Decentralized Energy Market-Based Structural Control

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Abstract.   Control systems are used to limit structural lateral deflections during large external loads such as winds and earthquakes. Most recently, the semi-active control approach has grown in popularity due to inexpensive control devices that consume little power. As a result, recently designed control systems have employed many semi-active control devices for the control of a structure. In the future, it is envisioned that structural control systems will be large-scale systems defined by high actuation and sensor densities. Decentralized control approaches have been used to control large-scale systems that are too complex for a traditional centralized approach, such as linear quadratic regulation (LQR). This paper describes the derivation of energy market-based control (EMBC), a decentralized approach that models the structural control system as a competitive marketplace. The interaction of free-market buyers and sellers result in an optimal allocation of limited control system resources such as control energy. The Kajima-Shizuoka Building and a 20-story benchmark structure are selected as illustrative examples to be used for comparison of the EMBC and centralized LQR approaches.

Key words: energy market-based control; structural control; decentralized control; market-based control; semi-active dampers; large-scale systems

1. Introduction

Structural control has rapidly matured over the past decade into a viable means of limiting structural responses to strong winds and earthquakes. To date, well over thirty structures,

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primarily in Asia, have been constructed with active and semi-active structural control systems installed (Nishitani and Inoue 2001). A structural control system is a complex mechanical system that entails installation of sensors to measure loadings and structural responses, actuators to apply forces and a computer (controller) to coordinate the activities of the system including the calculation of control forces based on sensor measurements.

Three types of structural control systems can be defined: passive, active and semi-active. Passive control is defined by a system entailing the use of passive energy dissipation devices to control the response of a structure without the use of sensors and controllers. Base isolation systems and dampers represent the most popular passive control technologies. Active control is defined by a control system that uses a small number of large actuators for the direct application of control forces. In a semi-active control system, semi-active control devices are used for indirect application of control forces. By changing their energy dissipation properties in real-time, semi-active devices utilize the motion of the structural system for the generation of control forces.

While success has been attained in applying active control solutions to civil structures, they suffer from some technological limitations. Active control systems are expensive to operate due to their high power demands, often on the order of tens of kilowatts (Symans and Constantinou 1999). Active control devices are ill suited for large seismic disturbances because their maximum attainable control forces are not sufficient. Furthermore, actuators have large form factors, necessitating their placement on the roof of structures.

In response to these limitations, semi-active control devices were developed. Small in size and highly reliable, they represent the future of structural control. Since semi-active device do not apply forces directly to a structure, only small amounts of power are required for operation, often on the order of tens of watts (Symans and Constantinou 1999). An additional benefit of semi-active control is the ability to limit structural responses resulting from large seismic disturbances. In 2001, the Kajima-Shizuoka Building, Shizuoka, Japan was constructed with eight semi-active variable dampers, making it the first building to implement semi-active structural control (Kurata et al. 1999).

In observing the trend established by the development of semi-active control systems, innovation will continue to improve upon the design of control devices. In time, semi-active control devices will have smaller form factors, consume less power and become inexpensive. As a result of these developments, adoption of semi-active control will continue to grow. Control systems of the future could potentially depend upon a large number of semi-active devices for control, resulting in a large-scale control problem.

Large-scale control problems require significant computational power for the rapid determination of control forces. Current structural control systems are highly centralized with a single controller employed for the determination of control forces. A centralized controller generally does not suit large-scale control problems because control force computations increase at faster than a linear rate with increases in system dimensionality (Lunze 1992). As an alternative to the centralized controller, decentralized control techniques can be considered for adoption. In designing a centralized controller, it is assumed that complete knowledge of the global system (*a priori* information) and complete knowledge of the system's response (*a posteriori* information) are known. For decentralized control, only partial knowledge of the system is known (*a priori* and *a posteriori* information) for the appropriate calculation of control forces. The limited information provided to a decentralized controller represents a reduction of computational burden placed on the controllers.

A variety of decentralized control approaches, both *a priori* and *a posteriori* types, can be considered for adoption in a structural control system. *A posteriori* decentralized control reduces the global system to a collection of interrelated subsystems, with each subsystem controlled by a local controller. Approaches similar to the widely used linear quadratic regulator (LQR) have been proposed for the determination of optimal decentralized controllers in an *a posteriori* type decentralized structural control system (Lynch and Law 2002a).

Most recently, the explosion in development of MEMS (microelectromechanical systems) sensing and actuation systems has resulted in many large-scale control problems. With the reliability of MEMS sensors and actuators lower than conventional counterparts, adaptive and flexible control methods are required with decentralized control solutions most popular. Researchers have explored using free-market concepts as one approach for controlling large-scale MEMS systems (Guenther et al. 1997). By modeling the control system as a free-market economy, where actuators are market buyers and power source are market sellers, an *a priori* decentralized control solution can result. Market-based control (MBC) methods have also been applied for controlling the computational load of microprocessors and for load-balancing in data networks (Clearwater 1996).

Lynch and Law (2002b) have proposed employing market-based control (MBC) for structural systems. To evaluate the feasibility of employing market-based control, a flexible framework was employed, comprised of linear market functions that permit control solutions to be solved algebraically. The optimal MBC solution yielded was effective in reducing responses in structures controlled by semi-active control devices. The scope of this paper is to revisit the MBC derivation in order to develop a rational framework for the approach. Towards that end, the

naturally occurring measures of energy in the dynamic structural system are used to define the market demand and supply functions. Termed energy market-based control (EMBC), the approach is tested and its control performance is compared to that of the centralized LQR controller. The Kajima-Shizuoka building and a 20-story benchmark structure are used as illustrative examples in this study.

