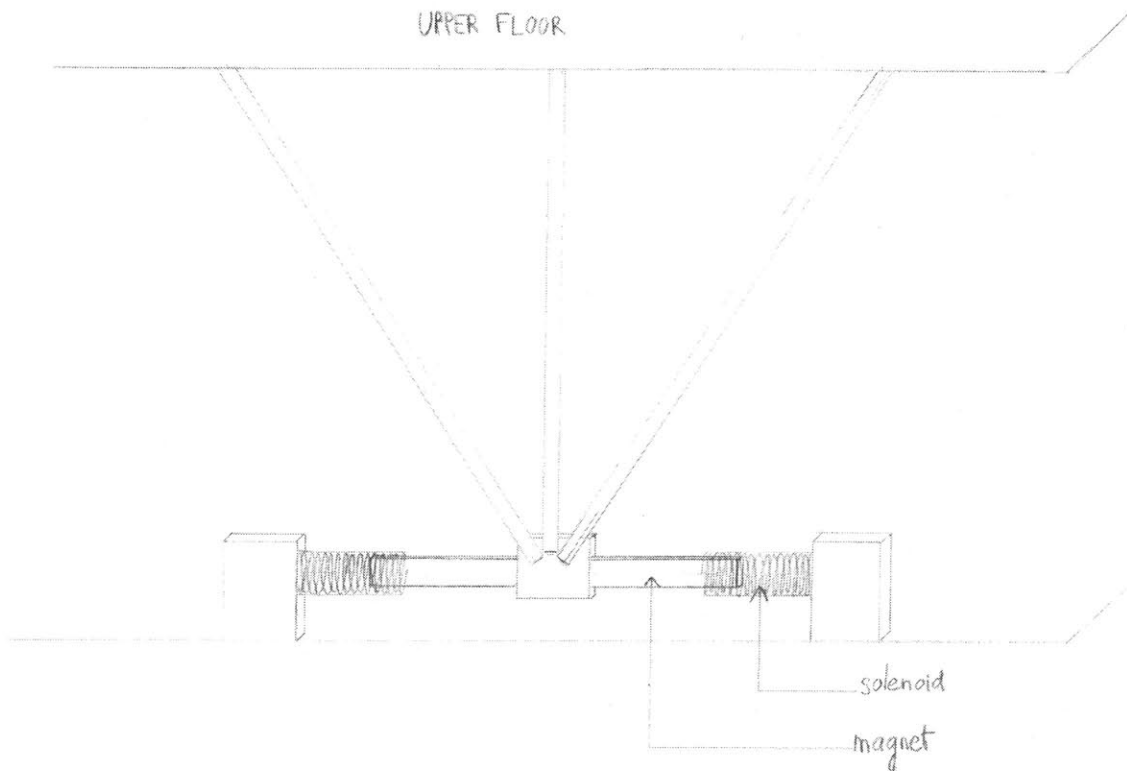


*Figure 18: Possible implementation of the solenoid/magnet induction damper*

*The magnets are related to the upper floor with a truss system. The solenoids are firmly attached to the lower floor.*

## 4.2 Implementation within a base isolation system

The implementation of magnetic induction dampers within a base isolation system relies on the same principle as the implementation between two adjacent floors. The main difference is that the relative velocity between the ground and the first floor in case of base isolation is much more significant than the inter-story velocity in a non-isolated building. Consequently, the effective damping is much higher in a base isolation system, even with a relatively small damping coefficient. It means that we can reach high damping with only few dampers. That is especially interesting in our case because magnetic induction dampers take much space.

We will not detail the implementation of magnetic induction dampers within a base isolation system. It would require further investigations to see how they can coexist with the bearings. However, in the next chapter, we will simulate a base-isolated building subjected to an earthquake and show the efficiency of this scheme.

## 4.3 Alternative way of using magnetic induction dampers: integrating them in tuned mass dampers

The main issue in the use of magnetic induction dampers in buildings is the physical device that let the relative velocity of the coil with respect to the magnet be equal to the inter-story velocity. It implies the connection of the moving coil to the upper floor by devices that often take some space in the building. Moreover, since that the force carried by magnetic induction dampers is quite small (of the order of a few thousands newtons), notably with respect to traditional viscous dampers (which can resist to forces of several hundreds kilonewtons), we cannot integrate magnetic induction dampers in structural members. Consequently, we have to put additional members, which do not carry any other loads than the magnetic induction damping forces. These members do not have to be large. However, this issue is the weak point of magnetic induction dampers. They require many extra devices to make their implementation possible.

An alternative way of using magnetic induction dampers is to integrate them in a tuned mass damper system. In this case, instead of being attached at both ends to adjacent floors, they can more simply relate a floor and the mass of the added tuned mass damper. This topic was the object of a study by Asegun Henry and Makola Abdullah from the department of Civil Engineering at Florida Agricultural and Mechanical University-Florida State University (2002). At the end, provided that the design parameters are chosen for optimal effective damping, the device behaves like a tuned mass damper (TMD), except that the damping constant of the TMD is not the result of traditional viscous dampers but the result of magnetic induction. The mechanical performances will be the same as those of a traditional tuned mass damper but the advantage is that one part of the damped energy will be turned into electrical energy. The voltage generated in the coil allows one to power other active structural motion control devices. In contrast, with traditional viscous dampers, the energy is purely dissipated in a compressible fluid, and it cannot be reused.

The translational linear generator used in this case is the same as the first one we proposed. It consists of a rectangular coil moving back and forth in a magnetic field

generated between two flat permanent magnets. Figure 19 below, taken from Asegun Henry and Makola Abdullah's presentation, shows the implementation of the device.
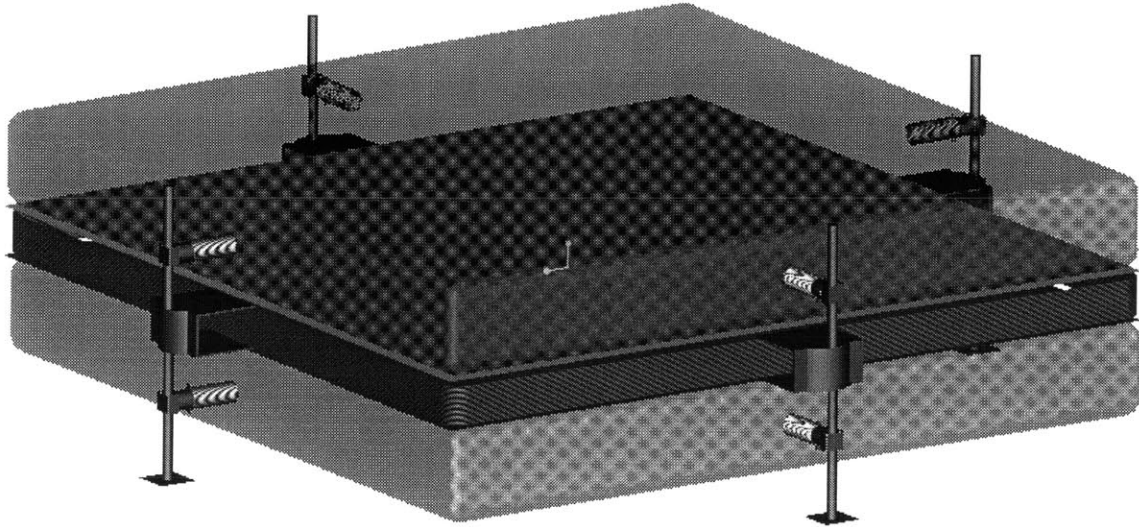


