Active Energy Control in Civil Structures
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ABSTRACT
This study explores the use of a linear PMDC machine as a regenerative force actuator for the mitigation of earthquake disturbances in civil structures. Unlike previous studies of this kind, the control system developed is purely active, meaning no "hybrid" control techniques are used, such as the combination of active force actuation and passive tuned mass dampers. Modeling methods for the machine as well as its associated drive electronics are briefly described. It is shown that for this purely active system, it is possible and feasible to develop regenerative excitation schemes which drive the machine primarily by absorbing power from the excited building. Such regenerative excitation makes it possible to isolate the actuator from the external power grid, which is necessary during earthquakes, where the quality, or even the mere availability of external power is questionable. Furthermore, results are presented which find the minimum reservoir of energy necessary to excite the machine during the beginning of the earthquake, and it is shown that the actuator local power supply will see a gain in energy across the duration of the disturbance. The control system design methods presented employ position feedback. Then, force limiting techniques are employed to regulate power flow in the machine. The effectiveness of this control design is evaluated on a 3-story building, and performance is briefly compared to that of semi-active control designs proposed elsewhere.

1. INTRODUCTION
Over the last few decades, extensive research has been conducted toward the mitigation of seismic disturbances in civil structures. This research has resulted in a wealth of literature on the subject, including force actuation methods, control system approaches, and reliable sensory systems, as well as syntheses of control and structural designs. Several approaches have led to the actual implementation of such systems, and there are currently over 30 buildings and 20 bridges which employ some kind of active structural control system.

In general, the control of such systems can be separated into a few distinct categories, based primarily on the placement of the actuator, and on the physical nature of the actuator itself. Passive systems have been around the longest, and generally are one of two types. The first of these is a tuned mass damper, placed at the top of the building, designed to resonate at the fundamental frequency of the structure. During wind or earthquake disturbances, the damper absorbs some of the energy injected into the building by the disturbance, reducing the maximum swing of the structure. The second type of passive system is a base-isolation system, which the idea is to deliberately design the structure to possess lower elasticity between the first floor and the ground. The intended effect here is to cause the upper floors in the structure to move more as a lumped mass, thus reducing the inter-story drifts between these floors.

These passive systems have seen several implementations, and have been shown to be quite useful in the mitigation of wind disturbances. However, studies have indicated that the performance of passive systems in the face of earthquakes is at best uncertain. Thus, active control methods have been applied to handle this problem. Many active systems have been proposed, but the two that dominate the literature are the active mass damper and the active tendon systems. An active mass damper is similar to a tuned mass damper, with the difference being that the mass at the top of the building is accelerated by an active actuator, such as an electric or hydraulic machine. Active tendon systems excite tendons strategically placed at various locations in the building to actively modify its elastic behavior. Of these two methods, active mass dampers have seen the most application in real structures, and extensive research has been conducted in the application of various control methods for these systems. Examples are position and velocity feedback, LQR/LQG control, H-infinity methods, adaptive control, neural networks and fuzzy control, sliding mode control, and acceleration feedback. These methods all show excellent enhancements in the protection of structures during earthquakes. However, three main problems limit the appeal of active control. First, they consume external power, which may not be available during a natural disaster, raising
questions of reliability. Second, they tend to possess rather large strokes, which is a problem both spatially and mechanically. Third, questions of stability robustness have been raised concerning these methods, as they have the potential, given sufficient perturbation of parameters in the structural model and control system, to destabilize the structure.

Of these issues, the most pressing one is arguably the heavy reliance on external power. To alleviate this tendency, some hybrid control schemes have been proposed, and some have actually seen successful implementation. Although actuators for these techniques tend to be of an ad-hoc nature, a mainstay of hybrid control actuation has been the hybrid mass damper\(^\text{20}\). This basically is a tuned mass damper with additional active excitation. These have seen success in alleviating the mass requirements for the actuator\(^\text{21}\), as well as for adaptively re-tuning the damper to the structure. While these methods do require external power, they tend to be more robust, as they will still operate in some capacity in the event a collapse of the external power system.