2. Decentralized Market-Based Control

The free-market economies are an efficient means of allocating scarce resources, such as labor and goods, amongst market participants. Free-markets are decentralized in the *a priori* sense because the market mechanisms operate without knowledge of the global system. The historically poor performance of centralized economies underscores the efficiencies of the decentralized marketplaces. The competitive mechanisms of a free-market can be extended for application to the control paradigm.

The complex workings of a free-market economy can be idealized by the behavior of market institutions such as consumers (buyers), firms (sellers), trade unions and governments. Economists idealize the behavior of market institutions by mathematical functions that encapsulate the behavior and decision process of each institution (Intriligator 1971). In borrowing these econometric concepts for control, the buyers and sellers are extensively utilized to derive market-based control (MBC).

First, the marketplace is defined by a scarce commodity such as control power, control forces, or control energy, just to name a few potential quantities. In the control marketplace, the role of market buyers and sellers are assumed by system actuators and power sources, respectively. The behavior of buyers is defined by individual utility functions, U_B, that measure the amount of utility derived by the buyer from purchasing the market commodity. Utility is a function of the price per unit commodity, p, the amount of commodity purchased, C_B, and response measures of the dynamic system, y. Similarly, the sellers are governed by individual profit functions, Π_S, that measure the amount of profit derived by the seller from selling the commodity. Profit is modeled as a function of the price per unit commodity, p, and commodity sold, C_S.

The goal of market buyers is to maximize their utility. In doing so, maximization of their utility functions is constrained by limiting the total purchase cost, pC_B, to be less than their instantaneous wealth, W. Maximization of the market sellers' profit functions is constrained by the maximum amount of commodity they possess, C_{MAX}.

$$\max \Pi_{S1}(C_{S1}, p) \quad \text{subject to} \quad C_{S1} \leq C_{MAX1}$$
$$\max \Pi_{S2}(C_{S2}, p) \quad \text{subject to} \quad C_{S2} \leq C_{MAX2}$$
$$\vdots \qquad\qquad\qquad (1)$$
$$\max U_{B1}(C_{B1}, p, y_{B1}(t)) \quad \text{subject to} \quad pC_{B1} \leq W_1$$
$$\max U_{B2}(C_{B2}, p, y_{B2}(t)) \quad \text{subject to} \quad pC_{B2} \leq W_2$$

The simultaneous optimization of the utility and profit functions of buyers and sellers is viewed as a static optimization problem of the decentralized marketplace since time is not explicitly modeled and the market is assumed frozen in time. This is in contrast to dynamic optimization where time is explicitly included in the market models (Chiang 1992). For example, the linear quadratic regulator (LQR) is a solution to a dynamic optimization problem.

Directly resulting from the static optimization of market utility and profit functions are the demand functions of market buyers and the supply functions of market sellers. The marketplace aggregates the demand functions of the individual buyers to obtain the global demand function of the market. In a likewise manner, the market aggregates the supply functions of all sellers to determine the market's global supply function. At each point in time, the demand function and supply function of the market share a point where they intercept. This equilibrium point represents a state of competitive equilibrium that sets the equilibrium price of the commodity. With the equilibrium price found, the static optimization of the marketplace is complete and a transfer of commodity can exist between the market sellers and market buyers. This solution is termed Pareto optimal in the multi-objective optimization sense. Pareto optimal is defined by a market in competitive equilibrium where no market participant can reap the benefits of higher utility or profits without causing harm to other participants when a resource allocation change is made (Mas-Colell, Whinston, and Green 1995).

During an external excitation to the system, the marketplace goes into action with the market re-optimized at each time step for the determination of an efficient control solution. The demand and supply functions change in time, necessitating a re-evaluation of the marketplace at each time step with individual demand and supply functions aggregated and equated. When an equilibrium price is determined, all market buyers purchase their desired commodities and transfer wealth to the market sellers. The amount of commodity purchased by the market buyers (actuators) is converted into control forces to be applied to the structure. After money has been exchanged, the money obtained by the market sellers is evenly distributed back to the market buyers to represent income for their future purchases.

In solving a static optimization problem at each point in time, the resulting control solution of the MBC approach indirectly accounts for changes that occur in the system over time. In some sense, the approach can be viewed as a piece-wise static optimization solution to the dynamic optimization problem. A clear advantage of the MBC solution is its ability to account for changes in system properties as they occur in real-time, resulting in robust control solutions with respect to actuation failures (Lynch 2002).

The earlier derivation, proposed by Lynch and Law (2002b), began with linear demand and supply functions to describe the behavior of market buyers and sellers bidding for the limited commodity of control power, P. While the supply function is held fixed, the demand function is modeled to be sensitive to changes in the structural response. With greater responses, the intercept of the demand function is designed to increase while the slope is to decrease. The behavior of the demand function is illustrated in Fig. 1.

After the equilibrium price of power, p, was determined at each point in time, market buyers would use their wealth, W_i, to purchase power. To ensure a means of adjusting the sensitivities of the linear demand and supply functions to changes in the structural response, various constants were included. Specific to the market demand functions, four constants (Q, R, S, and T) were used:

$$P_{D_i} = \left(-\left| \frac{1}{Tx_i + Q\dot{x}_i} \right| p + \left| Rx_i + S\dot{x}_i \right| \right) W_i \qquad (2)$$

The variable, x_i, represent the displacement response of the structural degree-of-freedom corresponding to the ith market buyer.