*Figure 19: Structural magnetic induction damper integrated in a tuned mass damper [8]*

The coil is fixed to the floor, whereas the magnets and the mass of the tuned mass damper, rigidly linked together, are connected with springs to the floor. The design parameters of the tuned mass dampers, which are its mass, stiffness and damping, are such that the added mass will oscillate out of phase with the floor, at the design frequency. As already mentioned, the damping force within the tuned mass damper is due to magnetic induction and depends on various parameters such as the number of coil turns, the magnitude of the magnetic field...

In the study from Asegun Henry and Makola Abdullah, the performances of the device were theoretically tested using the El Centro earthquake, with the tuned mass damper placed at the top of a one-story building. They finally ended up with an average harvested electrical power of about 400 Watts for the duration of the earthquake, that is about 30

seconds. This value is close to the value we found for our first magnetic induction damper (P = 572 W), integrated between two building floors.

This study is interesting because it demonstrates that it is possible to implement magnetic induction dampers in a way that does not require much space in the building. This solution avoids having to deal with the issue of how to relate the moving coil to the upper floor. Furthermore, it can provide enough power to supply active control sensors or devices with energy during an earthquake. However, we do not obtain a real magnetic damper. In this thesis, we wanted to investigate the potential of magnetic induction dampers in buildings, in terms of their damping capabilities and the electrical power they can generate. The idea of a magnetic induction damper integrated in a tuned mass damper does not really fit into our investigation's scope in the sense that damping in a TMD is essentially provided by the inertia force of the added mass and not by the dashpot relating the primary mass and the added mass. Also, the advantage of induction-based damping, which does not involve any mass parameter, is not put forwards here. Finally, as a mean of dampening vibrations due to earthquakes, the use of tuned mass dampers is limited because they have to be tuned for a particular frequency. They consequently cannot be effective for broad band excitation.

# CHAPTER 5: APPLICABILITY TO BUILDINGS SUBJECTED TO EARTHQUAKES – SIMULATIONS AND DISCUSSION

The aim of this chapter is to assess the applicability of magnetic induction dampers in buildings, and especially their efficiency in dampening structural motion due to earthquakes. We will first of all try to estimate the order of magnitude of the power transmitted to a building by an earthquake. Then, we will model some buildings, compute the number of magnetic induction dampers required to dampen an earthquake with a reasonable damping ratio, and finally estimate the electrical power generated. Responses of typical buildings subjected to earthquakes will be simulated with Jerome J. Connor's MotionLAB.

## 5.1 Estimation of the power transmitted to a building by an earthquake

In part 3.5, we have assessed the expected capabilities of the proposed magnetic induction damper. Now, we want to estimate the order of magnitude of the power transmitted to a building by an earthquake, so as to determine if it can provide a realistic way of dampening strong dynamic excitations.

We first derive a rough estimate of the power transmitted to a building by an earthquake, taking the example of a three-story building, whose primarily first mode is excited. In this case, the input power due to an earthquake can be approximated by the following equation:

$$E_I = \frac{1}{2} M_1 \cdot V_{eq}^2 \, ,$$

where $M_1$ is the modal mass of the building for first mode and $V_{eq}$ is the equivalent velocity, which can be taken equal to 1.2 m.s$^{-1}$.

Then,

$$M_1 = \int \rho \cdot \Phi_1^2 \cong \frac{1}{3} M_t \, ,$$

where $M_t$ is the total mass of the building.

A characteristic value for the mass $M_t$ of a three-story building is $M_t = 3 \; 10^6$ kg.

Finally we obtain $E_I = 7.2 \; 10^5$ J.

From $E_I$ we derive the average power transmitted by the earthquake by dividing it by the typical duration of an earthquake, which is 20 seconds.

Hence, $P_{earthquake}$ = **36 kW**.

This basic calculation was made possible by rough approximations and will need to be approved by more deep simulations. Notably, only the energy transmitted to the first mode was taken into account here. Furthermore, the energy transmitted by an earthquake depends on many parameters such as the intensity of the earthquake, as well as the characteristics of the building. This value will turn out to be a lower bound value. Subsequent simulations will show that it is more likely to be around a hundred kilowatts.

## 5.2 Simulation on a non-isolated building

*Model*

We want to simulate the response of a non-isolated six-story building subjected to an earthquake. We model the building as a discrete multiple-degree-of-freedom shear beam, as shown below by figure 20.
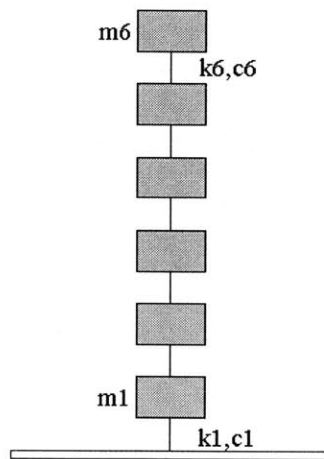


*Figure 20: Building modeled as a discrete shear beam, no base isolation*

We take for the floor masses m1 = m2 = m3 = m4 = m5 = 10000 kg; m6 = 20000 kg.

The stiffness is scaled in order to have a linear first mode shape, and then it is calibrated for seismic excitation. For that we use MotionLAB, from Jerome J. Connor, 2001, and in particular the Shear Beam program. The earthquake that is used is El Centro, with a scale factor of 2. The resultant ground acceleration time history is shown in appendix A. The objectives of the design are a first mode damping ratio of 0.05 and a maximum inter-story displacement of 0.02 m. This study is inspired by problem 5.7 in Jerome J. Connor's book *Introduction to Structural Motion Control*.

*Results*

Results are shown in appendix B. The first important results are that we can meet the design objectives with element stiffness of the order of $10^7$ newtons per meter (see exact distribution in appendix B), and a uniform element damping of 302 260 $kg.s^{-1}$. We also

obtain from the simulation that the maximum element inter-nodal displacement rate is about $0.26 \text{ m.s}^{-1}$ (average on the six floors).

## Interpretation and discussion

The element damping that we need in this example is 302 260 $\text{kg.s}^{-1}$. The damping coefficient that we ended up with for one single magnetic induction damper (see section 3.5) is 6480 $\text{kg.s}^{-1}$. Consequently we can deduce that we need $\frac{302260}{6480} \approx 47$ such dampers per floor to provide a damping ratio of 0.05 for the first mode and therefore dampen earthquake vibrations efficiently. This number first seems to be pretty large.

