Regenerative electromagnetic dampers in high-rise buildings

by

Matthew Schwabauer

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

The GE Johnson Department of Architectural Engineering and Construction Science
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2020

Approved by:

Major Professor
Dr. Bill Zhang

Copyright

Abstract

High-rise buildings constantly sway due to the influence of wind. This movement is especially noticeable for tall and slender buildings because they inherently have smaller stiffness than shorter, less slender buildings and therefore have larger drifts. This issue can be mitigated with the use of a tuned mass damper (TMD) which reduces the wind-induced dynamic response of high-rise buildings. Conventional TMDs have viscous dampers to help dissipate energy of the building motion through heat transfer to the environment. This report proposes a new type of damper that can be used instead of viscous dampers that would convert the dissipated building energy into electricity. The proposed type of damper is called an electromagnetic (EM) damper and uses induced Eddy currents to create the damping effect needed to mitigate building movement. The report reviewed experimental and numerical studies that have been conducted on this novel energy regeneration system. These studies found that in a specific case 27.4% of the total energy stored in building oscillation can be converted to electricity. This report followed a case study, Taipei 101, and calculated that the building stores 108 kW of power during a light breeze. Applying the efficiency found in the aforementioned studies to Taipei 101 provides 30 kW of electricity that could be produced from this regenerative TMD system during light wind conditions. Regenerative TMDs with EM dampers have the potential to produce a significant amount of electricity while maintaining effective movement control for high-rise buildings, but the current cost of these devices is too high to be economically feasible with current technology.

Table of Contents

List of Figures

Chapter 1 - Introduction

Buildings are an essential part of human life and culture. The ability to provide shelter for oneself might have been the difference between life and death for early humans. The first structures were primitive and made of packed clay, stone, or wood (Chang & Swenson, 2020). They were primarily designed for protection, but as society grew, buildings developed other purposes and eventually became symbols of power and wealth. The dawn of the first industrial revolution brought new materials to the market which allowed for greater innovation in the construction industry (Chang & Swenson, 2020). As material strength increased and cities became overcrowded, the idea of a high-rise building began to spark interest.

Prior to the invention of steel frames in the 1870s, buildings were mostly supported by load bearing walls which limited the height of the building due to the excessive wall thickness required to support multiple floors (Craighead, 2009). Steel frames allowed walls to become cladding rather than a structural element which reduced weight, increased floor area, and allowed buildings to soar higher. The world's first skyscraper, a 10-story Home Insurance Building, was built in Chicago in 1885 and sparked the race for "The World's Tallest Building." Since 1885, there have been 17 buildings to take the title of the tallest building in the world (Craighead, 2009). The first buildings to break the height record used cast iron columns, wrought iron beams, wooden floors, and masonry cladding. These skyscrapers were very heavy, stiff, and had a lot of inherent damping that kept story drift relatively small. The second generation of high-rise buildings began in the early 1900s and consisted of concrete encased steel frame structures (Craighead, 2009). This method of construction made buildings very strong, but the interior floor space was not very attractive due to the large number of structural elements. A new era of high-rise construction emerged after World War II with the basic principles still in use today. This third generation of skyscrapers focused on using materials efficiently to keep cost as low as possible while maintaining a large usable space for the occupants. Buildings in this time period were normally clad in glass and could be taller than previous buildings due to the decrease in weight and increased strength. The '60s and '70s saw a boom in high-rise buildings, especially in the United States with some of the world's most iconic skyscrapers built in this time period. The 875 North Michigan Avenue building, formerly known as the John Hancock Center, was completed in 1969 in Chicago and is 344 m (1,128 ft) tall. The two World Trade Centers in New York City were completed in 1972 and 1973 with the first one being 417 m (1368 ft) tall and the other 415 m (1362 ft) tall. Other notable buildings in this era are the Aon Center, completed in 1973, and the Willis Tower (formerly Sears Tower), completed in 1974, both in Chicago. Figure 1 shows a graph of the amount of buildings over 150 m tall completed between 1955 and 1985 with the associated heights of those buildings.

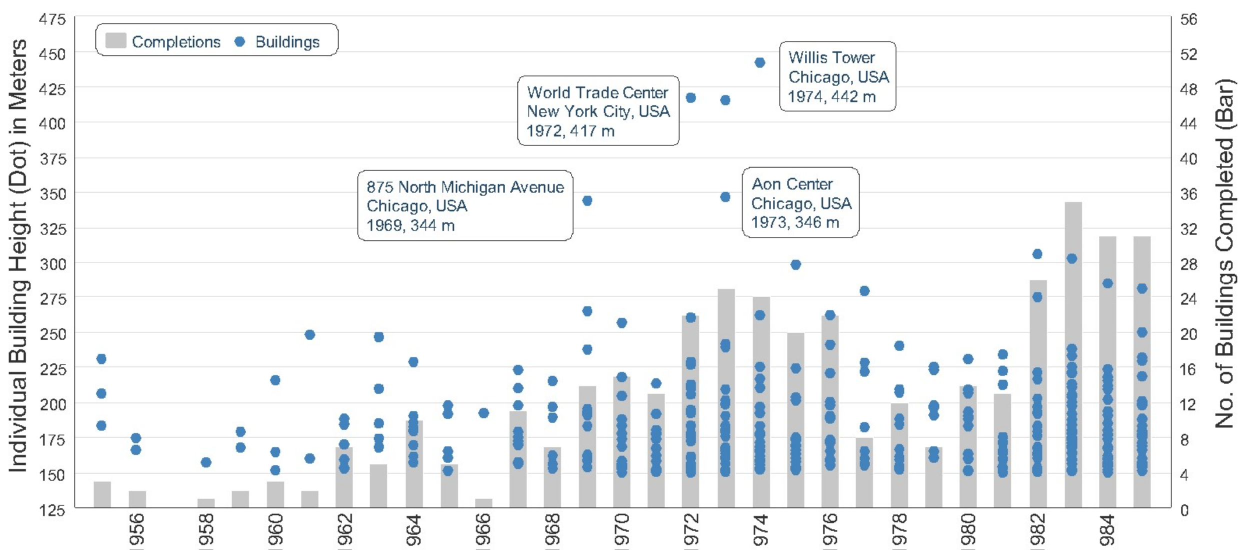

Figure 1 Buildings above 150 m tall built between 1955-1985

(Adapted from The Skyscraper Center, 2019)

These lighter and taller structures have less stiffness and damping than previous buildings which make them vulnerable to wind induced movements. A building that is too flexible can cause people to feel uncomfortable or crack brittle materials like masonry or glass. They can also have inherent structural stability issues. Buildings that are too stiff can have members that are overdesigned, expensive, and take up area that could be used as floor space. The goal of modern high-rise building design is to minimize both structural member sizes and building sway. Traditional design methods can only take buildings so far; other methods of movement control were going to be needed if buildings were to grow any taller.

There are many methods for controlling building motion, but this report will focus on tuned mass damper (TMD) systems with an emphasis on electromagnetic (EM) dampers. A TMD is a device installed in a structure that reduces the amplitude of the dynamic response. A traditional design for a TMD is a large mass located in the structure, typically toward the top, that counteracts the movement of the building. The constant sway due to the wind stores energy in the form of building motion that has the potential to be converted to electricity. Taller buildings are more flexible, have greater sway due to wind induced vibrations, and store more energy than shorter buildings. According to the Council on Tall Buildings and Urban Habitat (CTBUH), a tall building is typically defined as any building taller than 50 m (165 ft). The skyline of most cities is filled with buildings classified as tall according to CTBUH, but there are only 149 supertall buildings and 3 megatall buildings in the world. A supertall building is classified as being taller than 300 m (984 ft), and a megatall building is any building above 600 m (1,968 ft). While many tall buildings have a TMD system, the energy stored in the building motion is not large enough to feasibly use a regenerative EM damper TMD system to produce electricity. Supertall and megatall buildings have a significant amount of energy stored in their movement which makes regenerative dampers for these buildings attractive. For these reasons, this report will discuss methods for reducing the overall movement of supertall buildings while producing usable electricity using a TMD system with a regenerative EM damper.