More recently, a new philosophy on structural control has developed, called semi-active control. Semi-active control systems are defined as those which are incapable of injecting energy into the system, made up of the structure and actuator, but which can selectively dissipate, or channel, the energy in the system to achieve favorable results. Of these methods, the most success has been obtained using magnetorheological dampers, which are capable of varying their viscosity upon the application of a magnetic field to the fluid. Systems have been proposed\(^\text{22}\) which place such a damper between the first floor and ground of a three-story structure, and results indicate formidable improvements in the inter-story drifts and absolute accelerations of the floors.

Regenerative excitation schemes have been addressed in the literature\(^\text{18,23}\) as a means of reducing the power and energy requirements for active control. In regenerative excitation schemes, a linear force actuator is designed with the capability of both bidirectional power flow, allowing it to expend as well as recover energy. A method was developed whereby a machine with a bidirectional power drive was used to accelerate a tuned mass damper. The control methodology was dual-mode. During times of low disturbance magnitude, a localized power source was charged through the actuator. Then, during periods of severe disturbances, the actuator was to actively excite the tuned mass damper to suppress the disturbance. During these periods of high disturbance magnitudes, the approach was essentially hybrid control, with efforts made to reduce, and possibly eliminate, the reliance on external power. Favorable results were obtained for sliding mode control designs.

Inspired by these ideas, the methods proposed here differ in a few respects. In the previous work on regenerative excitation, all control systems were designed for a hybrid mass damper. The justification was that the power requirements are typically less for hybrid control than for fully active mass dampers, and that hybrid methods were more reliable in the event of a power failure in the active system. Here, we compare hybrid to active mass dampers from the standpoint of regeneration, eventually concluding that little is gained by hybrid solutions insofar as power ratings are concerned. Additionally, the methods proposed here regulate the energy involved in the control by limiting power flow magnitudes in the actuator. It is shown that through such regulation, a finite energy capacity \(E\), for a local battery supply may be designated ahead of time. Furthermore, the building may be controlled for an arbitrary length of time with this battery, due to the cyclical discharge and recharge behavior of the actuator. This leads the way for a concrete designation of power supply requirements for the actuator system.

This paper is organized as follows. In the next section, we will talk in more detail about the implementation of a regenerative electromechanical actuator, and discuss its power flow characteristics. Then, we will talk about regenerative properties of the actuator when implemented in hybrid and active control systems. Here, we will show that for a very basic type of control, position feedback, active control systems exhibit much more favorable regenerative behavior, as well as lower power requirements. Following this, in the fourth section, we will discuss the implementation of a semi-active system, using the regenerative actuator, together with a battery power source, and will show how the energy capacity of the battery might be extracted from the properties of the actuator. Also, we will discuss the influence of the size of the battery on the level of performance attainable for the control system. Finally, we will draw some conclusions and suggest future directions for the work.

### 2. THE ACTUATOR MODEL

In this section we present the model for a regenerative, linear electric actuator used to enact a force on the mass damper, and building. The elements comprising this actuator are a linear permanent magnet, brushless DC (PMBDC) machine, the power electronic drive, and a battery. Starting from the machine, we will develop the interaction between these elements, and arrive at a simplified model for the actuator.
A PMBDC machine consists of a stator, which is mounted to the structure, and a translator, which slides with minimal friction through the stator. A three-phase current is applied to coils in the stator, which realizes a travelling, sinusoidal magnetic field along the axis of motion of the translator. Permanent magnets, embedded in the translator, are placed such that they form a roughly sinusoidal, DC magnetic field, also along the axis of motion of the translator. The coupling between these two fields, when mismatched, results in a linear force on the translator, which causes it to accelerate, thus yielding linear motion. For this application, the translator is the mass damper, with mass $m_d$. Because the stator is attached rigidly to the structure, a linear force enacted to the mass damper results in an equal and opposite force on the structure.