We also can infer from the maximum element inter-nodal displacement rate the average power dampened by the structure and so obtain an idea of the power transmitted by the earthquake to the building. It is reasonable to assume that the mean square inter-nodal displacement rate v for the duration of the earthquake is given by

$$\left\langle v^2 \right\rangle = \frac{v_{max}^2}{2}.$$

This comes from the consideration that the inter-nodal displacement rate resembles a sinusoid (dominant first mode frequency).

The average dampened power per floor under these conditions is

$$P_{floor} = C \cdot \left\langle v^2 \right\rangle = 302260 \times \frac{0.26^2}{2} = 10200 \text{ W},$$

Thus for the whole building:

$$P = 10200 \times 6 = 61200 \text{ W}$$

This value represents the available average damped power for the duration of the earthquake. As the structure will still vibrate for a little while when the earthquake is over, the average power transmitted to the building by the earthquake is a little bit higher than this value. It should be around one hundred kilowatts.

One single magnetic induction damper is capable of harvesting an average power of

$$P_{ind.damper} = C \cdot \langle v^2 \rangle = 6480 \times \frac{0.26^2}{2} = 220 \text{ W}.$$

This value is a little bit lower than the expected performance. This is because v was slightly overestimated in the basic estimation in section 3.5.

We can conclude from this simulation that although a single magnetic induction damper can harvest a reasonable amount of energy (a few hundreds kilowatts), the scheme does not seem to be applicable given the high number of magnetic induction dampers required. To reduce the number of such magnetic induction dampers, we should find a way of magnifying the inter-story motion in the building. The mechanism relating the coil to the upper floor should be designed towards this objective. Supposing a linkage mechanism could magnify the response by factor of two or three, the scheme could be more efficient.

To harvest the mechanical energy due to earthquake dynamic loading, it may be much more efficient to implement these magnetic induction dampers within the base isolation system, where the energy of the building is mostly located.

## 5.3 Simulation on a base-isolated building

*Model*

This simulation follows the same method as before except that we now design a base isolation system. We still model the building as a discrete-multiple-degree-of-freedom shear beam, as shown below by figure 21.
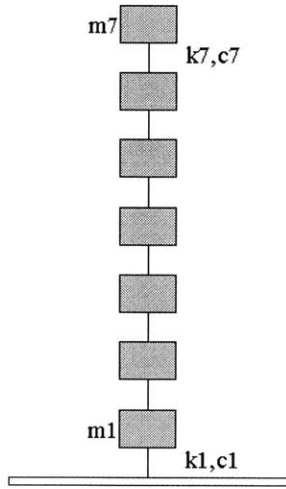


*Figure 21: Building modeled as a discrete shear beam, base isolation*

We take $m1 = m2 = m3 = m4 = m5 = m6 = 10000$ kg; $m7 = 20000$ kg.

The stiffness distribution is scaled for the typical base-isolated first mode profile and calibrated for seismic excitation. We still use El Centro earthquake, with a scale factor of 2. The design parameters are a first mode damping ratio of 0.05 and a maximum inter-nodal displacement of 0.4 m (between ground and first floor).

*Results*

Appendix C shows the results obtained with MotionLAB. The required stiffness distribution is plotted in one of the graphs. The damping distribution was determined by allocating 75 % of the damping to the bearing. We finally ended up with the following values for the damping coefficients:

$$c1 = 23\ 385 \text{ kg.s}^{-1} \text{ and } c2 = c3 = c4 = c5 = c6 = c7 = 187\ 080 \text{ kg.s}^{-1}$$

These parameters finally produce a maximum inter-nodal displacement rate of 1.3 m.s$^{-1}$ between the ground and the first floor. This high value is responsible for the high damping that occurs within the base isolation system.

*Interpretation and discussion*

First of all, we can notice that the damping coefficient of the base isolation system is pretty low (c1 = 23 385 kg.s$^{-1}$) with respect to the typical values of the damping coefficients in the building. More specifically, we need only $\frac{23385}{6480} = 3.6$ magnetic induction dampers similar to the one we proposed. Therefore, it seems possible to perform the whole damping of the base isolation system with magnetic induction dampers. Moreover, such a single magnetic induction damper in this case harvest the following amount of power:

$$P_{ind.damper} = C \cdot \langle v^2 \rangle = C \frac{v_{max}^2}{2} = 6480 \times \frac{1.3^2}{2} \approx 5500 \, \text{W}$$

This value stands for the average power harvested by one single induction damper for the duration of the earthquake. It is much larger than the value predicted in section 3.5 because in the case of base isolation, the relative velocity between the ground and the first floor is much larger than the typical inter-story velocity in buildings subjected to earthquake. Considering that the whole damping of the base isolation system is done with magnetic induction dampers, we can harvest $P_{harvested} = 3.6 \times 5500 \approx 20\ 000$ W. This value represents a significant amount of the power transmitted by the earthquake to the building.

This simulation confirms that integrating magnetic induction dampers in the base isolation system of a building could be of great interest. This way, we really harvest the energy of the earthquake before it affects the structure. The main issue for that would be how to incorporate these dampers into the base isolation system. This topic would require further investigation.

# CHAPTER 6: CONCLUSION

In this study, we first discussed the concept of energy harvesting before applying it to the dampening of structural vibrations of buildings through magnetic induction dampers. We proposed designs of structural magnetic induction dampers, as well as their possible implementation in buildings. After roughly estimating the expected performances, we simulated the response of several types of buildings to an earthquake. Results showed that such magnetic induction dampers are theoretically capable of dampening significant amounts of power. The implementation of the dampers between two adjacent floors of a building should be done in a manner that magnifies the relative velocity between the two floors. This way, their efficiency would increase. It also appeared that integrating magnetic induction dampers within the base isolation system of a building could be of great interest, as the relative velocity between the ground and the first floor is high.

What we have done in this thesis tends to prove that structural magnetic induction dampers may be efficient devices for harvesting energy in buildings subjected to strong dynamic excitations. The harvested electrical power could be smartly used to supply other active control devices, or to recharge batteries. In order to confirm the feasibility of such dampers, further investigations should be carried out about their possible implementation in a

building, and more specifically on how they could be incorporated into a base isolation system. Ultimately, one should build a model to test the experimental performances and see whether these match the expected results.

Only few studies so far have investigated the use of induction-based devices to create electrical power from mechanical vibrations in civil engineering structures. Some have shown that little power could be generated through the use of some embedded transducers. However, making induction-based dampers still seems to be an innovating concept. It may turn out to become effective in the future, notably as part of the further developments in active structural motion control.

# REFERENCES

J. Connor. *Introduction to Structural Motion Control*. Prentice Hall. 1999.

P. Kiameh. *Power Generation Handbook: Selection, Applications, Operation, and Maintenance*. McGraw-Hill. 2002.

J.R. Cogdell. *Foundations of Electric Power*. Prentice Hall. 1999.

J. Connor. *MotionLAB, Shearbeam*. MIT. 2001

A. Henry, M. Abdullah. *Structural Magnetic Induction Damper*. Florida Agricultural and Mechanical University-Florida State University, Department of Civil Engineering. 2002.

