Mitigation of Wind Induced Movement of Buildings Using the Modified Friction Device

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Abstract:

Building higher skyscrapers increases the concern of wind induced motion. Indeed, in order to ensure serviceability and safety standards, it is the engineers' responsibility to investigate the response of high-rise buildings to wind excitation. Tuned mass dampers are usually used to limit the response of the buildings to wind. However, these devices are generally tuned for a particular bandwidth of frequencies. Therefore, in order to improve the effectiveness of these devices, control schemes must be implemented. For this thesis, the design of a modified friction device (MFD) has been studied. Requiring only a small amount of energy, the MFD is a new kind of semi-active damper that provides stability, accurate control and effectiveness. Using a MATLAB program, it was possible to model a primary structure hit by a certain wind excitation. The modified friction device was designed to counterbalance the effects of wind and decrease displacements and accelerations. It was placed on the top of the building where the displacements are generally the highest. The parameters of the MFD were examined, and many simulations were run in order to optimize the action of the device on the mitigation of wind excitation. The results demonstrate that the MFD effectively mitigates wind induced motion in buildings. Therefore, this thesis corroborates the benefits of implementing modified friction devices in civil structures.

Thesis Supervisor: Jerome Connor
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Introduction

Competition, the economy, social factors and sometimes political purposes are all reasons driving people's enthusiasm to build higher and higher. As a matter of fact, with a growing population requiring housing and the need to avoid an uncontrolled expansion of city boundaries, urban planning has increasingly focused on building higher. Thus, recent years have been characterized by the construction of tall and slender buildings all over the world.

When designing high-rise buildings, it is critical to study the impact of wind in the vibration of the structures. To ensure comfort, serviceability and safety standards in high rise buildings exposed to dynamic loading (such as vortex shedding), structural engineers are required to enhance the structural features of tall buildings in order to limit their maximum amplitudes and accelerations.

In this context, the notion of energy dissipation is of great importance. Indeed, the more we allow a structure to dissipate energy, the lower the oscillations it will have. It is common to implement devices such as tuned mass dampers in high rise buildings in order to provide additional damping. These devices can be further improved by control schemes.

Since a passive tuned mass damper can be efficient only for a certain band of frequencies, active control has to be granted to the device in order to improve the oscillation control performance and widen the range of applicability of the tuned mass damper (TMD). Because of the stability risks induced by energy sources used in active control, semi active control has been developed. This type of control has the benefits of passive control while ensuring the stability of the structures. It is able to achieve such stable control because it utilizes a lower external energy than the active schemes. The small amounts of energy required make semi-active TMDs relatively reliable devices because they can operate continuously even during a power failure. This is due to the fact that this energy can be supplied by simple batteries.

However, semi-active TMDs have several limitations, such as fluid and mechanical constraints, electronics reliability and the need for an external power source. These limitations prevent them from being used in civil engineering structures. To address these problems, the modified friction device (MFD) has been developed [11]. Including a spring, a damper and a variable friction element, all placed in parallel, the MFD is characterized by its significant damping forces (about 200 kN) relying on only 12-volt batteries. These improvements corroborate the reliability of implementing active damping systems in civil structures. To ensure proper operation of the MFD, it is vital that engineers model the effects of the device on civil engineering structures. Previous studies have highlighted the effectiveness of the MFD regarding vibration mitigation of earthquake loadings. However, more studies must be undertaken to ensure the mitigation of wind vibration due to the MFD. Thus, the relevant operation of the MFD, in agreement with the model used, has to be confirmed. The research reports consequently in the building's motion control enabled by the modified friction device.

The purpose of this thesis is to enhance the feasibility and effectiveness of the MFD regarding wind vibration mitigation. To achieve this goal, the parameters of the established device are optimized in order to provide better efficiency and thus grant the best possible control (control of displacements, velocities and accelerations). In order to do so, a MATLAB program simulating the contribution of the MFD is studied. The model employed involves a structure hit by a certain wind excitation. An MFD coupled with a TMD, both placed at the top of the structure, allow the dissipation of the motion induced by the wind excitation. In this model, the MFD parameters and their roles in wind excitation mitigation are analyzed.

1 Mitigation of Wind Induced Vibrations in High-Rise Buildings

1) The Wind Characterization

The effects of wind on buildings are widely diverse because of the complex interaction between the wind flow and civil engineering structures. Depending on the type of structures, different effects can be generated: static, dynamic and aerodynamic effects. The multiple eddies produced by wind are responsible for various behaviors: the gust effect, the turbulent nature of wind, and the vortex shedding phenomenon.

Wind engineering research aims to characterize the wind-induced motion of structures in order to avoid the failure of buildings due to the dynamic effects. Therefore, phenomena such as buffeting and vortex shedding are analyzed by researchers. Slender buildings are concerned by the dynamic response induced by these effects. Thus, wind tunnel testing is generally used to make sure that the displacement at the top of buildings is small enough to ensure the comfort of inhabitants, which are sensitive to vibration and motion. [1]

In order to limit wind effects on structures, and reduce the vortices that are produced, the aerodynamic design is of utmost importance. Indeed, the shape of a structure plays a major role in decreasing the wind-induced movement of buildings. Changing the cross sectional shape by chamfering corners or adding openings in the structure reduces the wind excitation of slender buildings. By modifying the wind flow, all these changes help to set up a more effective design and decrease the cost of the materials needed. In order to achieve these goals, two types of changes can be implemented. On one hand, with negligible modifications in the design, the modification of the corners (such as fins, slotted and chamfered corners, corner recessions, roundness of corners) and the building's orientation can be set up to reduce the wind induced motions of tall buildings. These minor modifications are shown in Figure 1. [13]

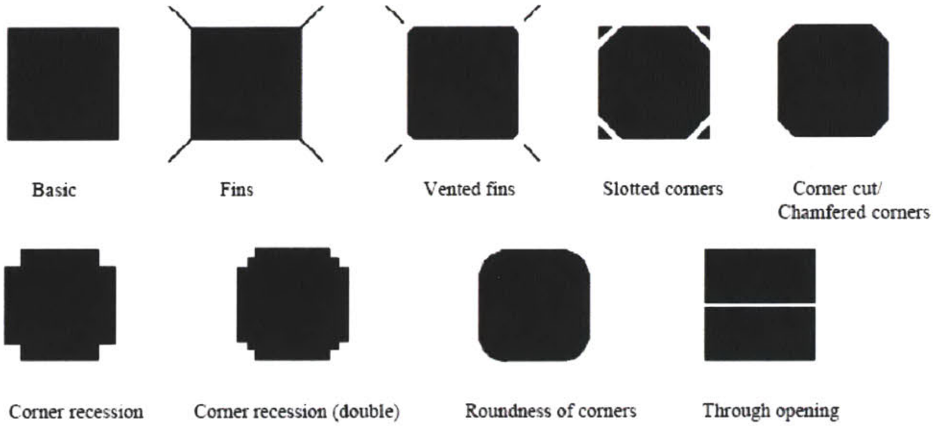

Figure 1: Various aerodynamic geometries reducing more or less the wind effects [13]

On the other hand, it is sometimes necessary to implement major modifications in the design to ensure the structural stability regarding wind loadings. These changes can range from openings at the top of buildings to major changes of the structural concept (twisting of the building or change of the building shape). Other modifications such as tapering and setbacks can also help the wind flow follow the most effective pattern. Figures (2-a) and (2-b) highlight these features. Shown in Figure (2-a), the shape of the Burj Khalifa skyscraper is the most effective that could have been chosen to scatter the wind flow for a building of such a height. The holes of the Marina city towers, presented in Figure (2-b), allow the reduction of the forces induced by wind. [13]

Figure 2-a: The shape of the Burj Khalifa's base [19]

Figure 2-b: Marina city towers [13]

2) The Control of Structures Provided by Damping

It is of utmost importance for engineers to study the vortex shedding phenomenon in order to control the dynamic response of tall buildings. Indeed, engineers have to do their best to decrease the vibrations due to wind. Many parameters control the dynamic response of a tall building such as its shape, its stiffness, its mass, and its damping. Engineers have to analyze all these parameters in order to achieve the optimal response of buildings to vortex shedding, and thus improve the dynamic characteristics of slender structures. However, damping is hardly a measurable parameter because it depends on many aspects such as the structural frame, the foundations, the claddings, and the materials. Through the implementation of an external mechanical damping system, it is possible to control and improve the performance of the dynamic response of slender buildings by getting rid of the uncertainty relative to damping.

The vibration mitigation is often provided by the implementation of tuned mass dampers. These devices allow for the reduction of the buildings' oscillations and the possible damages caused by vortex shedding. Tuned mass dampers also help to ensure human comfort standards by decreasing the resonant response up to half its original value. They ideally oscillate in anti phase with the structure and thus dissipate energy through the reduction of the vibrations of the building.

Tuned mass dampers can passively or actively control the response induced by any loading applied to the structure. The following thesis will develop the concept of active control implemented in tuned mass dampers in order to mitigate the induced wind vibrations. [4]

2 Wind Engineering

1) The Turbulent Character of Wind

Regardless of the location of measurements, wind speed is not constant over time because of its turbulent character associated with the gust effect. At the surface level, the gustiness is generated by the interaction of wind with the topography and nature of the surface. Then, the gustiness decreases with height. Moreover, the intensity of gusts varies with the period during which the building is affected. Indeed, in order to experience the gust effect, large buildings must be struck by gustiness of long duration. For the same duration of gusts, a small structure will be more affected compared to a larger one. Tall buildings are mainly affected by gusts lasting three to four seconds. Thus, compared to low-rise buildings, high skyscrapers will be characterized by smaller pressures. Furthermore, the gusts produced by wind turbulence have a large range of frequencies and amplitudes. Therefore, to achieve an integral wind engineering design, it is more accurate to take into account the gust effect in the wind speed. The gust factor approach allows us to take into consideration the increase of the loading applied to buildings in the along-wind direction.

Regarding the non-turbulent wind, its associated loading can be considered quasi static because of the long period of the mean velocity (30-60 seconds). However, once the gustiness of wind is taken into consideration, we can no longer assume that the wind loading is quasi-static unless the duration of the loading associated with the gust is greater than the natural period of the building. [5]

2) Vortex Shedding

Vortex Shedding is the phenomenon associated with the transverse oscillation of a structure. This transverse motion is induced by the pressure difference generated by the wind vortices that exist between the two sides of the building. Alternative low pressure zones are produced, making slender buildings move from the high pressure zones towards the low pressure zones. This action causes transverse motion to happen.

All the structures have critical wind speeds at which vortex shedding occurs. If the building's natural frequency coincides with the vortex shedding frequency, the structure will resonate. This effect results in great forces and deflections, and a very large increase of the displacement at the top of the building.

When it comes to the buildings' response due to wind, the most important parameters that have to be taken into consideration are the along wind and the transverse wind. The along wind (drag forces) is characterized by a great loading and is responsible for the maximum deflection. However, for a tall building, the dominant response to wind is due to the crosswind and causes the maximum acceleration to occur in a plane perpendicular to the direction of wind [2]. A two dimensional flow of wind is illustrated in Figure 3 to show the difference between the along wind and the across wind.

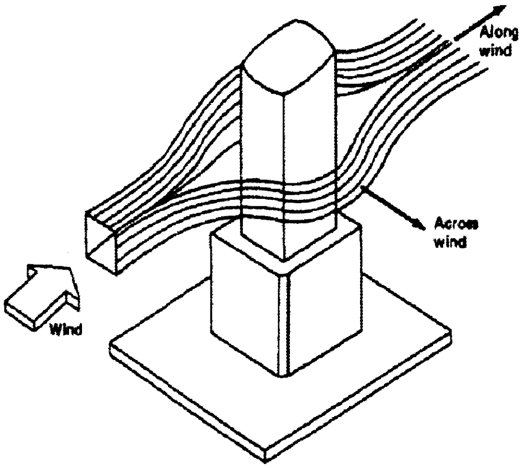

Figure 3: Simplified two dimensional flow of wind (Taranath, 1988)

When the wind blows across a tall building, vortices are shed periodically and alternately from the two sides of the structure. These vortices lead to the creation of a fluctuating across wind component in the transverse direction. This phenomenon, which produces structural vibrations perpendicularly to the direction of wind, is called the von Karman vortex street or vortex shedding.

