Strategies For Mitigating Wind-Induced Motion in Tall Buildings through Aerodynamic and Damping Modifications

by

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ABSTRACT

The advent of modern structural systems, spurred by advances in construction methodology and high strength materials, has driven the height of modern skyscrapers beyond what was once deemed possible. Although science and technology has been able to increase the strength of building materials such as steel and concrete, their material stiffness has remained virtually unchanged. The end result is a wave of taller, slender and more flexible skyscrapers that are very susceptible to wind-induced excitations. Ever mindful of the fact that human comfort levels are affected by perceived structural responses, engineers must employ various strategies to satisfy serviceability constraints. This thesis presents an overview, in addition to successful applications, of the various aerodynamic and damping modifications that are used to control wind-induced motion in tall buildings. Finally, a modified gyrostabilizer, akin to those used in luxury yachts, is proposed as a possible active control mechanism. The feasibility of this device was studied using simple statics and rigid body dynamics.

Thesis Supervisor: Jerome J. Connor

Title: Professor of Civil and Environmental Engineering

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INTRODUCTION

As defined by the *Council on Tall Buildings and Urban Habitat* (CTBUH), there is no thorough definition as to what makes a tall building. The general consensus is that a tall building is one that meets a certain proportion, with regards to its aspect ratio, and employs "tall building technologies" such as vertical transportation systems and structural resisting systems for lateral loads. However, for the purpose of analysis, this paper addresses tall buildings as those that are over 200m high and have an aspect ratio, quotient of building height to building width, of 7 or greater.

The advent of modern structural systems, spurred by advances in construction methodology and high strength materials, have driven the height of conventional skyscrapers beyond what was once deemed possible. Currently, the world's tallest building, the Burj Khalifa in Dubai, UAE, stands at over 828m tall but a few proposed designs threaten to break the 1600m (one mile) mark. Additionally, the construction materials such as concrete and steel have seen their performance significantly improved. In the case of concrete, the maximum compressive strength has been increased from 6000psi to 20,000psi (Nawy, 2008) while steel has seen its yield strength improved from 60ksi to 120ksi (Risser and Humphrey, 2008).

Consequently, modern tall buildings have gotten lighter in comparison to their predecessors and their aspect ratio has also increased from a norm of about 7 to as high as 20, as is the case with the Highcliff residential building in Hong Kong (The Skyscraper Museum, 2009). While the improved strength has also provided minimal gains in the modulus of elasticity (material stiffness) of concrete, the material stiffness of steel has remained unchanged despite the improvement in material strength. The end result is a taller, slender and more flexible structure that is highly susceptible to wind-induced excitations.

In the design of tall buildings, the structural response refers to the resulting displacement, velocity or acceleration of the structure when a load is applied.

Human discomfort is induced by perceived motion and accelerations in tall buildings therefore, it is important for designers to keep these factors below the threshold level. Using AISC design guidelines, the total drift need not exceed H/400, where H is the total height of the building. Also, the Permanent International Association of Navigation Congresses (PIANC), states that the onset of motion sickness occurs in about 50% of human beings at an acceleration of 0.02g or 0.196m/s^2 (PIANC, 1981).

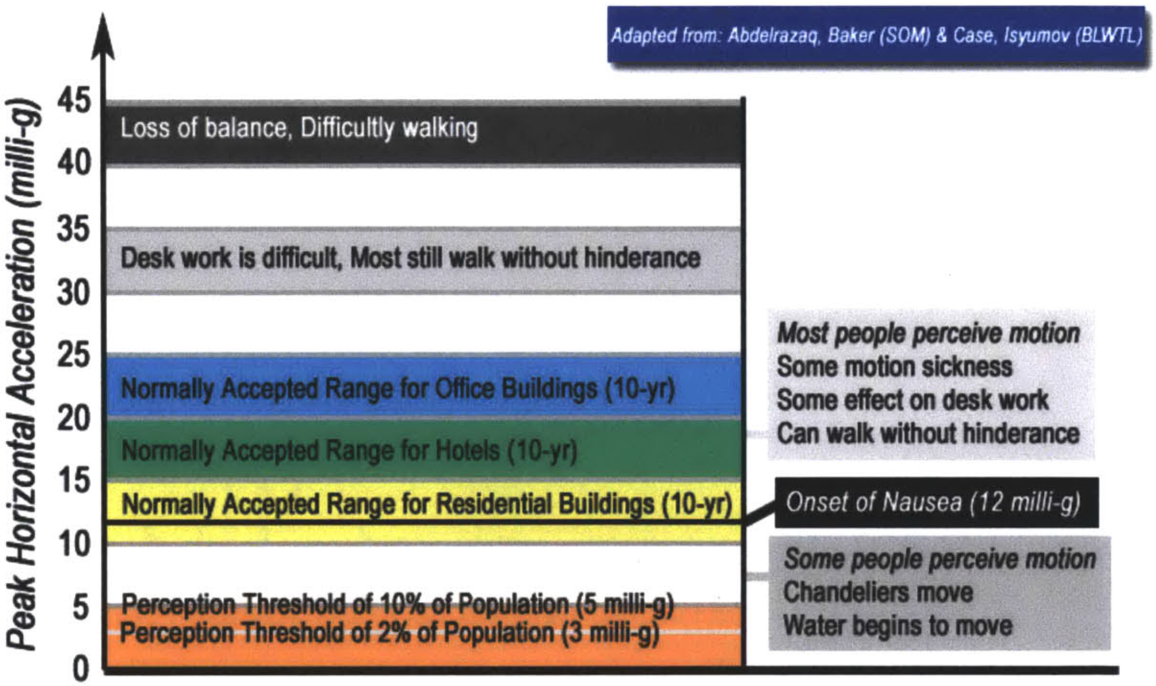

Figure 1: Effects of Perceived Acceleration in Humans [27]

To ensure that structures meet these serviceability constraints, the design of tall buildings is slowly shifting towards a motion based design (MBD) approach over the traditional strength based design (SBD) with the belief that satisfying motion constraints would ultimately meet strength requirements. By increasing the mass, the stiffness, modifying the damping characteristics or improving the aerodynamic capability of a structure, engineers can effectively control structural motion.

Increasing the mass requires the unsustainable practice of adding nonessential building materials or overdesigning the structure. Additionally, increasing stiffness, through the inclusion of various structural systems, is effective against steady state and quasi-static loading but could be very expensive for the owner. As a result, this paper will focus on aerodynamic and damping modifications as solutions to structural motion due to dynamic wind loading.

Chapter 1: WIND INDUCED MOTION

Wind induced responses of tall buildings primarily occurs in three different patterns. It can cause drag, in which the structure moves in the direction of the wind. It can also cause torsion, in which the wind acts as a torque to induce twisting. Finally, it can cause transverse or across wind motion, in which the structure moves perpendicular to the direction of the wind (Ching et al., 2009). Of these patterns of motion or modes, the across wind motion dominates the design of tall buildings because pressure differences on the walls parallel to the direction of motion can give rise to vortex shedding, whirlpools of air, strong enough to affect human comfort.

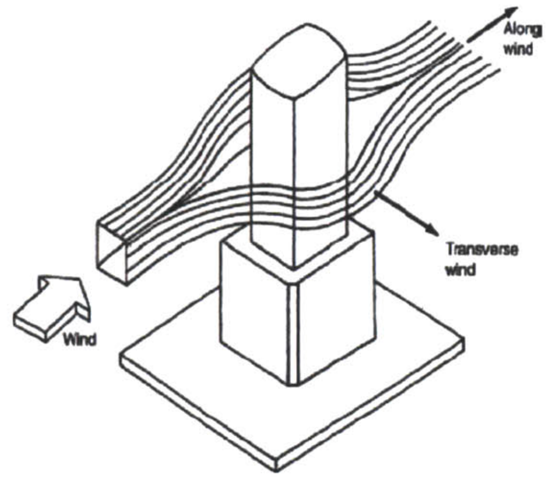

Figure 2: Patterns of Wind Motion [49]

DETERMINING WIND VELOCITY

In order to decrease the likelihood of seismic induced torsional vibrations, resulting from eccentricity in floor plates, tall buildings have traditionally been designed to be symmetric prismatic structures (Tanaka, Tamura, et al., 2010). However, these shapes lack the aerodynamic properties to properly resist wind-induced motion at increased heights. Due to frictional drag, wind speeds are much lower at the earth's surface but they quickly pick up pace as the elevation increases (Figure 3). The height at which the frictional drag becomes negligible is referred to as the "gradient level" and it is affected by the degree of surface roughness and other projections, such as buildings, trees, and mountains that hamper the flow of wind at the surface.

Hence, as buildings get taller, wind loads gain prominence over seismic loading and ultimately govern the structural design. The relationship between wind speed and height variation is usually given by the following equation,

$$\frac{V}{V_r} = (\frac{Z}{Z_r})^a$$

where, V = wind speed, Z = height and V_r is the known wind speed at a reference height, Z_r. The exponent, "a", varies with changing surface conditions and atmospheric stability but its typically assumed to be 0.143 under neutral stability conditions. The "a" can be as low as 0.087 in broad expanses of flat land and as high as 0.2 in built up urban areas, signifying that the "gradient level" is much higher in cities than in the open plains (Taranath, 2012).

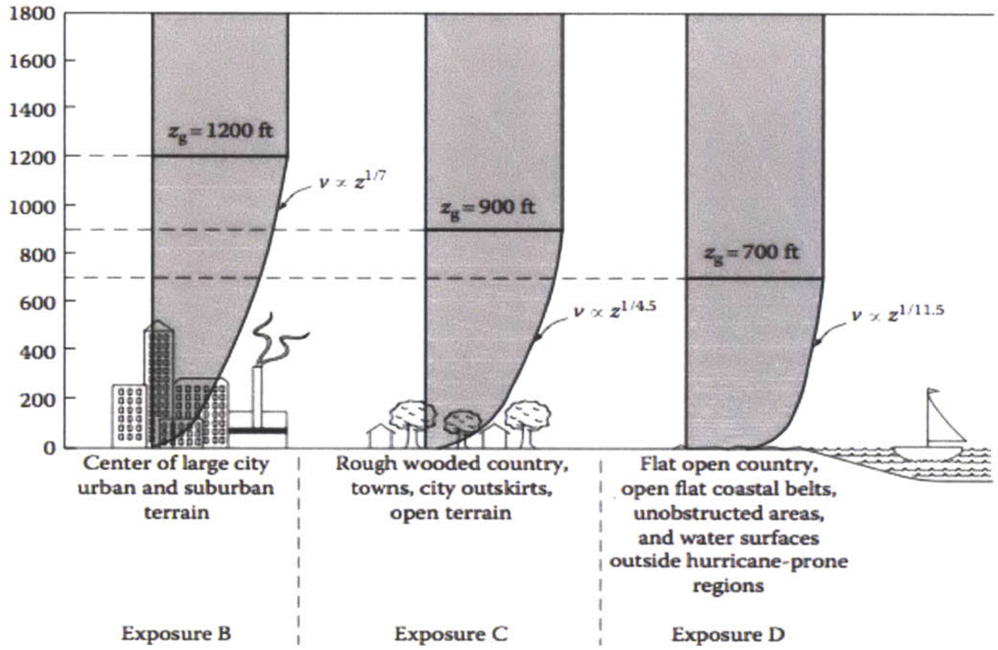

Figure 3: Vertical Wind Profile [49]

DETERMINING WIND LOAD AND STRUCTURAL RESPONSE

The *American Society of Civil Engineers'* design code (ASCE 7-05) provides a simplified and analytical procedure for calculating wind loads. The simplified method is constrained to regular-shaped buildings with a maximum height of 60ft. On the other hand, the analytical method has no height restriction but it can only be used on regular shaped buildings that are not sensitive to accelerated wind flow resulting from channeling (through other tall buildings or local topographic features), across-wind (transverse) loading and vortex shedding (ASCE, 2006).