Only one constant (β) is included in the market seller's supply function. The inverse of β represents the fixed slope of the market supply function:

$$P_{SUPPLY} = \frac{1}{\beta} p \qquad (3)$$

For the marketplace comprised of m market buyers and n market sellers, the equilibrium price of power at each time step can be algebraically determined:

$$p_{eq} = \frac{\sum_{i=1}^{m} W_i |Rx_i + S\dot{x}_i|}{n/\beta + \sum_{i=1}^{m} W_i /|Tx_i + Q\dot{x}_i|} \tag{4}$$

This derivation of MBC represents just one of many permissible derivations. The linear marketplace functions were selected to only encapsulate increased demand with increased system response and constant market supply. While easy to implement, the MBC derivation lacked a rational framework and suffers from having to adjust too many tuning constants in order to obtain optimal control results. In response to these limitations, the MBC approach is revisited and a re-derivation of market functions is performed using a rational framework based on measures of energy in the dynamic system.

3. Energy Market-Based Control

3.1 Structural Energy from Vibrations

The energy balance of a structural system during a seismic disturbance can easily be derived. First consider the equation of motion of an n degrees-of-freedom structural system subjected to a seismic disturbance and using controls to limit responses that would result:

$$M\ddot{y}(t) + C\dot{x}(t) + Kx(t) = Du(t) \tag{5}$$

The displacement response vector of the system is $x(t)$, the control forces applied to the system by m actuators are represented by $u(t)$, and the absolute displacement is $y(t)$. The absolute displacement of the system, $y(t)$, is simply the input ground displacement, $x_g(t)$, added to each term of the relative displacement vector, $x(t)$. The mass, damping, and stiffness matrices are n x n in dimension and are denoted by M, C, and K, respectively. It is assumed that the mass, damping and stiffness matrices are symmetric. D is the n x m location matrix for the application of control forces.

Eq. (5) represents the equilibrium balance of forces in the structural system at any point in time. Integrating the forces over the response path from the initial position, x_o, to the final position, x_f, yields the energy of the balanced system (Wong and Yang 2001):

$$\int_{x_o}^{x_f} \ddot{\boldsymbol{y}}^T \boldsymbol{M} d\boldsymbol{x} + \int_{x_o}^{x_f} \dot{\boldsymbol{x}}^T \boldsymbol{C} d\boldsymbol{x} + \int_{x_o}^{x_f} \boldsymbol{x}^T \boldsymbol{K} d\boldsymbol{x} = \int_{x_o}^{x_f} \boldsymbol{u}^T \boldsymbol{D}^T d\boldsymbol{x} \qquad (6)$$

The first term on the left-hand side of Eq. (6) reflects the kinetic energy of the system while the third term represents the strain energy of the system. Both measures of energy are based upon conservative forces and are therefore path independent. Their measure is only dependent upon the current and initial positions of the system.

Assuming the system is initially at rest, the kinetic and strain energy of the system can be rewritten and Eq. (6) updated:

$$\frac{1}{2} \dot{\boldsymbol{y}}^T \boldsymbol{M} \dot{\boldsymbol{y}} + \int_{x_o}^{x_f} \dot{\boldsymbol{x}}^T \boldsymbol{C} d\boldsymbol{x} + \frac{1}{2} \boldsymbol{x}^T \boldsymbol{K} \boldsymbol{x} - \int_{x_o}^{x_f} \boldsymbol{u}^T \boldsymbol{D}^T d\boldsymbol{x} = \int_{x_o}^{x_f} \ddot{\boldsymbol{y}}^T \boldsymbol{M} d\boldsymbol{x}_g \qquad (7)$$

The four terms of the left-hand side of Eq. (7) represent respectively, kinetic energy (KE), damping energy (DE), strain energy (SE) and control energy (CE). These four energies balance the input energy (IE) resulting from the ground motion as shown on the right-hand side of Eq. (7).

3.2 Derivation of Energy Market-based Control

The derivation of energy market-based control (EMBC) is centered upon a marketplace allocating the scarce commodity of control energy. In the marketplace, each floor of an idealized lumped mass structural model represents a single market buyer while sellers of control energy are represented by the batteries used to power semi-active variable dampers installed in the structure. The method begins with the selection of demand and supply functions that reflect measures of energy in the system. The demand and supply functions will each contain a "tuning" constant that can be used to vary their sensitivities for each implementation of the controller.

In the energy marketplace, the scarce commodity of control energy is used to determine the magnitude of control forces applied to the structural system. The form of the demand function is selected to reflect two intentions of the market buyers. First, when the price of control energy is zero, the demand of the market buyer is equal to the input energy of its degree-of-freedom. Second, the demands of the market buyers asymptotically converge toward zero at infinite prices.