C.B. Williams, A. Pavic, R.S. Crouch, R.C. Woods. *Feasibility study of vibration-electric generator for bridge vibration sensors*. IMAC-XVI Proceedings. 1997.

[1] http://www.rsc.rockwell.com/energyharvesting
[2] http://www.owec.com
[3] http://www.wavegen.co.uk/tech.html
[4] http://www.dur.ac.uk/Engineering/StaffInfo/mam/waveproj.pdf
[5] http://www.ece.uwaterloo.ca/~ece362/DC_Machines.pdf
[6] http://membres.lycos.fr/schneid/Electr/Redre.htm
[7] http://www.taylordevices.com/fvd_alt1.htm
[8] http://wusceel.cive.wustl.edu/reujat/2002/henry.ppt

# APPENDIX A

El Centro Ground Acceleration Time History
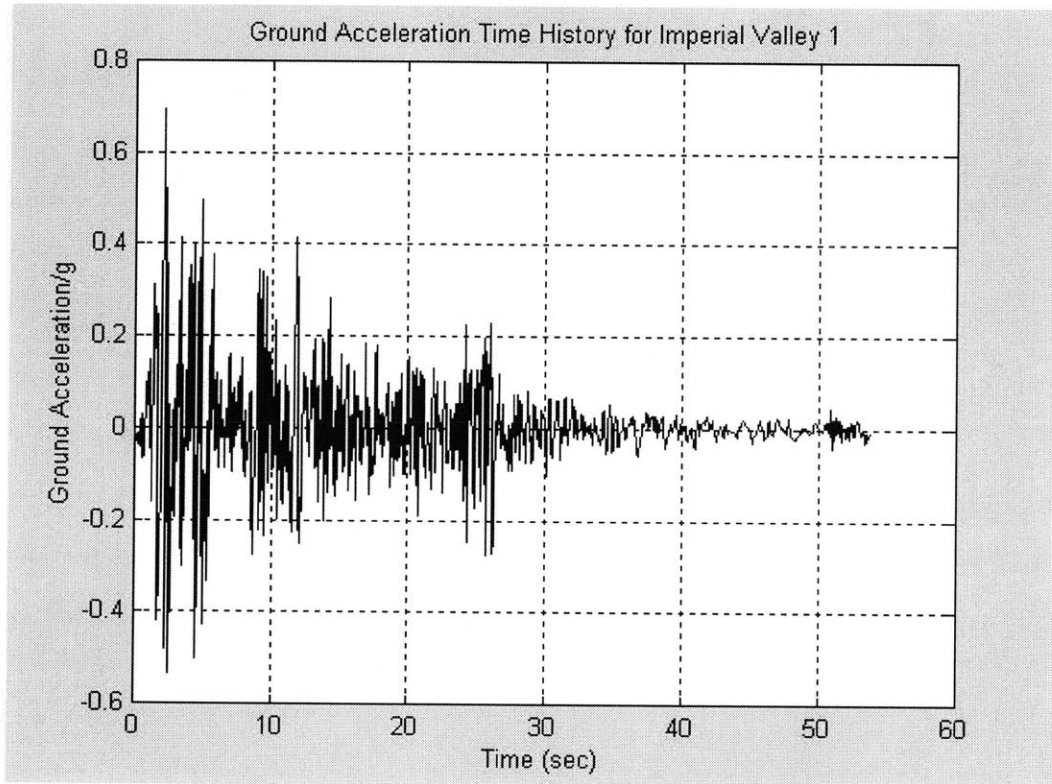