However, modern skyscrapers are complex structures, with non-uniform and irregular shapes. Additionally, they are easily excited by across wind loading and vortex shedding. Therefore, the aforementioned methods are not applicable for calculating wind loading and structural responses in modern tall buildings. Either wind tunnel testing or computational fluid dynamics must be used to estimate the aerodynamic characteristics of modern tall buildings.

Wind Tunnel Testing

Wind tunnels provide designers a reliable way to accurately study the flow of air and measure the wind loads acting on a building. They are tube-like structures with a fan at one end that produces strong winds, which are then channeled through a scaled model of the structure in question. The scaled model of the structure, along with other surrounding buildings, is placed at the opposite end of the tunnel (Figure 4). Pressure sensors located in the tunnel record the building's interaction with the wind and the introduction of colored smoke or fine mists of liquid allows the designers to visually observe the flow of air around the structure.

The results obtained from the wind tunnel test can be used to determine the base overturning moments in addition to the wind load distribution over the height of the building. The structure's response in various directions can also be determined and then used to evaluate the occupant's comfort level by comparing the obtained results again serviceability limits (Taranath, 2012). In the event that the structure's response exceeds the serviceability constraints, designers can adjust the building's shape or

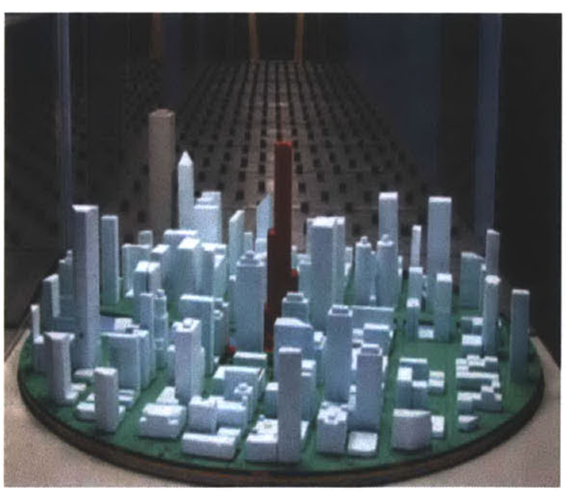

Figure 4: Chicago's Trump Tower in Wind Tunnel [5]

orientation, relative to the direction of wind, and also include various control mechanisms to improve the building's aerodynamic performance.

The ability to detect a problem and adjusts a building's characteristics before construction starts offers significant savings for the owner and it assures that the structure will satisfy occupant comfort levels. According, to RWDI Consulting Engineers, wind tunnel testing should be done early in the planning stage especially for buildings that are 22 stories or more, in non-hurricane prone regions, and higher than 10 stories in hurricane prone areas. For building's located in an unusual topography or surrounded by other buildings, wind tunnel testing is imperative to guarantee the safety of the project and optimize cost efficiencies (RWDI, 2012). In spite of their advantages, wind tunnel testing is still very expensive and time consuming, as a geometrically similar model needs to be created before a suitable scaling law is applied to determine values in the actual structure (prototype).

Computational Fluid Dynamics

Computational Fluid Dynamics (CDF) involves using numerical methods in addition to other algorithms to predict fluid motion. Computer simulations are used to model the flow of a fluid around a structure. To conduct the analysis, the geometry of the structure is defined, often with Computer Automated Design (CAD) software. Then the relevant physical conditions are defined before the initial and boundary conditions are applied. Finally, the equation is solved using an iterative process before the results are outputted and interpreted by designers (Davidson, 2002).

In comparison to wind tunnel tests, this program allows designers to conduct multiple, cheaper and faster analysis on the aerodynamic performance of a building. However, the accuracy of this model is bounded by the quality of the software's algorithm and the building's defined geometry (Davidson, 2002).

Chapter 2: AERODYNAMIC MODIFICATIONS

The shape of the buildings significantly mitigates the increased flexibility and inadequate damping that comes with building taller structures with high strength materials. In the design of tall buildings, a unique collaboration between the architect and the engineer is needed to properly align the shape of a building with its structural components. This has the added benefit of disrupting wind patterns around the building to effectively reduce the wind excitations.

The various aerodynamic modifications can be divided into the following groups:

- Tapered Cross Section and Setbacks
- Helical Shapes
- Addition of Openings
- Corner Modification

TAPERED CROSS SECTIONS AND SETBACKS

Tapering can be defined as the reduction of cross sectional area as a building rises while setbacks are a series of recessions in the exterior walls as the structure's height increases. Besides allowing greater natural light penetration to the street and broader view of the sky from the street, tapering and setbacks serve practical aerodynamic purposes. They help to reduce wind-induced excitations by disrupting the flow pattern of wind around tall buildings.

Figure 5: Burj Khalifa in Dubai, UAE [22]

The benefit of this modification is best observed in the Burj Khalifa (Figure 5) where the designers used setbacks to taper the building's cross-sectional area. As the "Y" shaped tower rises with seeming ease and effortlessness, the wings setback in a spiral pattern such that the tower's width decreases at these location. This helps to reduce the cumulative weight of the structure on the foundation but perhaps, more important than any other function, the constantly changing shape of the Burj Khalifa serves to confuse the wind by denying the wind vortices, the opportunity to reorganize (Feblowitz, 2010). If left unchecked, these vortices, whirlpools of air current, could move the building sideways, in the direction perpendicular to the wind flow, creating severe motion problems in the process. Despite this strategic design, the 206-story Burj Khalifa still oscillates slowly back and forth by about 2 meters at the very top (Feblowitz, 2010).

The effectiveness of this modification is further supported by the design of the proposed Kingdom Tower in Jeddah Saudi Arabia (Figure 6). When completed, the tower will be over 1000m and conceptual designs show a tapered shape would be used to reduce wind loading on the tower. As noted by lead architect, Adrain Smith, a taper is the only viable shape that would effectively deal with wind loads at this elevation. In an interview with *Construction Week* George Efstathiou, an architect behind the Burj Khalifa, states that, "the structure costs would become so high in a straight tower, and the movements would be untenable. The firms with high rise experience knew they had to taper, or change the shape a little bit, or roughen the surface in order to confuse the wind" (Ephgrave, 2011).

Figure 6: Proposed Kingdom Tower in Jeddah, Saudi Arabia [29]

It is well established that setbacks and tapering have been invaluable in dealing with wind forces. Nonetheless, Thorton Tomasetti, structural engineering firm for the Kingdom Tower, indicate that the asymmetrical shape and linear taper does a better job of disrupting the wind and mitigating vortices that develop around tall buildings. Upon impact with the tower, the resulting wind vortexes are forced to rebound at different frequencies due to the constantly changing cross-sectional area (Thornton Tomasetti, 2011). This leads to a significant reduction in the building's response in comparison to traditional shapes.

HELICAL SHAPES

Another way designers try to mitigate the effect of the wind is by employing helical shapes that are not only elegant and graceful but also serve a structural function. These are buildings in which the floor plates rotate as the structure rises. This approach was used in the design of the Infinity Tower in Dubai, UAE (Figure 7). Standing at 330m, the 80-storey, reinforced concrete residential tower twists 90 degrees to give every apartment a stunning view of the sea or marina (Broomhall, 2011). The shape was tested using computer simulations and a wind tunnel. The results revealed that the helical shape exhibited better aerodynamic performance in comparison to a traditional square model of similar proportions. Lead designer, Bill Baker notes that, "its twisted shape greatly reduces wind forces on the tower. Its shape 'confuses the wind' in such a way that wind forces cannot organize themselves" (Broomhall, 2011).

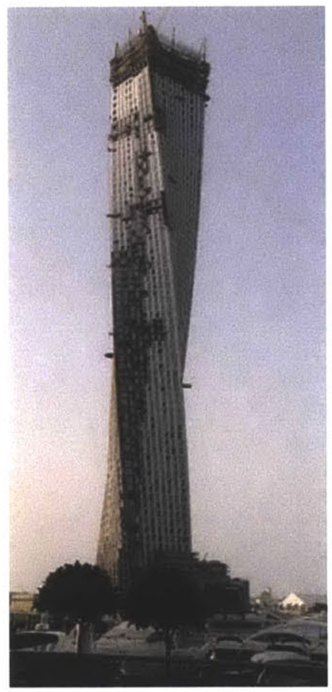

Figure 7: Infinity Tower in Dubai, UAE [56]

In China, construction on the Shanghai Tower has already begun (Figure 8). When completed in 2014, it will stand at approximately 640meters to become the tallest building in China. The design of the structure was driven by the need to reduce structural responses to the typhoon level winds common to Shanghai. Series of wind tunnel tests were conducted that inspired a helical structure that work in unison with the central core to reduces wind loads. The end result is a structure that not only reduces lateral loads by up to 24% (Xia, Poon, et al, 2010) but also embodies sustainable features such as a rain catchment system that can be used for the building's air conditioning and central heating.

In comparison with several building shapes of similar height and volume, Tanaka et al determined that helical shapes performed better in the transverse wind direction. Although traditional square shaped tower showed superior performance in safety design under wind speeds corresponding to a 500 year return period, their research indicated that that helical models showed superior aerodynamic behavior in both safety and occupancy comfort for wind speeds corresponding to a 1 year return period. Finally, vortex shedding pattern in helical models was observed to be irregular and unorganized at all elevations of the model and most importantly, for all wind directions (Tanaka, Tamura, et al., 2010). As a result, Tanaka et al were able to conclude that of all the models tested, the helical models showed the most effective aerodynamic characteristics against wind induced motion.

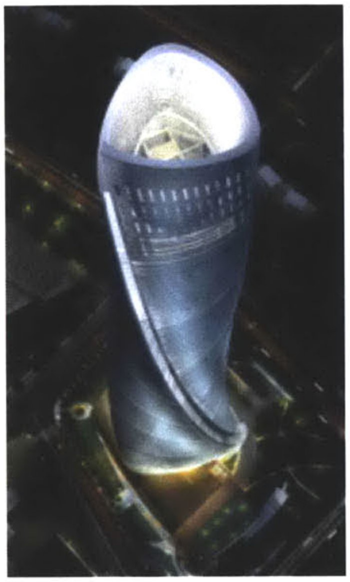

Figure 8: Shanghai Tower in Shanghai, China [59]

ADDITION OF OPENINGS

Yet another means for reducing lateral motion in tall buildings lies in the addition of openings, particularly at the top where tall buildings are most susceptible to time varying responses. This modification was included in the design of the Shanghai World Financial Center (SWFC) where a 50m high trapezoidal opening was embedded in its design (Figure 9). The opening was specially designed to relieve wind pressure at the top of the building. Research conducted by Okada and Kong on square models and an aspect ratio of 8, showed that the addition of openings, as small as 1.5% of the model's width on each exterior wall, reduced the transverse motion by approximately 20-25% (Okada and Kong, 1999).