These two defining characteristics suggest exponential functions could be suitable candidates for the demand function of each market buyer. The exponential demand function of the ith market buyer that is chosen for this implementation is presented in Eq. (8).

$$CE_i = W_i \left| \ddot{y}_i(t) m_i dx_g \right| e^{\frac{-2p\alpha}{\dot{y}_i^2 m_i + x_i^2 k_i}}$$

(8)

As specified, if the price of control energy is zero, the market buyer would seek to counteract the input energy from a seismic disturbance with control energy applied by the actuator that is attached to its degree-of-freedom. The energy of the input ground motion influencing the ith degree-of-freedom is represented by the y-axis intercept of the exponential demand function of Eq. (8). The demand function must remain positive and therefore the absolute value of the input energy is used for the exponential function. The rate of decay of the exponential function is set as an inverse function of the kinetic and strain energy associated with the buyer's degree-of-freedom. The rate is designed to decrease as the degree-of-freedom experiences greater kinetic and strain energies due to its response; smaller decay rates permits the demand function to seek more control energy. The kinetic energy of the degree-of-freedom is depicted by the first term of the denominator of the exponential term. The second term represents a modified version of the strain energy associated with the degree-of-freedom. Each market buyer is provided with an amount of wealth, W_i, that can be freely spent to purchase control energy. It is intuitively clear that if a buyer has more wealth, it would be inclined to buy more control power when needed. Conversely, if the buyer posses a small amount of wealth, it would exhibit less demand. To embody this behavior, the wealth of each buyer is used to scale the market demand function. A tuning constant, α, is also provided in the demand function's exponential term in order to provide for variations of the demand function's sensitivity. Fig. 2(a) illustrates the behavior of the modeled demand function.

The control system's battery sources represent the market sellers whose actions are described by supply functions. Stored within each battery is an amount of control energy that can be sold to market buyers in the marketplace. Again, two observations of the market seller's behavior are required before specifying a suitable supply function. First, if the price of power is set to zero, no market seller would be willing to sell. Second, as the price grows to infinity, each market buyer would be willing to sell all of its remaining control energy denoted by L_i. As a result, the following exponential supply function is proposed:

$$CE_i = L_i\left(1 - e^{-\beta p}\right) \tag{9}$$

Eq. (9) provides an origin intercept satisfying the condition that at zero price, no market seller would be willing to sell control energy. Furthermore, the supply function exhibits an asymptotic convergence to the remaining battery life, L_i, at very large market prices. The constant β is provided for making adjusts to the supply function during implementation in a structure. Fig. 2(b) presents a graphical interpretation of the market seller supply function.

With the demand and supply functions of all market participants established, the Pareto optimal price at each time step can be readily determined. The aggregate demand function is set equal to the aggregate supply function to determine the competitive equilibrium price of energy for a given time step. A graphical interpretation, as shown in Fig. 3, is the price of control energy corresponding to the point where the global demand and supply functions intersect. It can be shown that this intersection point always exists. The solution represents a Pareto optimal price of control energy for the marketplace.

The amount of control energy that is purchased by each system actuator is used to determine the applied control force. Given the instantaneous control energy purchased by an actuator, the control force u_i can be determined from Eq. (10).

$$CE = u_i \Delta x_i \tag{10}$$

After control energy has been purchased, the energy is subtracted from the system battery sources. Similarly, the amount of energy purchased by an actuator times the market price per unit energy determines the amount of wealth removed from each actuator's total wealth. Wealth attained by market sellers is evenly distributed to the market buyers to represent wages for their labor; therefore, wealth is conservatively maintained by market buyers.

4. Application to Analytical Structures

The performance of the newly derived EMBC solution is to be evaluated using two large-scale structural systems. First, the five-story Kajima-Shizuoka Building with ten semi-active variable dampers is utilized. Next, a 20-story steel structure with 36 semi-active variable dampers is selected. To excite the structures, three earthquake records are chosen: El Centro

(1940 NS) and Taft (1952 NS) represent far field records and Northridge (1994 NS – Sylmar County Hospital) is a near field record. All three earthquakes are scaled so that their absolute peak velocities are 50 cm/sec. For both structural systems, an EMBC solution is directly compared to a traditional centralized LQR solution.

4.1 Analytical Approach

The same analytical approach is used to model both structural systems. First, each structural system is modeled as a lumped mass structural system that experiences elastic responses. No nonlinear (material or geometric) responses are considered in the analysis. The intention of the analysis is to assess the effectiveness of the EMBC solution in a linear structural system. Both structures employ the semi-active hydraulic damper (SHD) designed by Kajima Corporation, Japan (Kurata et al. 1999). SHD devices are generally attached to the apex of a V- or K-brace and a floor of the structure. The relative motion between stories induces motion in the damper with a desired control force generated by selecting a damping coefficient of the variable damper. The Kajima's SHD is capable of a maximum control force of 1,000 kN and a maximum shaft displacement of +/- 6 cm. The coefficient of damping of the device can be adjusted to any value in the range of 1,000 to 200,000 kN-s/m. To power the internal mechanism used to change the coefficient of damping, each SHD consumes 70 W of power.

Due to the flexibility of the bracing used to connect the SHD device to the structural system, the bracing and SHD are modeled as a Maxwell damping element (Hatada et al. 2000). A Maxwell element is a spring and dashpot in series whose force, $p(t)$, is determined from the second-order differentiable equation:

$$\dot{p}(t) + \frac{k_{eff}}{c_{SHD}} p(t) = k_{eff} \, \dot{x}(t) \tag{11}$$

The combined stiffness of the bracing element and the inherent stiffness of the damper are combined as k_{eff}.

4.2 Kajima-Shizuoka Building

The Kajima-Shizuoka Building is used to illustrate the implementation of the derived EMBC control solution. The structural details of the building are presented in Fig. 4 (Kurata et al. 1999). A total of ten semi-active hydraulic dampers, capable of changing their damping coefficient in real-time, are installed in the structure's weak longitudinal direction. To quantify the performance of the EMBC solution, the structure is controlled for the El Centro, Taft, and Northridge seismic disturbances. The performance of the EMBC controller will be directly compared to that of a centralized LQR controller.