On one hand, when the wind speed is low, the vortices are shed symmetrically and at the same time on both sides of the structure. This action results in the cancellation of the across wind component and the absence of motion in the transverse direction. On the other hand, when the wind speed is high, the vortices are shed alternately from one side and then from the other. This behavior generates in the transverse direction alternate impulses right and left, which are responsible for an important motion of the building if damping is not implemented. This mechanism is demonstrated in Figure 4. Furthermore, the frequency of wind in the along direction is twice as important as the transverse one. [5]

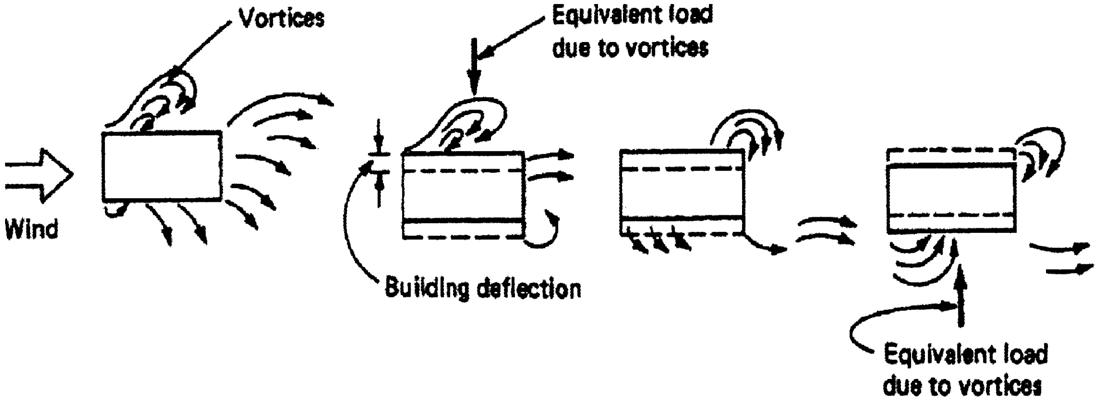

Figure 4: Vortex shedding phenomenon (Taranath, 1988)

For circular cylinders, the character of vortex shedding forces depends on the Reynolds number. For low Reynolds numbers (2 < *Re* < 60), the creation of two symmetric vortices, which are characterized by a steady flow, is noticed. For a value of the Reynolds number greater than 100, the wind flow becomes even more turbulent with even more vortices. The following increase of the Reynolds number results in the separation of the flow at the edges [12]. This turbulent character can be observed in Figure 5, which shows the vortices developed by the impact of Wind on a structure.

The frequency of vortex shedding depends on the mean wind speed at the top of the building, the nature of the wind flow, the Strouhal number S (a dimensionless parameter characterizing the shape), the diameter of the building (characterizing the size of the structure), and finally the surface roughness.

Up to a wind velocity limit of 50 mph associated with a Strouhal number of 0.21, the variation between the Strouhal number and the wind speed is irregular. Beyond this wind velocity (wind velocities between 50-115 mph), the Strouhal number is constant and equal to 0.20.

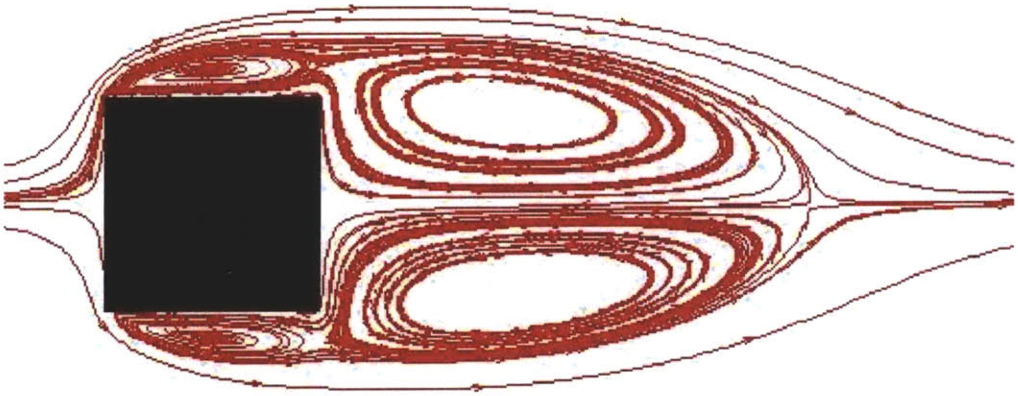

Figure 5: Vortices created by the impact of wind on a structure [17]

3) Comfort Criteria: Human Response to Building Motion

The buildings' motion due to wind can be significant. Therefore, the associated large oscillations and increasing displacements can be responsible for the partial or total failure of the structure. Although engineers make sure to design buildings that are going to resist to structural damages, small oscillations of the building remain possible. However, these small oscillations sometimes lead to human discomfort. Thus, the main challenge of engineers is, beyond the resistance and stability of the structure, to ensure the comfort of people through acceptable amplitudes of oscillations.

The horizontal force that causes human discomfort is directly associated with the horizontal acceleration ($F = m \cdot a$). Therefore, the acceleration is the parameter that allows us to characterize the effects of buildings' motion on humans. Studies have shown that motion perception of humans is activated for accelerations of the order of the milli-g. Given that it is utopian to design a building without any motion, it is important to determine the maximum acceptable acceleration that would not disturb the occupants of a tall building. In order to do so, many studies have been conducted to define the perception limits. These studies have been based on the maximum accelerations, which often occur at the top of buildings. [8]

Human comfort is associated with the human perception to the motion of buildings. Therefore, it is hard to characterize it. In order to try to come up with a possible analysis of the comfort criteria, many physiological and psychological parameters characterizing human comfort have been studied such as the occupants' experience, activity, and orientation. Given that high-rise buildings are the most affected by wind loadings, research has been undertaken in the frequency range the most adequate for slender structures, which is between zero and one Hz. This range of frequencies defines the response of slender structures quite well. Moreover, the frequency and acceleration associated with building motion are interconnected. Therefore, Table 1 indicates the human response to building motion in function of the acceleration at the top of the structure [8].

Table 1: Human perception levels adapted from [1]

LEVEL	ACCELERATION (milli-g)	EFFECT
1	< 5	Humans cannot perceive motion
2	5 - 10	a) Sensitive people can perceive motion b) Hanging objects may move slightly
3	10 - 25	a) Majority of people will perceive motion b) Level of motion may affect desk work c) Long-term exposure may produce motion sickness
4	25 - 40	a) Desk work becomes difficult or almost impossible b) Ambulation is still possible
5	40 - 50	a) People strongly perceive motion b) It is difficult to walk naturally c) Standing people may lose balance
6	50 – 60	Most people cannot tolerate motion and are unable to walk naturally
7	60 – 70	People cannot walk or tolerate motion
8	> 85	Objects begin to fall and people may be injured

Given different magnitudes of wind in a region and different kinds of buildings, the parameters associated with human perception vary. Indeed, the return period of the excitation decreases when the probability of significant wind increases. In addition, in the same region, the acceptable acceleration (ensuring comfort) varies with the nature of buildings. As a matter of fact, in North America, the acceptable acceleration for residential buildings is 10-15 milli-g, whereas it is 20-25 milli-g for office buildings. This difference can be explained by a higher rate of occupancy for the residential buildings due to nightlife.

Thanks to a global analysis of the human comfort parameters, the International Standards Organization (ISO) has set up the acceptable accelerations at the top of buildings for a return period of five years. As shown in Figure 6, the established plot couples the natural period of buildings with the accelerations at their top that should not be exceeded for a return period of five years. For example, for a building with a natural period of seven seconds, the acceleration should not exceed 20 milli-g for a return period of five years [5].

Given that most of the studies have been conducted with available data (in this case data relative to office buildings), the results found through the plot are more relevant for office buildings. Acceptable accelerations for residential buildings are often 20% to 30% lower because of the highest rate of occupancy. Knowing that for a specific tall building, it is possible to find its natural period, this period is used through the plot to find the maximum allowed acceleration at the top of the building for a return period of five years.

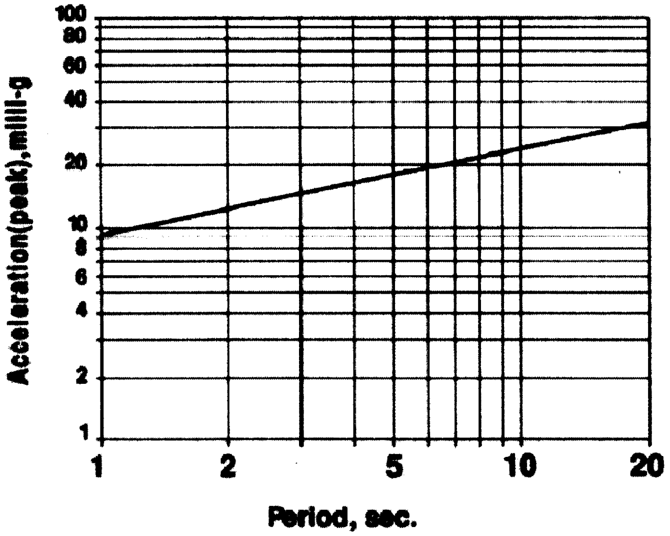

Figure 6: Guideline for five year acceleration in buildings (RWDI Inc, 2008)

In the US, more and more buildings are being constructed in hurricane and typhoon regions. Given that these areas are characterized by strong winds that can strike at any time and thus lead to significant buildings' motion, it is relevant to reduce the return period from five years to one year while decreasing the acceptable accelerations to values 30 % lower than those set up for a return period of five years.

The occupants of these buildings may decide to stay just before the storm strikes and thus feel discomfort because of excessive oscillations of the buildings. Therefore, in those areas, a return period of one year for the wind has to be taken into consideration.

4) Wind Design

When it comes to the design of high rise buildings, wind engineering is of utmost importance. However, wind is not a parameter that can be controlled because of its complexity and uncertainty. Therefore, Codes are struggling in establishing the standards that have to be respected for wind engineering design. Thus, the Standards that exist have to be taken as indicators and are not specifically responsible for the possible failure of the structure.

To design a structure according to the standards of the Codes, three characteristics have to be achieved:

- Stability against overturning
- Strength of the buildings' components while ensuring resistance against failure during its service life
- Serviceability of the structure while keeping the deflection and drift of the structure small enough to avoid cracks on non structural elements

Wind engineering design can be approached with a Static Analysis method or a Dynamic Analysis method. Based on the quasi-steady approximation, the static method is usually applicable and appropriate for low rise buildings (structures less than 50 m high) because they can be assumed to be fixed with wind. Meanwhile, the dynamic analysis is adequate for tall and slender structures subjected to wind excitation. The Codes treat wind forces as static. However, Dynamic Analysis has to be undertaken for slender structures in order to ensure their stability.

Wind is a parameter in perpetual change. Indeed, the amplitudes and frequencies of wind fluctuations can vary in a very broad range over time because of the turbulent nature associated with wind. When it comes to wind design, and in order to simplify these permanent fluctuations, most international Codes have decided to use the quasi-steady approximation. This method is based on the replacement of the dynamic wind pressure by the use of a conservative static wind pressure: the maximum peak pressure affecting the building. This maximum peak pressure is a function of the gust dynamic wind pressure weighted with some pressure coefficients. Wind tunnel tests can determine these coefficients [1].

Assuming that the maximum value for wind speed is characterized by the maximum peak pressure, it is easy to analyze the impact of wind engineering on structures. Indeed, the fluctuations of the gust dynamic wind pressure will be used to determine the pressures applied to the structure. Applicable to small scale structures, the quasi-steady approximation remains an approximation good enough to find the wind forces applied to high rise buildings. In addition, this method has the advantage of using existing meteorological information on wind gusts, thus making the design of wind engineering easier.

In the United States, wind engineering can be approached using the Code ASCE7-05. This code calculates the wind pressure hitting a building by taking into consideration many parameters such as: the topography of the soil, the exact direction of wind and the gust effect. The velocity pressure evaluated at height z is given by:

$$\boldsymbol{q_z} = 0.613 \cdot K_z \cdot K_{zt} \cdot K_d \cdot V^2 \cdot I \ (\frac{N}{m^2}),$$

where

K_z is the velocity exposure coefficient

K_{zt} is the topographic factor

K_d is the wind directionality factor

V is the basic wind speed

I is the importance factor

The above formula exhibits the increase of the velocity pressure with the increase of the building height. The higher the location at which the pressure is applied, the greater is the importance factor. This effect results in an increase of the velocity pressure with height. This feature is illustrated in Figure 7. Moreover, the topographic factor increases when the density of the city decreases. The increase of this factor also leads to an increase of the velocity pressure, as shown in Figure 7.

Figure 7 exhibits the fact that the average wind speed increases with height until it reaches a limit: the gradient wind velocity. Near the Earth surface, frictional effects are significant and lead to a relatively small wind velocity. As the height increases, the frictional effects decrease, making the wind speed grow. This process happens within a layer delimited by the ground where the wind velocity is almost zero, and the gradient height where the wind velocity reaches the gradient wind velocity [5].

The wind velocity increases following a parabolic shape until reaching an asymptote. The asymptote, which defines the gradient wind velocity, is characterized by the insignificant frictional effects at great heights and the air movements driven by pressure gradients in the atmosphere. Meanwhile, the parabolic shape is caused by a retarding effect occurring at the surface level and decreasing with height. Moreover, the gradient height depends on the surface conditions (type of terrain: compact city or not, countryside or close to the sea).

Moreover, the boundary layer can vary from 500 m to 3000 m depending on the surface roughness of its surroundings.