The main body of this report consists of five main chapters. The first chapter is the introduction. The following chapter will discuss the dynamics of high-rise buildings, describing the motion of the building due to an external force and how to control that motion using a variety of techniques. This chapter will also introduce two different types of dampers used to reduce building sway, viscous dampers and EM dampers. The next chapter will discuss energy regeneration and how it can be applied to a supertall building. Some industries already utilize energy regeneration into their products with great success. The amount of potential energy that is stored in the motion of buildings is difficult to precisely calculate and will thus be estimated using a procedure described in this chapter. No large-scale productions of this type of system have been implemented into a real building currently, but some researchers have created small-scale prototypes for experimental studies. This chapter will review these experimental studies and discuss the findings. Chapter 4 will compile the information from the previous chapters and apply the theoretical information to an existing building. This chapter will discuss the feasibility of retrofitting a supertall building having an existing TMD system with a regenerative EM damper. The last chapter will be a summary of the information presented in this report and will also include a discussion about future work.

Chapter 2 - Building Dynamics and Movement Control

The first step to designing a high-rise building is to understand how the building responds to dynamic loading. Traditionally, a building is designed for static gravity loads and equivalent static lateral loads. This method for designing a building works well for low-rise buildings but is not adequate for tall buildings. A more accurate method for evaluating building dynamics is required for high-rise buildings. This chapter provides an introduction into how buildings behave under lateral forces and the methods used to control the movement of the building.

Dynamics of High-Rise Buildings

High-rise buildings experience higher speed wind than that near the ground surface and are constantly oscillating back and forth in the wind. Even a light breeze can cause the building to sway. For example, the Willis Tower in Chicago will sway an average of 6 inches to either side according to the Council on Tall Buildings and Urban Habitat. When the building moves laterally, it induces additional stresses into the structural system. Not only does the structure have to resist the force of the wind, but it also must attenuate and stop the motion of the building. For short buildings, the lateral displacement of the building due to wind is relatively low, and the additional required strength needed to resist the dynamic load can easily be accounted for with equivalent static lateral loads. For tall buildings, the additional load on the building due to the dynamic forces is much higher than that of shorter buildings, and dynamic loading needs to be considered. Dynamic wind effects include gust buffeting and vortex shedding (Taranath, 2012). The random nature of wind loads can amplify the forces on high-rise buildings. Wind can also cause resonance in high-rise buildings since those buildings have longer fundamental periods. In summary, dynamic wind loads will cause the building to sway more than static wind loads. The shape of the building has a major impact on the dynamic response as well. To counteract some of the dynamic wind effects, supertall buildings are often designed to be aerodynamic. An aerodynamic building will have less gust buffeting and vortex shedding and therefore less building vibration.

Buildings generally have enough strength and stiffness to withstand the ultimate wind limit state. According to Taranath (2012), wind loads rarely, if ever caused major structural damage to buildings except in the case of tornados. The main concern for wind loading on tall buildings is to control the serviceability limit state. Modern high-rise and supertall buildings use lightweight, high-strength materials that make them more susceptible to building sway from wind. During strong windstorms, these buildings can have so much movement that objects start to vibrate, doors swing open, and books fall off shelves (Taranath, 2012). The occupants can feel very uncomfortable in buildings that move too much and too fast. People can start to experience vertigo and disorientation. Even if the acceleration of the building is kept to a minimum so that the occupants would have a hard time detecting movement, visual cues from the environment can still cause people discomfort.

Engineers have to understand the dynamic response of the building they are designing in order to keep the building movement beneath the serviceability limits. When a wind load acts on a building, it will bend the building slightly and cause it to sway and oscillate even after the wind ebbs. The oscillations will continue with smaller and smaller displacement until the building stops swaying. The time it takes for the building to make one complete cycle is called the period. Buildings typically vibrate in their first mode natural frequencies, also called the fundamental natural frequency. It takes more energy to vibrate the building in higher mode shapes, so wind typically doesn't oscillate the building above the fundamental natural frequency. Figure 2 below shows a diagram of a building oscillating under wind loads.

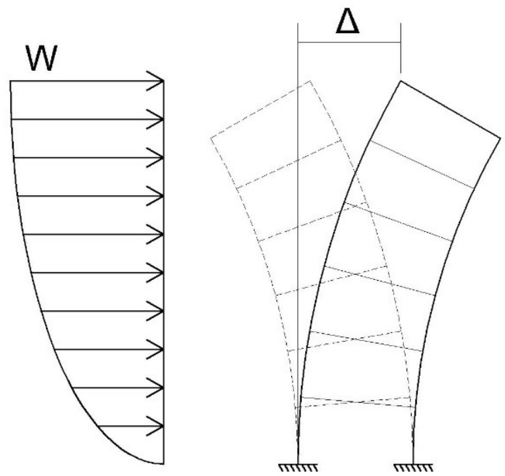

Figure 2 High-rise building oscillating under wind load

The wind in Figure 2 shown has a force *w* acting on the building and causing it to oscillate with a deflection of Δ. The force of the wind increases in magnitude with the height of the building. A high-rise building has a greater deflection towards the top of the building because of the accumulative displacement from the floors below. The increase in wind load at the top of the building also contributes to the larger displacement with respect to the height of the building.

Calculating the displacements due to lateral wind load for each floor of the structure can be challenging because it is difficult to accurately model the dynamic response of high-rise buildings. A structure of a building is made of many individual elements and has many degrees of freedom (DOF). When designing a supertall building, an in-depth multi-degree of freedom (MDOF) model is typically created to get a clear picture of the building's dynamic response. This complex model uses finite element analysis (FEA) to better represent real world conditions. The computer model is combined with a wind tunnel test to find the loads on the building. A full MDOF model with a FEA and wind tunnel tests are not always needed, and a more simplified version can be very helpful in preliminary design. The dynamic model can be simplified to a generalized single degree of freedom (SDOF) system, which is easier to understand and calculate.

Single Degree of Freedom Systems

The most basic dynamic model for a building can be represented as a simple spring-mass system, as seen in Figure 3, that consists of three elements: a spring, a mass, and a damper.

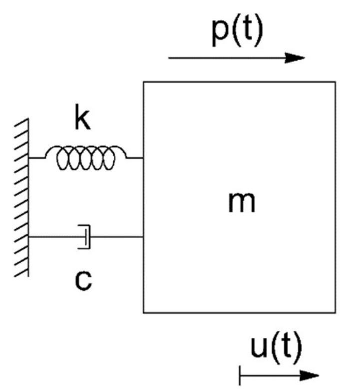

Figure 3 Spring-mass-dashpot diagram

The equation of motion (EOM) for a SDOF system with an excitation force with respect to time *(t)* is shown below.

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = p(t) \tag{1}$$

This EOM is the basic building block for understanding dynamics; it describes the motion for a simple spring-mass system and dynamic properties can easily be calculated once the EOM is formed. The structural system has a total effective stiffness that represents the spring. The mass of the system is represented by *m*, the damping coefficient is represented as *c*, and the stiffness coefficient is *k*. The applied force, *p(t)*, is a function of time. The displacement, velocity, and acceleration of the DOF are also functions of time and are denoted as $u(t)$, $\dot{u}(t)$, and $\ddot{u}(t)$, respectively. The fundamental natural frequency of a simple spring-mass system can be found in the equation below.

$$\omega = \sqrt{\frac{k}{m}} \tag{2}$$

The natural frequency of a dynamic system can help describe how the system will behave. The acceleration, velocity, and displacement at any given time can all be estimated once the EOM is formed. A basic SDOF building model is shown below.

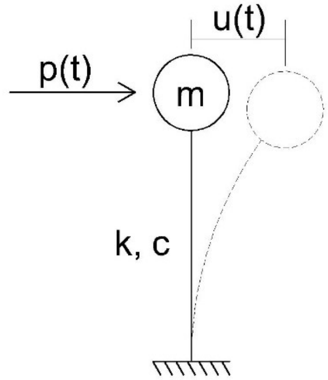

Figure 4 A SDOF building model

A SDOF system shown in Figure 4 can represent some building structures very well, such as single-story buildings or a water tower, where the majority of the mass is lumped into one location. For multi-story buildings, the model may not be accurate to get meaningful results, so a multi-degree of freedom model is necessary.

Multi-Degree of Freedom Systems

Theoretically any given system has an infinite number of DOFs. With finite element method and modern computational technology, high-rise building structures can be modeled as a multi-degree of freedom (MDOF) system down to the member level which can have thousands or even tens of thousands of DOFs. However, building structures mostly have majority of their mass concentrated at floor levels, so a lumped mass MDOF system can be used to model high-rise building structures with satisfactory accuracy. Figure 5 shown below is a diagram of a simple rectangular high-rise building.