For implementation of the EMBC controller, the demand and supply constants, α and β, are to be chosen. After initially setting both constants arbitrarily to unity, it is determined that the supply and demand functions are sufficiently sensitive to yield excellent control results. Had the initial choice of α and β resulted in a control solution unresponsive to significant structural responses, they could be varied until a responsive solution is attained. In addition to the demand and supply constants, the wealth of each market buyer is to be chosen. Similar to the selection of α and β, the initial wealth, W_i, of each market buyer is chosen using trial and error until a suitable control solution is obtained. For implementation in the Kajima-Shizuoka Building, each floor of the structure that contains two actuators is provided with an equal amount of initial wealth.

$$W_1 = 1000; \quad W_2 = 1000; \quad W_3 = 1000; \quad W_4 = 1000; \quad W_5 = 1000 \qquad (12)$$

The total amount of power initially provided by the system power source is roughly calculated based upon the observation that the control system battery in the Kajima-Shizuoka Building is designed to last for 8 continuous minutes with 10 SHD devices each drawing 70 W of power. As a result, the total energy provided to the system battery sources is set to 1.25×10^{10} J.

$$L_T = 1.25 \quad x \quad 10^{10} \quad J \qquad (13)$$

An LQR controller is also designed for the structure. Linear quadratic regulation is a dynamic optimization approach that can algebraically determine the minimum point of a cost function that includes the cost of response of the system and the cost of control effort:

$$J = \int_0^\infty \left(X^T Q X + U^T R U \right) dt \qquad (14)$$

The cost function is written in a quadratic form to ensure that the function's minimum point is attainable and is not a cusp. Two weighting matrices, Q and R, are provided to vary the relative emphasis of particular degrees-of-freedom and between response and control. Both Q and R must be positive definite to ensure the function is upward convex. Eq. (14) poses the response of the structural system, X, in state space form. The vector X includes both the displacement and velocity terms.

$$X = \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix} \tag{15}$$

For the Kajima-Shizuoka Building, Q and R are chosen to weigh with heavier emphasis the absolute velocity response of the system degrees-of-freedom. Heavier emphasis on velocity response will ensure the control solution represents equivalent increased system damping.

$$Q = \begin{bmatrix} 0 & 0 \\ 0 & I \end{bmatrix} \quad \text{and} \quad R = 1x10^{-13}[I] \tag{16}$$

Fig. 5 presents the maximum absolute interstory drift of the Shizuoka Building when no control is used and when the LQR and EMBC controllers are employed. As shown, both the LQR and EMBC controllers are effective in reducing the drift response of the structure, with minimal differences between the two control solutions. During the El Centro disturbance the maximum interstory drift of the second floor, initially 6.3 cm, is reduced to 1.75 cm by the LQR controller and 2.1 cm by the EMBC controller. For the Taft record, the forth story's maximum interstory drift is reduced from 5.58 cm to 0.92 cm using the LQR controller and 1.08 cm using the EMBC controller. Only for the Northridge seismic disturbance does the LQR controller exhibit slightly superior performance when compared to the drift response of the EMBC controller at the 2nd and 3rd stories. As anticipated, the LQR solution always provides superior control performances as compared to the EMBC solution because it represents an optimal solution derived with complete *a priori* knowledge of the system.

4.3 Twenty-Story Benchmark Structure

Next, a 20-story steel structure, designed for the Southern Los Angeles region as part of the Structural Engineers Association of California's SAC project, is considered (Spencer et al. 1998). The structure represents a realistic large-scale structural system for control. The structural properties of the 20-story benchmark structure are presented in Fig. 6. A total of 36 SHD devices are strategically placed in the structure. EMBC and LQR solutions are implemented for the 20-story benchmark structure.

An EMBC controller is designed first. The constants for tuning the demand and supply functions of the energy marketplace are again set to unity values ($\alpha = 1$ and $\beta = 1$). Each floor of the structure containing actuators represents a market buyer and is provided with an initial wealth of 1,000.

$$W_1 = 0; \quad W_2 = W_3 = W_4 = W_5 = 1000; \quad W_6 = 0;$$
$$W_7 = W_8 = W_9 = W_{10} = 1000; \quad W_{11} = 0; \quad W_{12} = W_{13} = W_{14} = W_{15} = 1000; \quad (17)$$
$$W_{16} = 0; \quad W_{17} = W_{18} = W_{19} = W_{20} = 1000;$$

The total control energy provided to the system power source is 8 x 10^{11} J. This amount of reserve control energy should be sufficient for roughly 5 minutes of continuous use by the system's 36 SHD devices.

$$L_T = 8 \quad x \quad 10^{11} \quad J \tag{18}$$

The LQR controller is designed using the Q and R weighting matrices presented by Eq. (19). In choosing an appropriate Q matrix, a heavy emphasis has been place on the velocity response of the structural system.

$$Q = \begin{bmatrix} I & 10I \\ 10I & 100I \end{bmatrix} \text{ and } R = 1x10^{14}[I] \tag{19}$$

Fig. 7 plots the maximum absolute interstory drift of the 20-story benchmark structure for the selected seismic disturbances. The EMBC controller exhibits excellent control results with a performance comparable to that of the centralized LQR controller. In contrast to the control solutions of the Kajima-Shizuoka Building implementation, the differences in the EMBC and LQR controller performances are significantly smaller for the 20-story structure. It is suspected that the larger marketplace consisting of 20 market buyers is responsible for the EMBC solution converging towards the optimal centralized solution of the LQR controller.