The choice of a linear PMBDC machine for the force actuation was made based on several generalizations. Most importantly, unlike AC (i.e. linear induction) machines, PMBDC machines do not require an external excitation for regeneration. Furthermore, they tend to have higher torque-to-force ratios than other machines, and tend to have higher peak-to-rated torque ratios as well. A linear machine was chosen over a rotational one, complete with a ball-screw mechanism at the shaft to facilitate linear motion, because linear machines tend to have higher efficiencies due to the absence of gear reduction and the ball-screw mechanism. For an application such as this where we must rely on the actuator to recapture energy to be used again, this efficiency during regeneration is crucial. The resistance in the windings of the stator and in the battery dominate the power losses in the system. In general, the power converter will have high efficiency, and the losses in the field can be considered negligible.

The power electronics used to realize a force $f_d$ on the mass $m_d$ of the translator is shown in Figure 1. The coils in the base of the machine are excited by three-phase current $i_a$, $i_b$, and $i_c$, which are supplied to the terminals of the machine by the power electronic converter. This converter manufactures these currents from a DC battery source with voltage $V_{dc}$ and energy capacity $E_c$. At the heart of this study lies the fact that the converter to be used is a bidirectional power converter, which has the capability to sink as well as source current to and from the battery. Resultantly, the converter is capable of allowing power to flow from the battery to the machine, as well as in the opposite direction. This results in the possibility not only of translating electrical energy into mechanical, but also for regeneration; the conversion of mechanical energy into electrical.

The control system which is used to realize the output force of the actuator takes as feedback signals the armature currents of the machine, together with its linear position $x_d$. From this position signal, a force command $f_d^*$ can be converted to appropriate current commands $i_a^*$, $i_b^*$, and $i_c^*$ for the three stator coils. Using information about the command and actual currents, appropriate DC to AC conversion and filtering is performed by the PWM regulator on the power electronic converter. In the interest of brevity, we will not delve in the inner workings of the power converter and motor beyond this, nor will we attempt to model the dynamics of the battery voltage. These ideas are adequately represented in the literature [refs]. The general conclusion is that the time constants involved in realizing a force $f_d$ from its command $f_d^*$ for such converters are insignificant in the face of the low-bandwidth nature of the vibration of a civil structure, and the acceleration of an earthquake. Here, we will assume these dynamics are negligible, and all simulation results will assume $f_d = f_d^*$.

The point of underlying importance is the bidirectional power flow capability of the power electronic drive. The common terminology for a bidirectional drive is "four-quadrant," referring to the partitioning of the speed and force capabilities of the drive into four quadrants, as shown in Figure 2. As illustrated here, quadrants I and III have the actuator force and velocity with the same sign, resulting in a positive power flow out of the actuator. This results in energy discharge

![Figure 1: PMBDC machine with power electronic drive and force control system](image)
from the battery. Likewise, quadrants II and IV show the force and velocity of the actuator with opposite signs, resulting in a negative power flow out of the actuator, recharging the battery.

In quadrants I and III, the actuator may expend only a finite amount of net energy, which is entirely derived from the battery. In quadrants II and IV, the actuator may recharge the battery, or may redirect the regenerated power, to be dissipated through a load. This capability yields two convenient properties. The first of these is that, for any energy signal, any closed-loop system which uses this actuator is guaranteed to be stable, by the fact that the actuator has only a finite energy capacity to contribute to the system, resulting in a bounded-energy system. Secondly, the actuator requires no external power for operation. Thus, the energy properties of such actuation avoid many of the drawbacks of active control. Due to the bounded-energy nature of the actuator, and thus its guaranteed stability characteristics, it is a candidate for the implementation of semi-active structural control.

3. REGENERATIVE CONTROL

If a finite energy capacity battery is used for this regenerative actuator, it becomes important that the control system design is such that it manages energy expended by the battery in an economical way. Here, we concentrate on some simple linear control designs for civil structures, and the differences in power flow which arise between active an hybrid control systems. We will show that it is possible to attain lower power ratings and energy requirements with active, rather than hybrid, mass damping. We will do this through example, by comparing the power, energy, and force required of the electric actuator for active and hybrid systems with equivalent closed-loop behavior.