Additional studies to understand the effect of through building openings at various elevations on tall buildings were carried out by Tamura. His research indicated that the effectiveness of through building openings dwindles if they are placed at lower levels of a building (Tamura, 1997). Therefore, utmost care must be taken when deciding where to place through building openings so as not to induce higher velocities through the opening, thereby adversely affecting occupancy comfort. The benefit of placing openings at the top to reduce wind-induced motion was well understood by the designers of the SWFC in China and the Kingdom Center in Riyadh, Saudi Arabia.

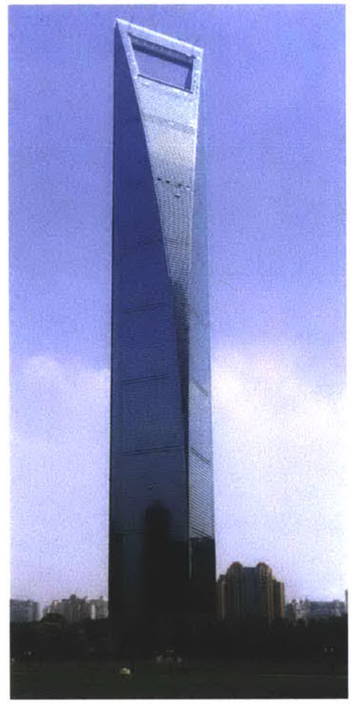

Figure 9: Shanghai World Financial Center [4]

CORNER MODIFICATIONS

Figure 10: Various Corner Modifications

The introduction of chamfered corners, slotted corners and corner recessions to the corners of the basic square model have been found to significantly reduce structural motion, with these improvements becoming more noticeable as the corners are progressively rounded. Slotted and chamfered corners function by causing disruptions to the vortex shedding process. Wind tunnel tests conducted on models with and without the aforementioned modifications by Kwok et al reveal improved performance under wind loading.

Their findings showed that slotted corners reduced drag on the models. However, chamfered corners were more effective with upwards of 40% reduction in drag in comparison to plain models (Kwok et al., 1988). Additionally, for chamfered corners under low velocities, Melbourne and Cheung (1988) showed that modifications up to 10% of the building's width had negligible impact on transverse wind responses. Under substantial chamfering such that the building's shape approached a hexagonal or octagonal shape, significant reduction was observed.

Figure 11: Taipei 101 [9]

Corner recessions present yet another method of modifying the geometry of traditional square towers. By removing the corners, a designer can reduce a structures response to wind-induced motion. This approach has proven to be especially beneficial in the design of the Taipei 101 in Taiwan (Figure 11) as it provides a 25% reduction in base moment when compared to the original square section (Irvin, 2006). Additionally, Kawai's research, on square models with aspect ratio of 10, reveals that corner recessions up to 5% of the width of a building are invaluable in increasing its aerodynamic damping but they are ineffective in suppressing vortex shedding (Kawai, 1998). Conversely, his studies show that when these corner recessions are large enough, they can promote instability at low velocities.

Of all corner modifications, rounding the edges appears to be the most effective means of improving aerodynamic performance of tall buildings against wind excitations. From his research, Kawai concluded that the magnification of wind induced motion decreases as corner roundness increases (Kawai, 1998). Also, research confirms that buildings with rounded shapes offer better aerodynamic behavior and in comparison to square or rectangular shapes, they allow for greater building height at comparatively lower cost. Finally, wind loads for rounded shapes have been experimentally shown to be reduced by as much as 20% to 40% when compared to equally sized square or rectangular sized buildings (Scheueller, 1977).

Figure 12: Aqua Tower in Chicago, USA [11]

The aqua tower in Chicago employs this rounded corner modification to great effect. According to the designers, it was initially believed that a separate tuned mass damping system might be needed to control wind-induced motion in the structure. However, after exhaustive wind tunnel analyses were carried out, it was eventually determined that the round and wave-like edges of the building effectively disrupted the flow of wind around the tower. This not only reduced the wind load on the Aqua Tower but also eliminated the need for a supplemental damping system (CTBUH, 2011).

Chapter 3: SUPPLEMENTARY DAMPING MODIFICATION

When aerodynamic modifications are not sufficient enough to control wind-induced motions, auxiliary damping systems are needed. Damping refers to a structure's ability to dissipate energy and decay amplitudes of motion by transforming vibrational energy into thermal energy. As defined by Connor, "it reduces the build up of strain energy and the system response especially near resonance conditions, where damping governs the design" (Connor, 2003). Without damping, structural motion would continue indefinitely but the introduction of damping progressively reduces the effect of dynamic loading, which ultimately halts vibratory motion (Figure 13).

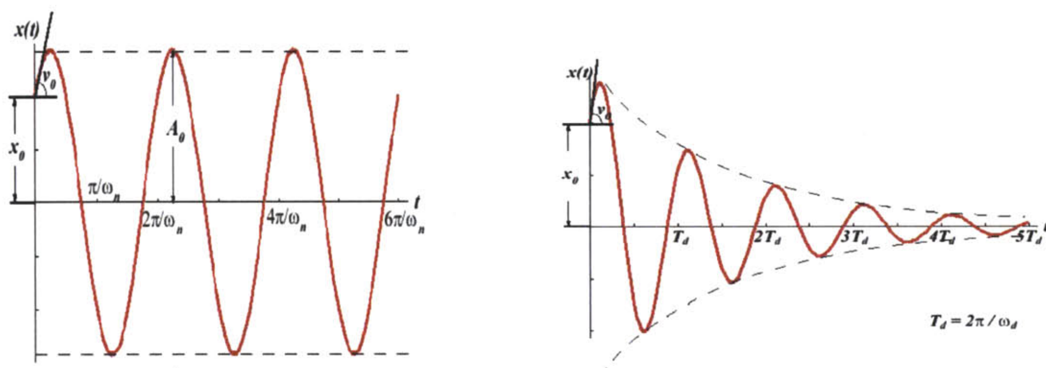

Figure 13: Undamped Response (left) and Damped Response (right) [15]

In buildings, the presence of cracks in concrete, friction in steel connections and interior wall partitions provide inherent damping for the structure. However, these inherent features only provide less than 1% of critical damping in tall buildings, which makes them very sensitive to lateral excitations (Kinetica Dynamics, 2012). Building materials like steel and glass have low inherent damping and although reinforced concrete has measurably higher damping characteristics, studies have shown that its damping value is still low, in the order of 5-10% of critical damping.

The inclusion of specially designed damping devices, strategically placed within a tall building, can effectively reduce wind-induced motions. Several types of damping devices are typically used in tall buildings but they can be primarily divided into three systems namely, passive systems, active systems and semi-active systems. Passive systems are the most widely used damping modification. They are generally low cost and require no energy input to function. Because they are unable to adapt to changing loading conditions, a reliable estimate of the design loading is needed for any passive system to be effective (Connor, 2003).

On the other hand, active systems are able to collect information on the present loading conditions of a structure, evaluate the data and then generate control forces that push on the structure to counteract the lateral load. This iterative process allows active systems to modify their properties as the loading conditions change. However, a lot of external energy is required to power the actuators that are needed to generate the counteracting forces. They also have a relatively high maintenance cost but, in comparison to passive systems, they can work under a wider range of frequencies. As a result, active systems are more effective at controlling structural motion but passive systems command a larger market share because of their lower prices and reliability (Ali, Moon, and et al, 2007).

Finally, semi-active systems are a special class of damping devices that incorporate the best properties of passive and active systems. They maintain the adaptability of active systems, are able to operate over a wide range of frequencies and are almost as effective in controlling structural motion. However, they require little external energy to generate control forces and similar to passive systems, they require little maintenance and lack the potential to go out of control and destabilize the structure (Kareem, Kijewski, and et al, 1999).

PASSIVE DAMPING

Tuned Mass Dampers

The introduction of a Tuned Mass Damper (TMD) is an attractive option in reducing excessive lateral motions. They function by adding solid or liquid mass to the top of a building, which produces a force that acts opposite to a building's direction of motion. In effect, the TMD adds a second degree of freedom to the structure that allows its own mass and internal damping to be tuned to the fundamental frequency of the primary structure. Therefore, when the fundamental mode of the primary structure is excited, the TMD swings out of phase thereby helping to reduce or neutralize motion (Ali, Moon, and et al, 2007).

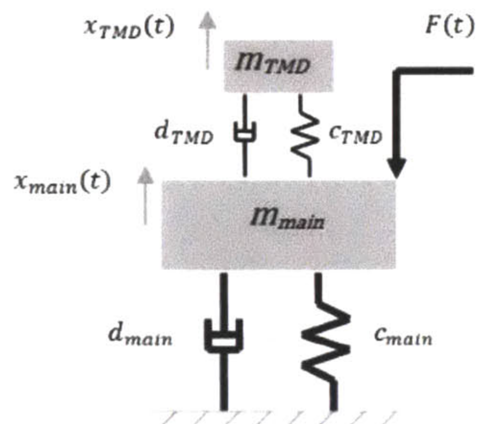

Figure 14: TMD [33]

The effectiveness of a TMD's location with respect to the primary structure's height is giving by the following relationship;

$$\sqrt{\frac{h}{H}}$$

where "h" is the height of the TMD and "H" represents the building's height. Therefore, the most logical location to place a TMD is at the top of a building as its effectiveness quickly diminishes as its height decreases. This was well understood by the designer's of the Taipei 101 in Taiwan where a giant 730-tonne pendulum type TMD was installed to counteract the building's movement. Representing approximately 0.1% of the building's weight and located near the top of the building, the TMD can swing 5ft in any direction and has been shown to effectively reduce wind-induced motion by 30-40% (Eddy, 2005).

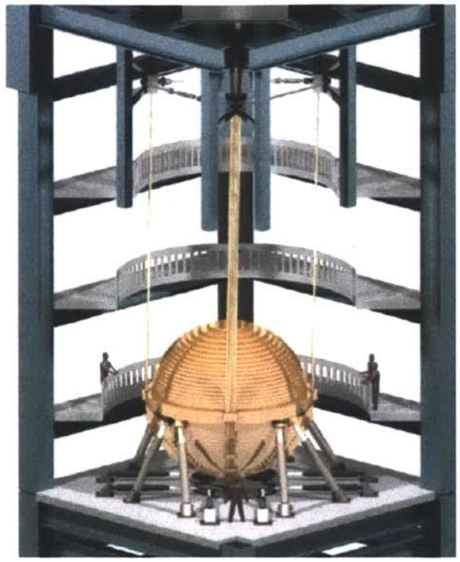

Figure 15: Pendulum TMD in Taipei 101 [41]

Additionally, a sliding type TMD modification was used in Boston's John Hancock Tower. Shortly after construction was completed, the 241m building had to be retrofitted to correct excessive sway in the building's top floors. Severe wind induced motion essentially made the building inhabitable as it caused nausea in the occupants. Two 300-tonne box-shaped TMDs were installed at opposite ends of the 58^{th} floor of the tower to control the motion. Changing lateral loading conditions are continuously monitored and the dampers become activated when structural acceleration reaches $0.0294 m/s^2$. The modification has been shown to reduce the structure's motion by up to 50% (Kareem, Kijewski, and et al, 1999).