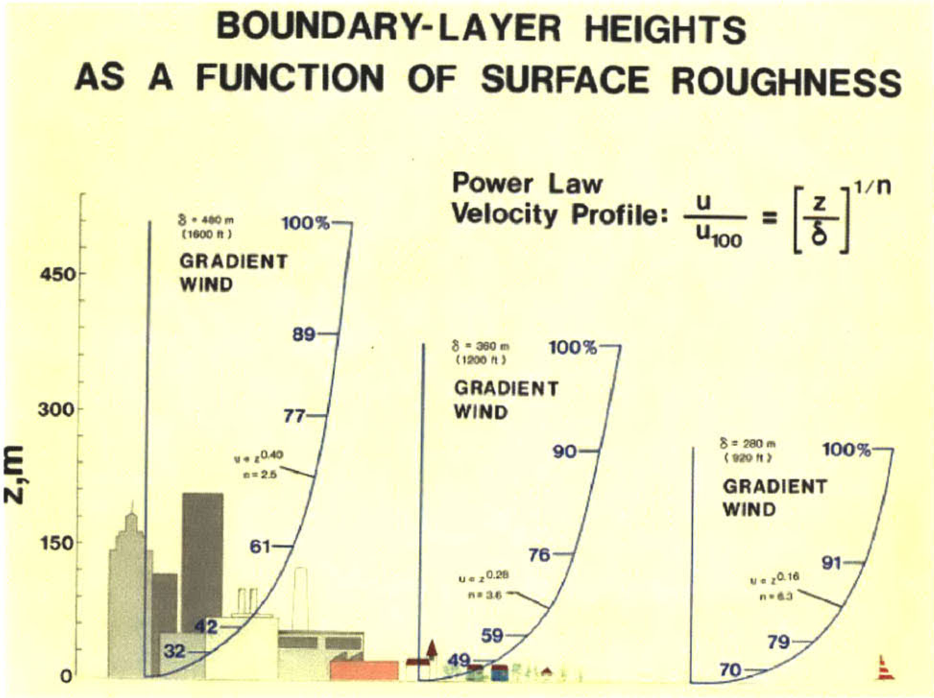

Figure 7: Distribution of wind loading with height [18]

The wind distribution shown in Figure 7 highlights the fact that wind effects increase with the height of the building. This wind distribution clearly corroborates the expected distribution of buildings' stresses indicated in Figure 8.

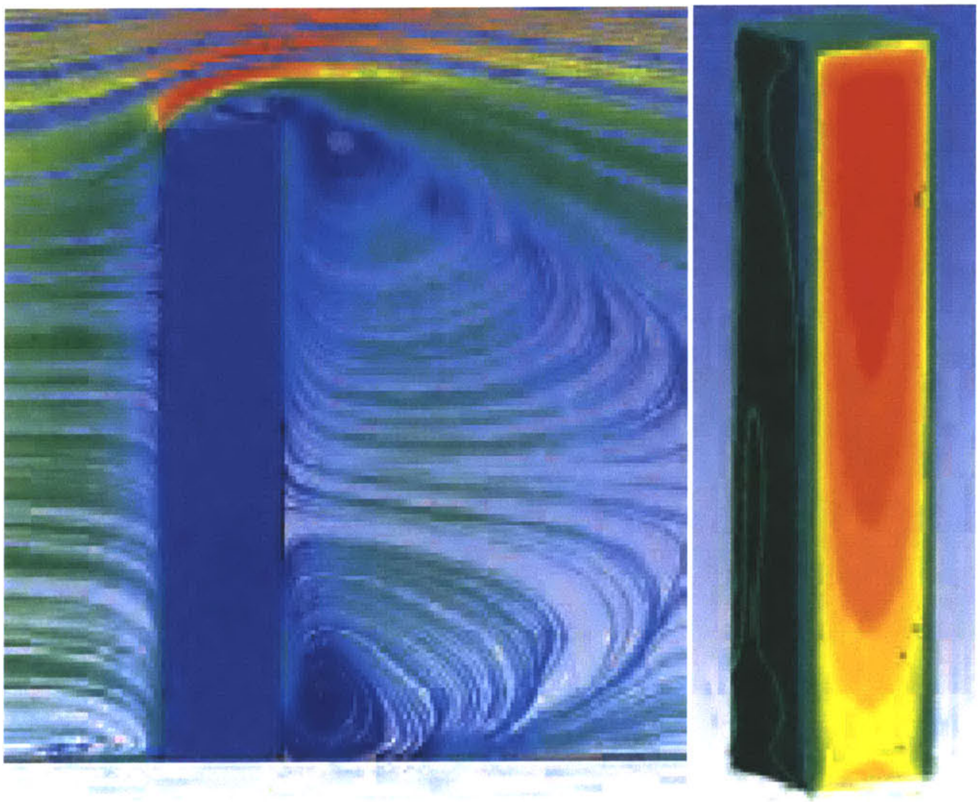

Figure 8: Stresses generated by wind loading on buildings [1]

3 TMD, Active Control and Energy Dissipation

1) Tuned Mass Dampers (TMDs)

A tuned mass damper (TMD) or harmonic absorber is a device implemented in structures in order to decrease the structure motion caused by an external harmonic vibration. An external force such as wind that applies a force on a building makes the building undergo accelerations. If theses accelerations are high, they can generate human discomfort. Tuned mass dampers that are cost effective devices to add damping, are therefore implemented. These devices are even more implemented in skyscrapers because of the mitigation of the wind induced movement that has to be provided. This system has been used for example in the PETRONAS Towers as shown in Figure 9. This Figure presents the components of the tuned mass damper employed.

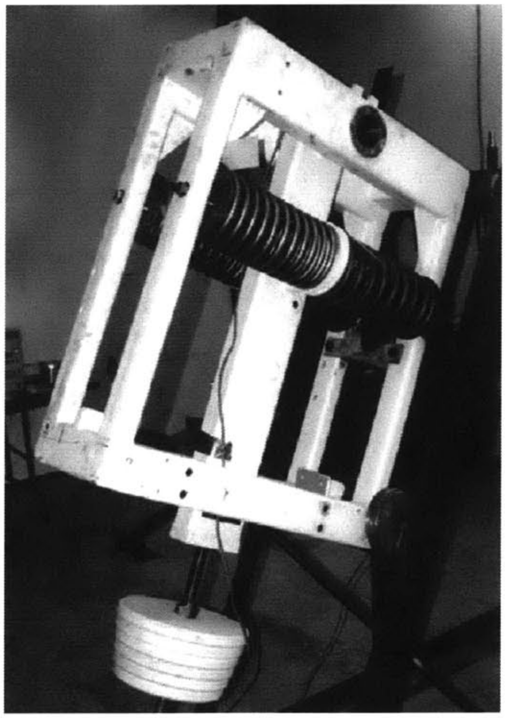

Figure 9: One of the TMDs designed for the PETRONAS Towers [7]

Composed of a mass, spring, and a damping element, the tuned mass damper is always positioned at the level of the structure where the greatest displacements are measured. This location allows the TMD to fully fulfill its role by optimizing the dissipation of energy and thus effectively reducing the dynamic response of the structure. Regarding buildings, since the maximum acceleration is felt at the top of the structure, the TMD is usually positioned there in order to mitigate the effect of an external force and to avoid discomfort, damage or worse structural failure. The implementation of the TMD at the top of the structure consequently decreases the displacements that have amplitudes that may reach a meter or more. However, the down side of TMDs is that they are massive structures that occupy a significant space.

The TMD is established in such a way that its motion is opposed to the building motion. The inertia of the important mass of the structure is therefore counterbalanced by the motion of the TMD. Once the building starts vibrating because of external forces, the TMD begins operating. As Figure 10 demonstrates, the motion of the TMDs is opposed to the vibration direction of the building. When the external force leads to a right motion of the building, the TMD generates a force to the left thus damping the building's oscillation. When the building is hit by strong winds the TMD can move up to a distance of 2 to 5 feet. [6]

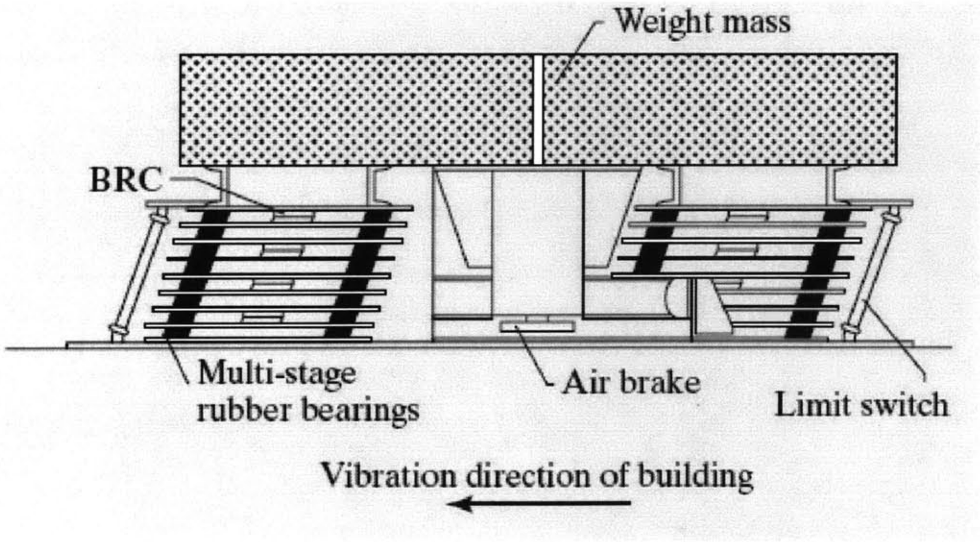

Figure 10: Tuned mass damper with spring and damper assemblage [4]

In order to cancel the horizontal displacement of a structure, the frequency and amplitude of the TMD should be nearly the same compared to the frequency and amplitude of the structure. In this case, any motion or push of the structure due to wind is directly counterbalanced by an equal and opposite effect produced by the TMD. This allows canceling the displacement of the structure. Once the wind strikes the building, if the frequencies or amplitudes of the TMD and the structure don't match, their opposite effects won't match leading thus to an absence of damping on the building motion. Figure 11 shows the response of a TMD when a structure moves.

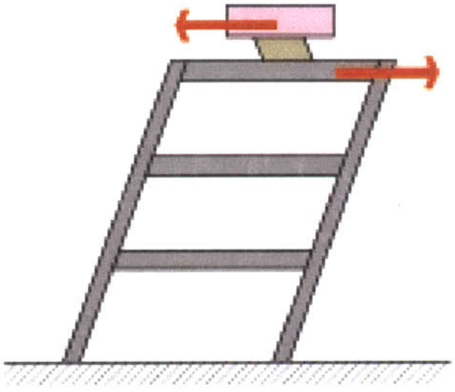

Figure 11: Response of a TMD to the motion of a structure [16]

The spring, mass and damper of the TMD are "tuned" in order to get a frequency matching the frequency of the structure. Therefore, the TMDs are tuned to avoid resonance of the building. Indeed, the excitation of the structure at its natural frequency makes the TMD resonate out of phase with the structural motion. The device is activated when acceleration is felt by the structure. The motion of the device implemented, monitored with sensors, results thus in the dissipation of energy. The effectiveness of a TMD depends on three parameters:

- the mass ratio : ratio of TMD mass to modal mass of the structure (m/M)
- the damping ratio of the TMD (effectiveness of the damping on the energy dissipation)
- the tuning ratio: ratio of the frequency of the TMD to the frequency of the structure (the ideal case would be a tuning ratio of 1 in order to cancel the opposite effects of the external force and the TMD).

Generally, the mass of the TMD is small compared to the total mass of the building (about 1%). This TMD has to be tuned when implemented. However, the building period changes over time because of the variation of its occupants, the adding of non-structural elements or the decrease of the building stiffness due to strong winds. That is why, with the change of the building period over time, the tuning of the TMD has to be refined. Studies have allowed enhancing the effectiveness of a TMD while decreasing the excitation frequency bandwidth. Therefore, a single TMD is not effective when structure has more than one critical mode because the TMD is ideally tuned only for one particular mode. Thus, if many of the building modes are excited, especially the higher modes of the structure, many TMDs tuned to different frequencies will be necessary. Moreover, when an event with wide-band excitations hits the building (such as a seismic event) the TMD, tuned for a specific range of frequencies, proves to be ineffective.

Given that a TMD is a device that is efficient for a particular mode (generally the first mode of the structure); it is logical to think that the addition of several TMDs will make the building resist better to wind induced oscillations because a wider range of frequencies will be controlled. However, studies have showed that the implementation of a second TMD leads to insignificant improvements regarding the structural response of a building to wind or seismic loading. This is due to the fact that the mass participation ratios of the other critical modes keep decreasing. Thus, the addition of TMDs tuned for modes whose mass participation ratios are diminishing won't ameliorate significantly the vibrations of a building. [6]

Studies have also allowed highlighting that the effectiveness of a TMD increases with the decrease of the inherent damping ratio of the structure. Besides, for a given damping ratio for a structure, the effectiveness of a TMD increases with the increase of its mass ratio. [6]

Given the peak acceleration for a given return period, wind tunnel testing helps choosing whether a TMD should be implemented or not. As a matter of fact, wind tunnel testing is one of the most accurate methods used in order to define the impact of wind on buildings. Often required for high rise buildings, wind tunnel testing constitutes a really precise measurement because it takes into account the specific parameters of the analyzed building such as the site conditions or the aerodynamic shape of the building.

Since a TMD is powered by electricity, if a power surge happens, the TMD doesn't fulfill its role of energy dissipation. This can prevent the decrease of building motion and thus affects the stability of the structure. That is why the TMD has to be connected to an emergency power system.

The wind excitation hitting a building can be defined when the maximum amplitude and the frequency of the wind excitation are known. Generally, if the frequency of the excitation is not known, the worst case scenario is assumed in order to model the design. This scenario is taken by choosing the frequency of the excitation to be equal to the fundamental frequency of the building. P can be found through wind tunnel testing. Indeed, this amplitude is calculated using the peak acceleration usually measured at the top of the building along a certain period of time. It can be noticed that taking time as a scale factor for wind excitation might be erroneous because of the possibility of missing the peak acceleration. It is thus better to use a steady state function.

