Regenerative Electric Actuators for Active Control of Civil Structures

by

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(ABSTRACT)

A novel technique is investigated for utilizing the motion caused by environmental forces on a civil structure to generate electrical energy when the structure's response is within safety limits. When strong winds and earthquakes occur, the utility power source which supply energy to the actuator in an active control system is usually not reliable. With a regenerative electric actuator, recovered energy can be used to reduce the peak oscillations of the structure by applying forces (through actuators which use the recovered energy) counter to the environmental forces even if the utility power is not available. The use of a regenerative electric actuator allows a precise control of the amount of damping being provided by the actuator. Another advantage of using regenerative electric actuators is the reduction of the required energy capacity of the electrical source. This translates into lower energy ratings for the electrical source, and lower equipment and maintenance costs. This study is the first of its kind to propose and investigate active control of civil structures using regenerative electric actuators. This study is also the first of its kind to investigate the applicability of sliding mode control to civil structures using regenerative electric actuators. Sliding mode control provides a natural synthesis of the on-off nature of pulse width modulation control and control force saturation, and guarantees stability for the control law. It is also invariant to parameter changes and external disturbances. New direct-control schemes for neural network and adaptive fuzzy control of civil structures using regenerative electric actuators are proposed and investigated. These allow on-line control of the structure without the need for either an accurate model of the system or a specific learning stage. Since the error at the output of these controllers will be unknown in the direct-control scheme, the error at the system output is used to train or update the controller parameters. Simulations are conducted for wind and earthquake excitations using linear and nonlinear models. It is shown that the use of regenerative electric actuators is a viable and a reliable alternative for active control of civil structures.

To Maria Nona and Alana Rae

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Nomenclature

m_s	mass of the structure
k_s	spring or stiffness coefficient of the structure
c_s	damping coefficient of the structure
$u(t)$	control force
$f(t)$	external excitation force
y_s	structure's displacement with respect to an inertial reference frame
z_s	structure's displacement with respect to the ground
A	system matrix
B	control coefficient matrix
H	disturbance coefficient matrix
w	external disturbance vector
x	state vector
u	vector of control forces
$\ddot{y}_0$	ground acceleration
F_k	restoring force due to the spring/stiffness element
α	ratio of postyielding to preyielding stiffness
D_y	yielding displacement
v	nondimensional auxiliary variable
$\lambda, \beta, \gamma, \eta$	hysteresis parameters of stiffness element
y_d	damper's displacement with respect to an inertial reference frame
z_d	damper's displacement with respect to the structure
y_0	ground displacement with respect to an inertial reference frame
m_i	mass of floor i
c_i	damping coefficient of floor i
k_i	stiffness or spring coefficient of floor i
y_i	displacement of floor i with respect to an inertial reference frame
f_i	wind force exerted on floor i
u_i	control force exerted on floor i
M	mass matrix
C	damping coefficient matrix
K	stiffness coefficient matrix

$\mathbf{y}$	vector of displacements with respect to an inertial reference frame
z_i	relative displacement between floor i and floor i-1 or between floor i and the ground
$\mathbf{m}$	vector of masses
$\mathbf{f}$	vector of wind forces
m_b	mass of the base floor
c_b	damping coefficient of the base floor
k_b	stiffness coefficient of the base floor
z_b	displacement of the base floor with respect to the ground
m_d, m_g	mass of the damper
c_d, c_g	damping coefficient of the damper
k_d, k_g	stiffness coefficient of the damper
$\mathbf{G}$	actuator infuence matrix
$\mathbf{F}_c$	vector of nonlinear damping forces
$\mathbf{F}_k$	vector of nonlinear stiffness forces
$\mathbf{K}_e$	elastic stiffness coefficient matrix
$\mathbf{K}_i$	inelastic stiffness coefficient matrix
$\mathbf{v}$	vector of auxiliary variables
u_k	control force exerted by active variable-stiffness device
$k(z)$	variable stiffness coefficient
z	interstory deformation
c_c	viscous damping coefficient of active variable damper
u_c	control force exerted by active variable-damping device
n	positive number
f_w	wind force
p	magnitude parameter of wind force
ω	frequency parameter of wind force
K	proportional feedback gain
T_d	actuator time delay
T_m	measurement time delay
$p_a(t)$	actuator instantaneous power
$e_a(t)$	energy drawn by the actuator from the electrical source
Z_{pas}	maximum interstory drift for passive control
Z_{pro}	maximum interstory drift for proportional control