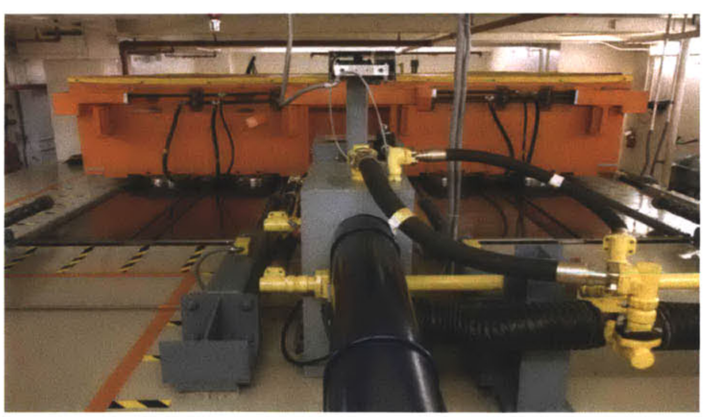

Figure 16: Sliding TMD in John Hancock Tower [51]

Liquids can also be used in place of solids to absorb vibratory energy. A tuned liquid damper (TLD) uses the irregular motion of liquids, primarily water moving out of phase with the primary structure, to dampen motion. When a lateral load is applied, the cohesion between liquid particles and the adhesion to the holding vessel generates friction forces that dissipate energy. The liquid is in turn dampened by flow restricting screens that create friction, in the form of turbulence. Besides requiring minimal maintenance and being very efficient at low amplitudes of vibration, TLDs are an attractive option because they can be designed using swimming pools or water tank located near the top of a building (Ali, Moon, and et al, 2007).

Situated 700ft above San Francisco Bay, a 50,000-gallon water tank prevents excessive lateral motion in the One Rincon Hill Tower (Figure 17). Wind tunnel test indicated that without supplementary damping devices, the residential tower could sway by as much as 16 inches, enough to induce motion sickness in the occupants. However, the designers note, "that the tank is designed to counteract any sway by swishing water from one side of the building to the other. If the wind blows from the south, the water will be moved to the north, offsetting the pressure of the wind" (Nolte, 2007).

Figure 17: TLD in One Rincon Hill Tower in San Francisco, USA [40]

Viscous and Viscoelastic Dampers

As the name implies, viscous dampers dissipate energy by using viscous fluids that resist shear and strain linearly with time when a force is applied. These dampers are usually composed of a closed cylinder, filled with an incompressible viscous fluid, which is attached to a piston with small orifices. When a lateral load is applied, the viscous fluid is forced through the orifices, causing friction, which in turn creates a damping force opposite to the direction of motion and proportional to the applied velocity. If properly installed, viscous dampers can drastically reduce structural motion by increasing damping levels to as much as 50% of the critical (Taylor and Constantiou, 1996).

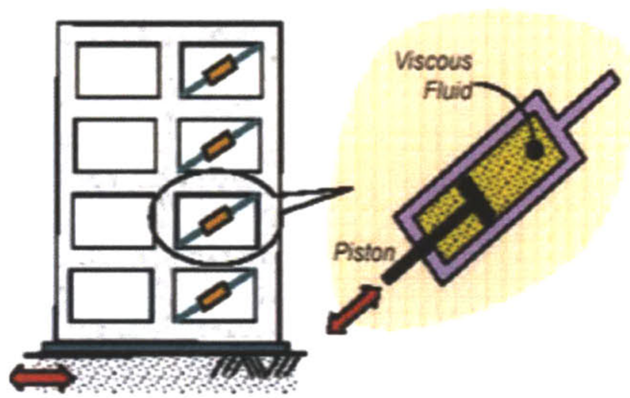

Figure 18: Viscous Damper [13]

The counteracting force produced by the viscous damper is given by the following equation:

F=C*(V^α) where,

F = Reaction force

C = damping coefficient

V = velocity

α = Constant exponent, dependent on shape and size of orifice but usually a value between 0.3 and 2.

Viscous dampers possess a number of distinct advantages that have allowed them to distinguish themselves from other damping devices. The inclusion of viscous dampers not only allows tall buildings to be built with less lateral stiffness, which reduces the overall cost for the owner, but they also help to reduce wind induced motion by a factor of approximately 2 to 3 (Taylor and Constantiou, 1996). Also, the fact that viscous dampers require little maintenance and no external power source to function makes them a very attractive option for designers and owners alike. Unlike tuned mass dampers that require valuable floor area, the viscous damper can be installed as a single diagonal in the building's bracing system and concealed within exterior walls and interior partitions (Figure 18).

Similar to viscous dampers, viscoelastic dampers act as shock absorbers to dissipate energy over a wide range of frequencies. Essentially, a viscoelastic material such as rubber is placed between steel plates and when a lateral load hits the building, the resulting motion causes the damper to experience shear deformation, which dissipates energy. They are equally effective in concrete and steel frame structures. Research conducted by Wang et al revealed that structural displacement and acceleration could be reduced by as much as 21.4% and 17.9% respectively when viscoelastic dampers are introduced (Wang et al., 2011). This modification was employed in the old World Trade Center in New York, where over 10,000 visco-elastic dampers were installed between support columns and floor trusses (Taranath, 2012).

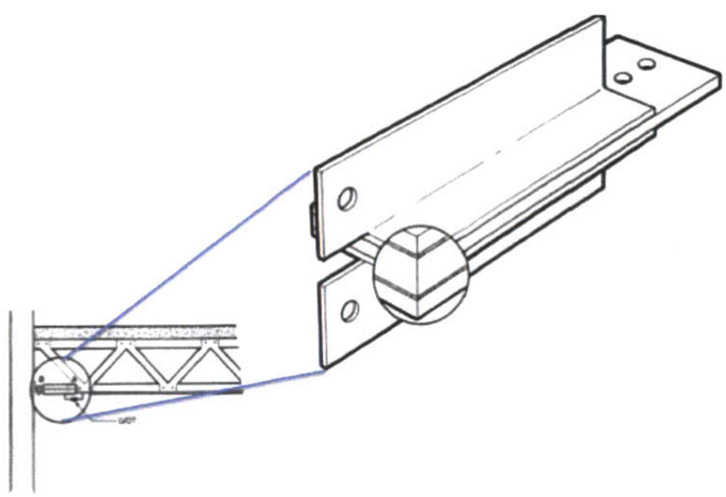

Figure 19: Viscoelastic Damper in the old World Trade Center [32]

One major disadvantage of viscoelastic dampers is that they are highly sensitive to variations in frequency and temperature. Under shear deformation, the temperature within the damper rises as external energy is transformed to heat. This reduces the damper's stiffness making it less effective in controlling motion. As a result, viscoelastic materials less susceptible to variations in temperature have been developed. Shear thickening or dilatant materials may be used in place of place of viscoelastic materials because their viscosity increases as shear deformation increases. In other words, a dilatant material gains strength or thickness as the force increases.

ACTIVE DAMPING

Active Mass Driver

In this scheme, a sensor, a computer, an actuator and a mass damper work together to control structural motion. The sensors are used to continuously measure the changing lateral loads and then the information is sent to a computer that analyzes the data. The feedback is then sent to the actuator to generate a counter-acting force, equivalent to the present loading conditions, in the TMD (Yamamoto Masashi, Satoru Aizawa, et al., 2002).

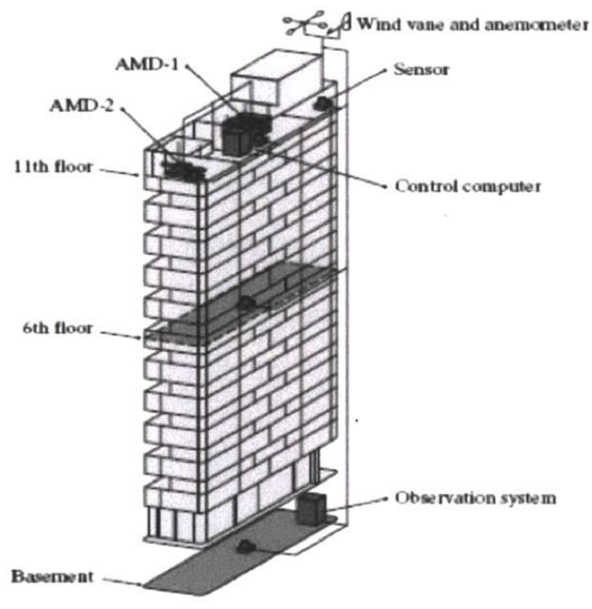

Figure 20: Active Mass Driver System Installation [10]

Due to the adaptability of this system, active mass drivers are more efficient in comparison to passive tuned mass dampers and therefore, require smaller damper masses (Kareem, Kijewski, and et al, 1999). However, active tuned mass drivers require significantly more maintenance and also pose reliability concerns because they could be knocked out of commission in the event of a power failure.

Active Mass Drivers were installed on the 38th floor of the HERBIS Plaza in Osaka, Japan. Two 160- tonne ice storage tanks were used as the moving mass and free vibration simulations revealed that this scheme increased the equivalent damping of the structure by 8% (Yamamoto Masashi, Satoru Aizawa, et al., 2002).

Hybrid Mass Damper

A hybrid mass damper is one that tries to combine the best features of both the passive tuned mass damper and the active mass driver. Nonetheless, because the system still requires an actuator to function, it is still classified as active control mechanism. This system functions as an active mass driver to effectively control structural responses at low frequencies. It also has the capacity to work as a passive damper against strong winds and large earthquakes or in the event of power failure. As a result, the system is able to maintain functionality across a wider range of frequencies when compared to the passive TMD and it is also able to achieve the same effectiveness as an AMD with much greater energy efficiency and lower maintenance costs.

In the 296m Yokohama Landmark Tower in Japan, two 170-tonne hybrid mass dampers were installed to improve residential habitability. Under normal conditions the system is restrained using a breaking device. However, when the system senses accelerations in excess of $0.02 m/s^2$, it automatically becomes operational and switches between an active control state and a passive control state as directed by the sway of the building.

The efficiency of the system allowed designers to use 20% of the mass that would have been required in a passive TMD system in order to yield the same result. Also, the hybrid mass damper uses 20% of the energy input that would have been required from an active mass driver to achieve the same result. The end result is a system that increases the equivalent structural damping to more than 10% and also reduces structural vibrations, under strong winds, by approximately 42%.