Consider a three-story structure with the second-order relationship

\[ M_3 \ddot{x} + C_3 \dot{x} + K_3 x = \Gamma \dot{\eta} - M_4 \Lambda \ddot{\eta}_g \]  

(1)

where the states \( x \) are the floor displacements relative to the ground, expressed as \( x = [x_1 \ x_2 \ x_3]^T \), \( f \) is the total control force on the structure by a hybrid mass damper (made up of the active actuator force \( f_d \) and passive force \( f_p \) from a spring/damper system), and \( \ddot{\eta}_g \) is the acceleration of the ground. The stiffness, damping, and assorted input matrices for this structure are

\[
M_x = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} \ kg, \quad C_x = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \ \frac{Ns}{m}, \quad K_x = 10^5 \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \ \frac{Nm}{m}, \quad \Gamma = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}, \quad \Lambda = \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]
This model has been tested in numerous experiments at the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre-Dame, and provides a convenient benchmark for the comparison of semi-active controllers.

For the actuator, mounted atop the structure, we assume the mass $m_d$ is equal to 1% of the total mass of the building. We will also assume for now that all force and power signals are within their limits. The equation for the total force on the mass damper is then

$$f = F_d - k_d x_d - c_d \dot{x}_d$$

where $x_d$ is the displacement of the mass $m_d$, relative the third floor, and $k_d$ and $c_d$ are the spring and viscous damping constants for the hybrid damper. Here, the spring, mass, and damper are tuned to the fundamental frequency of the building. Furthermore, $k_d$ and $c_d$ are chosen for a damping coefficient of 0.707. The total system is illustrated in Figure 3.

For this example, we will excite the structure with the El Centro earthquake disturbance (scaled to the time and size proportions of the test model), shown in Figure 4. For hybrid and active control systems resulting in identical closed-loop structural performance, we will evaluate their power and energy requirements. We first consider a hybrid control system. We will simplify matters by using proportional feedback control, where the feedback signal is taken to be the displacement of the third story, relative to the ground. The control force for the hybrid system is then

$$f_d = K x_3$$

For a gain $K$ of $1.7 \times 10^5$, the top-story response $x_3(t)$ is shown in Figure 5. This reflects a sizable improvement in the maximum displacement of the structure, which is reduced from 0.962cm for the uncompensated case, to 0.247cm for the closed-loop system.

We next note that exactly the same response may be achieved using purely active means. To see this, we simply redefine the active control force $f_a$ as

$$f_a = K x_3 + K_p x_d + K_v \dot{x}_d$$

where the feedback gains $K_p$ and $K_v$ are equal to $-k_d$ and $-c_d$ respectively. For active control, the spring and damper are removed from the system, yielding $f = f_a$. This fully active control system is then mathematically equivalent to the hybrid system in (2), and exactly the same response is obtained for $x_3$ for the closed-loop system.
Although the closed-loop responses for the two systems are exactly the same from the point of view of the structure, the force, power, and energy characteristics for the linear electric actuator are quite different for these two cases. Figure 6 shows these three signals for both cases. Comparing force magnitudes, the active control case requires a 10% lower force to realize the same closed-loop system. Furthermore, examining the power flows for the active and hybrid cases, we see that the hybrid case shows power flow in essentially one direction out of the electric actuator, indicating that very little regeneration occurs over the duration of the disturbance. On the other hand, the fully active system shows a power flow characteristic which oscillates, indicating that the battery for the actuator is recapturing much of the energy injected into the structure by the control system. The active case shows power flow magnitudes less than half those of the hybrid case, indicating that, in this case, hybrid control does not really relax the power rating of the actuator.

The comparison of the expended energy for the two cases is quite dramatic. While the hybrid case continually requires energy from the battery, the active case not only regenerates the energy used by the control system, but also extracts additional energy from the earthquake, resulting in a net gain of energy. At $t = 3s$, the energy expended in the hybrid case is 325J, while the active case has actually generated about 7 Joules of energy. From such a comparison, we can conclude that if we desire a minimal energy required for the realization of the control force $f$, active control is much more desirable. From the standpoint of battery sizing, this means that, using active control, a much smaller battery can be used to realize the same control force of a hybrid system.