2) Active Control and TMDs

Since a passive tuned mass damper can only be efficient for a certain band of frequencies, it is logical to grant active control to the device in order to improve the oscillation control performance and widen the range of applicability of the TMD. Active devices are more developed and used in order to enhance the effectiveness of TMDs. One of their roles is to minimize the relative displacement of the TMD. Active systems also allow lowering the necessary space of the TMD by decreasing the size of its mass.

Active control is characterized by the use of actuators whose energy comes from an external power source. In those active systems, sensors are needed to measure the vibration level of the structure and gather data over the life cycle of the building. The data is then sent in real-time to computers and software to analyze the excitation of the structure and establish the control forces needed. The actuators finally respond to the data analyzed in order to supply and transmit the specific amount of energy needed to control the energy flows of the structure. The role of the actuators will be to dissipate or add energy to the structure in function of the demand. The actuators produce the complementary forces needed by the TMD to better mitigate the vibrations in the building. The duality between sensors and actuators is major in the increase of the active control effectiveness. Thus, the range of frequencies covered by a TMD is wider, improving the effectiveness of the device. The active force acting between the structure and the TMD leads to higher levels of damping in the building improving the effectiveness of the TMD. As a matter of fact, the mass of the TMD is driven by the actuator allowing thus to increase and control the equivalent damping ratio of the TMD.

The concept of active control has first been applied to the field of civil engineering by Yao in 1972. In 1975, Yao dug deeper in the field by studying active control for wind induced vibrations in tall buildings [9]. Since then, in order to improve the serviceability and stability of high rise buildings, a lot of research has been carried out to try to optimize the relationship between sensors and actuators. Concerning wind engineering control, three major active devices have been developed and set up in high rise buildings:

- the AMD (active mass driver shown in Figure (12-a)): a TMD for which the damper is replaced by an actuator. For such a scheme, the passive energy dissipation normally permitted thanks to the damper removed is replaced by the control forces generated by the actuator.
- the ATMD (active tuned mass damper shown in Figure (12-b)): a TMD for which an actuator is added to the existing spring and damper. The active tuned mass damper is also called "hybrid" control system because it keeps all the components of the passive TMD.
- the DUOX system (shown in Figure (12-c)): an AMD (auxiliary mass + actuator) added to a passive TMD. The addition of the AMD allows generating a complementary force that is out of phase with the passive TMD decreasing thus its relative displacement. [9]

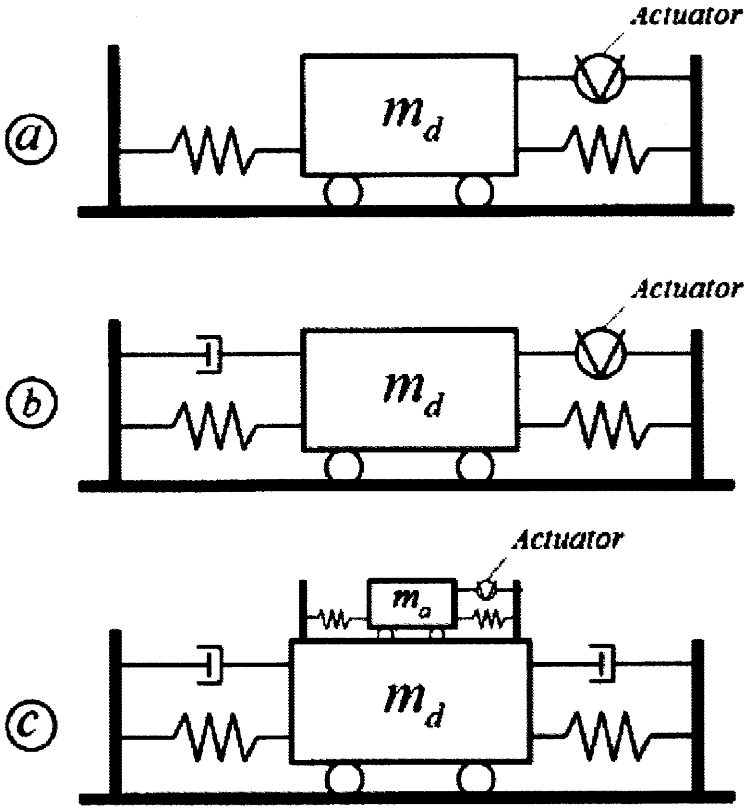

Figure 12: Different active TMDs schemes [9]

The active TMD's synchronized response to wind dynamic loading and the amelioration of the controlled bandwidth make the effectiveness of the active control. Nevertheless, active devices significantly rely on external power energy and any power failure leads to the inability to use them. The problem is that power failures often happen during extreme events (such as wind storms) and it's during those times that the controls are the most needed. Moreover, engineers are often reluctant to rely on sensors controlling the demands of energy needed by a building. Indeed, they know that any dysfunction of those electronic devices can result in many stability issues in the structure.

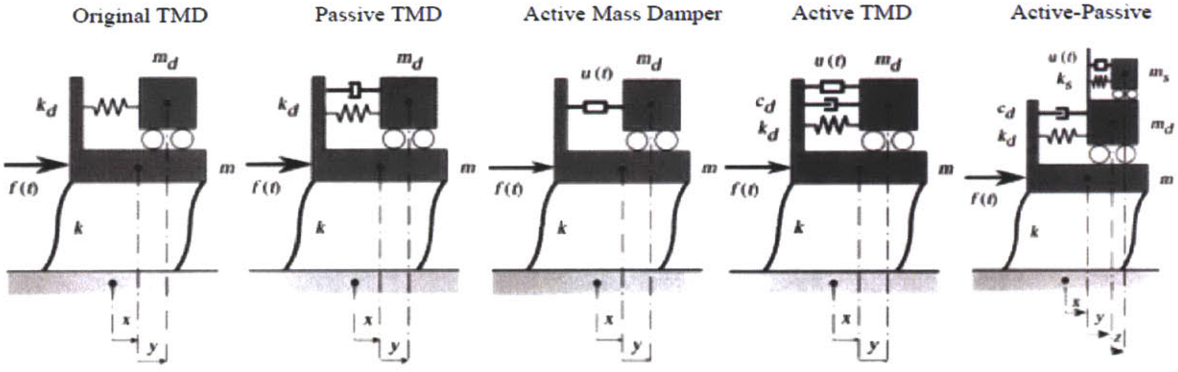
Original TMD Passive TMD Active Mass Damper Active TMD Active-Passive

Figure 13: Evolution of the schemes of tuned mass dampers [3]

During the past 30 years, significant progress has been made regarding active control for what are called "Dynamic Intelligent Buildings". The control system associated to active TMDs has been evolving a lot since 1980. Indeed many breakthroughs have been achieved in the field of active control for the civil engineering field throughout the years. Figure 13 shows the evolution of TMDs.

The concept of Active TMD for buildings has been developed by Morison and Karnopp in 1973 [3]. Then, Soong was one of the first engineers to test and optimize active TMDs in order to highlight the benefits of using active control in passive TMDs. Then, Abdel-Rohman undertook some research to analyze how to optimize the components of a TMD when the input of energy is changed. Later on, through the acceleration feedback approach, Mackriell examined the implementation feasibility and efficiency of ATMDs in the context of high rise buildings subjected to wind loading. As for the engineer Ideka, his studies regarding the LQR control theory and its applications greatly helped the field of stroke of actuators. [9]

The first active TMD was implemented in 1989 in an office building in Tokyo (the ten-story Kyobashi office building). The range control brought by this kind of device is widened. Indeed, the damping is efficient in many structural modes contrary to a passive TMD. The design of an active tuned mass damper is suggested in Figure 14. The moving mass on top of the device is driven by units placed in the X and Y direction. Fixed on frames, these units allow the active mass drivers ensuring the dissipation of energy. Moreover, studies have showed that the implementation of an active TMD reduces the building vibrations by about 25%. [9]

Finally, the main issues encountered by active TMD devices are their cost and lack of stability. The maintenance needed for such devices increases the cost. On the other hand, the implementation of complex electronic components within those active control systems increases the instability risks. All of those disadvantages make engineers look for alternatives to TMDs totally based on active control.

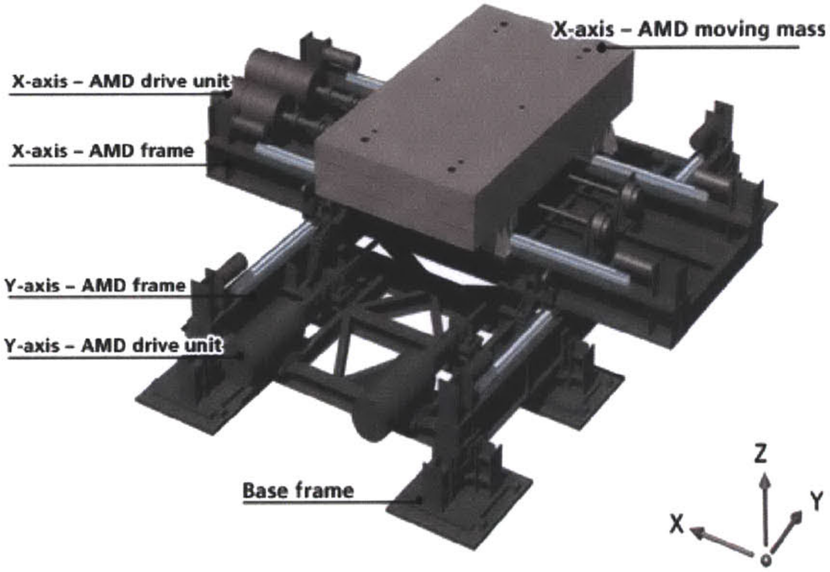

Figure 14: Design of an active mass driver [15]

3) The Choice of a Semi-Active Tuned Mass Damper

A) Semi-Active Tuned Mass Dampers

Because of stability issues induced by active control, semi-active control has been developed. This kind of control has the benefits of passive control while ensuring the stability of the structures due to a lowest external energy used compared to the active schemes. Instead of implementing actuators that control the forces needed, semi-active control is based on the ability to change forces through variable stiffness and damping devices. Thus, in order to change those parameters, only a small amount of energy is necessary. This energy can simply be provided for example by a battery. Moreover, unlike active control for which energy can be added, semi active TMD only dissipate energy.

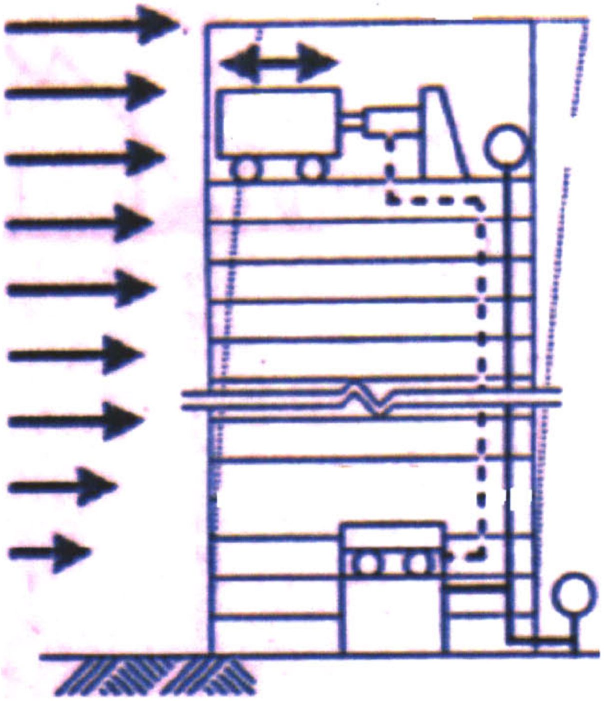

Figure 15: Building with a semi-active TMD hit by a wind [14]

The small amounts of energy required (that can be supplied by a battery) make semi-active TMDs reliable devices because they can operate continuously even during a power failure. Therefore, these devices are stable and energetically cost effective. However, semi-active TMDs, similarly to active TMDs, are driven by sensors and computer-controlled feedback that can be risky if there are electronic failures. This feedback control is pictured in Figure 15. Indeed, in this case, a sensor placed in a particular floor transmits the information to the actuator on top, resulting thus in the supply of the force needed to mitigate the oscillations induced by wind. Furthermore, semi-active TMDs have limitations in the range of forces that can be reached because of the restricted stroke length. Those limitations have to be investigated in order to optimize the devices [9].

In spite of all the research that has been made regarding semi active TMD and all the proven benefits, no semi-active TMD has been yet set up in civil engineering buildings because of the significant cost of implementation.

B) The Modified Friction Device (MFD)

Fluid and mechanical issues, electronics reliability and the need for an external power source are all reasons explaining the reluctance to use semi-active TMDs in civil engineering structures. Tackling all these issues, the modified friction device (MFD) has been developed.