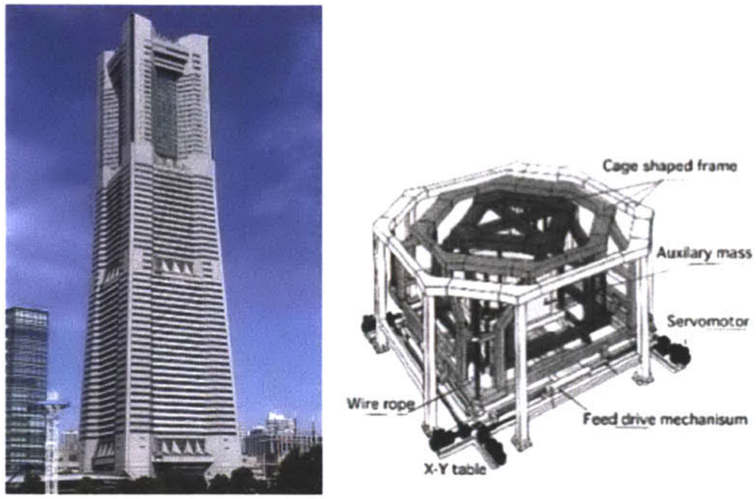

Figure 21: Hybrid Mass Damper in Yokohama Landmark Tower [1]

SEMI ACTIVE DAMPERS

Magneto-rheological (MR) damper

MR dampers are semi-active control devices that function similar to viscous dampers. However, they substitute the viscous fluid with a magneto-rheological fluid that changes its rheological characteristics when exposed to a magnetic field. Essentially, the introduction of a magnetic force alters the mechanical properties of MR fluids from a free flowing and linearly viscous liquid to a semi-solid with controllable yield strength (Yang, Spencer Jr., et al., 2002). The phase transformation occurs within milliseconds and the resulting increase in yield stress is proportional to the magnitude of the applied magnetic field. Unlike visco-elastic materials, MR fluids can function under a wide range of temperatures, from -40 to 150°C, with negligible variation in its properties and require as little as 12 to 24 volts to function (Yang, Spencer Jr., et al., 2002).

The MR damper designed by Lord Corporation is a cylindrical unit with a three-stage piston that has a diameter slightly smaller than the housing unit. It is 1m long, weighs 250 kilograms and can exert a force in excess of 200,000N on a structure (Lord Corporation, 2012). The MR fluid is stored in the cylinder and movement of the piston causes the fluid to flow through the space between the piston and the exterior cylinder. To create a damping force, electrical currents create a magnetic field along the surface of the piston, which in turn transform the MR fluid to a semi-solid. This changes the viscosity of the fluid and severely impedes motion of the pistons thereby creating a damping force opposite to the direction of motion.

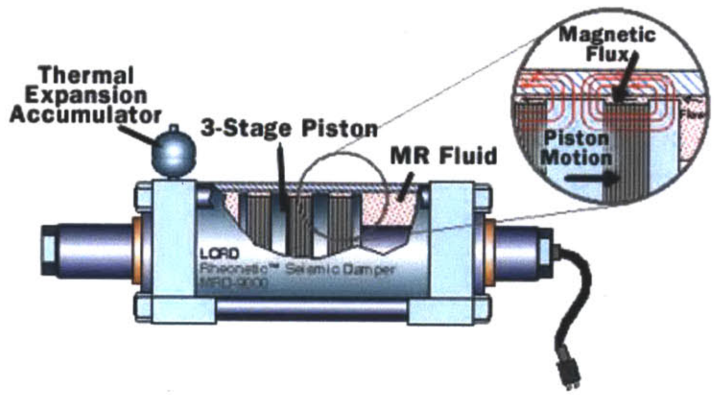

Figure 22: Magneto-Rheological Damper [31]

Whereas the shear stress of viscous fluids is dependent on just the dynamic viscosity of the fluid and the velocity gradient of the fluid, the shear stress of the MR fluid is given by the following equation

$$\tau = \tau_y(H) + \eta(\frac{dv}{dz})$$

where τ_y= *shear stress,* H = *magnetic field intensity,* η = *viscocity and* $\frac{dv}{dz}$ = *velocity gradient.*

The fact that the shear stress of the MR fluids is not wholly dependent upon velocity and fluid viscosity enables better control of motion over a broader range of frequencies. Unlike passive systems that are tuned once according to the estimated frequency of the primary structure, MR dampers continually optimize their damping characteristics by varying the rheology or stiffness of the fluid (Lord Corporation, 2012). Finally, in contrast to active systems, MR dampers can function in a passive damping mode in the event of power outage.

Electro-rheological Damper

The theory behind the Electro-rheological (ER) damper is virtually identical to the MR damper. However, in place of the MR fluid, an ER fluid is used to control motion. As defined by Gavin, "ER fluids are suspensions of polarizable particles in a dielectrically strong suspension" (Gavin, 1998). When an electric field is introduced, the particles are polarized, which restricts their vibration and forms a chainlike structure along the direction of the electric field (Figure 23). This not only changes the viscoelastic property of the fluid but also increases the yielding strength by several orders of magnitude (Gavin, 1998).

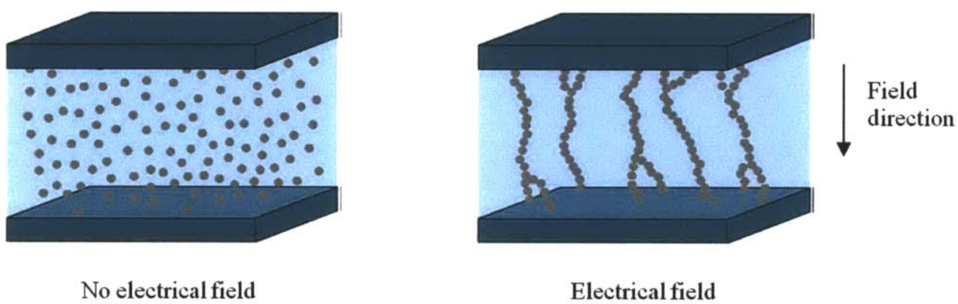

Figure 23: Behavior of ER fluids under Electric Current [46]

Active Variable Stiffness

These are systems that work by altering the rigidity of the structure in response to present loading conditions. In essence, a V-shapes brace is installed on each floor of the structure along with a variable stiffness device (Kareem, Kijewski, and et al, 1999). When the system is inactive, the braces are free to move laterally. However, when motion sensors detect accelerations capable of disrupting comfort levels, the system becomes active. In effect, the variable stiffness device locks the braces in place to reduce lateral motion (Figure 24). To make the system adaptive to changing conditions, the force used to restrain motion can be calibrated such that it becomes correlated with varying lateral loads. Finally, viscous fluids, piezoelectric materials, shape memory alloys and rheological fluids may be used to control or restrain the motion of the braces.

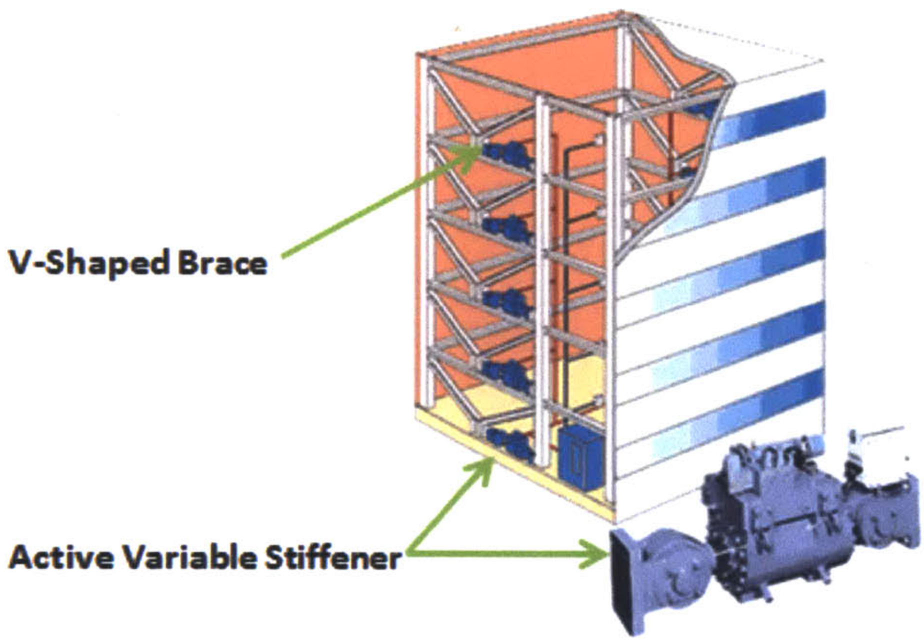

Figure 24: Active Variable System [26]

Chapter 4: PROPOSED DAMPING MODIFICATION

GYROSTABILIZER

The idea of using a gyroscope, as a stabilizing agent is not new as it is widely used in the film, shipping, and aerospace industry. In the film industry, stabilizing gyroscopes are touted as the remedy to "shaky camera images". When attached to a camera, a stabilizing gyroscope significantly reduces camera movement, thereby allowing a movie producer to capture sharp images from unusual positions such as a moving helicopter or airplane. In the shipping industry, they are used to dampen the rocky motion of cruise ships or luxury yachts (Figure 25). This creates a more pleasant ride for the passengers by preventing the onset of seasickness. Finally in the aerospace industry, they are used to control rolling motion of unmanned aerial vehicles and satellites.

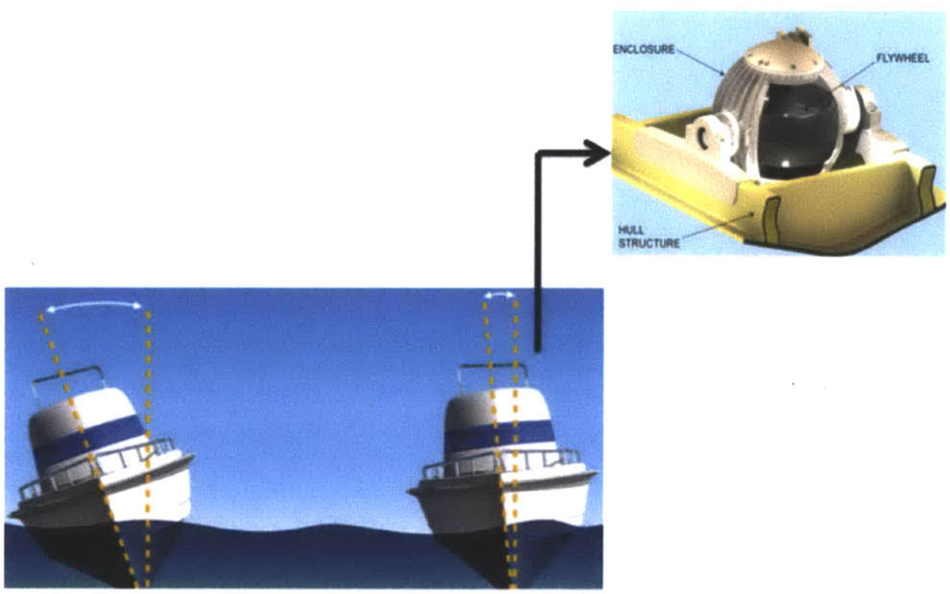

Figure 25: Yacht Motion with (right) and without (left) anti rolling gyroscopes [18,55]

Essentially a gyroscope is a spinning wheel, suspended in a gimbal that resists forces that try to alter its axis of rotation. The fact that the orientation of its rotational axis is not affected by the tilting of its base makes it a very attractive tool for navigation purposes or providing stability. Along with my classmate, Xi Zhang (MEng 2012), the proposition of using a spinning flywheel to control wind induced structural motion was studied using simple statics and rigid body dynamics [58].