To determine the energy capacity for the active control, Figure 7 shows a magnified time history of the net energy expended by the actuator. Note that the energy stored in the battery oscillates in time. For such behavior, the minimum energy capacity needs to be only large enough to store the maximum net energy discharged by the actuator. Excess regenerative
energy can easily be dumped as heat, through the use of load resistor banks. Thus, \( E_c \) for the battery is equal to the maximum peak-to-peak energy rise. This maximum is labeled on the plot, indicating that for active control, \( E_c \) is approximately 12.1J. This is much less than the 325J required for hybrid control.
4. CLIPPED-POWER ENERGY CONTROL

At this point, we have presented data which suggests that a fully active controller, using a four-quadrant linear electric machine as an actuator, can be used in combination with a battery to form an effective semi-active control device. In this section, we will illustrate how we might dictate the energy capacity of the actuator, $E_c$, as part of the system design.

4.1 Designating a Battery Energy Capacity

Limitations are placed on a control system for a machine to ensure that it stays within its force, power and velocity ratings. Operation of the machine beyond its limits, which are maintained by proper force command limiting, can lead to irreparable damage. These limits in the machine's performance are illustrated in Figure 8a.

![Figure 8: Four-quadrant limitations for symmetric (a) and asymmetric (b) power limiting](image)

Typically, power limiting is done in the symmetric way depicted in Figure 8a, with both positive and negative power flow being limited equally [ref]. Here, we propose asymmetric power limiting for such a linear electric actuator. Under such limiting, in quadrants I and III where the machine is motoring, the maximum allowable power will be designated $P_+$. In quadrants II and IV where the machine is generating, the maximum allowable power will be designated $P_-$. We will further designate that $P_+$ must be significantly greater than $P_-$. Such designations on power limiting, together with the previously described force limiting, yield a four-quadrant limitation shown in Figure 8b. We will show that this asymmetrical power limiting yields favorable regenerative behavior in vibration suppression.

Suppose for the active control system described by (4), we were to instigate force and power limiters. Specifically, let the force limit $F_{\text{max}}$ be 1kN. Furthermore, let the positive and negative power limits, $P_+$ and $P_-$ be 80W and 1000W, respectively. For this scenario, with the same gain as before, the third-floor position, actuator force, and power are shown in Figure 9. As can be seen, the power-limiting has had a somewhat detrimental impact on the displacement of the building, which now has a maximum value of 0.391cm for the closed-loop system, a 59% decrease from the uncompensated case. The power signal, as expected, shows a hard limit at 80W.

Figure 9 also shows the energy expended by the battery. This plot indicates that the energy discharge and regeneration processes are cyclical, with a frequency equal to twice the fundamental frequency of the structure. During the first part of the cycle, the battery discharges energy, yielding a positive power, and a rising energy value in Figure 9. Because of the asymmetrical power limitation, the slope of this energy rise is limited to 80W. Because the power flow out of the actuator is oscillatory, at twice the fundamental frequency of the structure, the maximum time for this rise is about half the fundamental period. Following the energy discharge from the battery, the actuator undergoes regeneration. Because regenerative power has a much higher limit, the negative slope of the energy curve during this period is capable of much larger magnitudes than the discharge period. Thus, the actuator has a tendency to recover all lost energy, fully recharging the battery.

Because we know regeneration can only occur continuously for half the period of oscillation of the structure, $T_{st}$, and because the maximum power attainable during that period is limited to $P_+$, it follows that there is a maximum energy, $P_+T_{st}$, which can be discharged upon each cycle. Because the actuator recovers all discharged energy in the regeneration part of the cycle, this finite energy is the minimum energy capacity, $E_c$, required of the battery for operation. Thus

$$E_c = P_+ \frac{T_{st}}{2} E_c$$

(5)
For this particular example, this energy capacity is 7.4 J.