The MFD is based on the friction that can be provided by the semi-active scheme shown in Figure 16. Implemented around two steel plates, the friction pad generates the amount of friction needed by the system. Moreover, between the two steel plates, solenoids are set up in order to enable the electric current to vary. Therefore the force supplied by the MFD can be changed and adjusted according of the force required. [11]

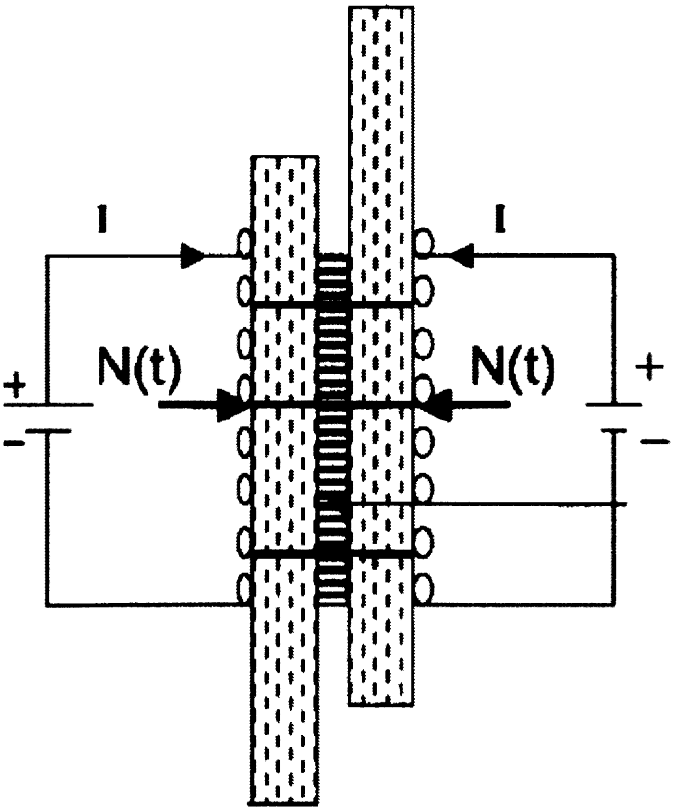

Figure 16: Variable friction device [9]

Composed of a variable friction element, a spring and a damper, all placed in parallel, the MFD shown in Figure 17 has been designed in such a way that when no voltage is implemented, the force applied is 20 kN. Therefore, given that the desired force provided by the MFD is 200 kN, the remaining 180 kN have to be granted by the variable friction device. Thus, the MFD is characterized by its great damping forces (about 200 kN) relying only on 12-volts batteries. The necessary control that has to be provided by the friction device is consequently monitored by the fluctuation of voltage of the batteries. [11]

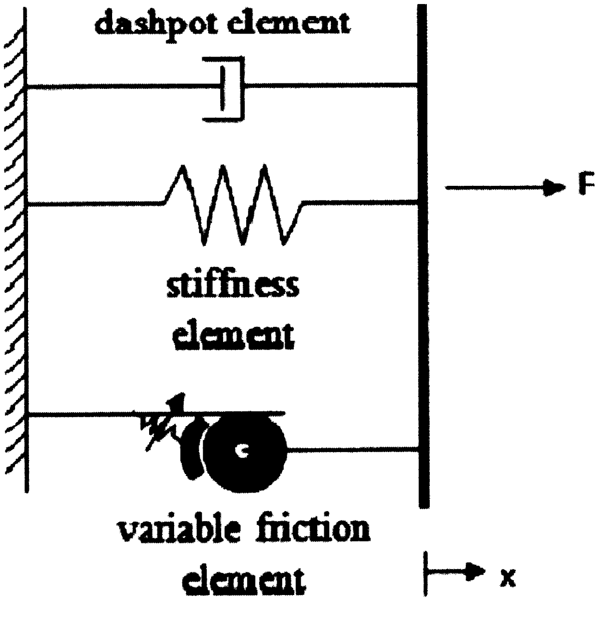

Figure 17: Design of the modified friction device [11]

By using a braking system, widely used for cars, the design of the MFD, which is an active device, becomes more reliable. All the improvements made allow us progressively considering the implementation of semi-active damping systems in civil structures.

The braking system employed for the design of the MFD is described below. Such a scheme helps the forces needed to be established more easily because of the hydraulic actuator employed in the device [11]. The variable friction element of the MFD is shown in Figure 18.

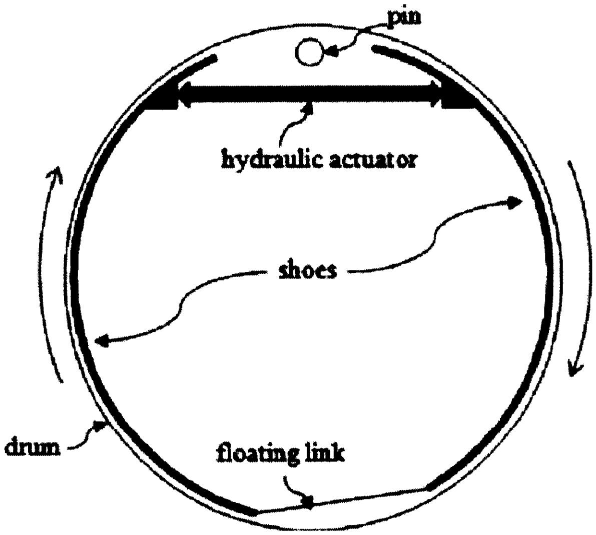

Figure 18: Design of the variable friction element [11]

The uniqueness of this system relies on the effectiveness of the friction provided. First, the control system transmits to the actuator the force that has to be applied. This hydraulic actuator compresses or expands in function of the friction required. The force granted by the actuator is then transferred to the shoes, and results in a reaction at the level of the floating link. Finally, all the mechanism described above leads to the expansion of the shoes. This action provides the frictional forces required because the shoes get in contact with the drum. [11]

The MFD studied in this thesis has a maximum damping force of 200 kN (45 kips). The force associated with the whole MFD is:

$$F_{mfd} = F_{friction} + k_{mfd} \cdot x + c_{mfd} \cdot \dot{x}^{\beta},$$

where:

$F_{friction}$ corresponds to the force generated by the braking element

K_{mfd} is the spring of the MFD

C_{mfd} is the dashpot of the MFD

x is the stroke of the MFD

$\dot{x}$ is the velocity of the MFD

Moreover, the friction element is characterized by a hysteresis behavior. When the actual force provided by the friction element is below the force required, the voltage of the battery is maximum (known as the passive-on case). Once the two forces become equal, the velocity and voltage associated with the MFD both go to zero (known as the passive-off case or the fail-safe mechanism). When the velocity of the MFD changes sign, the voltage switches again to a full voltage in order to enable the control of the structure. [11]

The MFD has been introduced in this thesis to highlight its effectiveness regarding the mitigation of building motion under wind excitation. It is of utmost importance to ensure acceptable peak amplitudes for the structure. Studies have showed that, compared to passive schemes, the mitigation of building vibrations due to earthquakes is much more efficient when the MFD is implemented. This effectiveness brought by the MFD allows decreasing the cost generated by the damping implemented in slender structures. It is also essential to enhance the effectiveness of the MFD to mitigate the oscillations of a building hit by wind.

Being of vital importance in this kind of scheme, the feedback control generated by this device has to be optimized. For this reason, all the parameters of the MFD have to be investigated in order to provide the best and most reliable possible control.

4 Study of the MFD

In this Chapter, the MFD's parameters and their roles on wind excitation mitigation are analyzed. For this purpose, a MATLAB program simulating the contribution of the MFD has been studied. The model employed involves a structure hit by a certain wind excitation. A modified friction device coupled with a TMD, both placed at the top of the structure, allows dissipating the motion induced by the wind excitation. The goal of this study is to optimize the parameters of the device implemented in order to provide optimum effectiveness and thus grant the best possible control (control of displacements and velocities).

1) Modeling of the Controlled System

A) The Physical Model

The physical model used to describe the whole structure is a three degree of freedom system.

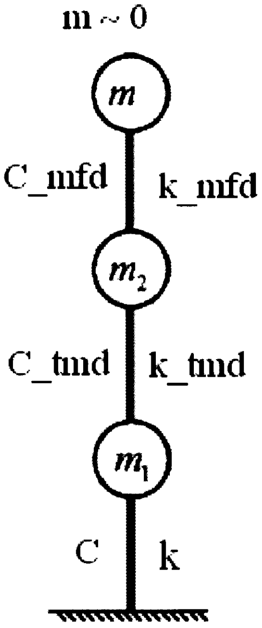

Figure 19: Model implemented in the MATLAB program

First, with a total mass "m" of 10^6 kg, the building has been modeled as the first degree of freedom with a natural frequency of 0.6164 Hz. This mass has been connected to the soil through the fundamental mode stiffness of the structure. Then, the building has been subjected to wind excitation. The wind excitation hitting the building has been modeled as a sinusoidal function characterized by a random frequency ranging from 0 to 4 Hz (in which the fundamental frequency of the building is included) and a maximum amplitude taken between 70 and 100 KN ($Wind = P \cdot sin\,(f.t)$).

Second, the TMD has been modeled as the second degree of freedom with a mass 100 times smaller than the mass of the primary structure. With a mass ratio $\mu = 0.01$, the mass of the TMD is thus $M_{tmd} = m \cdot \mu = 10^4\, kg$. The stiffness and damping elements of the TMD are characterized by the formulas below:

$$k_{tmd} = M_{tmd} \cdot (f_{opt} \cdot W_n)^2$$

$$C_{tmd} = 2 \cdot \xi \cdot W_n \cdot M_{tmd}$$

Where f_{opt} and ξ are the optimal tuning and damping parameters as defined below:

$$f_{opt} = \frac{\sqrt{1 - 0.5 \cdot \mu}}{1 + \mu}$$

$$\xi = \sqrt{\frac{3 \cdot \mu}{8 \cdot (1 + \mu) \cdot (1 - 0.5 \cdot \mu)}}$$

All the parameters defined previously enable to establish the general matrices of the two degree of freedom system modeling the structure and TMD.

$$M = \begin{pmatrix} m & 0 \\ 0 & m \cdot \mu \end{pmatrix}$$

$$K = \begin{pmatrix} k + k_{tmd} & -k_{tmd} \\ -k_{tmd} & k_{tmd} \end{pmatrix}$$

$$C = \begin{pmatrix} k + k_{tmd} & -k_{tmd} \\ -k_{tmd} & k_{tmd} \end{pmatrix} \cdot \frac{c_{tmd}}{k_{tmd}}$$

Where:

M is the mass matrix of the combined structure building + TMD

K is the stiffness matrix of the combined structure building + TMD

C is the damping matrix of the combined structure building + TMD

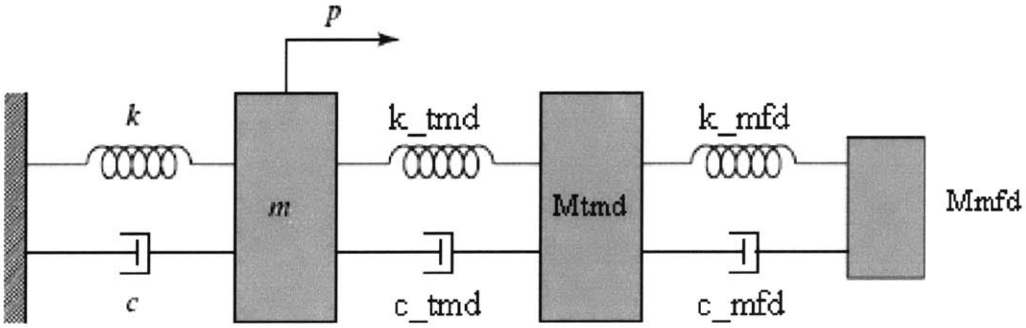

Figure20: Single degree of freedom system with TMD and MFD

Finally, characterized by a negligible mass in comparison with the mass of the structure and TMD, the MFD has been modeled as the third degree of freedom. The stiffness of the MFD has been chosen to be $2 \cdot 10^4\ kN/m$ and its damping element is $1.2 \cdot 10^7\ kg \cdot s^{-1}$.

Moreover, the control provided by the modified friction device is scaled thanks to a control weight matrix that allows choosing the influence weight of the MFD.

Furthermore, the behavior of the MFD has been defined assuming many considerations.
First, a battery of 12 volts grants the energy needed by the device. The MATLAB program is set up in such a way that the voltage could be predefined by the operator (by keeping it constant) or could be set up automatically (in which case the control is on). In addition, the voltage delay of the battery has been applied to the model. This voltage delay is employed in the voltage dynamic. Indeed, it makes the actual voltage of the device catch up with the voltage required.
By operating outside the hysteretic behavior, a sliding controller has been employed in order to find out the voltage needed by the MFD and enable the actual force to reach the force required. Therefore, the monitoring operation is intended to reduce the difference between the required force and the applied force to zero.

Moreover, the fail-safe parameter has been taken into account. The fail-safe condition allows minimizing the effects of failures by reducing the harm that can be caused to people or to the other devices implemented in the structure. Such a scheme helps to mitigate the unsafe consequences of failures.

Another factor injected in the MATLAB program is the possibility of an earthquake. However, given that only the mitigation of wind excitation is of interest, the analysis of earthquake simulation has been turned off in the program.

The MFD modeled in the program has been coupled with different maximum force capacities (90 kN, 200 kN or 1350 kN). This panel of choices offers the chance to analyze the effects of the change of the force capacity on the quality of the control. Nevertheless, for the study undertaken, the maximum force has been set at 200 kN.