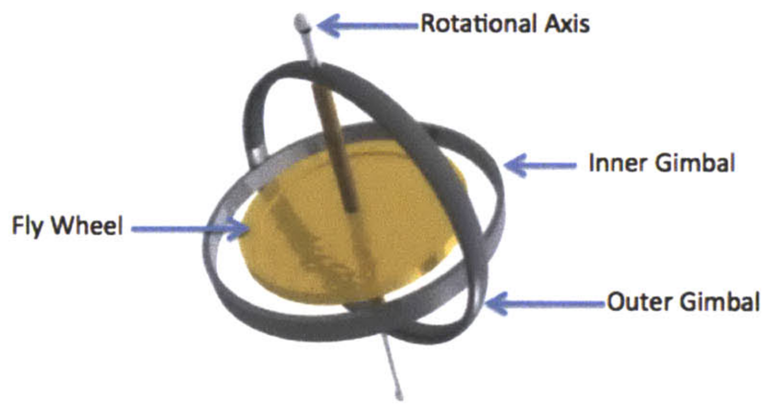

Figure 26: Gyroscope [55]

UNDERSTANDING GYROSCOPIC MOTION

The behavior of a spinning gyroscope can best be described as non-intuitive. When the wheel of a gyroscope is at rest, it behaves just like any object subject to gravitational loading. Try to balance it on its ends and it falls. Induce a torque in the system and the gyroscope complies. However once the wheel begins to spin, its behavior appears to defy gravity. A spinning gyroscope is able to balance on its end as long as the wheel continues to rotate fast enough. Additionally, when a torque that attempts to tilt its rotational axis is introduced, the gyroscope resists and begins to *precess* or rotate around another axis.

This phenomenon can be explained using the law of conservation of angular momentum. The law states that *the total angular momentum of a system has constant magnitude and direction if no external torque is applied to the system*. In other words, a spinning object will try to maintain, or resist change to its angular momentum but when this equilibrium is disrupted, the object tries to compensate by changing its angular velocity or direction of spin (Navy Mars, 2012).

In the classical example of an ice skater spinning with her arms outstretched, her velocity increases once she retracts her arms. This occurs as a result of the change in her mass distribution. Specifically, her body tries to conserve its angular momentum by increasing its velocity (Woodford, 2011). A spinning gyroscope offers no resistance to forces that do not interfere with its axis of rotation but it will resist forces, such as gravity, that try to change its rotational direction. This property allows the gyroscope to balance on its ends and it is also the reason why a spinning coin or a rotating wheel remains standing.

The angular momentum of a spinning gyroscope, the direction of which can be determined by the right hand rule, is defined as

$$L = I\omega$$

where I is the moment of inertia about the axis of rotation ($I = 0.5MR^2$, for a solid disk of uniform mass distribution) and ω is the angular rotation.

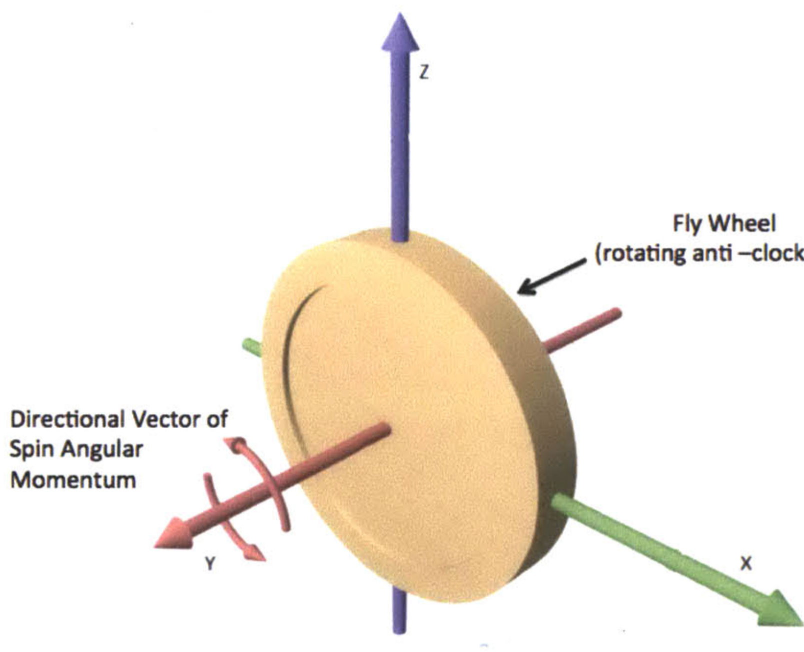

Figure 27: Spin Angular Momentum [55]

The ability of a gyroscope to maintain its rotational axis is defined as rigidity or gyroscopic inertia. The weight, the mass distribution, and the rotational speed of the wheel contribute to this property and as they become larger, the rigidity of the wheel increases.

When a torque is introduced to the system, the spin angular momentum always moves, at right angles, in the direction of the torque (Navy Mars, 2012). Using the flywheel shown in Figure 27 as an example, a force, applied in the YZ plane that tries to tilt the axis of rotation will cause the gyroscope to rotate around another vertical axis as the spin angular momentum vector chases the resulting torque vector (Figure 28). On the other hand, a momentary torque, applied in the XY plane that tries to turn the rotational axis will cause the gyroscope to tilt (figure 29). The tilting or turning of the gyroscope's rotational axis, as a result of external torque, is called precession. The precession continues indefinitely until either the net torque in the system is zeroed out or the spin angular momentum vector and the torque vector end up in the same direction (Navy Mars, 2012).

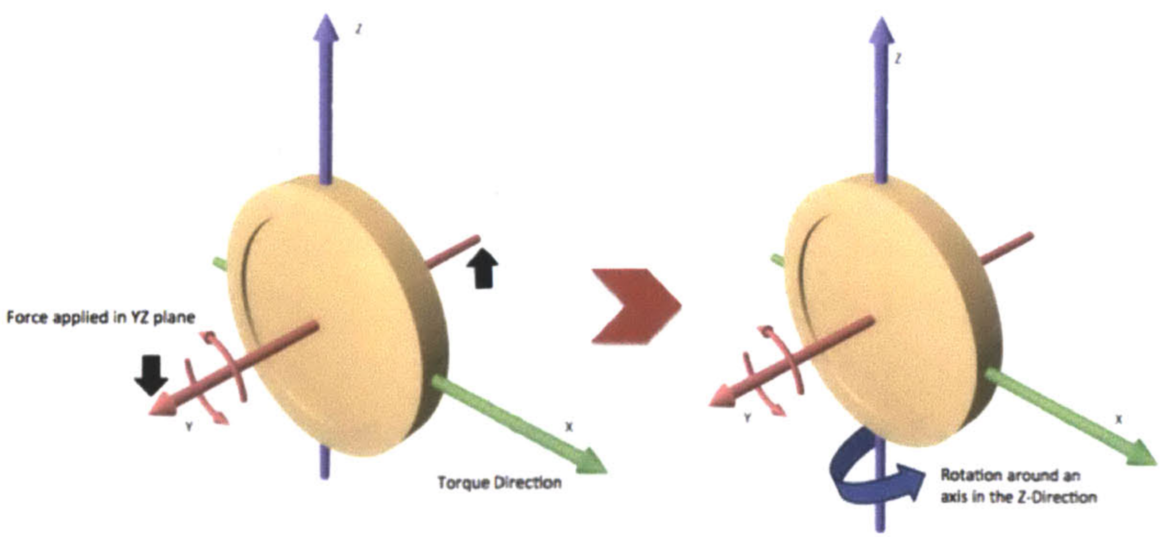

Figure 28: Gyroscope Reaction to force in the YZ plane [55]

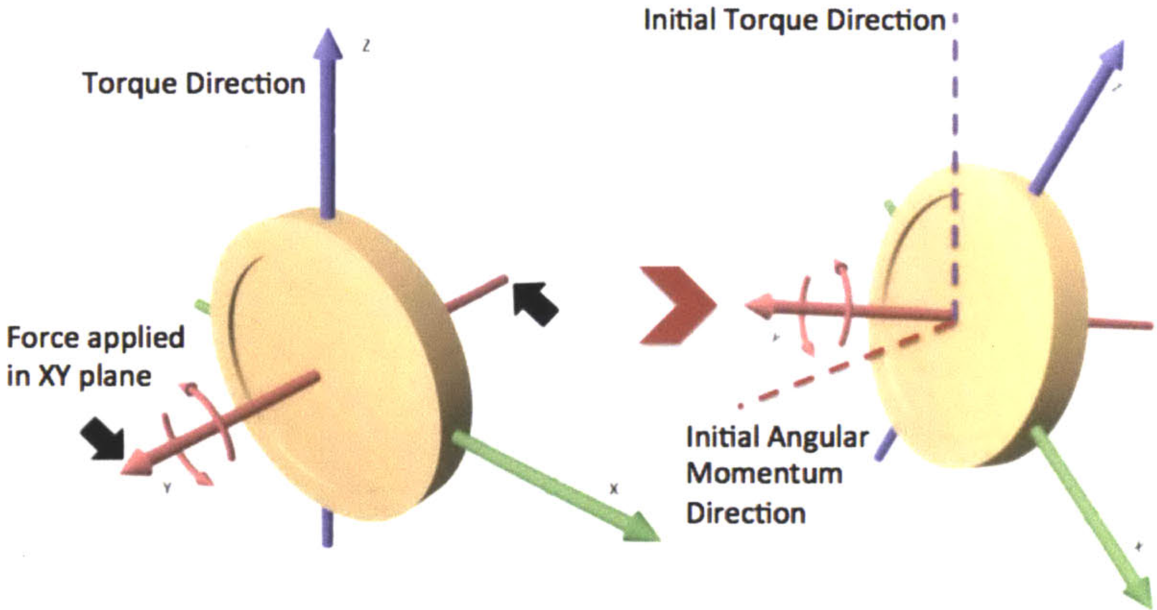

Figure 29: Gyroscope Reaction to Force in XY Plane [55]

Interestingly enough, the gyroscope doesn't react to an external force at the point at which it was applied. Instead, it's reaction occurs at a location that is 90° later in the direction of rotation. This lag in time allows the gyro to determine the amount of pressure created by a change in direction, which in turn is used to determine a rate (frequency) of precession (Flight Learning, 2012). The frequency of precession is determined by taking the ratio of the torque to the spin angular momentum. Therefore, the greater the applied force, the faster the flywheel's angular momentum vector moves in the direction of the resulting torque.