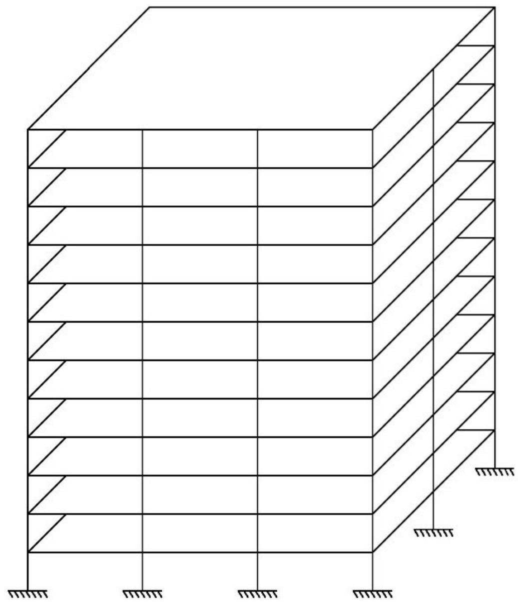

Figure 5 MDOF building model

For the high-rise building shown in Figure 5, equations of motion (EOMs) in matrix form can be formulated on the DOFs of lumped masses at all floor and roof levels.

$$\boldsymbol{m\ddot{u}(t)} + \boldsymbol{c\dot{u}(t)} + \boldsymbol{ku(t)} = \boldsymbol{p(t)} \tag{3}$$

Each parameter is a matrix, and the size of the matrix depends on the number of DOFs. The mass matrix is represented by $\boldsymbol{m}$ and is multiplied by the acceleration matrix, $\boldsymbol{\ddot{u}(t)}$**.** The damping coefficient, $\boldsymbol{c}$, is multiplied by the velocity matrix, $\boldsymbol{\dot{u}(t)}$, and the stiffness matrix, $\boldsymbol{k}$, is multiplied by the displacement matrix, $\boldsymbol{u(t)}$. The forcing function is a vector and is represented by **p(t)**. Increasing the DOFs greatly increases the size of the EOMs, and the EOMs for a system with a lot of DOF can become very complicated. The natural frequencies of the system can be determined by solving the eigenvalues. The solutions of EOMs can be obtained by directly solving the equations or by using modal analysis method.

Generalized Single Degree of Freedom Systems

If the dominant mode of displacement of a high-rise building structure is known or can be approximated, a generalized SDOF system can be used to represent the structure. Although it has only one DOF, this model can accurately predict the dynamic behavior of high-rise and supertall buildings. It has a similar format to the SDOF model discussed above, but instead of lumping the entire mass of the building into a single location, the mass is either distributed along the building or lumped at each floor level. The displacements along the height are defined in terms of the generalized coordinate $z(t)$ through the shape function $\psi(x)$ (Chopra, 2017). The shape function relates the displacements along building height to a single generalized displacement. The accuracy of the generalized model relies heavily on the accuracy of the shape function. If the shape function accurately represents the deflected shape of the system's dominant mode, great accuracy can be achieved. Figure 6 below shows a generalized SDOF system with distributed mass and elasticity on the left and a generalized lumped mass on the right.

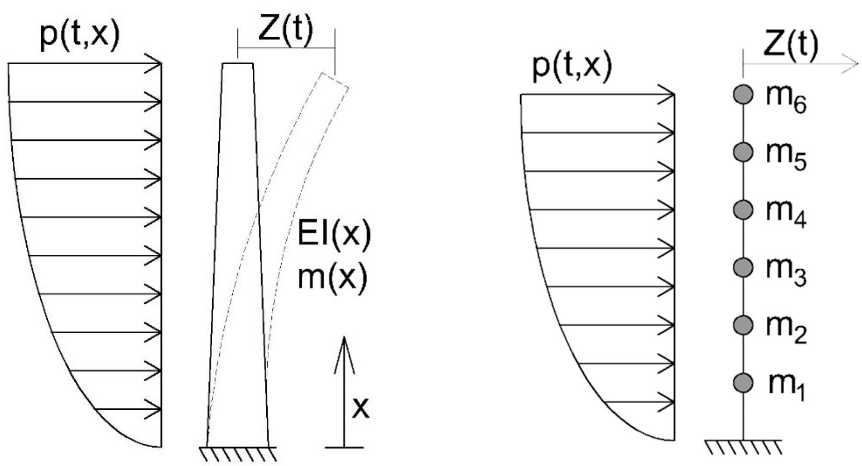

Figure 6 Generalized SDOF system a) distributed mass and elasticity b) lumped mass

When modeling a building, most of the parameters can be readily calculated. The mass of the building can be estimated accurately from the materials and dimensions of the building, and the generalized mass can be calculated as follows

$$m' = \int m(x)\psi^2(x)dx + \sum_i m_i\psi^2(x_i) \quad (4)$$

where the mass can either be a function of *x* as shown in *m(x)* or as lumped masses at story levels. If the damping coefficients are estimated, then the generalized damping coefficient can be calculated using the following equation

$$c' = \int c(x)\psi^2(x)dx + \sum_i c_i\psi^2(x_i) \quad (5)$$

Similarly, the generalized stiffness is calculated in the equation below.

$$k' = \int k(x)\psi^2(x)dx + \sum_i k_i\psi^2(x_i) \quad (6)$$

Where the stiffness can be a function of *x*, or it can be inter-level stiffnesses. The effective stiffness is also reduced if there are compressive axial forces. The equation below shows the loss in stiffness due to an axial force, *N*.

$$k'_G = \int N(x)[\psi'(x)]^2dx + \sum_i N_i[\psi'(x_i)]^2 \quad (7)$$

The generalized force is a function of time and can be calculated using the equation that follows.

$$p'(t) = \int p(x,t)\psi(x)dx + \sum_i p_i(t)\psi(x_i) \quad (8)$$

Once all the parameters are calculated or determined, the EOM can be formulated. The EOM for the generalized model is similar to the SDOF system, but it is with respect to the generalized coordinate defined by the shape function. The equation below shows the new EOM for the generalized system.

$$m'\ddot{Z}(t) + c'\dot{Z}(t) + (k' - k'_G)Z(t) = p'(t) \quad (9)$$

The displacement is a function of both time and location along the system. To find the displacement at a given location, the generalized coordinate *Z(t)* is multiplied by the shape function *ψ(x)*, as shown below.

$$u(x,t) = \psi(x)Z(t) \tag{10}$$

The fundamental natural frequency is determined the same way as a SDOF system.

$$\omega = \sqrt{\frac{k' - k'_G}{m}} \tag{11}$$

The generalized coordinate method can help keep the dynamic model simple and easy to work with while accurate dynamic behavior can be captured provided the shape function is closely resembling building's dominant movement. The greatest difficulty of formulating the EOM for the generalized method is coming up with an accurate shape function. The accuracy of the whole model depends on the accuracy for the shape function (Chopra, 2017). The shape function is normally determined by the boundary conditions for the system, but the theoretical boundary conditions may not reflect how a real high-rise building behaves.

Controlling Building Movement

Advances in technology have allowed buildings to grow taller than ever before. However, the consequence of a taller building is less stiffness and increased building sway. High-rise buildings in the early 1900s had to deal with these design challenges for the first time (Chang & Swenson, 2020). This had not been a huge issue with previous buildings, and engineers needed a way to reduce the amount of movement under external loading. The first high-rise buildings increased stiffness to reduce sway, but this came with increased cost. As buildings grow taller, this method becomes ineffective and large height-to-width ratios of contemporary skyscrapers make it impractical. Other methods of movement control were going to be needed if high-rise buildings were to become more economical and practical. Tuned Mass Dampers (TMDs) are one of the methods that have been employed. The concept of the modern tuned mass damper dates back to 1909 when an inventor named Frahm created a device called dynamic vibration absorber (Frahm, 1909). In 1928, Ormondroyd and Den Hartog showed that introducing damping to the absorber increased the effectiveness of the device significantly. The image below (Figure 7) is taken from the patent for Frahm's vibration absorber.