R_{pas}	root-mean-square value of interstory drift for passive control
R_{pro}	root-mean-square value of interstory drift for proportional control
Y_{pas}	maximum displacement with respect to the ground for passive control
Y_{pro}	maximum displacement with respect to the ground for proportional control
$\mathbf{A}_d$	discrete-time system matrix
$\mathbf{E}_d$	discrete-time input matrix
$\mathbf{r}(k)$	discrete-time input vector
$\mathbf{a}(\mathbf{x},\mathbf{u},t)$	n-vector function
$\mathbf{u}^*(t)$	admissible control
$\mathbf{x}^*(t)$	admissible state trajectory
J	performance index
$h(\mathbf{x},t)$	scalar function
$g(\mathbf{x},\mathbf{u},t)$	scalar function
t_0	initial time
t_f	final time
$\mathcal{H}$	Hamiltonian function
$\mathbf{p}(t)$	vector of Lagrange multipliers or costate variables
δx_f	variations in the final state
δt_f	variations in the final time
$\mathbf{x}_0$	final state
H, **Q**	real, symmetric, positive semi-definite weighting matrix
R	real, symmetric, positive definite weighting matrix
$\mathbf{p}^*$	admissible costate trajectory
P	Riccati matrix
K	feedback gain matrix
α, β	scalar weights
I	identity matrix
Q11	first diagonal element of **Q**-matrix for single-degree-of-freedom system
Z_{lq}	maximum interstory drift for linear quadratic control
R_{lq}	root-mean-square value of interstory drift for linear quadratic control
Y_{lq}	maximum displacement with respect to the ground for linear quadratic control
q_{11}, q_{22}	scalar factor in **Q**-matrix
$\mathbf{f}(\mathbf{x},t)$	vector of nonlinear state functions
σ	switching manifold

σ_i	ith switching surface
$\mathbf{S}$	coefficient matrix of switching surface
$\mathbf{u}_{eq}$	equivalent control
$\mathbf{v}$	external disturbance
$\Delta\mathbf{A}$, $\Delta\mathbf{B}$	system perturbation
$\mathbf{T}$	orthonormal transformation matrix
$\mathbf{z}$	transformed state vector
$\mathbf{A}_{11}$, $\mathbf{A}_{12}$	partition of transformed system matrix
$\mathbf{A}_{21}$, $\mathbf{A}_{22}$	partition of transformed system matrix
$\mathbf{0}$	null matrix
$\mathbf{B}_2$	partition of transformed control matrix
$\mathbf{S}_1$, $\mathbf{S}_2$	partition of coefficient matrix for switching surface
$\mathbf{z}_1$, $\mathbf{z}_2$	partition of the transformed state vector
$\mathbf{Q}$	constant, symmetric, positive definite weighting matrix
t_s	time it takes to reach the sliding manifold
$\mathbf{Q}_{11}$, $\mathbf{Q}_{12}$	partition of weighting matrix $\mathbf{Q}$
$\mathbf{Q}_{11}$, $\mathbf{Q}_{12}$	partition of weighting matrix $\mathbf{Q}$
q_i	diagonal element of weighting matrix $\mathbf{Q}$
s_{ij}	element of switching surface coefficient matrix $\mathbf{S}$
$\mathbf{K}$	switched feedback-gain matrix
k_{ij}	element of feedback-gain matrix $\mathbf{K}$
Ψ	matrix of boundary values for switched feedback gains
ψ_{ij}	boundary values of switched feedback-gains
Z_{sm}	maximum interstory drift for sliding mode control
R_{sm}	root-mean-square value of interstory drift for sliding mode control
Y_{sm}	maximum displacement with respect to the ground for sliding mode control
d	desired plant output
y	plant output
u_k	kth output of the neural network controller
y_q	qth plant output
e_q	error at the qth plant output
d_q	qth desired plant output
n_q	weighted-sum of inputs to the plant's output unit q
a_q	output of neuron unit q

$f(n_k)$	activation function
w_{ij}	connection weight between units i and j
η	learning rate
K_i	input scaling factor
G, K_o	output gain factor
E_u	squared-error at output of fuzzy controller
u_d	desired output of fuzzy controller
E_y	squared-error at system output
e_y	system output error
θ	fuzzy controller parameter
μ_{ji}	degree of membership of jth input for rule i
$\bar{u}_i$	center of the output membership function for rule i
$\bar{x}_{ji}$	center of the jth-input's membership function for rule i
σ_{ji}	spread of the jth-input's membership function for rule i
m_c	momentum factor
n_t, n_{tg}, n_{td}	linear-to-rotational transformation ratio
T_L	load torque
T_e, T_{eg}, T_{ed}	actuator electromagnetic torque
J	moment of inertia of actuator
B	rotational damping coefficient of actuator
ω	angular speed
e	efficiency
p	pitch
v_{ks}	voltage of phase k
i_{ks}	current of phase k
R_s	stator phase resistance
L_{ii}	self-inductance of phase i
L_{ij}	mutual inductance between phases i and j
e_{ks}	induced electromotive force (emf) for phase k
E_p	peak value of induced emf
K_b	induced-emf constant
ω_r	rotor speed in electrical radians per second
P	number of poles