*Figure 22: El Centro Ground Acceleration Time History (MotionLAB)*

# APPENDIX B

Simulation on a non-isolated building subjected to an earthquake

MotionLAB Plots

Shear Beam Program
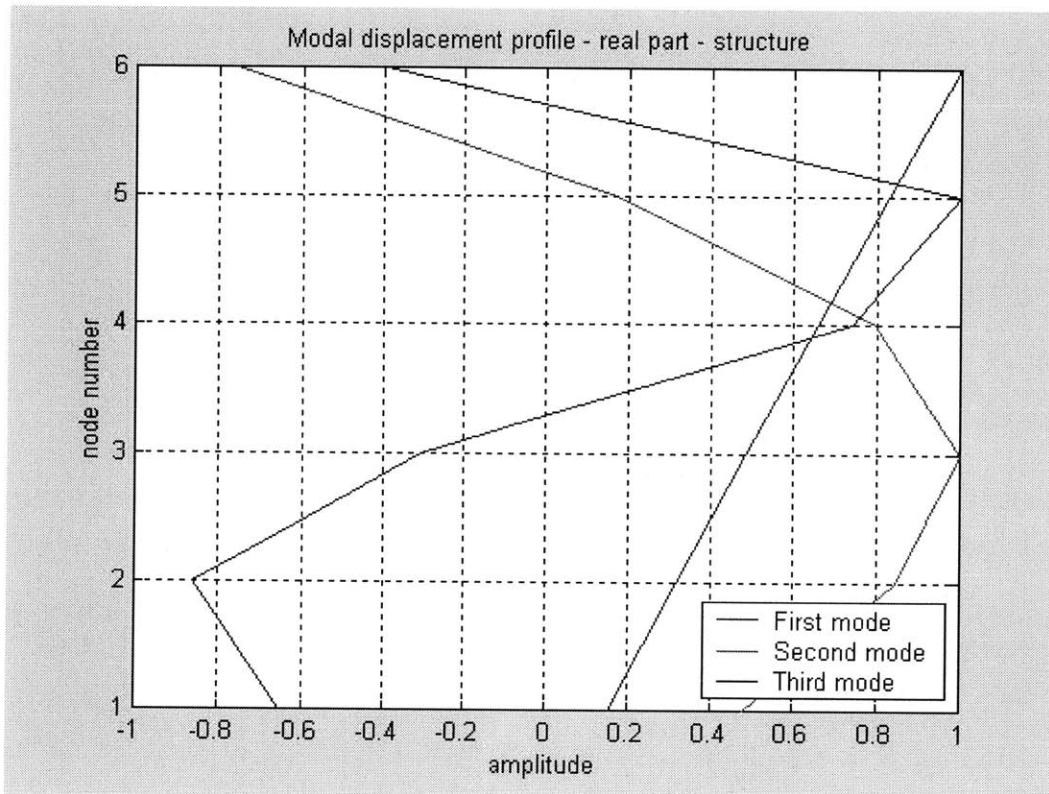


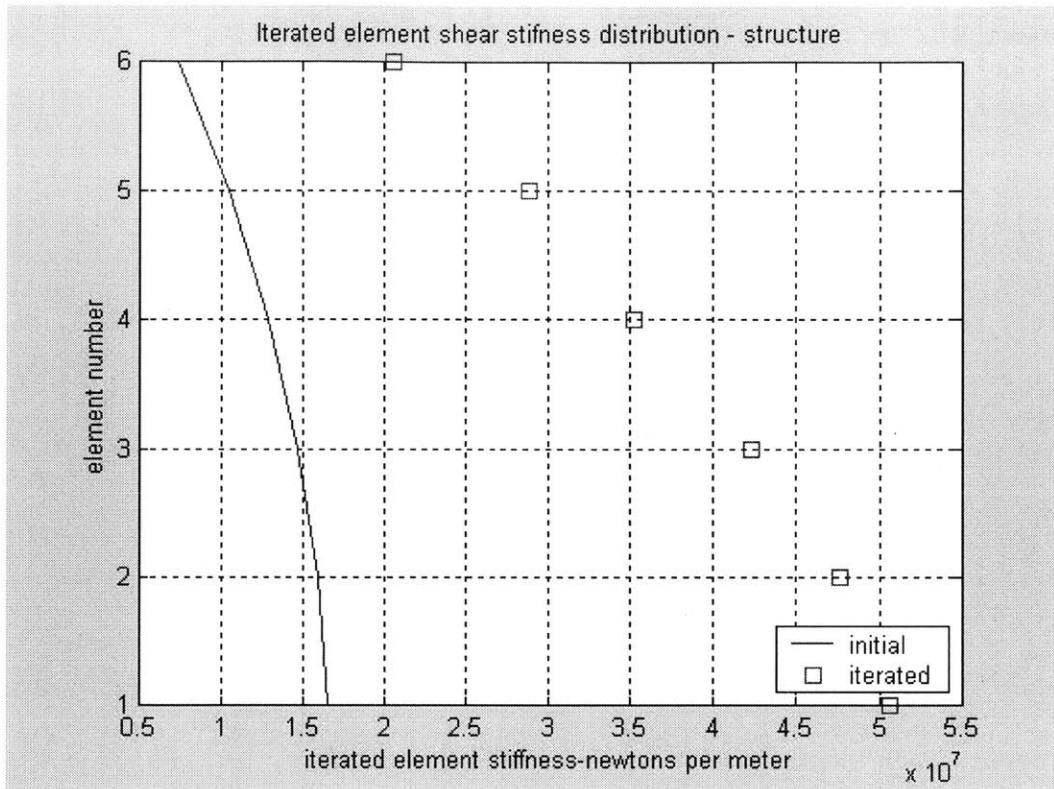*Figure 23: Modal displacement profile, no base isolation (MotionLAB)*

*Figure 24: Iterated element stiffness, no base isolation (MotionLAB)*
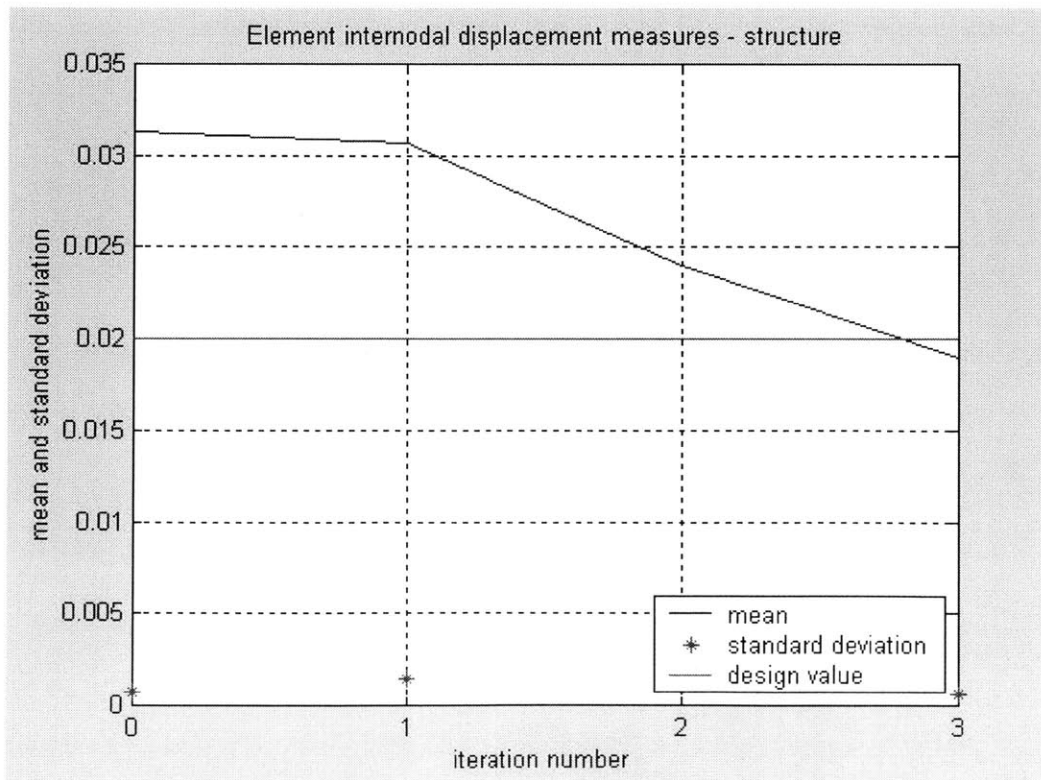