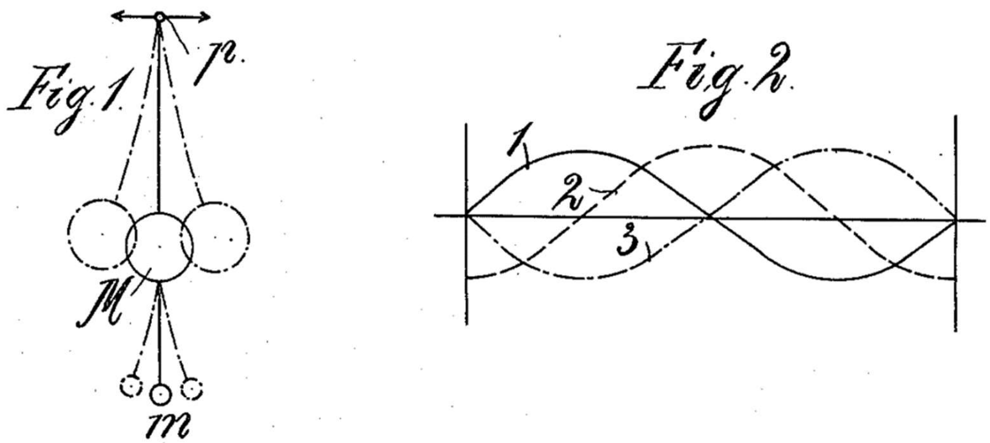

Figure 7 Illustration of the fundamental principle of Frahm's invention
(Copied from Frahm, 1909)

The illustration shown in Figure 7 demonstrates how Frahm's invention will work in principle. The smaller mass, *m*, counteracts the movement of the larger mass, *M*, because they are out of phase. The solid curve 1 shown in the right figure is the force applied to the system. Curve 2 is the vibratory movement of the larger mass *M* due to the force *p*, and curve 3 is the vibratory movement of the smaller mass *m*. The large mass is 90° out of phase with the force, and the little mass is 90° out of phase with the larger mass. This means that the smaller mass is 180° out of phase with the force and thereby counteracts the force and damps the system.

After analyzing the dynamics of the building and predicting typical movement, decisions must be made about what methods will be needed to keep the sway in check. As discussed previously, the most basic way to control building movement is to increase the overall stiffness of the building and therefore reduce the displacement or sway. This can be expensive, so some modern buildings have started to incorporate damping systems including TMDs. This chapter will discuss three methods of damping building vibration with an emphasis on TMDs.

Tuned Mass Damper System

A TMD system consists of a large mass usually located near the top of a high-rise building that is tuned to the same frequency of the building but is out of phase in order to impart an opposition force to the movement of the building. According to Connor (2003), a typical mass for the TMD is 1%-5% of the total mass of the building. Connor also notes that additional mass to the TMD enhances performance but also increases the total weight of the building which would require a larger structural system. There are three major components to the TMD: spring, mass, and damper. The spring provides a restoring force to the mass that allows the mass to oscillate back and forth. The mass provides an inertia force counteracting on the building when combined with an acceleration. The damper dissipates the energy of the TMD system and reduces the time it takes for the building to stop swaying. Figure 8 shows a diagram of a TMD and how the motion of the TMD can help counteract the motion of the total building.

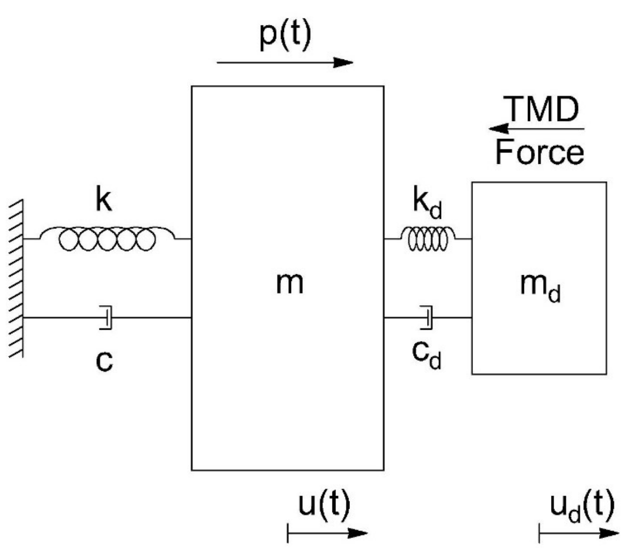

Figure 8 Diagram of tuned mass damper

The larger mass shown as *m* represents the building and the smaller mass, m_d, represents the TMD. The building and the TMD have their own stiffnesses, damping coefficients, and displacements. The TMD is tuned to have the same natural frequency of the building, but the motion is delayed due to a phase shift and the two masses counter each other's movement.

Tuned Liquid Damper System

A tuned liquid damper (TLD) system is similar to a TMD system, but it uses liquid in a large tank that is forced to move through a restricted area of the tank when it sloshes during building movement. The shape of the liquid tank and how the liquid is restricted determines the natural frequency of the TLD (Svensson & Castlen Rist, 2016). The figure below illustrates a TLD.

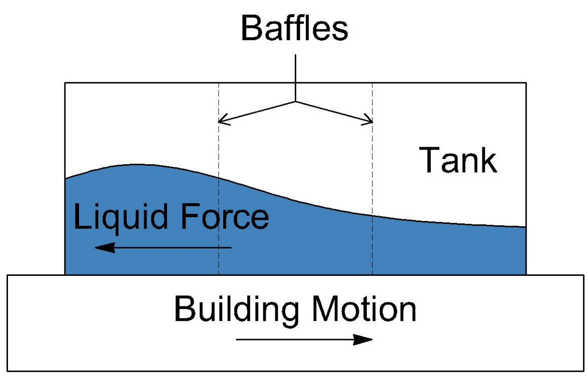

Figure 9 Tuned liquid damper

Liquid moves in the opposite direction of the building which creates a force against the movement of the building and ultimately reduces the overall sway. The baffles shown are designed so the liquid will slosh at the same natural frequency of the building in order to ensure optimum TLD design.

Pendulum Tuned Mass Damper System

A pendulum TMD system uses a large mass attached from a cable to the building. When the building is excited by a force, the pendulum TMD is delayed in its movement until the building moves enough for the pendulum to begin to move. The pendulum TMD is designed to have the same frequency as the building, but it is delayed, counteracting the movement of the building. The figure below shows a pendulum style TMD.

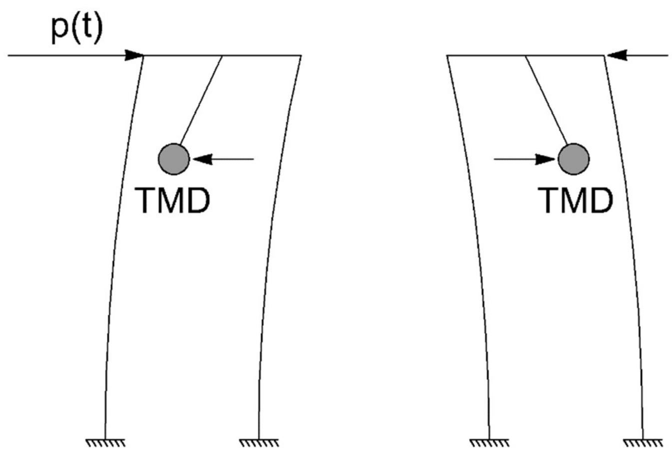

Figure 10 Pendulum tuned mass damper

It can be seen in Figure 10 that the pendulum TMD moves in a way that counteracts the building sway. As the building moves to the right, the pendulum TMD moves to the left and vice versa. If the pendulum is on a cable, the TMD system can work in all directions. The other option for a pendulum style TMD is to have a fixed shaft that can only oscillate in one plane. This design would require two pendulum TMDs in two orthogonal directions.

Dampers

A damper is a device that dissipates energy from mechanical oscillations. They are used to reduce the overall amplitude of the dynamic response of the system. Typically, dampers are installed as part of the TMD system that helps to reduce building movement. A TMD system with dampers is more effective in movement reduction and energy dissipation. The most common type of damper is the fluid viscous damper, the details of which are introduced below. One problem with most viscous dampers is that they dissipate energy as waste heat. This problem may be solved by the newly emerged electromagnetic dampers that have the potential to regenerate some of that energy into electricity. This section will introduce viscous dampers and compare them to electromagnetic dampers.

Viscous Dampers

Viscous dampers dissipate mechanical energy (commonly kinetic energy) in the form of thermal energy (heat). The force that a viscous damper exerts on the mass to which it's attached is proportional to the velocity of the mass. This relationship between the velocity of the mass and the force exerted by the damper is usually linear but can be adjusted to be nonlinear. Figure 11 shows a typical viscous damper.