ω_m	rotor speed in mechanical radians per second
$f(\theta_r)$	position-dependent function
θ_r	rotor position in electrical radians
I_p^*	current magnitude command
T_e^*	torque command

CHAPTER 1

Introduction

1.1 THE PRINCIPLE OF REGENERATIVE ELECTRIC ACTUATION

Mitigation of wind- and earthquake-induced oscillations in civil structures, such as buildings, is of crucial importance for the safety of the people in the building and for the protection of the structural integrity of the building itself. Passive damping in the form of tuned mass dampers (TMD) is a widely prevalent practice for tall buildings. Basically, a TMD consists of a mass attached to a structure such that it oscillates at the same frequency as the structure but with a phase shift. It is found that the TMDs have better performance with wind forces than with earthquake excitations. To counter this high frequency excitation of the earthquake, various semi-active control methodologies have come to fore recently. All of these rely on energy for actuation from an external supply which most likely is the utility power supply. As the utility power supply itself may be under threat and therefore unavailable during strong-wind and earthquake episodes, it is important that the energy source to counter the oscillations of the building must itself be derived from these oscillations. The energy from the environmental forces could be converted into electrical energy and stored for re-use by an actuator which produces a counter-force to the environmental forces. Therefore, the actuator has to be an electrical one as it can handle energy flow in both directions, i.e., it can generate electrical energy when given a mechanical input (generation mode) as well as produce mechanical energy when given an electrical input (motoring mode). The interconnection between the building and the electric actuator is through the medium of the tuned mass damper. It must be noted that during generating and motoring modes, the energy taken out of the TMD can be precisely controlled. That indirectly amounts to a controlled damping of the building. This is a significant factor because the controlled damping is able to accommodate most safety criteria for the building displacement, velocity, acceleration, inter-story shift and its velocity, etc.

The electric actuation being proposed has the unique advantage of being able to operate even in the absence of a power source such as the utility power supply. This is unlike other or most of the semi-active and active control systems being proposed for civil structures. Therefore, the reliability of the control system is increased manifold, hitherto considered impossible both in concept and in practice. Furthermore, the electric actuation has the advantage of controlling the damping during both the energy-acquisition mode and in the force-application mode. Therefore,

control is guaranteed at all times, unlike other systems. The space and volume requirements for the electric actuator seem to be feasible and within the constraints of the housing required for most of the other control systems. Hence, it should not be of any concern from the point of view of implementation.

1.2 OBJECTIVES OF THE STUDY

The study makes the following original contributions: (1) The study is the first of its kind, to propose and investigate active control of civil structures using regenerative electric actuators. (2) The study investigates a sliding mode controller for regenerative electric actuators (REA), with a control structure composed of linear feedback with switched gains. Other researchers have concentrated on a control structure composed of a sum of the equivalent control and an augmentation of this equivalent control. The performance of the proposed sliding-mode controller is evaluated for both wind and earthquake excitation. Previous studies considered only earthquake excitation. (3) While other studies have focused on indirect-learning or generalized-learning architectures, the present study proposes a neural network controller for the REA with a specialized-learning architecture. This allows the controller to be trained on-line and fine-tuned while performing its function. Hence, it is able to operate even in the presence of nonlinear or time-varying system parameters or operating conditions. Investigations are made for both wind and earthquake excitation. (4) Lastly, an adaptive fuzzy controller for the REA is proposed. It uses a steepest-descent algorithm as the adaptation mechanism. Previous investigations considered only nonadaptive schemes or neuro-fuzzy structures.

A novel technique is investigated for utilizing the motion caused by environmental forces on a civil structure to generate electrical energy when the structure's response is within safety limits. When strong winds and earthquakes occur, the utility power source which supply energy to the actuator in an active control system is usually not reliable. It is during these instances that active control is needed most. With a regenerative electric actuator, the recovered energy is used to reduce the peak oscillations of the structure by applying forces (through actuators which use the recovered energy) counter to the environmental forces even if the utility power is not available. To achieve this, a tuned mass damper is used as the intermediary for the energy transfer between the structure and the actuator. The use of a regenerative electric actuator allows a precise control of the amount of damping being provided by the actuator. Another advantage of using regenerative electric actuators is the reduction of the required energy capacity of the electrical source. This translates into lower energy ratings for the electrical source, and lower