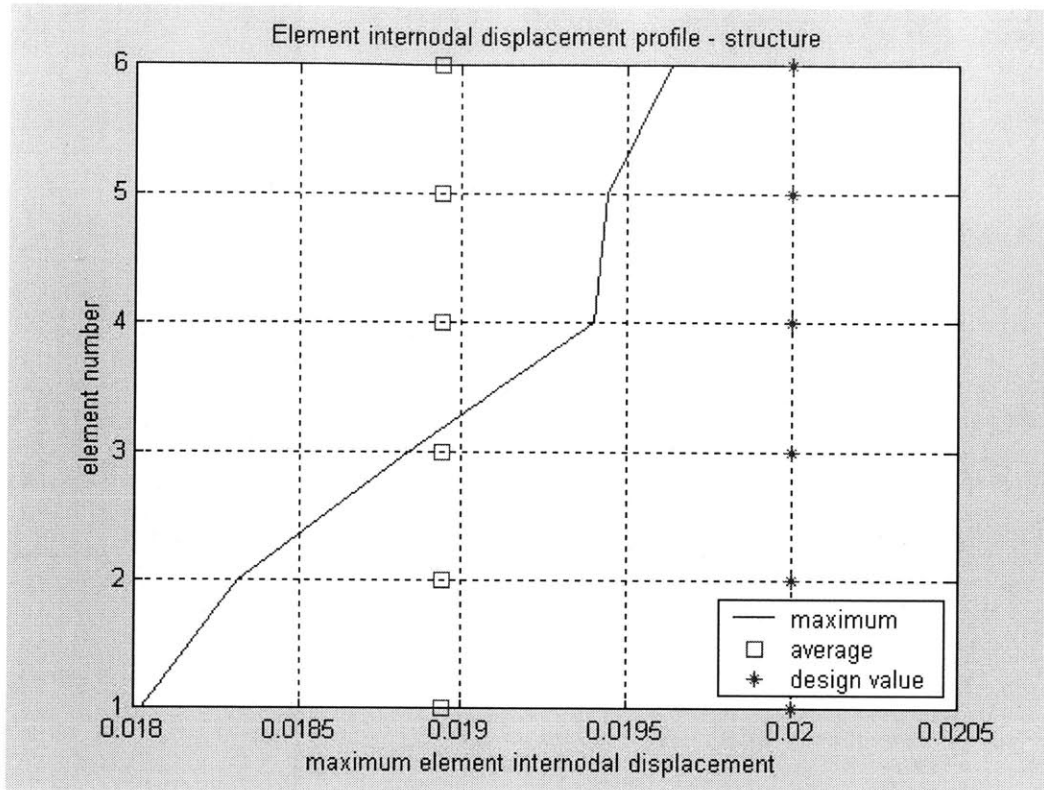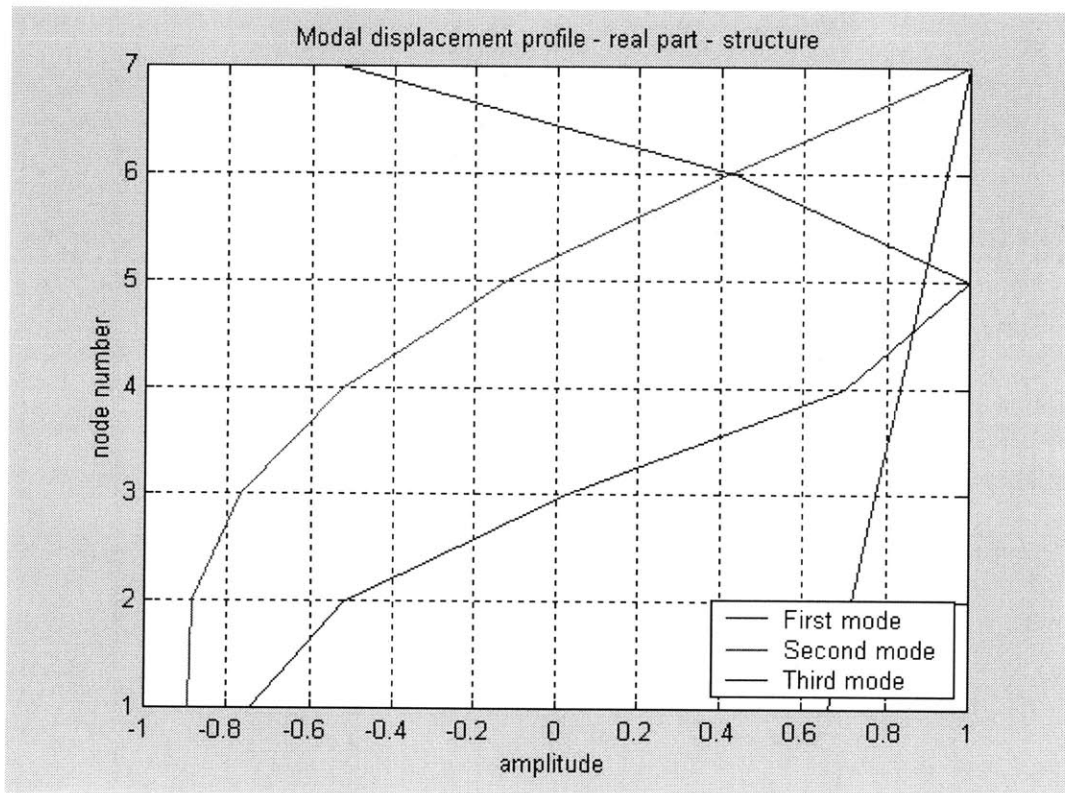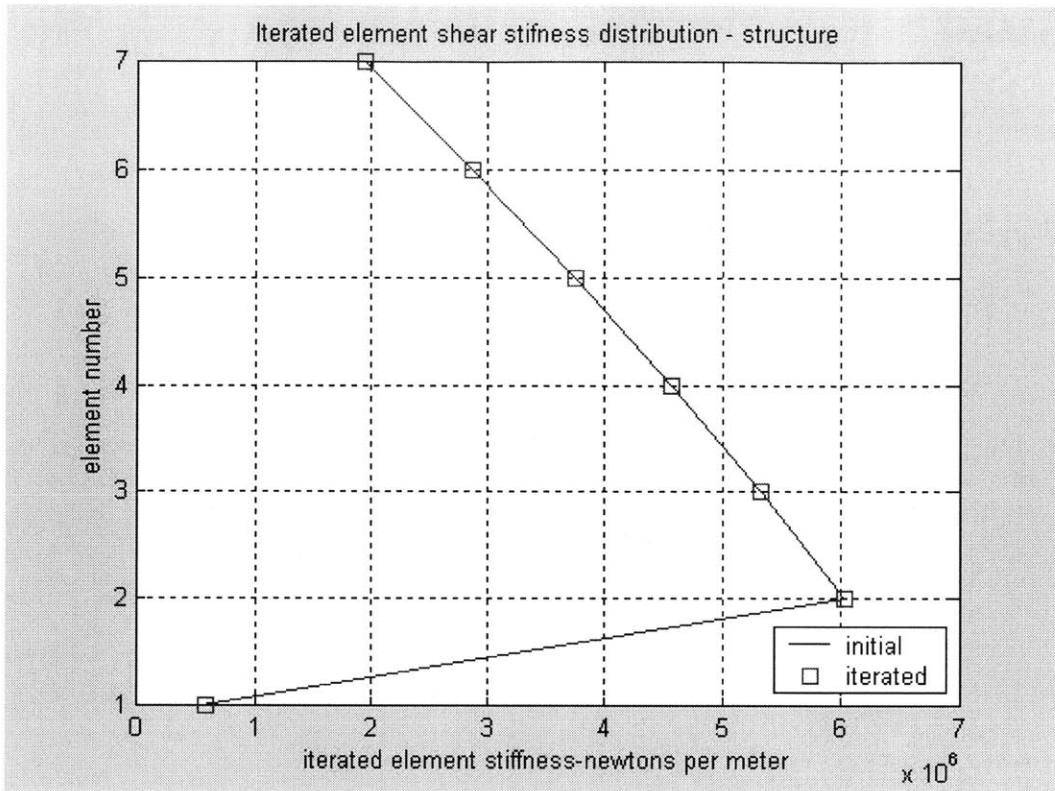*Figure 25: Inter-nodal displacement versus iteration number, no base isolation (MotionLAB)*