The most important feature of the program is the fact that it keeps in memory the behavior of the MFD in function of the behavior of the building. This feature allows predicting the next steps undertaken by the structure.

- **Design of the sliding controller**

In order to select the voltage needed, the Lyapunov function has been used through the implementation of a sliding controller:

$$V = \frac{1}{2} \cdot s^2$$

With:

$$s = F_{act} - F_{req}$$

Where:
V is the voltage needed
s is the sliding surface
F_{act} is the actual force granted
F_{req} is the force required

In order to compute the required voltage, the Lyapunov function has to be minimized. In order to do so, the derivative of this function is expressed below:

$$\dot{V} = s \cdot \dot{s}$$

Using the definition of the sliding controller surface, the derivative of the Lyapunov function can be rewritten as follows:

$$\dot{V} = s \cdot (\dot{F}_{act} - \dot{F}_{req})$$

Using the LuGre Model and the equations below,

$$F_{act} = F_{friction} + k_{mfd} \cdot x + c_{mfd} \cdot \dot{x}^{\beta}$$

$$\dot{V} = -\varepsilon \cdot s^2$$

The voltage required can be expressed as follows:

$$v_{req} = v_{act} + \frac{(-\sigma_2 \cdot \ddot{x} - k_{mfd} \cdot \dot{x} - \beta \cdot c_{mfd}\ddot{x}^{\beta-1} + \dot{F}_{req} - \epsilon \cdot s)}{\eta \cdot F_{c,0}} \cdot sgn(\dot{x})$$

Where:

$F_{c,0}$ is the nominal friction Coulomb

η takes into consideration the voltage delay

v_{act} is the voltage input

v_{req} is the required voltage

σ_2 is a constant defined in the LuGre Model

ϵ models the uncertainty of the model (this parameter is positive)

- **Parameters of the MFD**

Table 2: Parameters of the MFD studied

α	2
β	1
$\dot{x}_s$	0.002 m/s
F_{cmax}	168 kN
F_s ($= 1.17 \cdot F_{cmax}$)	196.66 kN
k_{mfd}	$2 \cdot 10^4$ kN/m
c_{mfd}	$1.2 \cdot 10^7$ kg.s^{-1}
σ_0	$1 \cdot 10^9$ N/m
σ_1	$1 \cdot 10^8$ N.s/m
σ_2	$6.5 \cdot 10^6$ N.s/m
η	0.02
ξ	100

- **Parameters of the structure**

Table 3: Parameters of the structure studied

m	10^6 kg
μ	0.01
$K_{building}$	$1.5 \cdot 10^7$ N/m
Frequency of the Building	0.6164 Hz
Frequency of the wind	Ranging from 0 to 4 Hz
Amplitude of the wind	70 to 100 kN
Fail-safe	On
R	0.0005775

- **Matrix controlling the influence of the MFD**

$$Q = 1000 \cdot \begin{pmatrix} 1000 & 0 & 0 & 0 \\ 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 0.0001 \end{pmatrix}$$

B) The Mathematical Model

The mathematical equation that governs the motion of the system is:

$$\boldsymbol{M \cdot \ddot{U} + C \cdot \dot{U} + K \cdot U = W + F}$$

Where:

U is a 2*1 vector describing the displacement of the combined system (structure + TMD)

K is a 2*2 matrix describing the rigidity of the combined system (structure + TMD)

C is a 2*2 matrix describing the damping of the combined system (structure + TMD)

M is a 2*2 matrix representing the mass matrix of the combined system (structure + TMD)

F is a 2*1 vector modeling the force of the MFD

W is a 2*1 vector modeling the wind excitation hitting the building

However, a quadratic equation can be problematic to solve. Indeed an equation of this form can lead to issues finding the control force F needed by the MFD. Therefore, the equation has to be simplified through the process of the state-space formulation of the system. The state-space formulation allows changing a quadratic equation to a first-order equation thanks to the state vector X.

The equation of motion can be rewritten:

$$\ddot{U} = -M^{-1} \cdot \left(C \cdot \dot{U} + K \cdot U\right) + M^{-1} \cdot (W + F)$$

Using the matrix notation, it is possible to reformulate the above equation as follows:

$$\begin{pmatrix} \dot{U} \\ \ddot{U} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -M^{-1} \cdot K & -M^{-1} \cdot C \end{pmatrix} \cdot \begin{pmatrix} U \\ \dot{U} \end{pmatrix} + \begin{pmatrix} 0 \\ M^{-1} \end{pmatrix} \cdot (W + F)$$

Using the state vector

$$X = \begin{pmatrix} U \\ \dot{U} \end{pmatrix}$$

the equation of motion can be expressed with the state- space formulation as follows:

$$\dot{X} = A \cdot X + Bw \cdot W + Bf \cdot F \qquad \mathbf{(1)}$$

Where:

$$A = \begin{pmatrix} 0 & 1 \\ -M^{-1} \cdot K & -M^{-1} \cdot C \end{pmatrix}$$

$$Bw = \begin{pmatrix} 0 \\ 0 \\ \frac{1}{m} \\ 0 \end{pmatrix}$$

$$Bf = \begin{pmatrix} 0 \\ 0 \\ -\frac{1}{m} \\ \frac{1}{m \cdot \mu} \end{pmatrix}$$

With:

A is a 4*4 matrix taking into consideration the mass, stiffness and damping of the model

B_W is a 4*1 vector modeling the effect of the wind on the structure

B_f is a 4*1 vector modeling the effect of the MFD on the structure

W the wind force applied to the structure

F the force granted by the MFD in order to counterbalance the effect of wind

Thanks to this process, solving Equation (1) becomes easier. As a matter of fact, a simple integration of the state-space formulation gives the displacement of the MFD needed to control the motion of the structure. In order to define the necessary control, the clipped optimal control method is used. The clipped scheme is an easy control rule to implement and apply. This scheme thus allows the control generated by the MFD to be reliable.

In order to be able to dispense the exact amount of control needed by the structure, a Linear Quadratic Regulator (LQR) has been added to the device. The role of this LQR is to define the electric current required by the MFD in order to provide the necessary control. Thus, the LQR scheme allows optimizing the input of energy needed to set up the control.

Before integrating Equation (1), the control force F has to be defined. In order to do so, the quadratic function defined below has to be minimized.

$$J = \frac{1}{2} \cdot \int_{0}^{\infty} (X^t \cdot Q \cdot X + U^t \cdot R \cdot U) dt$$

Where:

Q is the matrix controlling the influence of the MFD

R is the matrix taking into account the cost induced by possible uncontrolled forces

The necessary feedback control provided by such a method is given by the formula below:

$$F(t) = -K_c \cdot X(t)$$

Where K_c (solution of the Ricatti Equation) represents the gain and is formulated as follows:

$$K_c = (P \cdot Bf)^{-1} \cdot (A^T \cdot P + P \cdot A + Q)$$

Given the optimal control force, it is possible to find the response of the structure to the wind excitation. The integration of Equation (1) gives:

$$\boldsymbol{X}(t) = e^{\boldsymbol{A} \cdot (t - t_0)} \cdot \boldsymbol{X}(t_0) + \int_{t_0}^{t} e^{\boldsymbol{A} \cdot (t - t_\tau)} \cdot (\boldsymbol{Bf} \cdot \boldsymbol{F}(\tau) + \boldsymbol{Bw} \cdot \boldsymbol{W}(\tau))\, d\tau$$

Where: **e** is the exponential matrix.

Finally it is possible to discretize the solution and modify the previous equation in the form of:

$$\boldsymbol{X_{j+1} = e^{A\cdot\Delta t} \cdot X_j + A^{-1} \cdot (e^{A\cdot\Delta t} - I) \cdot (Bf \cdot F_j + Bw \cdot W_j)}$$

Thus, with an initial state vector X_0, it is possible to define the behavior of the structure in response to wind loading. With such a formula, the effects of the MFD's behavior on the building's motion can be tracked little by little.

2) Analysis of the Results of the MFD Optimization

In this section, the behavior of the MFD under wind excitation is analyzed. A particular structure modeled in MATLAB is hit by wind. The wind has a random frequency ranging from 0 to 4 Hz. The goal of this analysis is to emphasize the mitigation of the structure's motion due to the combined system composed of the TMD and MFD. After presenting the behavior of the MFD in response to the excitation, the dissipation of the building's energy and the mitigation of the oscillations of the structure and TMD are going to be exhibited.

A) Analysis of the Relative Velocity of the MFD

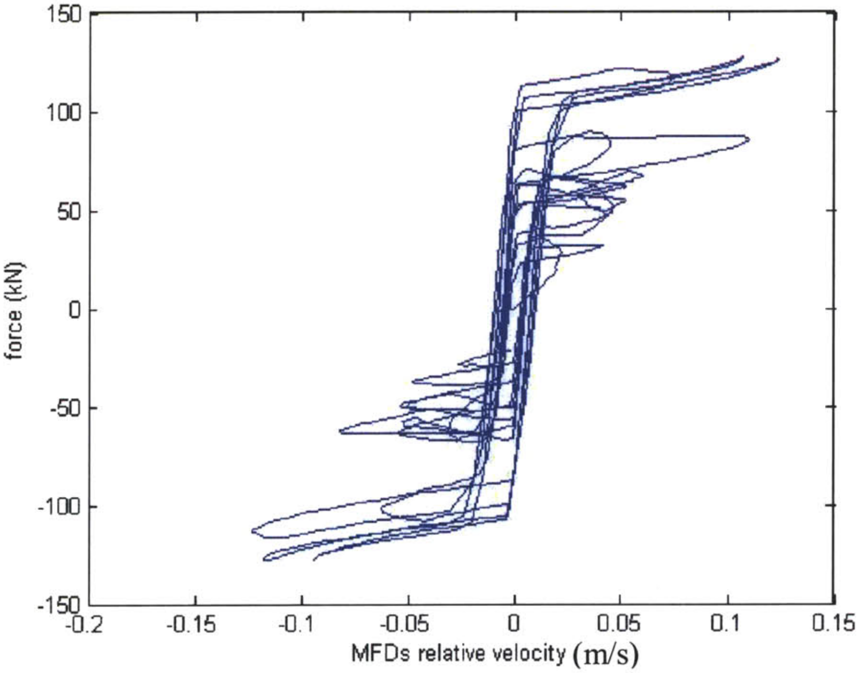

Figure 21: Force generated by the MFD versus its relative velocity

The plot of the force of the MFD versus its relative velocity corroborates the classical static model of Coulomb with viscous friction. It was predictable because the MFD that has been designed includes a variable friction element.

The friction force for such a model is given by the following formula:

$$F_{friction} = F_v \cdot |v|^{\alpha} \cdot sgn(v)$$

The Coulomb model with viscous friction can be ideally modeled according to the profile below:

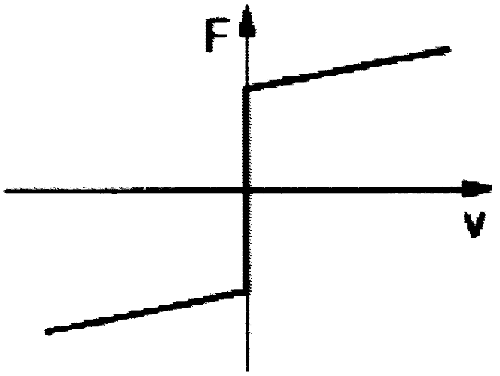

Figure 22: The Coulomb model with viscous friction [10]

Therefore, as highlighted by the similarities between the two graphs, practice is in line with theory.

Indeed, it is possible to notice through the Figure 21 obtained in MATLAB that when the MFD has no relative velocity, there is no force provided by the device.

Once the relative velocity of the MFD starts increasing, the force increases rapidly while following a steep slope. Unlike the ideal model of Coulomb with viscous friction, the slope is not infinite. This feature confers continuity to the practical model. Moreover, it enhances the device by avoiding an abrupt change of force. The continuity of the force generated by the MFD is enabled by setting up the voltage on. As a matter of fact, when the voltage is on, the necessary control is provided little by little through a voltage that adapts itself according to the force needed by the structure.

When the relative velocity of the MFD overcomes 0.01 m/s, the slope of the force versus the MFD relative velocity decreases significantly. This corresponds to the right part of the ideal model of Coulomb with viscous friction.

While the relative velocity of the MFD increases from 0.01 m/s to the MFD's maximum relative velocity, the force provided also increases little slowly reaching the MFD's maximum force. This maximum forces ranges from 40 to 100 kN. Once the force reaches this value during a certain time, the structure starts moving the opposite direction. When this happens, the MFD also starts moving in the reverse direction. Therefore, the MFD's relative velocity changes sign in agreement with the ideal model but with more continuity. This makes the MFD reach significantly quickly a relative speed of - 0.1 m/s, generating a force of - 100 kN in the optimal case.

Finally, the relative velocity of the MFD changes sign again; and the mechanism of the device repeats itself over and over until obtaining the total mitigation of the building's motion under wind excitation.