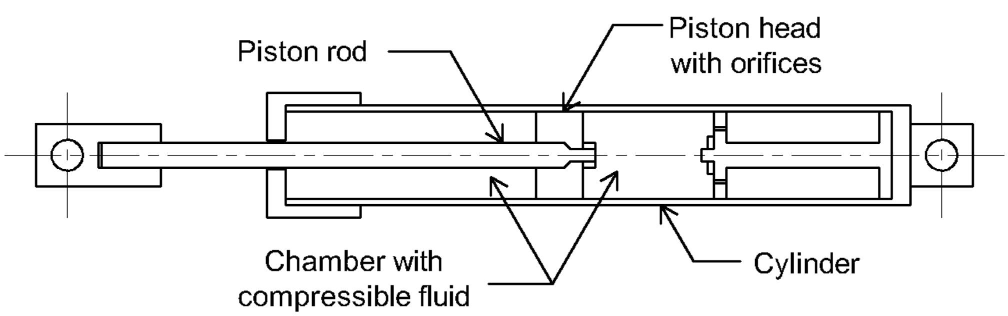

Figure 11 Diagram of viscous damper
(Copied from Agrawal & Amjadian, 2015)

As the piston rod moves through the cylinder, a difference of pressure is created between the two chambers which causes the fluids to try to equalize the pressure. To equalize the pressure, the fluids must move through the orifices. This movement through the orifices overcomes a lot of friction which generates heat. There are two main types of fluid viscous dampers, laminar flow or turbulent flow (Viscous Dampers, n.d.). Laminar flow fluid dampers push high viscosity fluid through large openings and turbulent flow fluid dampers push low viscosity fluid through small openings. Turbulent flow dampers are commonly used as shock absorbers in automobile suspension, while laminar flow dampers are commonly used for structural damping because the turbulent flow dampers respond more effectively to high velocity movement. The opposite is true for the laminar flow dampers.

Electromagnetic Dampers

Electromagnetic (EM) dampers create resistive force through induced Eddy currents in the metal when the metal experiences a change in magnetic flux. This change in magnetic flux is usually caused by a magnet moving past a fixed piece of metal. This is similar to how generators produce electricity. EM dampers imitate the effects of a perfect viscous damper. These dampers are also proportional to the velocity of the relative movement. The faster the movement, the greater the resistive force. The swirling Eddy currents inside the metal are usually wasted as heat energy into the system; however, they can be used to produce electricity that may be able to supplement the building power supply. Figure 12 below illustrates an electromagnetic damper.

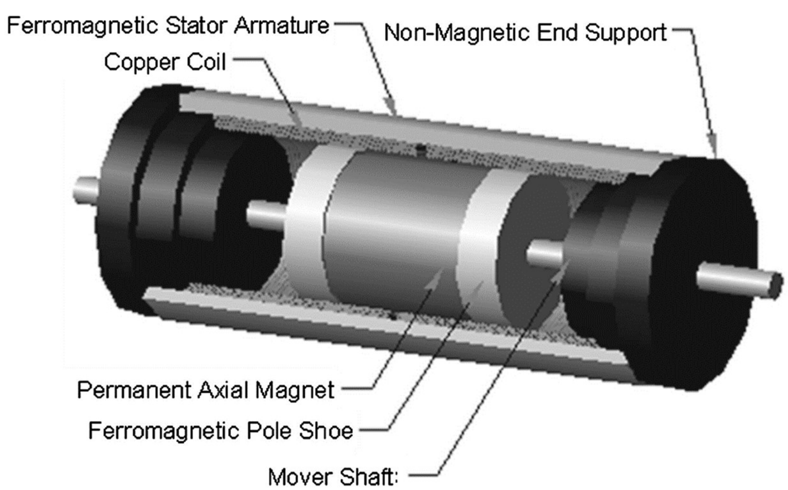

Figure 12 Diagram of electromagnetic damper
(Copied from Palomera-Arias et al, 2008)

The EM damper could have a similar design as the fluid viscous damper that is commonly used for structural applications, which makes retrofitting a structural system with an EM damper very simple for buildings that already have fluid viscous dampers installed. At the time of this report, there is limited information about EM dampers for structural applications because their use is currently limited to small-scale devices in non-structural applications. However, estimates for performance and cost analysis can be made using assumptions about current technology and trends towards the future. The main reason that EM dampers have not seen very much use in large-scale applications is the cost effectiveness is low for these applications. EM dampers can be much more expensive than traditional fluid viscous dampers for the same amount of damping. Palomera-Arias conducted a feasibility study in 2005 regarding EM dampers for structural applications and found that while they can be a viable alternative based on performance, they would be five times more expensive than fluid viscous dampers based on 2005 estimates. The study concluded that while the technology is not currently economically competitive, the cost should decrease with future advances in technology.

Chapter 3 - Energy Regeneration

Electricity drives our society and is an integral part of day to day life. Many of the products that make life easier rely on electricity on some level. These devices lose electricity or energy when they are being used mainly in the form of waste heat. Effective methods to reclaim the waste energy will be very beneficial for a sustainable future. Energy regeneration is promising and is currently being used in many fields.

Current Energy Regeneration Technology

Industries that deal with dynamic systems have started to implement regenerative energy technology. This technology is especially effective when the systems have a large moving mass or repetitive motion. These systems build up high potential energy by lifting heavy weights vertically or high kinetic energy by accelerating large masses. These systems must eventually be decelerated, or the masses stopped. The process of decelerating a large mass requires a large amount of energy, which is usually dissipated as waste heat. If a motor is used to accelerate the system, the motor can run in reverse and be used as a generator. When the system decelerates, mechanical energy is put into the motor which creates electricity. Traditionally, this electricity would run through large resistors that would dissipate the energy as wasted heat (Energy Regeneration, n.d.). This energy can instead be stored in a battery bank to be used again to accelerate the system later. This section will discuss various methods that other industries outside building construction are using to regenerate energy.

Most electric vehicles (EVs) utilize a technique called regenerative braking which converts the car’s momentum into useful electricity that can be stored for later use (Energy Regeneration, n.d.). This electricity is produced using technology that is already inside the wheels of the car. As shown in figure 13, when the hybrid car or EV slows down, the regenerative braking system kicks in.

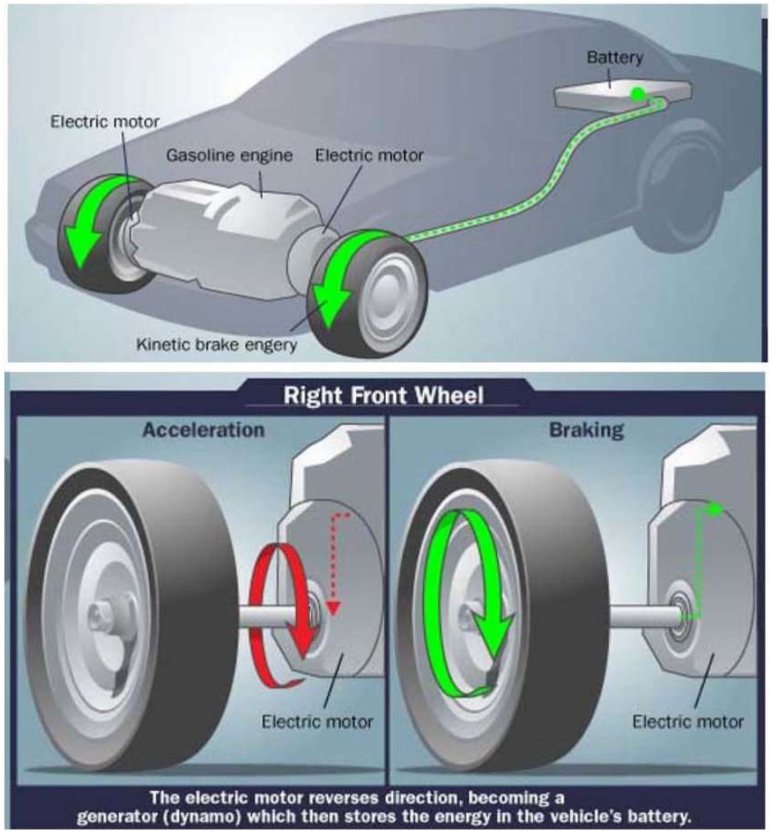

Figure 13 Regenerative breaking in electric car
(Copied from de Oliveira Borges et al., 2017)

The momentum of the car is trying to make the wheels turn, and the motors or generators attached to that wheel resist that movement by converting the motion of the wheel into usable electricity. Regenerative braking has been found to increase the total range of electric vehicles and improve fuel efficiency. According to Wei et al (2018), more than 25% of vehicle kinetic energy can be recycled while under normal urban driving cycles.

Other industries that have incorporated regenerative power into their systems include elevators, escalators, trains, and busses (Energy Regeneration, n.d.). Elevators and escalators are similar and regenerate energy when occupants are lowered from a higher level to a lower level (Energy Regeneration, n.d.). When passengers are transported from a high level to a low level, they are converting some of their potential energy into electricity by letting gravity turn the motor and thus produce electricity. Producing regenerated electricity in elevators and escalators requires an additional up-front cost for a more sophisticated drive system. Each application must be evaluated to see if the extra cost is justified.