52

*Figure 26: Inter-nodal displacement profile, no base isolation (MotionLAB)*
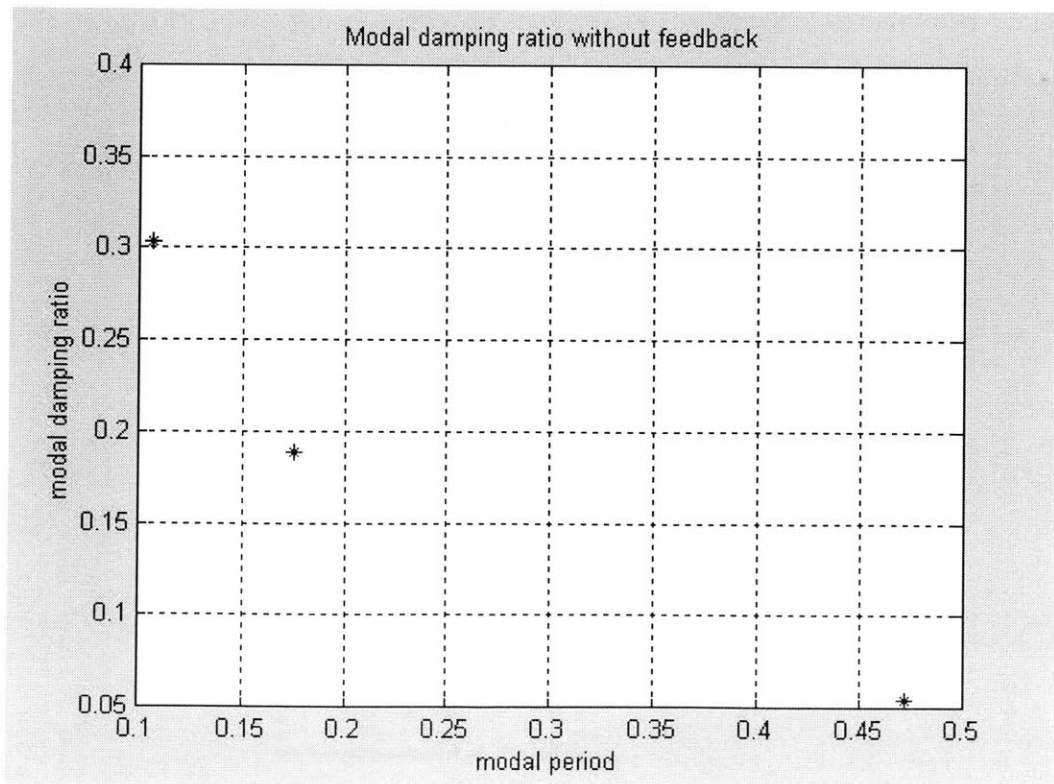


*Figure 27: Modal damping ratio, no base isolation (MotionLAB)*
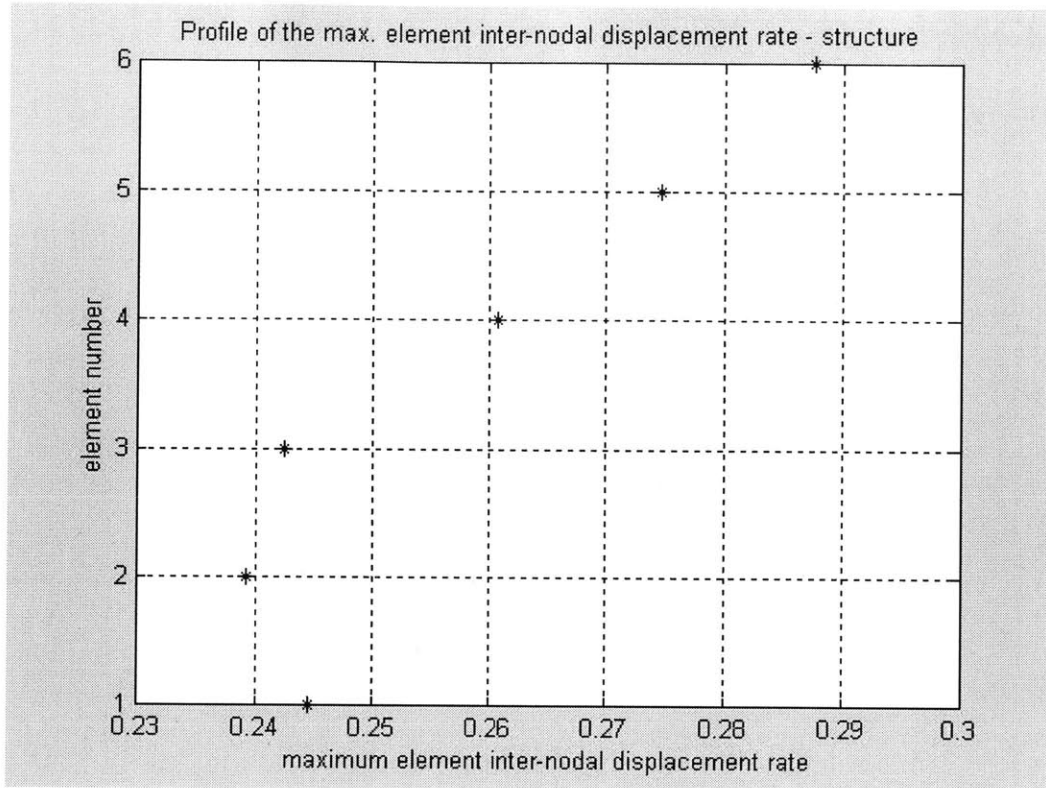
*Figure 28: Maximum inter-nodal displacement rate, no base isolation (MotionLAB)*

# APPENDIX C

Simulation on a base-isolated building subjected to an earthquake

MotionLAB Plots

Shear Beam Program



*Figure 29: Modal displacement profile, base isolation (MotionLAB)*

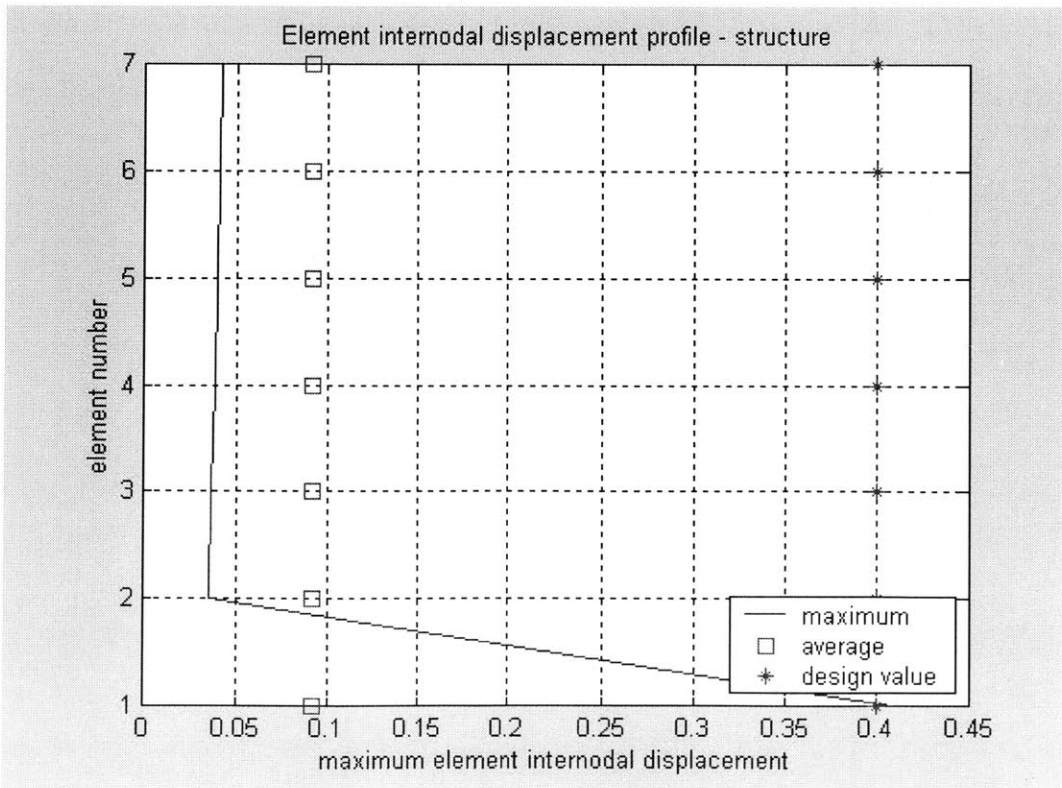*Figure 30: Iterated element stiffness, base isolation (MotionLAB)*