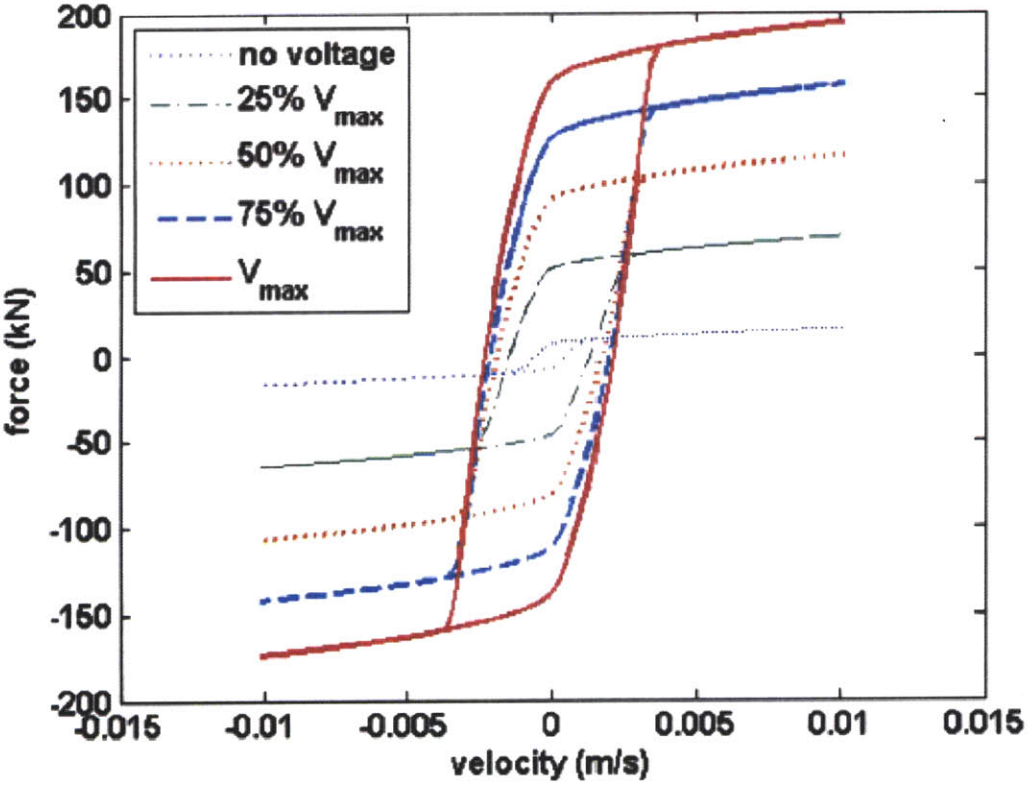

Figure 23: Force versus velocity for various voltages describing the Bouc-Wen model [20]

The Bouc-Wen model also corroborates the plot found for the MFD's relative velocity. Indeed, as for the theory, emphasized in Figure 23, the results found in MATLAB exhibit a certain dependence on voltage. It is possible to notice such dependence through the practical plot of the MFD's relative velocity that exhibits different curves with different plateaus of forces.

Through the theoretical model, it is possible to see that the various plateaus of the MFD's relative velocity are due to the varying voltage (the voltage is on).

B) Analysis of the Relative Displacement of the MFD

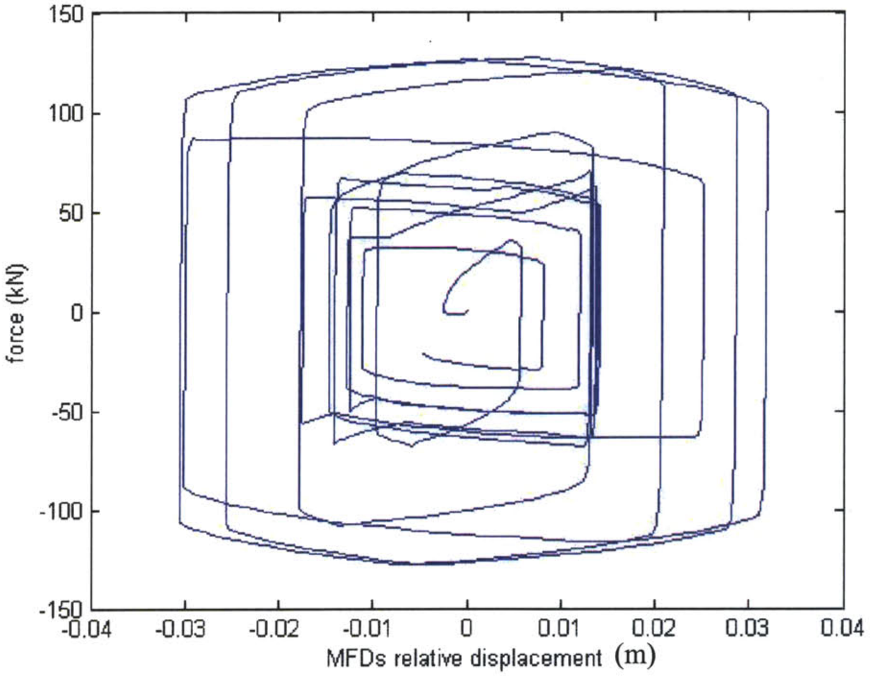

Figure 24: Force generated by the MFD versus its relative displacement

The plot of the force of the MFD versus its relative displacement reveals a hysteretic behavior governing the model.

In reality, it is possible to notice a range of different hysteresis loops. Following a non-linear behavior, the plot of the force of the MFD versus its relative displacement highlights variable hysteretic patterns. In fact, the plot above enhances different hysteresis loops with changing relative displacements and changing forces.

Such a model is known as the Bouc-Wen Model. This model is widely used in the field of civil engineering, and particularly in the field of structural control. As a matter of fact, the Bouc-Wen Model is often employed for damping devices implemented in buildings. The Bouc-Wen model has been used in the development of semi-active structural control models in civil engineering.

Since the results are consistent with the Bouc-Wen model, it is possible to say once again that the practice perfectly matches the theory.

First, as illustrated in Figure 24, when there is no displacement, there is no force provided by the MFD.

Once the MFD starts moving, the force first jumps from 0 to 40 kN. The maximum force is not obtained at the beginning because when the structure is initially hit by wind, the motion of the structure is not that significant. Therefore, the maximum relative displacement of the MFD for the first loop is slightly low because the structure's motion changes direction relatively quickly. This is in agreement with expectations. Indeed, at the beginning of the loading, low voltage is only needed in order to counteract the slight movement of the building induced by wind. Moreover, given that the battery grants roughly low voltage, the maximum relative displacement of the MFD for the first loop is not that significant because the structure moves the opposite way relatively quickly. As shown in Figure 24, the MFD's maximum relative displacement for the first loop reaches only 0.005 m.

Then, the MFD's relative displacement decreases until reaching the value of 0 m. At this point, the structure and the tuned mass damper (TMD) have the same displacements. After this state, the structure keeps moving the same way and the TMD the opposite way until reaching the maximum negative displacement for the MFD of -0.01 m. At this moment, both the velocities of the structure and TMD go to 0. The inertia of the important mass of the structure is therefore counterbalanced by the motion of the TMD.

Finally, the motion of both of them switches direction. This action leads to a jump of the force from a negative to a positive value that is greater in absolute value. The mechanism of the device repeats itself over and over with greater maximum displacements and forces. This finally leads to the total mitigation of the building's motion due to wind excitation.

Furthermore, it can be observed that the forces generated by the MFD and its maximum relative displacements vary from one hysteresis loop to another. This effect can be explained by the variation of voltage. In fact, the voltage is on and tries to adjust itself in order to apply the exact force needed by the structure. This adjustment of voltage leads to different forces applied to the MFD. Depending on the forces generated by the actuator, the combined system structure – TMD is going to move more or less. Therefore, the relative displacements are not the same from one loop to another.

The statement about the variable forces can be confirmed through the theoretical graph of the Boucle-Wen model shown in Figure 25. As a matter of fact, it is possible to notice that depending on the voltage applied, the force generated varies. The more important is the voltage, the greater is the force provided. For example, with full voltage, the Bouc-Wen model below provides a force of 200kN. When the voltage is reduced by two, the force is almost reduced by two. Given that the voltage is on for the MFD, the same behavior is taking place. As it can be highlighted through the various forces applied in Figure 24, the higher is the voltage of the battery, the greater is the force applied.

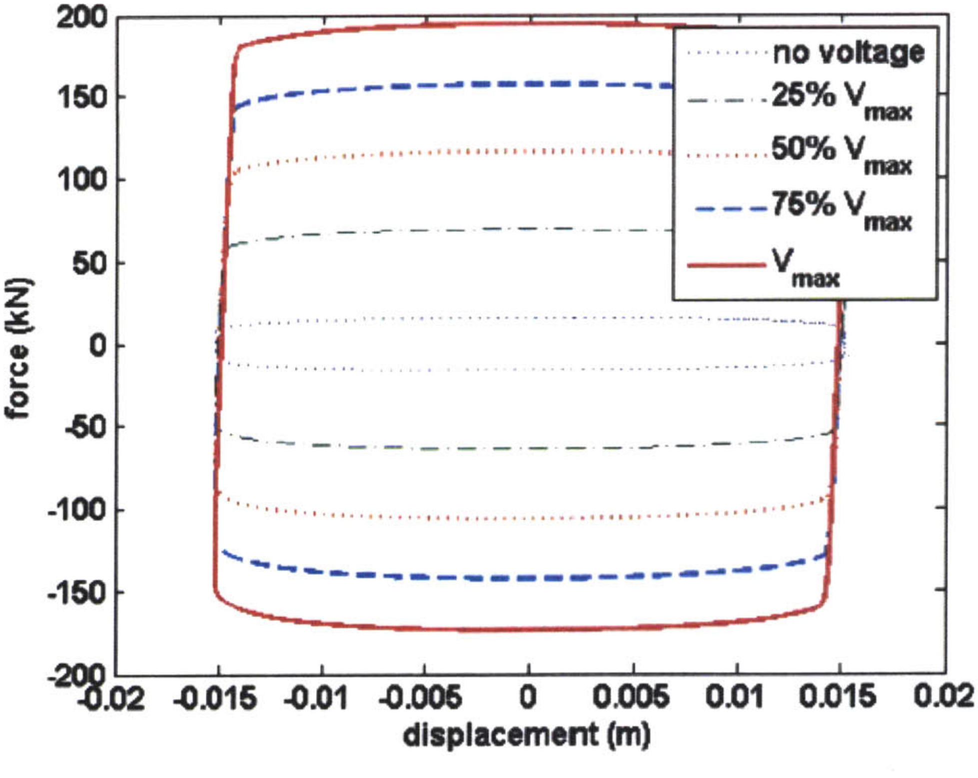

Figure 25: Variable hysteresis loops for different voltages describing the Bouc-Wen model [20]

C) Analysis of the Force Generated by the MFD

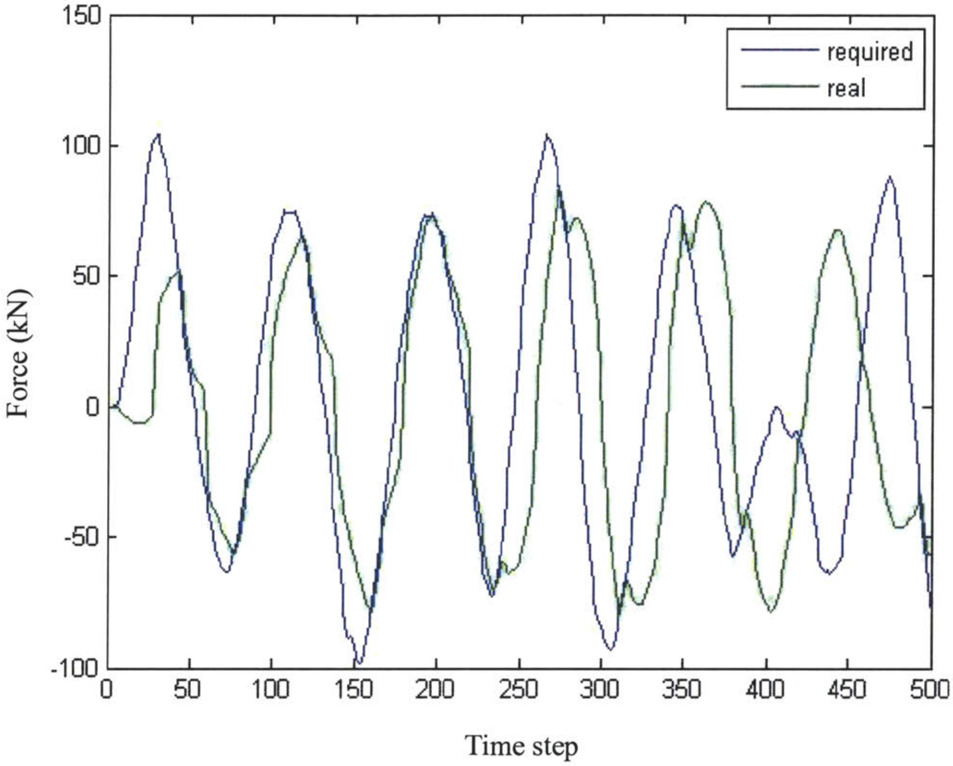

Figure 26: MFD required and real forces versus time

The plot of the MFD's force versus time reveals that the actual force applied by the actuator on the structure tends to approximate the force required.

This fact reinforces the model made for the MFD. Given that the goal of the system is to provide the necessary force to mitigate the building motion induced by wind, the closer the actual force is to the required force, the better the model will be.

The significant adequacy between the two curves in the graph above testifies the relevance of the model.