As energy regeneration technologies advance and become more mature, potential applications can be found in tall buildings since these building store a tremendous amount of energy while they sway. Before energy regeneration technologies can be installed into high-rise buildings, they must first be evaluated to determine if it is economically feasible. The next section will discuss how much energy is stored in high-rise building movement and consider the feasibility of regenerative technology in those applications.

Theoretical Potential Energy of Supertall Building

Buildings are never able to take a break from swaying in the wind. There is almost always some lateral force applied to the building that makes the building sway. As buildings get taller, the energy in the oscillation of the building motion can be very significant. Buildings have intrinsic damping from external and internal frictions of materials, nonstructural components, inelasticity of materials, soil-structure interactions, etc. Normally, the energy in the building movement is dissipated by the damping in the system. Energy is also lost to the ambient environment in various forms. Additional damping can be added with the use of a TMD system and structural dampers in order to control the movement. This section will discuss how much energy is stored in building oscillation and how much of that energy may be usable to produce electricity.

As discussed previously in Chapter 2, buildings can be modeled as a generalized SDOF system to simplify calculations and analysis. When the system is acted upon by an outside force, the system begins to oscillate. This oscillation movement causes the generalized mass to accelerate and decelerate which imparts a force within the system, and this force is carried down to the foundation via the structural system. Work, or energy, is defined as a force multiplied by a distance. The equation below shows the force for a spring.

$$F_k = k\Delta \tag{12}$$

The constant 'k' is the stiffness, and it is multiplied by the distance that the spring is either depressed or elongated to get the force. To get the work required to deflect a spring by a certain amount, the force needs to be integrated over a distance. The equation below shows the energy required to depress a linear spring with stiffness 'k' by a distance 'Δ'.

$$PE = \frac{1}{2}k\Delta^2 \tag{13}$$

As seen in the equations above, the system requires much more energy to cause more and more deflection because as deflection increases linearly, the energy required increases quadratically. This means that the high-rise building sway is the most important factor for energy regeneration potential. Shown below is an illustration of the potential energy that is stored in a vibrating system such as an oscillating building.

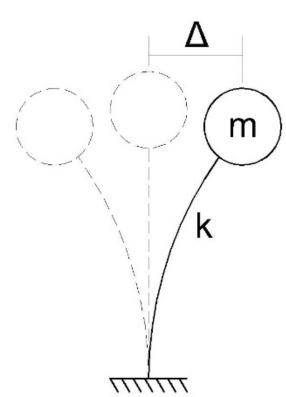

Figure 14 Potential energy in oscillating system

The total energy is linearly proportional to the spring stiffness and is proportional quadratically to the deflection. Slender high-rise buildings and long span structures tend to be more flexible and have larger deflections compared to lower buildings and shorter spans. This means that high-rise buildings or long-span structures are ideal for energy harvesting; they store a large amount of energy in their oscillations. A building that is twice as tall as another building will store more than twice as much energy as that building because the lateral drift increases dramatically along the height of the building. This is mainly caused by the cumulative effect of chord drift (Taranath, 2012). For example, a 40-story theoretical building with an effective stiffness of 83,000 kN/m and a displacement of 0.10 m would store 830 kW of power in its oscillations, while a building with the same stiffness but only half the displacement would only store 208 kW of power (Kordi & Alamatian, 2019). This demonstrates how critical the displacement of the system is to the potential energy it stores. There is a substantial amount of energy stored in the building oscillations, however, not all this energy can be converted into electricity. The next section will review experimental and numerical studies that have been conducted to investigate how much of the potential energy can be converted into electricity.

Review of Experimental and Numerical Studies

The energy dissipation from TMDs has been well studied and observed. The TMD system is one of the most popular methods for reducing wind induced high-rise vibrations and is very effective at keeping the building movement under the serviceability limits. However, there have been no full-scale examples of a TMD system having EM dampers in a high-rise building that is used for regenerative energy. The idea that the TMD system can regenerate electricity is relatively new but rapidly picking up momentum. As material science and manufacturing processes improve, the cost of these novel systems will decrease, and they will become more feasible.

Before a full scale regenerative TMD can be implemented in a building, experimental and numerical studies are necessary to help determine if it is feasible for full scale applications. Shen et al. (2011) set out to build a proof-of-concept for this novel type of TMD. The researchers first made a small-scale experiment using a pendulum style TMD and then ran a numerical study on a 76-story building in 2017 (Shen et al., 2017). This section will discuss both the experimental study and numerical study introduced in their reports.

The goal for this experiment was to collect information about the vibration control and energy-harvesting functions of the proposed regenerative TMD system. Instead of the conventional energy-dissipating dampers, Shen et al. (2011) replaced them with EM dampers that could convert part of the damping energy into electricity. Energy regenerative TMDs are similar to conventional TMDs but have more complexity due to the electrodynamics introduced by the regenerative process. Converting the mechanical vibrations from the building motion into electricity requires an energy-harvesting circuit (EHC) that will store the energy after it has been converted. The process of converting and storing this energy affects both the vibration control performance and energy harvesting performance of the system. According to Shen et al., previous studies overestimated the vibration control and energy-harvesting potential because they did not account for nonlinearities in the circuits or the EM damper, as well as mechanical and electrical losses. Their experimental and numerical studies tried to account for these nonlinearities and establish a more accurate model for the performance of a regenerative TMD.

The researchers decided to use a pendulum style TMD for the experiment. The frequency of the oscillations of the TMD are tuned to be as close as possible to the natural frequency of the primary structure. The experimental structure tested by Shen et al. is idealized as a SDOF system and the pendulum only swings in one direction. This experimental model could be adapted to a full-scale building but there would have to be two different pendulum TMD's, one for each direction, or another configuration of TMDs would have to be used to get motion control for all directions. The figure below shows a diagram of the configuration for the regenerative TMD used in the study.

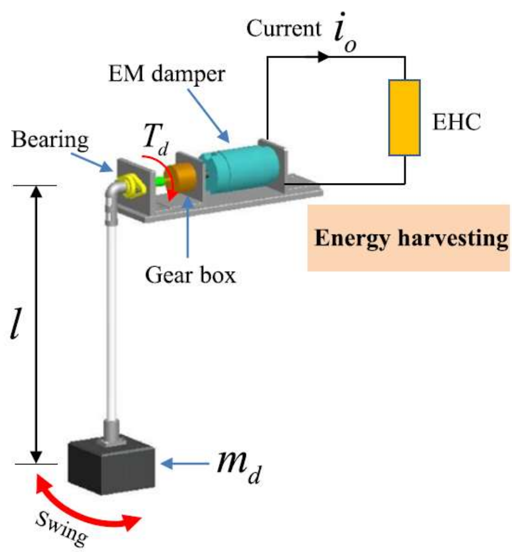

Figure 15 Configuration of pendulum-type energy regenerative TMD
(Copied from Shen et al., 2017)

For the pendulum style TMD used in this experiment, a mass is attached to a rigid bar that swings back and forth from the bearing when the building sways. The swinging motion of the pendulum creates a torque on the EM damper which produces electricity in the EHC. A gear box sits between the swinging mass and the damper to increase the efficiency of the power conversion. The mass of the TMD used in this experiment was 17.6 kg (38.8 lb), and the TMD had a natural frequency of 1.03 Hz.

After the experimental study, the researchers created a computer model for the physical device they were testing and published a new report on their findings (Shen et al., 2017). The researchers hoped to create a computer model that could predict the performance of full-scale implementation. The experiment was used to prove that the computer model accurately described the actual experimental results. The computer model could be adjusted to the empirical results if needed as well. The results of the experiment agreed well with the computer model for the regenerative pendulum TMD. The computer model was then used in the full-scale numerical study.

The benchmark building for the full-scale numerical study is 76 stories and 306 m (1004 ft) tall. It has a height-to-width ratio of 7.3 and represents a typical wind-sensitive high-rise building. A wind tunnel test at 1:400 scale was used to determine the wind pressures on the building. The mass of the TMD for the benchmark building is 500-tons with a mass ratio of 1.33%. The TMD was located at the top floor of the building. Once all the parameters for the building were put into the model, the numerical study could be simulated using various software.