These results suggest a three-part cyclical approach to energy control for regenerative electric actuators. We divide each cycle of discharge/regeneration into three parts, as illustrated in Figure 10. In part A of the cycle, energy is discharged from the battery. Part B starts with the regeneration part of the cycle. Part B ends when the battery is recharged to its capacity $E_c$. Part C of the cycle occupies the time after which the battery has been charged, and while the machine continues to consume power. During this time, the excess power is dissipated as heat.

4.2 Effects of Energy Capacity on Performance

At this point, we have developed a method whereby an actuator is designed to store a certain amount of energy, based on the fundamental frequency of the structure and the degree of protection we require. Furthermore, we have designed a method for controlling the power flow and energy in the actuator such that it continually regenerates its spent energy. The result is an actuator which essentially fits the description of a semi-active device which can store as well as dissipate energy.

Within this framework, we now perform a parametric study. Using the parameters for system already designed, we now observe the dependency of the performance of the closed-loop system on the parameters $E_c$ and the position gain $K$. The purpose of this study is to observe, for different position feedback controllers, the rate at which the closed-loop performance improves with increases in $E_c$. For this study, we will designate $F_{max} = 1kN$, and $P_{-} = 1kW$. The positive power limit $P_{+}$ will be varied from 0W to 400W, resulting in an $E_c$ variation from 0 to 37J. The gain $K$ will be varied from 0 to 200.

Figure 11 shows resultant parametric plots illustrating the dependency of the maximum third-floor absolute displacement $x_3$, maximum absolute third-floor absolute acceleration $\dot{a}_3$, and maximum force $f$ required for the control. The maximum displacement contours show very clear, continuous trends. As expected, the maximum swing of the building decreases as more energy is available from the battery. It also appears that, for minimum swing, the gain $K$ should be made as
Figure 10: The energy control cycle: A: Discharge; B: Regeneration; C: Dissipation

As a benchmark for comparison, we note that in studies performed with magnetorheological dampers, on the same three-story structure subjected to the same earthquake, a maximum swing of 0.212 cm was attained. Maximum third-floor absolute acceleration was 703 cm/s², and the maximum force was 941 N. Weighing the advantages and disadvantages of this approach over the other, we note first that the maximum forces obtained through this method are significantly less than those obtained in the magnetorheological case, possibly because the actuator here is located at the top of the structure, whereas the magnetorheological damper was placed at the base of the building. This is important because at the top of the structure, a given magnitude of force can apply a greater moment to the building than can the same magnitude force at the base. On the other hand, the solutions with magnetorheological dampers give a maximum displacement which is only achievable with rather larger energy capacities, and the low floor accelerations are only attainable with lower position feedback gains. It is quite possible that this tendency may not exist for other control systems. Data presented indicates that sliding mode control offers rather favorable regenerative properties for hybrid systems. Research efforts toward optimizing the nature of the feedback control system to minimize the battery energy capacity for active control is currently underway.

5. CONCLUSIONS

In this paper, we have demonstrated that a regenerative electric actuator may be used, in combination with a battery power supply, to mitigate damaging effects of earthquakes on civil structures. Specifically, we have shown that such an actuator may be used to suppress a disturbance for an arbitrary amount of time, while using a battery of finite energy capacity. We showed that through cyclical discharge and recharge cycles, this energy supply is continually recharged with the power injected into the building by the earthquake. This discharge/recharge cycle was shown to occur for active systems, but not necessarily for hybrid systems.

We then showed that power limiting may be instigated in the actuator control system to regulate the discharge rate of the battery in such a way as to ensure a finite energy capacity for the battery. The relationship of the power limit to the
maximum energy capacity, and the effect of this energy capacity on the performance of the system, were discussed. It was shown that a clear trade-off exists between the energy capacity of the battery and the level of protection offered to the structure. In comparisons with semi-active control studies using magnetorheological dampers, the energy capacity of the battery required for equivalent operation was found.

The controller design used for this study was a simple position feedback control scheme. There is no evidence to show that this approach is optimal for minimizing the energy capacity of the battery. Applications of sliding mode control, as well as other control methodologies, toward this semi-active, regenerative actuator are currently underway.

REFERENCES


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