CONCEIVABLE DESIGN

By exploiting the unique response of gyroscopes to an external torque, a possible stabilizing agent can be conceived to control wind induced motion in tall buildings. As shown in Figure 29, a similar gyroscope, with a horizontal spin angular momentum vector, can be installed in tall buildings. A force can then be applied to a spinning flywheel, inducing a tilt in the rotational axis that is opposite and out of phase with the direction of the building's motion. This creates a negative moment that is needed to stabilize or control the structure's response.

This control mechanism would function in a manner similar to an active mass driver in that a sensor would be required to constantly monitor the building's acceleration. Once excessive structural acceleration is detected, the sensor will alert a computer, which in turn analyzes the data and determines the right amount of force that should be applied to the gyroscope. Finally this information will be sent to an actuator to generate and apply a force on the gyroscope thereby, creating a negative moment needed to stabilize the building's motion.

In order to optimize the power required to rotate each flywheel, the inertia of the flywheel, friction at the bearings and air resistance need to be considered (Chatley, 1912). The torque, generated by the spinning flywheel, is defined as the rate of change of the angular momentum over a period of time and it is expressed as:

$$\tau_{flywheel} = \frac{d(L)}{dt} = I\frac{d\omega}{dt} = I(\alpha)$$

Assuming that the flywheel is connected to cylindrical bearings in y direction (as shown in Figure 30), the torque generated by the friction force between the flywheel and bearings, on both faces of the flywheel, can be written as:

$$\tau_{friction} = \mu(mg)(\mathrm{d}/2)(2)$$

where d is the diameter of the cylindrical bearings and μ represents the friction coefficient. Finally, the air resistance force, and corresponding torque, is assumed to be acting on both faces and along the edge of the flywheel (Chatley, 1912). The air friction acting on both faces of the flywheel can be expressed as:

$$F_{drag\ on\ faces} = 2 * [0.5(C)(\rho)(A)(v^2)] = (C)(\rho)(\pi r^2)(w^2 r^2)$$

Integrating between the limits of "r", the torque due to drag on the faces can be written as:

$$\tau_{due\ to\ drag\ on\ faces} = \int_0^R (C)(\rho)(2\pi r)(w^2 r^2)\,(dr) = \frac{(C)(\rho)(\pi)(\omega^2)(r^4)}{2}$$

The air friction acting along the edges of the flywheel is determined to be:

$$F_{drag\ on\ edge} = 0.5(C)(\rho)(2\pi r)(t)(\omega^2 r^2) = (C)(\rho)(\pi r)(t)(\omega^2 r^2)$$

Therefore the torque about the centroid of the flywheel can be expressed as:

$$\tau_{due\ to\ drag\ on\ edges} = F_{drag\ on\ edges} * r$$

$$\tau_{due\ to\ drag\ on\ edges} = (C)(\rho)(\pi)(t)(\omega^2)(r^4)$$

where ρ (density of air) = 1.29kg/m³, t =thickness of the flywheel, C = coefficient of drag and r = radius of flywheel. Using the above expressions and given a flywheel with an angular velocity of ω, the minimum amount of applied torque required to overcome the resistive torques (Figure 30) can be expressed as:

$$\tau_{applied} = \tau_{flywheel} + \tau_{friction} + \tau_{due\ to\ drag\ on\ faces} + \tau_{due\ to\ drag\ along\ edge}$$

However, if the flywheel is confined within a vacuum that is theoretically devoid of air or any other fluid (as is done with anti rolling gyros used in luxury yachts), then the third and fourth resistive torques, in the above equation, can be eliminated (Chatley, 2012). Using the remaining terms, the resulting acceleration of the system, as a function of the applied torque can be written as:

$$\tau_{applied} = I(\alpha) + (\mu)(mg)(\frac{d}{2})$$

$$\alpha = \frac{\tau_{applied} - (\mu)(mg)(\frac{d}{2})}{I}$$

Therefore if the angular velocity (ω, radians/sec) of a the flywheel is known, the time (in seconds) needed to reach a certain acceleration can be determined by dividing the angular velocity by the angular acceleration. The time obtained can then be used to calibrate an advance warning system to know how soon the modified gyrostabilizers should be turned on in order reach a minimum acceleration required to overcome the resistive forces.

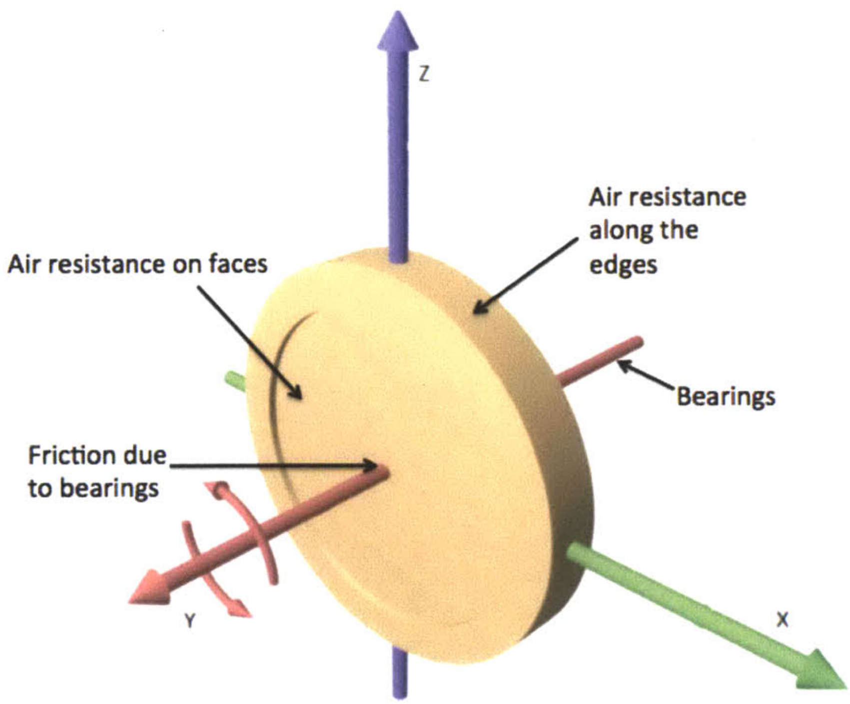

Figure 30: Resistive Torques acting on Flywheel [55]

To generate enough moment to control the structural motion, multiple modified gyrostabilizers could be installed at strategic locations within the structure. If the spin angular momentum vector is horizontal, they could be placed within cavities in the exterior wall in fashion similar to viscous dampers. On the other hand, if the spin angular momentum vector is vertical, they could be placed on the top floor and at other mechanical floors within the building, as is commonly done with tuned mass dampers.

Mechanism of a Gyroscope Attached to an exterior wall

A prospective, a model of a gyroscope connected to a building is created and shown below. The global axis depicted in Figure 31 will be referred to throughout the remainder of the report.

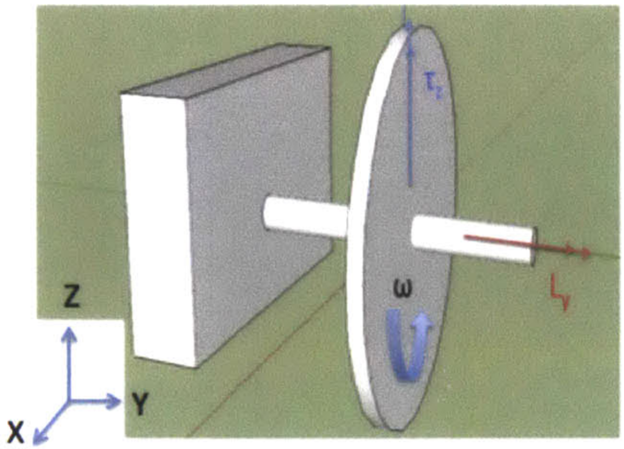

Figure 31: Prospective Flywheel Design

The flywheel is attached vertically to the building to prevent displacement in y direction. This means that if the building moves in the positive y direction, the flywheel would tilt clockwise (when looking along x-axis) thereby generating that a counteracting moment will on building's wall. The wheel, which is modeled as flat disk, has radius of r, mass of m, and rotating at speed ω. Therefore, the angular momentum can be expressed as:

$$L_y = \frac{mr^2\omega}{2}$$

As noted earlier, a couple exerted in the XY plane and separated by a distance "d", as shown in Figure 29 creates a torque on the gyroscope in the positive Z direction. This torque is represented as τ_z in the Figure 31. Assuming that the couple is created by a mass connected to a spring and dashpot, the resulting force and torque can be written as:

$$F = k_d u + C_d \dot{u}$$

$$\tau_z = F * d = (k_d u + C_d \dot{u}) * d$$

where k_d is stiffness constant of the spring and C_d is the damping coefficient of the dashpot. Additionally, if the flywheel is connected to the building by a torsional spring, a rotation around the x-axis will exert a moment on the building's wall. This moment can be denoted as

$$M_x = k_\theta \theta$$

where k_θ is the stiffness of torsional spring and θ represents the tilting angle. Finally, the bearings that support the flywheel are assumed to be rigid and strong enough to withstand the loads it might experience. A major concern is that the large moments transferred from the building to the flywheel via the bearings might be large enough to break the bearings.

To create a relationship between τ_z and M_x, it should be noted that when the flywheel tilts, as shown in Figure 32, the angular momentum vector also tilts by an amount θ.

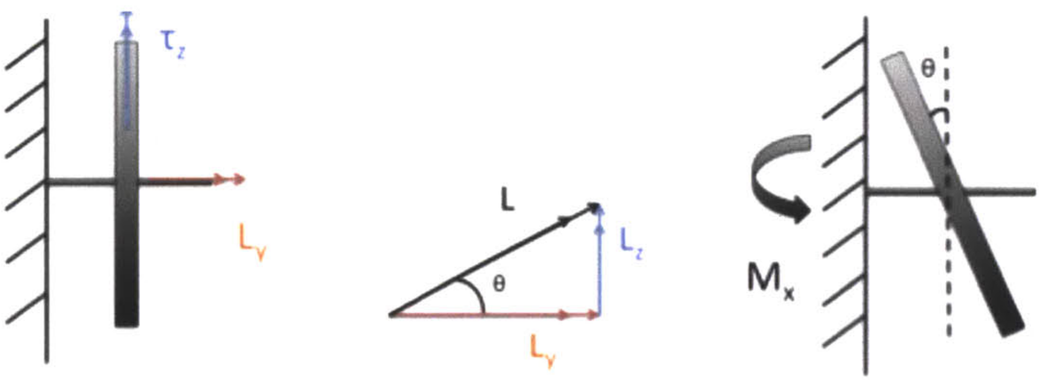

Figure 32: Change in Angular Momentum

The tilt angle is taken to be small therefore the tilt angle can be expressed as,

$$\theta = \tan\theta = \frac{L_z}{L_y}$$

Since τ_z is known, L_z can be calculated and expressed as,

$$\tau_z = \frac{dL_z}{dt}, \quad L_z = \int \tau_z \, dt$$

Combining all the expressions into the moment equation, M_x can be written as,

$$M_x = \frac{k_\theta \int \tau_z \, dt}{L_y} = \frac{2k_\theta d \int_0^t (k_d u + C_d \dot{u}) \, dt}{mr^2 \omega}$$

The dynamic wind load is taken to be periodic, so M_x will also be periodic and should theoretically compensate for the moment generated by wind loads.