The numerical study found that the energy regenerative TMD had a total damping coefficient close to the optimum value. This means that the energy regeneration process had little effect on the overall damping properties of the system. The energy regenerative TMD can produce electricity while still performing well as a vibration control system. The results also suggest that the regenerative TMD has slightly better vibration suppression performance over the optimally designed viscous damped TMD. The study concluded that the energy regenerative TMD is insensitive to damping detuning (a loss of damping efficiency due to the TMD and main structure having incompatible frequencies), which can be an issue for other forms of damping systems. The regenerative TMD system maintains good vibration control at different wind speeds and building displacements.

For wind conditions in the 8 to 12 m/s (18 to 27 mph) mean wind speed range, the power output for the system was found to be 108.6 to 604.7 W. When the mean wind speed is increased to 40 m/s (89 mph), the power output can be up to 51.7 kW. The numerical study found that the regenerative TMD system is capable of harvesting vibrational energy at a wide range of wind speeds, but the power output for the lower windspeeds is almost negligible. The power output for the benchmark building is relatively low in terms of pure power production, but it has high efficiency of converting the energy in building motion into electricity. The total efficiency of the system is dramatically increased at higher wind speeds. The system has a total efficiency of 12.8% when the mean wind speed is 4 m/s (9 mph) and a 35.9% efficiency when the mean wind speed is 7 m/s (16 mph) and maintains high efficiency as the wind speed increases. Figure 16 shows where the energy from the wind load is dissipated and the total efficiency of the system at a mean wind speed of 10 m/s (22 mph).

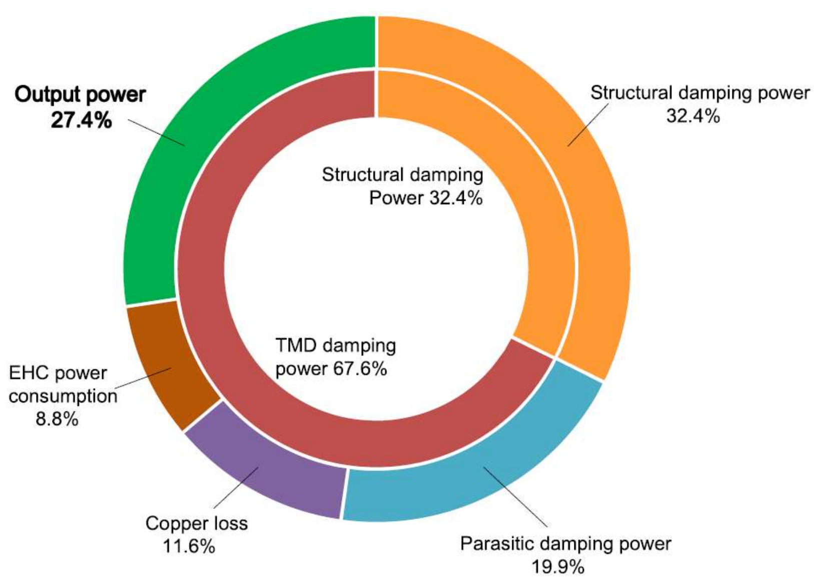

Figure 16 Distribution of the total wind excitation power in benchmark building
(Copied from Shen et al., 2017)

The distribution of the total wind excitation power is shown above where 32.4% of the energy is dissipated through structural damping and 67.6% of the energy is dissipated through the TMD. The process of converting the wind excitation power into electricity has some efficiency losses, so the total power output for the regenerative TMD system is 27.4% of the energy that was put into the building by the wind. This efficiency is decent, but there are still major losses in the conversion process. One method for increasing the power output of the system is to increase the mass ratio. This can have practical constraints but would help if the goal is power output.

The experimental and numerical studies conducted by Shen et al. are very helpful tools for understanding the potential for power output in regenerative TMDs. They developed a model to predict the performance of a regenerative TMD system that agreed well with experimental data. The efficiencies they found in the numerical study can be applied to other buildings to get a preliminary idea about how much energy could be expected from a similar system installed in a real building. For buildings that are almost twice as tall as the benchmark building, the potential power could be very large.

Chapter 4 - Case Study: Taipei 101

Taipei 101 is located in Taipei, Taiwan and was the world's tallest building from 2004 to 2010. It has 101 stories above ground and stands 508m (1667 ft) tall (Infanti et al., 2008). It also has the world's largest passive TMD with a mass of 660 metric tons. A picture of the building is shown in figure 17. The corners of the building are made at an angle to reduce vibrations from wind.

Figure 17 Picture of Tapei 101
(Photo from The Skyscraper Center, 2019)

Wind tunnel tests were performed to determine the wind-induced behavior of Taipei 101. The wind tunnel tests reported that the wind induced peak accelerations in a year would be 0.75% of gravitational acceleration, which does not meet Taiwanese building code. Taiwanese building code limits the 1/2-year return period acceleration not to exceed 0.51% of gravity. The peak acceleration response would need to be reduced to 0.51% of gravitational acceleration to meet code. The engineers decided that a TMD system located at the top and suspended by cables would be sufficient to reduce the overall building movement. Unlike previous implementations of TMDs in high-rise buildings which are mostly hidden, Taipei 101 designed the TMD as an architectural feature and attraction for visitors (Infanti et al., 2008). The photograph below demonstrates the architecture style of the TMD in Taipei 101.

Figure 18 Picture of Taipei 101 TMD
(Photograph from Plessis, 2010)

The TMD at Taipei 101 has eight viscous dampers that are designed for a maximum displacement of 750 mm in either direction (Infanti et al., 2008). The viscous dampers had to be carefully designed to ensure that the dynamic behavior of the building is desirable. The dampers also have to be designed to withstand the massive force from the movement of the TMD. When the building experiences exceptionally high wind or seismic forces, the viscous dampers are equipped with Relief Pressure Valves to limit the reaction force from the TMD. In addition to the high axial force, the viscous dampers also have to withstand high heat. The energy from the building swaying in the wind is dissipated by the viscous dampers and is converted into thermal energy. Each unit is designed to withstand 13kW of continuous power dissipation and even higher energy dissipation for shorter amounts of time (Infanti et al., 2008). Taipei 101 has eight viscous dampers installed, which means that they can dissipate over 100 kW of continuous power. This power is in the form of wasted heat and is a problem that has to be dealt with.

Taipei 101 is a perfect building to implement regenerative EM dampers in the TMD system. The building is very tall, thus undergoes large amount of sway. It already has a TMD and would just need to replace the viscous dampers with EM dampers. This swap between the dampers would not be inexpensive, but it would pay itself off with the energy savings from the new regenerative system. Other existing buildings with the right conditions could also be reconfigured with regenerative EM dampers for better building performance and electricity generation. The system can also be implemented for new constructions for similar tall buildings.

To get a preliminary estimate of the potential power output for a regenerative TMD installed in Taipei 101, dynamic behavior of the building must be known. Using the aforementioned generalized SDOF model, the energy of the building sway can be estimated once the dominant building movement mode is known. As shown in Equation (13), the stored energy in the building can be calculated by the generalized stiffness and the generalized displacement. Two researchers, Tuan and Shang (2014), developed a FEA model for Taipei 101 and were able to determine many properties from their analysis. They found that the generalized stiffness for the first mode of the building is 3.39 x 10^7 N/m and the average displacement during a light breeze is 0.08 m. Applying equation (13) to the parameters found in the FEA for Taipei 101 gives an average power stored in the motion of the building of 108 kW.

$$PE = \frac{1}{2}(3.39\ x\ 10^7\ \ N/m)(0.08\ m)^2 = 108\ kW \tag{14}$$

This is a significantly higher value than what Shen et al. (2017) found during their research, but this is only the energy stored in the building oscillation and not the actual power that can be generated from the regenerative TMD. Assuming that retrofitting Taipei 101 with regenerative EM dampers would have similar efficiencies as the benchmark building in the aforementioned experimental and numerical studies (Shen, et al., 2017), Taipei 101 could produce a significant amount of electricity. From the benchmark building, an efficiency of 27.4% of the total stored energy in the building oscillation can be stored as electricity. This would mean that Taipei 101 could produce 30 kW of power continuously under normal wind conditions. The amount of electricity that the system would produce can vary greatly depending on the wind speed as seen in the experimental study where almost no electricity would be produced at very low wind speeds, and a lot of power would be produced at high wind speeds. Because there are such great fluctuations inherent to this system, the electricity would need to be conditioned and regulated before it could be used in the building as a normal power source.