5. Conclusion

The need for new and innovative approaches to the large-scale structural control problem is growing due to advances in control device technology. With systems growing in dimensionality, decentralized control approaches are proposed for adoption. In particular, the novel market-based control (MBC) approach has been proposed. Decentralized in an *a priori* sense, past implementations of MBC show promising results when applied to large-scale structural systems.

In this paper, the MBC derivation has been revisited to provide an energy framework for a new derivation. Termed energy market-based control (EMBC), the energies of a dynamic structural system are used in deriving market demand and supply functions of buyers and sellers, respectively. With a physical entity, such as energy, as the cornerstone of the EMBC method, the approach will be more attractive to practicing control system designers. Furthermore, the EMBC approach compared to the original MBC derivation reduces the number of constants used for tuning market functions to two. Other methods can be considered for the modeling of the MBC marketplace that might be equally attractive. With the number of tuning constants reduced, future research is need to explore an appropriate method of setting constants to appropriate values during each implementation. In this study, a trail and error approach was taken to setting the demand and supply function constants, α and β, and initial wealth values of the market buyers.

The EMBC control solution was implemented in two large scale structures: the Kajima-Shizuoka Building and a 20-story benchmark structure. In both structural systems, semi-active SHD devices are installed to assist the structures in resisting large seismic disturbances. The structures are excited by two far- and one near-field seismic records to assist in assessing the performance of the EMBC approach. For comparison purposes, the widely used centralized LQR controller is also implemented. Both structures subjected to the three seismic records, the EMBC controller yields similar control performance as compared to the LQR solution.

Additional work is warranted to explore the robustness qualities of the EMBC approach. As a piecewise static optimization solution, the approach is responsive to changes in the structural system. Current research efforts have discovered that the EMBC approach is robust with respect to control device failures (Lynch 2002). The adaptive nature of the EMBC approach can potentially be leveraged to address geometric and material nonlinearities in the structural system.

The stability of EMBC has not been considered in this study. Semi-active control devices represent stable control systems in the bounded-input bounded-output (BIBO) sense. However, if

EMBC is to be adopted in an active structural control system, or in other applications, the stability of the approach must be investigated.

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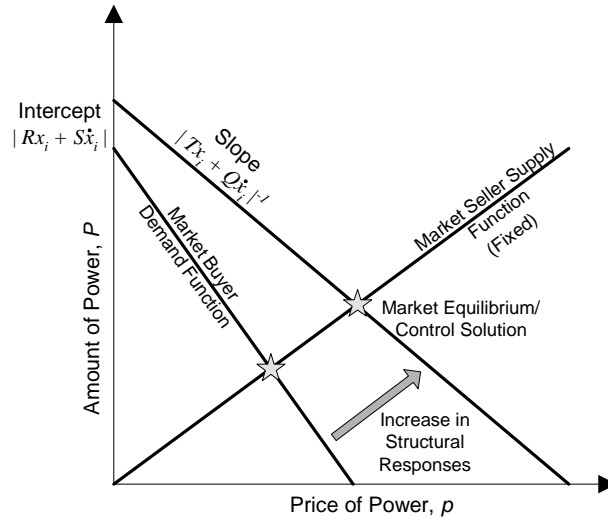
Figure 1 – Changes in the MBC demand function with increases in structural responses
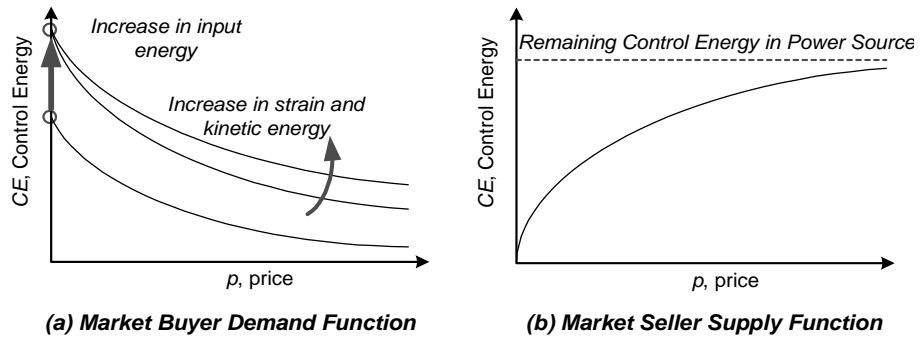

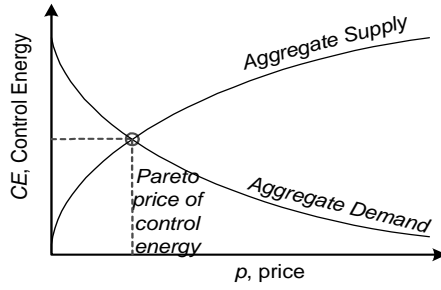Figure 2 - Energy market-based control (EMBC) demand and supply functions