However, as it can be shown in the plot of the MFD's force versus time in Figure 26, the required and real forces are sometimes not in phase. Such a singularity is observed for example for a time step around 400 in Figure 26.

When the MFD succeeds in meeting the needs of the structure, the voltage is on and usually increases. In this case, the actual force generated fits significantly well the force required.

However, there are some states that cannot be fulfilled. For example, when taking a look at the plot of the MFD's force versus its relative velocity in Figure 21, it is possible to observe that the top left and the bottom right sides of the dial cannot be reached. In such cases, the battery tries to deliver the necessary voltage but without success. This failure is due to the existence of conditions that cannot be reached by the MFD because they are not allowed by the model.

Thus, as illustrated in Figure 26, the existence of these conditions leads to the differences of phase between the signals of the actual force and the required force.

D) Analysis of the Voltage of the MFD's Battery

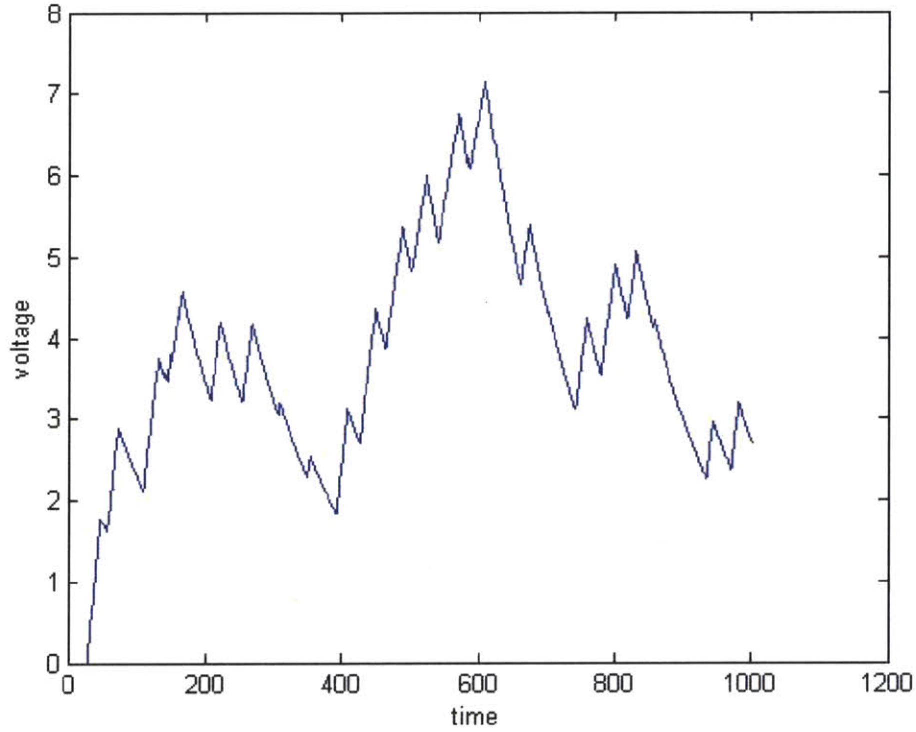

Figure 27-a: Voltage of the battery (supplying the MFD) versus time

When the MFD succeeds in meeting the needs of the structure, the voltage is on and tries to adjust itself in function of the demands of the structure. Indeed, the purpose of the battery and the power delivered is to approximate as closely as possible the constant energy demands of the building in order to reduce as much as possible the motion of the structure, without using more energy than necessary. Therefore, the actual force generated by the actuator has to be adjusted as well as possible to fit the force required by the structure in order to mitigate the wind vibrations.

Thus, the plot presented in Figure (27-a) is in agreement with the expectations. First, the structure is hit by the wind. This results in the increase of the voltage from 0 to 1.7 volts in order to increase the friction and thus stop the motion's amplification of the structure. Once the structure reaches its maximum displacement, the MFD has already fulfilled its role because the structure is already starting to move in the opposite direction. At that exact moment when the motion changes direction, no force is required by the modified friction device. Therefore, the voltage decreases. However, not even before having the time to decrease enough, the voltage has to increase again in order to counterbalance the opposite motion of the structure. Thus, the voltage increases from 1.7 to 3 volts. Once reaching the maximum negative displacement, the structure does not need the battery to supply energy. That is why the voltage decreases again. Then, the voltage increases again for the same reasons discussed earlier.

The mechanism repeats itself over and over with varying voltages until reaching the total mitigation of the building's motion under wind excitation.

The adjustment of the force provided by the MFD can be shown in Figure (27-b). Indeed, the plot emphasizes a force varying between -100 kN and 100 kN in response to the demands of the structure. On one hand, when a significant force is needed by the structure to mitigate the vibrations, the force reaches 100 kN. On the other hand, when the demands of the structure are lower, the force generated is lower.

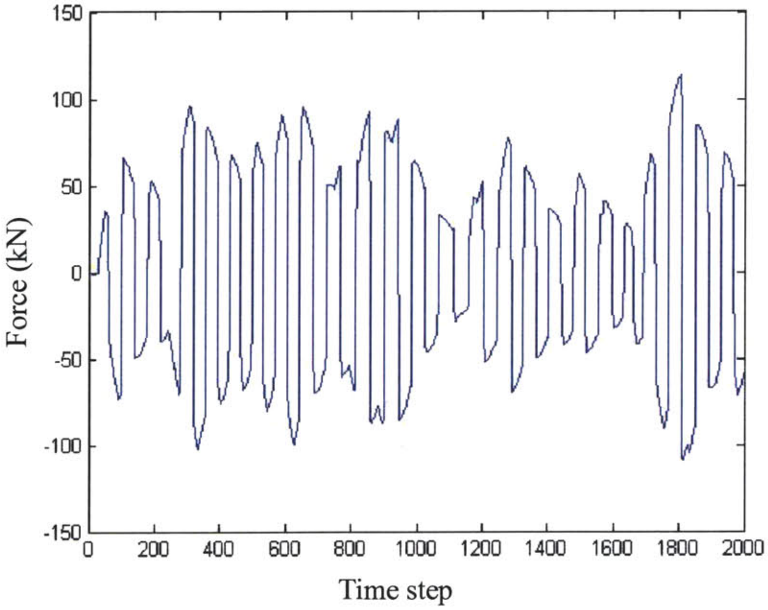

Figure 27-b: Force granted by the MFD

E) Analysis of the Velocity versus the Displacement

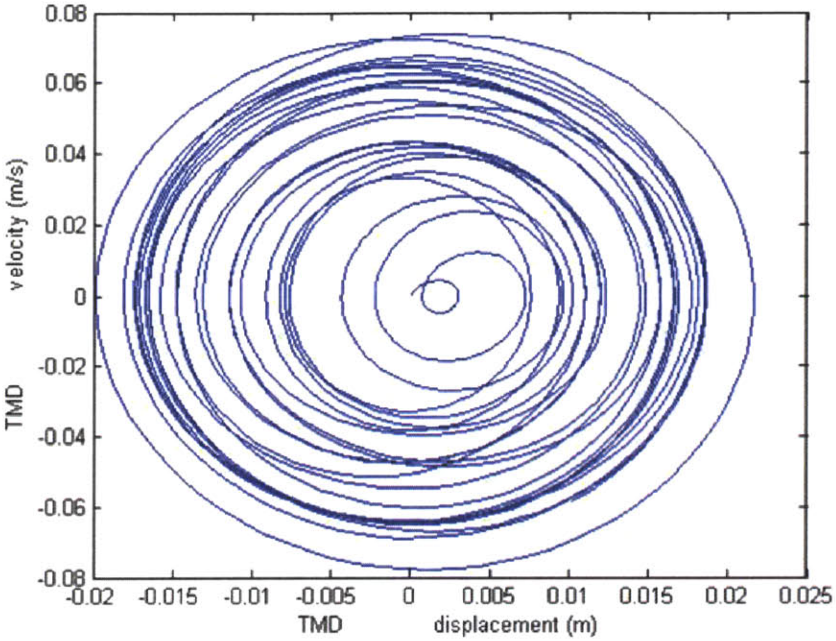

Figure 28: Velocity of the TMD versus its displacement

Figure 28 exhibits the energy dissipation of the TMD. This behavior is suggested through the different ellipses, which spiral to zero over time. Indeed, the elliptical behavior of the TMD shown above corroborates the decrease of the velocity and displacement of the TMD. The decrease of the size of the ellipses is associated with the decrease of the displacement and velocity of the tuned mass damper. Thus, it clearly appears that the motion of the TMD is damped over time. Given that the motion of the TMD is coupled with the motion of the structure, this behavior confirms the mitigation of the buildings' oscillations. Gradually, the displacement of the TMD goes to zero because the device dissipates the motion of the building thanks to its motion that counterbalances the motion of the structure. This effect results in the decrease of the vibration of the building and thus the decrease of the TMD's displacement.

As presented in Figure 29, the behavior found for the MFD is similar to the TMD. It is in agreement with the expectations because of the energy dissipation allowed by the friction element implemented in the MFD.

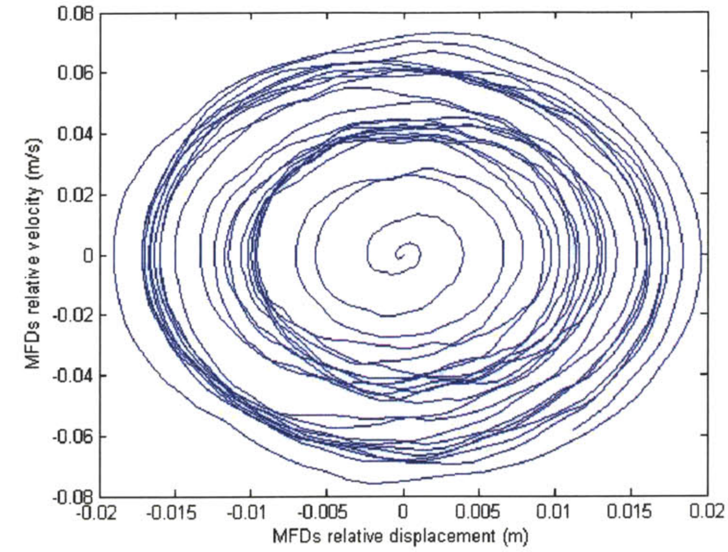

Figure 29: Relative velocity of the MFD versus its relative displacement

The MFD and TMD behaviors corroborate the mitigation of buildings' vibrations under wind excitation. As a matter of fact, the velocity and displacement of the structure are decreasing gradually until reaching the total dissipation of the oscillations. This effect can be shown in Figure 30. Indeed, it is obvious that the behavior of the structure ends up being localized in a zone where the displacements and velocities tend to 0.

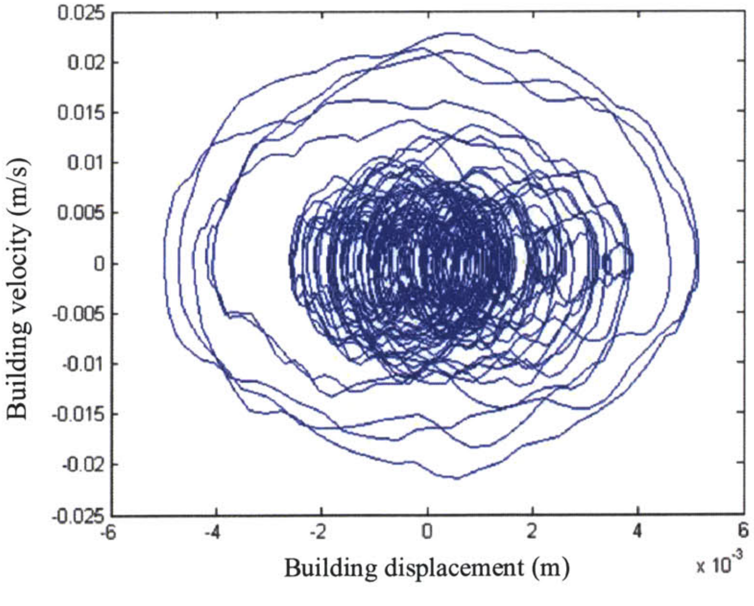

Figure 30: Velocity of the structure versus its displacement

Conclusion

Unique by the amount of damping force provided, the modified friction device draws its effectiveness from the friction brought by the brake. By using a braking system, widely used for cars, the design of the MFD, which is an active device, becomes more reliable. Monitored by an actuator that provides the forces required to enable the expansion of the car brake, the MFD addresses the limitations of semi-active TMDs regarding fluid and mechanical issues, and electronics reliability.

Moreover, the necessary control that has to be provided by the friction device is monitored by the fluctuation of voltage of batteries. The use of batteries of about 12 volts allows tackling the risk of instability raised by the need for an external power source. All the improvements made allow us progressively considering the implementation of active damping systems into civil structures.

Essential for the stability of the structure, the MFD has enhanced effectiveness regarding the mitigation of building motion under wind excitation. By investigating the parameters of the MFD, it has been possible to highlight that a low voltage delay ensures a significantly good mitigation of building oscillation under wind loading.

Setting up the voltage on has enabled to approximate as closely as possible the permanent energy demands of the building without using more energy than necessary. Therefore, the actual force generated by the actuator has been adjusted by the device as well as possible to fit the force required by the structure in order to mitigate the wind vibrations. This feature is crucial because it allows granting a better feedback control.

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