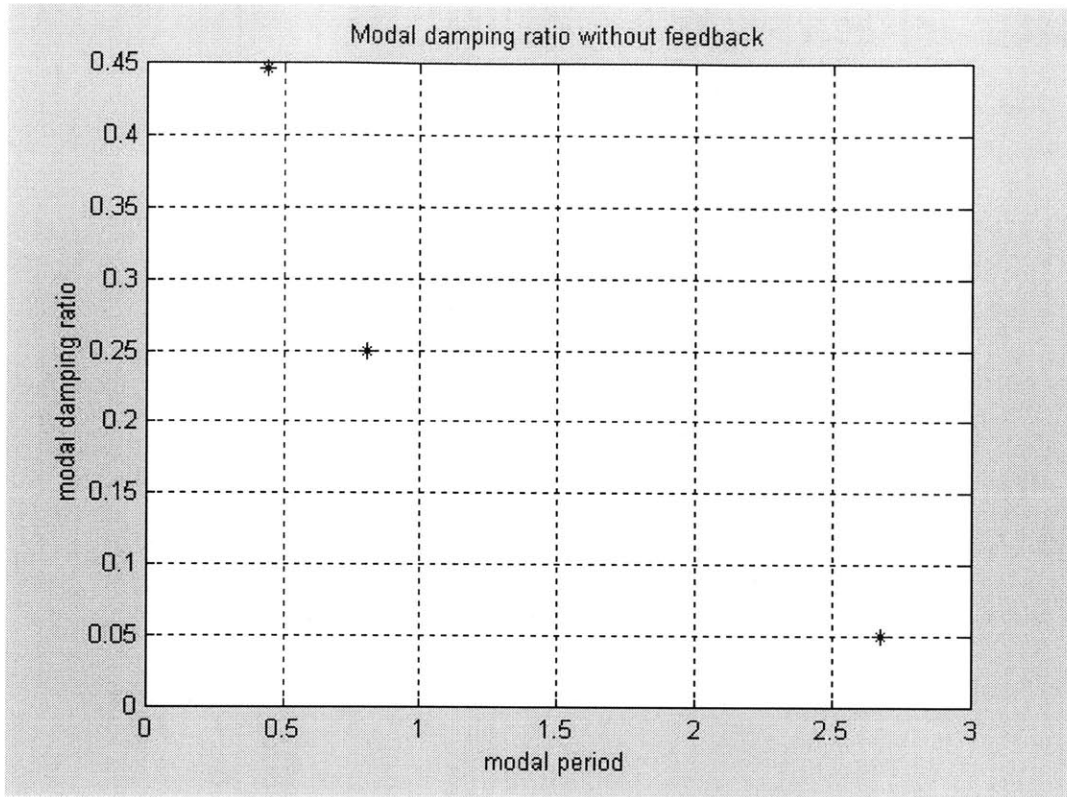*Figure 31: Inter-nodal displacement profile, base isolation (MotionLAB)*

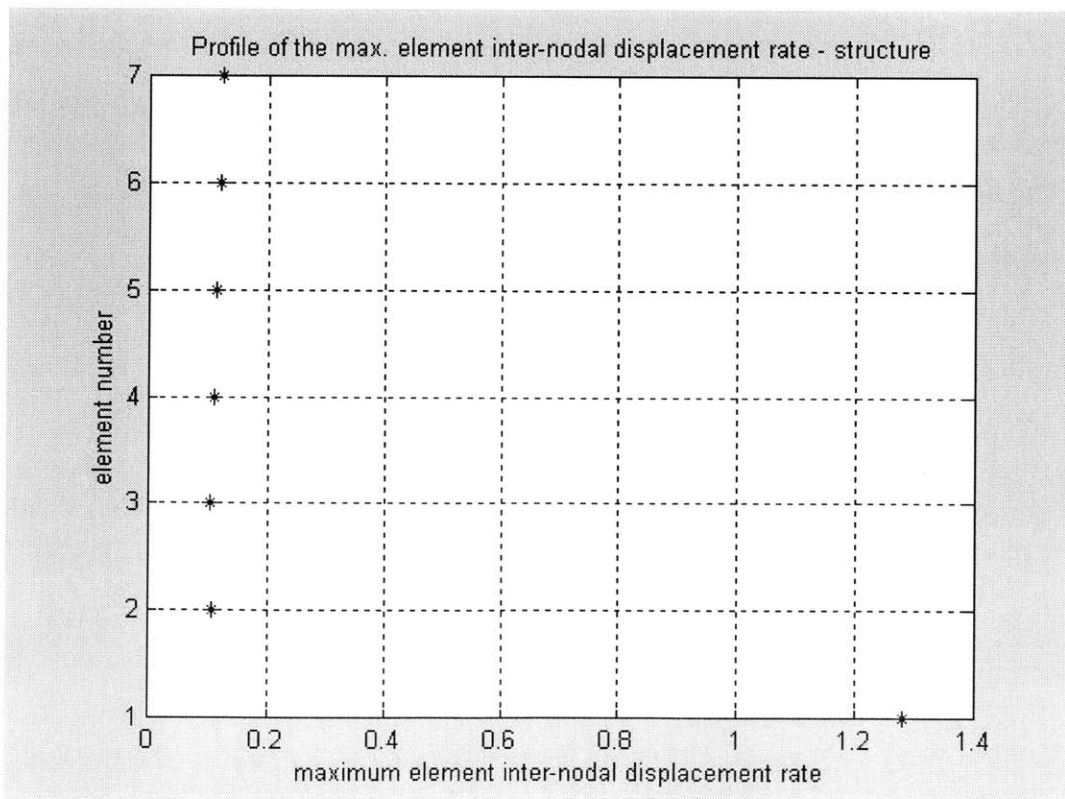*Figure 32: Modal damping ratio, base isolation (MotionLAB)*



*Figure 33: Maximum inter-nodal displacement rate, base isolation (MotionLAB)*