Figure 3 - Determination of the competitive equilibrium price of control energy

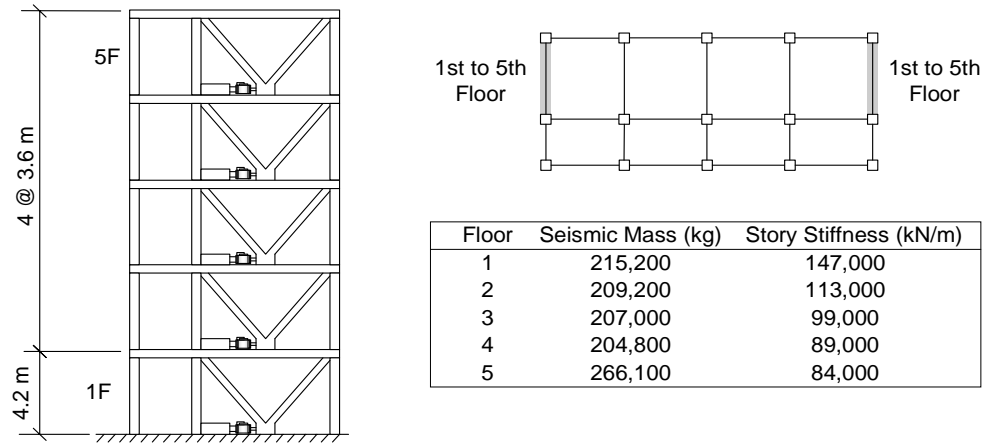| Floor	Seismic Mass (kg)	Story Stiffness (kN/m)
1	215,200	147,000
2	209,200	113,000
3	207,000	99,000
4	204,800	89,000
5	266,100	84,000

Figure 4 – The Kajima-Shizuoka Building, Shizuoka, Japan
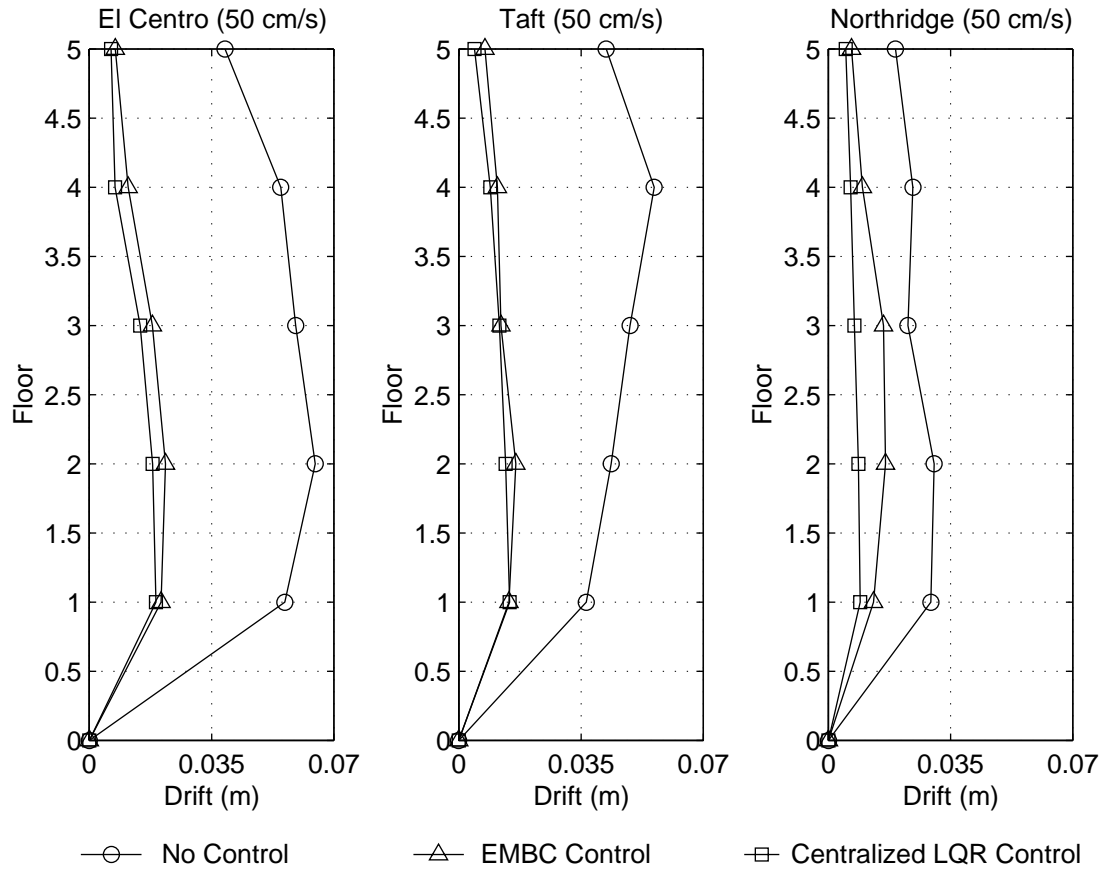
Figure 5 – Kajima-Shizuoka Building maximum interstory drift (LQR, EMBC)