A traditional square, steel tower with an aspect ratio of 8 (height of 80m and width of 10m) is used to test the feasibility of this device. The structure is assumed to be rigid and its performance under two wind velocities is evaluated. A 40m/s wind speed at the top of the building, close to extreme wind speed in Boston, and a less severe 10m/s wind at the top of the building are chosen to conduct the analysis (Figure 33).

Wind loading on Model

An exponential distribution of wind speed is assumed to act across the windward surface of the tower (Figure 33). Using a direct integration approach and taking the structure as a rigid cantilever, the base overturning created by the wind can be calculated.

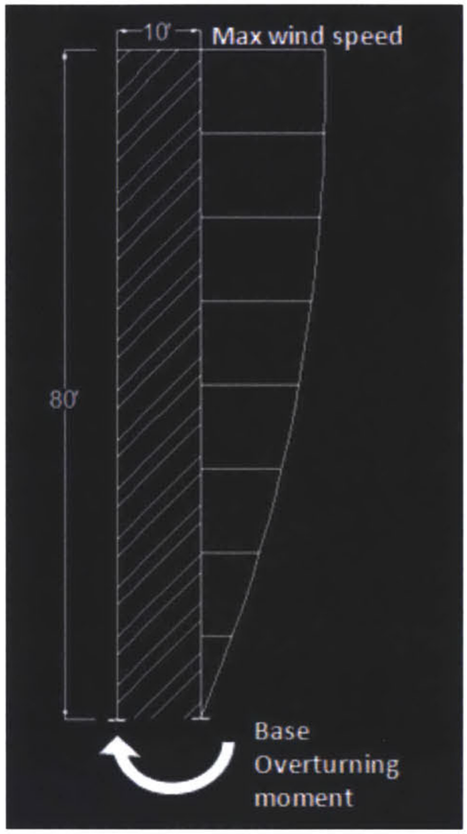

Figure 33: Wind Profile acting on windward side of building

For the 40m/s wind, the maximum moment at bottom of the building is calculated to be approximately 3000 KN-m while maximum moment is about 200 KN-m for the 10m/s wind. Using these moments, a conceivable design for the gyroscopes can be created using the aforementioned equations in the previous section.

Modified Gyrostabilizer Design

In the design of the gyroscope, the dimension, rotating speed, k_θ, k_d and C_d need to be addressed. If one of the above parameters cannot be designed with a realistic size and strength, the design will be deemed impracticable.

A torque can be generated in z direction when building moves with the aid of a rolling mass that is connected to a spring and dashpot. For a certain displacement, a torque will be created due to the periodic load from the damper. Alternatively, an automated hydraulic actuator can be used to generate this torque. When excessive structural motion is detected by accelerometers, data can be conveyed to an actuator. The actuator in turn can be calibrated to produce a torque that is not only needed to stabilize the building but also adaptable to changing loading conditions.

A disk with a weight of 10kg and a diameter of 2m is chosen as the flywheel. Five equally spaced flywheels are located across the width of the structure and also placed at every 10m so a total of 40 flywheels will be installed on each face of the building (Figure 34). If the tilt angle of the gyroscope is constrained to 1/300 radians and the rate of change of τ_z is determined to be 15 KN-m/s, then angular momentum of flywheel will be 4200 KN-m/s. For the 40m/s wind, with a base overturning moment of 3000KN-m, each gyroscope needs to resist 7.5 KN-m. Given the small tilt angle, a torsional spring stiffness of 22500 KN-m/rad is required to produce the required moment (Figure 35).

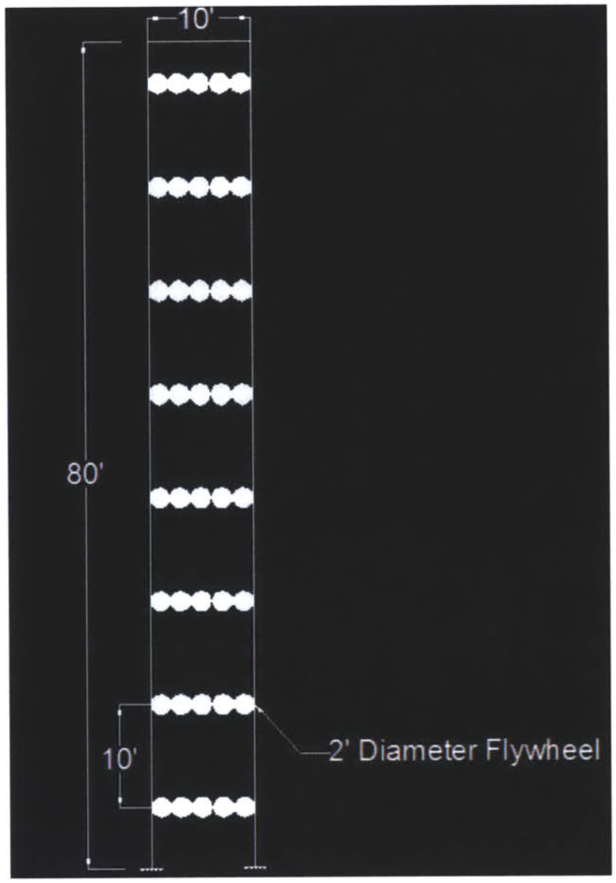

Figure 34: Flywheel Configuration on Model

As shown in Figure 35, a torsional spring, with a strand diameter of 0.05m, that satisfies the required stiffness will need to have a 10m coil diameter. The large size of the required torsional spring makes it impractical to place the proposed flywheel within the walls or any other part of the building. Even when 80 gyroscopes are considered (5 across the width of building and at vertical spacing of 5m), the required coil diameter of the torsional spring (5 m) is still very large. As a result, the conclusion is that, although this mechanism can be effective, it is inefficient to use the proposed gyroscope mechanism to control structural motion under excessive wind conditions.

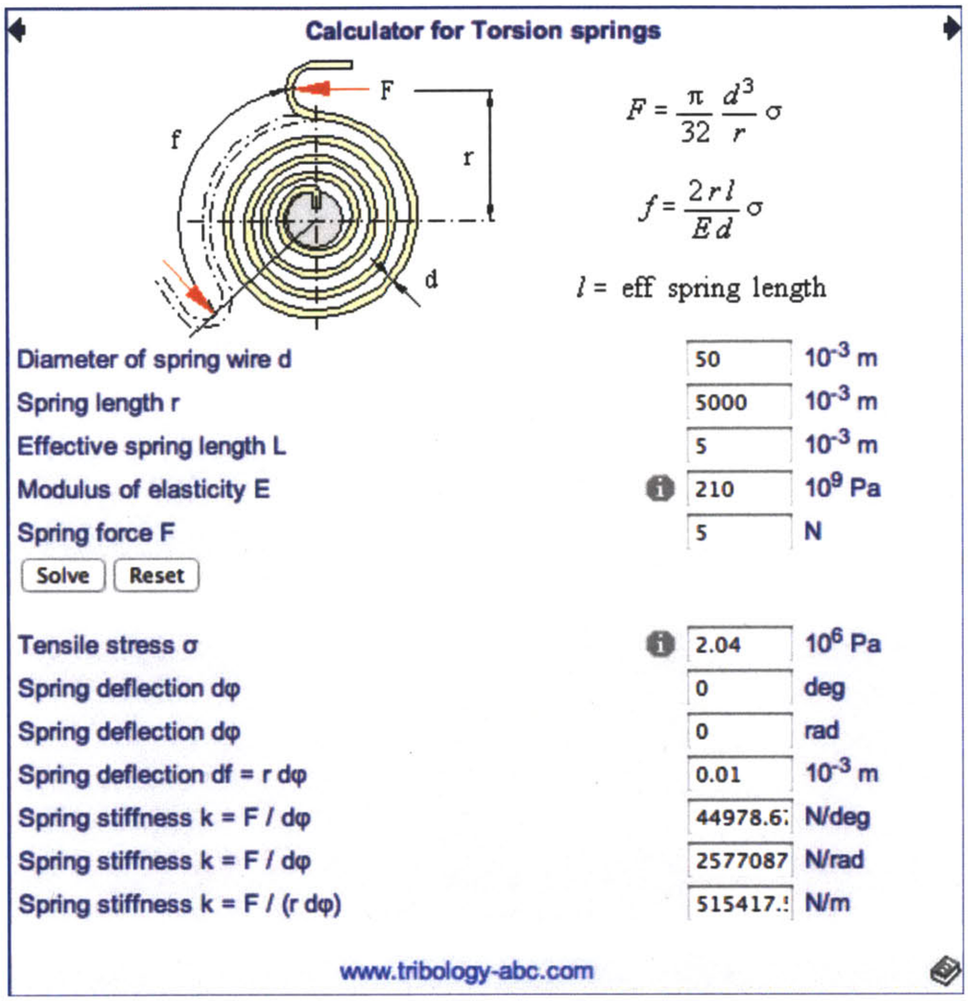

Figure 35: Calculation for Torsional Spring [7]

The analysis is repeated for a mild and more common wind speed of 10m/s, with an estimated base overturning moment of 200 KN-m. If the same number of flywheels and configuration are employed (Figure 34), the required stiffness for the torsional spring is determined to be about 1500 KN-m/rad. Despite the reduction in torsional spring constant, the diameter still needs to be 4m, which is still too large to fit within the an exterior wall section.

CONCLUSION

Similar to other active control mechanisms, this modification will be able to adapt to changing lateral loading in real time, thereby providing improved performance over passive damping modifications. Additionally, unlike viscous dampers, it would require no seals to retain fluids that could leak over time.

However, the system faces the same shortcomings as active damping devices. It would require a great deal of energy to function, making it an unattractive option for potential customers. It could also potentially destabilize the structure if the gyroscope is forced to tilt in the wrong direction. Additionally, the maintenance cost will be high, as periodic tuning of the springs would be required to ensure the system performs to its design standards. Finally, in the event of a power failure, the modified gyrostabilizers would be rendered useless, because they lack the capacity to function as passive damping devices without energy.

The flywheel can be sufficiently scaled to fit into the cross section of exterior walls because the required torque needed to generate the negative moment is inversely related to the size of the flywheel. In other words, as the size decreases, a larger torque needs to be generated by the rolling mass or the hydraulic actuator to create a sufficient counter-moment. Nonetheless, the practicability of this damping modification is hindered by the required size of the torsional spring and electrical demands.

If spring stiffness of the moment transfer mechanism (torsional spring), can be significantly improved so as to reduce its size, then the modified gyrostabilizer can be used to control structural motion. Alternatively, a better moment transfer mechanism, with a greater stiffness per rotation, can be developed to more efficiently transfer moment to the exterior wall. In this analysis, the derived relationship between moment, M_x, and the tilt angle, θ, is linear. Perhaps a device with an exponential relationship can be invented. This would provide a greater counteracting moment per degree of rotation and hopefully occupy less space.

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