Taipei 101 has the potential to produce a significant amount of electricity through the use of a regenerative TMD. The structure already needs to have a form of damping, so it makes sense to get an extra benefit from an otherwise wasted form of energy. Retrofitting the existing TMD with regenerative EM dampers would be costly, so a life cycle cost analysis would be beneficial to determine if the extra cost justify the energy saving. There also may be many challenges with implementing a full-scale regenerative TMD system because it would be the first of its kind. The type and size of EM dampers required for this regenerative TMD system to work is not currently on the market but could be manufactured for the specific job for an inflated cost. The first buildings to implement this type of system might have longer return on investments due to the high initial costs associated with experimental new technology, but the price should decrease as the market matures. This system is suitable for new construction and retrofitting existing systems and they would both help develop the technology further. A new high-rise building with a regenerative TMD would have the best chance for success because the building would be designed with the regenerative TMD in mind and could adapt the dynamic properties to optimize the performance and energy regeneration for this technology. Once this regenerative system has been proven to be effective, it could be adapted for other structural applications like long span buildings and structures that have similar deflection issues.

Chapter 5 - Summary and Future Work

Humans have always had a fascination with constructing bigger and more magnificent buildings, but it wasn't until the 19^{th} century when the first skyscraper was built and the race for "The World's Tallest Building" began. Tall buildings quickly began to pop up in cities all around the world. As buildings grew taller, lighter, and more complex, engineers had to create new design methods to keep buildings safe and satisfy serviceability requirements. The newest generation of skyscrapers are very susceptible to wind induced oscillation, which can cause problems with occupants' health and safety. The invention of the tuned mass damper (TMD) allowed high-rise buildings to grow in height while keeping building sway to acceptable levels.

The TMD usually has additional dampers attached to dissipate the energy of the oscillating building, and the most commonly used dampers are fluid viscous dampers which dissipate the energy via heat transferring to the environment. This report proposed a new type of damper called the electromagnetic (EM) damper that uses permanent magnets to induce electrical currents inside metal which can be converted into useful electricity. These EM dampers are usually more expensive than fluid viscous dampers currently, but they have the potential to produce electricity in a regenerative TMD system, which might make them economically feasible in the future.

Currently, there have been no full-scale applications of energy regeneration TMDs in tall buildings, but researchers have conducted experimental and numerical studies to estimate the effectiveness of these systems. One study found that 27.4% of the total energy stored in building oscillation could be converted to electricity under normal wind speed conditions. This efficiency was used to estimate how much energy Taipei 101 could produce if retrofitted with regenerative EM dampers. This report found that Taipei 101 could produce 30 kW of electricity during normal wind conditions. The potential for power production in supertall buildings can easily be seen, but there are still many challenges to overcome before a full-scale regenerative TMD system can be installed in a building.

Buildings are only going to get taller and have greater lateral displacement. This larger displacement indicates a greater amount of energy in building movement. Before this future can be realized, more work needs to be done on this topic. One of the main challenges with this proposed system is that the EM damper needed to produce electricity does not yet exist. Theoretical studies have shown that these dampers will perform well and produce electricity, but these results need to be verified by experiment of real full-scale EM dampers. Determining the parameters of these dampers is the first step to installing this system. The next challenge is trying to condition the electricity that the EM damper regenerates from building movement. The amount of electricity produced at any given time will vary greatly depending on the wind conditions. Storing the electricity would help level the power output and allow the electricity to be accessed when needed. Batteries are a great way of storing electricity and could be a possible solution for this problem. Buildings already use battery storage for renewable energy sources like photovoltaic systems or as battery backup, so a similar system could be implemented for this design. One other challenge with this system is determining an appropriate building to install the regenerative TMD. The effectiveness of this system is dependent on the site-specific wind conditions and the dynamic properties of the building. Buildings with regenerative TMDs would benefit from being in a windy area because they would sway more on average than buildings in less windy areas. The building would also benefit from being tall and slender with large lateral displacement for maximum power production.

While large lateral displacement in tall buildings can be an issue for serviceability requirements, it can also be utilized as a regenerative energy source. This report discussed a novel idea for using a TMD system with regenerative EM dampers to produce electricity with promising results. With current technology, tall buildings would be able to produce a substantial amount of power and simultaneously reduce the dynamic response of the building. While the current cost of this regenerative TMD system is relatively high compared to traditional TMDs with viscous dampers, future advances in technology will allow this system to be economically feasible. Before this system can be installed, however, more research must be conducted to ensure that it is ready for a full-scale building.

References

Agrawal, A. K., & Amjadian, M. (2015). Seismic component devices. In A. Pipinato (Ed.), *Innovative Bridge Design Handbook* (pp. 531–553). Elsevier. https://doi.org/10.1016/b978-0-12-800058-8.00020-7

Chang, P.-C., & Swenson, A. (2020). Construction. In *Encyclopædia Britannica*. https://www.britannica.com/technology/construction

Chopra, A. K. (2017). *Dynamics of Structures*. Hoboken, NJ. Pearson Education.

Connor, J. J. (2003). *Introduction to structural motion control*. Prentice Hall Pearson Education.

Craighead, G. (2009). *High-rise security and fire life safety.* (3rd ed.). Butterworth-Heinemann.

CTBUH Height Criteria. (2020). Ctbuh.Org; Council on Tall Buildings and Urban Habitat. https://www.ctbuh.org/resource/height

de Oliveira Borges, D. M., de Souza Floriano, R. A., de Souza Reis Pimenta, R., Amorim, R. J., & Coutinho, V. N. (2017, April). Kers system adaptation for a Formula Student vehicle. *2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)*. https://doi.org/10.1109/ever.2017.7935887

Energy Regeneration. (n.d.). https://www.reo.co.uk/files/energy_regeneration_engl_vorl_05-08_1.pdf

Frahm, H. (1909). *Device for Damping Vibrations of Bodies* (USPTO Patent).

Infanti, S., Robinson, J., & Smith, R. (2008). *Viscous Dampers for High-Rise Buildings*. https://www.iitk.ac.in/nicee/wcee/article/14_11-0060.PDF

Kordi, F., & Alamatian, J. (2019). Analytical Method for Designing the Tuned Mass Damper Based on the Complex Stiffness Theory. *Iran J Sci Technol Trans Civ Eng*, *43*(4), 673–684. https://doi.org/10.1007/s40996-018-0222-0

Ormondroyd, J., & Den Hartog, J. P. (1928). The Theory of the Dynamic Vibration Absorber. *Trans. ASME*, *50*, 9–22.

Palomera-Arias, R. (2005). *Passive Electromagnetic Damping Device for Motion Control of Building Structures* [PhD Thesis].

Palomera-Arias, R., Connor, J. J., & Ochsendorf, J. A. (2008). Feasibility Study of Passive Electromagnetic Damping Systems. *Journal of Structural Engineering*, *134*(1), 164–170. https://doi.org/10.1061/(asce)0733-9445(2008)134:1(164)

Plessis, A. du. (2010). Tuned mass damper on display in Taipei 101. In *Wikipedia*.

Shen, W. A., Zhu, S., Xu, Y. L., Shi, X., & Lee, W. C. (2011, July). *Experimental study of regenerative EM -TMD system for building vibration control*. Faculty of Construction and Land Use, Hong Kong Polytechnic University. http://hdl.handle.net/10397/7603

Shen, W., Zhu, S., Xu, Y.-L., & Zhu, H. (2017). Energy regenerative tuned mass dampers in high-rise buildings. *Structural Control and Health Monitoring*, *25*(2), e2072. https://doi.org/10.1002/stc.2072

Svensson, S., & Castlen Rist, V. (2016). *Methodology for preliminary design of high-rise buildings*. https://lup.lub.lu.se/student-papers/search/publication/8884631

Taranath, B. S. (2012). *Structural analysis and design of tall buildings : Steel and composite construction*. Crc/Taylor & Francis.

The Skyscraper Center. (2019). Skyscrapercenter.Com; Council on Tall Buildings and Urban Habitat. https://www.skyscrapercenter.com/

Tuan, A. Y., & Shang, G. Q. (2016). Vibration Control in a 101-Storey Building Using a Tuned Mass Damper. *Applied Science and Engineering*, *17*(2), 141–156. https://doi.org/10.6180/jase.2014.17.2.05

Viscous Dampers. (n.d.). Deicon Dynamics & Controls. Retrieved December 15, 2019, from http://www.deicon.com/viscous-dampers/

Wei, X., Xu, A., & Zhao, R. (2018). *Evaluation of Wind-Induced Response Bounds of High-Rise Buildings Based on a Nonrandom Interval Analysis Method*. Hindawi. https://www.hindawi.com/journals/sv/2018/3275302/