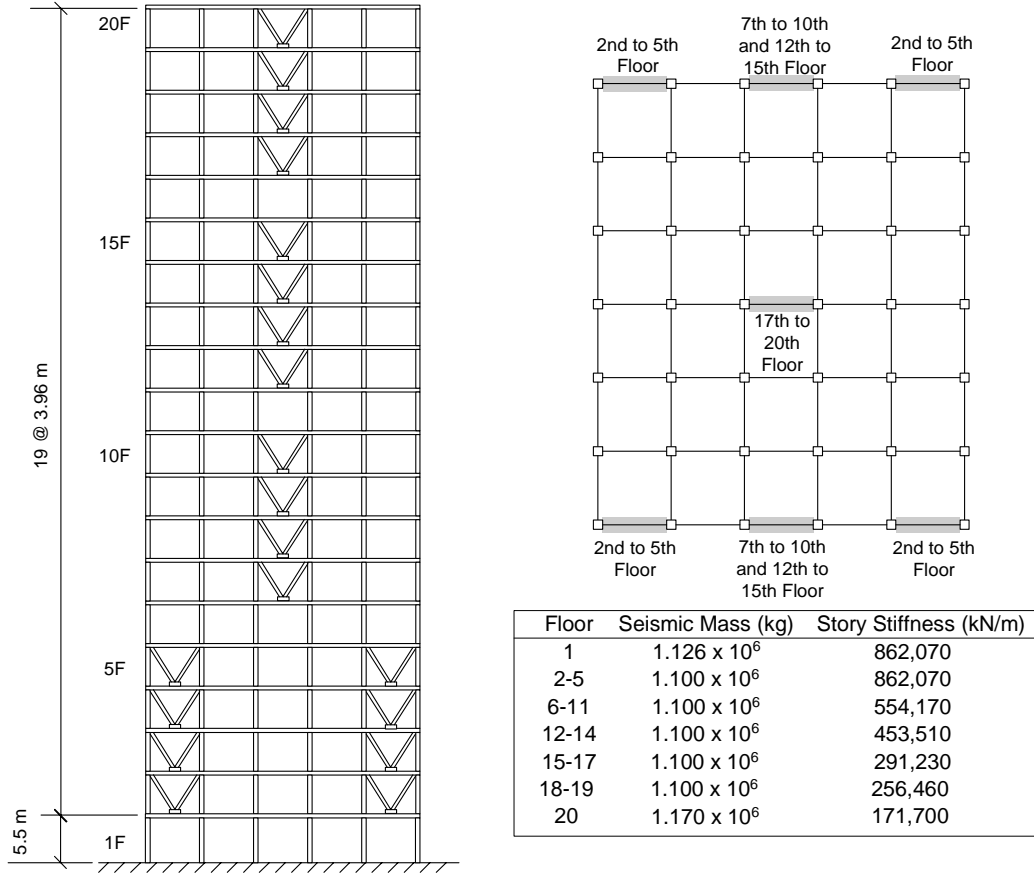Figure 6 – 20-story SAC benchmark structure

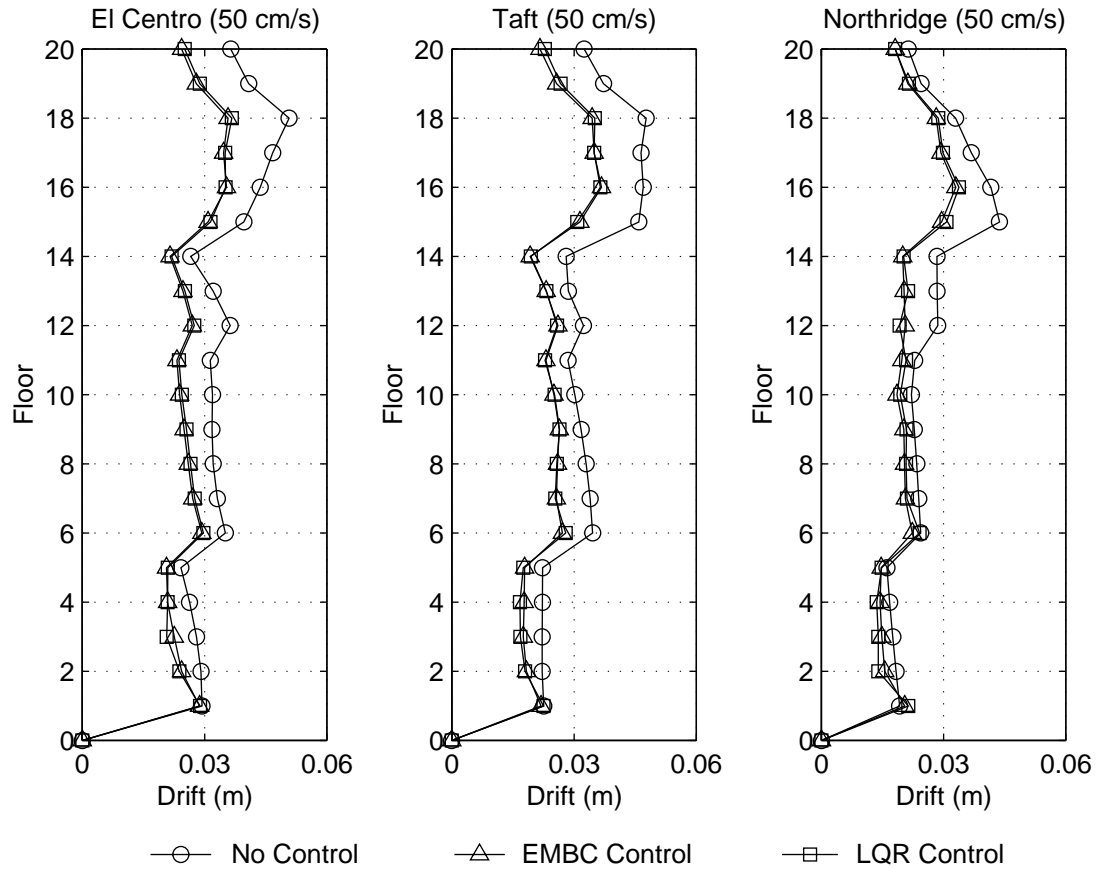| Floor	Seismic Mass (kg)	Story Stiffness (kN/m)
1	1.126×10^6	862,070
2-5	1.100×10^6	862,070
6-11	1.100×10^6	554,170
12-14	1.100×10^6	453,510
15-17	1.100×10^6	291,230
18-19	1.100×10^6	256,460
20	1.170×10^6	171,700

Figure 7 – 20-story benchmark structure maximum interstory drift (LQR, EMBC)