Tremor Suppression in the Human Hand and Forearm

by Seyedeh Marzieh Hosseini

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In the name of GOD

The Most Compassionate

The Most Merciful

DEDICATED TO

My husband and my parents

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Seyedeh Marzieh Hosseini, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Signature of Student: *Seyedeh Marzieh Hosseini*

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ABSTRACT

Tremor is a neurological disorder characterized by involuntary oscillations and poses a functional problem to a large number of patients. The most preferred description for tremor is an involuntary movement that is an approximately rhythmic and roughly sinusoidal movement. It results from a neurological disorder which can affect many daily activities. People who are affected by Parkinson's diseases (PD) have tremor on their upper limb especially in the forearm and hand. Difficulties associated with tremor in patients with PD have motivated the researchers to work on developing various methods for tremor suppression. There is some medical and non-medical treatment for tremor reduction. Despite the considerable experience in tremor management, current treatment based on drugs or surgery does not achieve an effective reduction in 25 % of patients.

For such case, many researchers concentrated on finding non-medical treatments for tremor diminution. Active force control (AFC) or active vibration control (AVC) is one of the most famous non-medical methods for tremor suppression and control. Active vibration control is an alternate way to control and attenuate the vibration. In this method a counter force which is equal to the original vibration force but in the opposite direction is applied to the vibrating structure to supress the vibration. Finally, the vibration of structures will be stopped as two opposite forces cancel each other. The AFC method for tremor attenuation in the human forearm and hand is considered in this thesis. An AFC system is proposed which has a piezoelectric actuator and a classic proportional-derivative (PD) controller. Tremor behavior is investigated in three different models. The first model is a four degrees-of-freedom (4-DOF) biodynamic model of the human hand, which is the combination of mass-spring-damper system. The second model is a one degree-of-freedom (1-DOF) musculoskeletal model of the elbow joint with two links and one joint which includes two muscles, biceps, and triceps as the flexor and the extensor of the elbow joint. The third model is a three degrees-of-freedom (3-DOF) musculoskeletal model including wrist flexion-extension (FE), radial-ulnar deviation (RUD), and pronation supination (PS). The musculoskeletal model contains four muscles; extensor carpi radialis longus, extensor carpi

ulnaris, flexor carpi ulnaris and flexor carpi radialis. First, simulation of the tremor generation in the model is performed and then the performance of the AFC system for suppressing tremor is investigated in all three models. A single piezoelectric actuator is embedded in the AFC system for controlling the behavior of the PD controller. MATLAB Simulink is used to analyze the model. Results show that the proposed AFC-based system with a piezoelectric actuator and a PD controller is very effective in suppressing the tremor for the three models.

Using piezoelectric material as a smart material for AVC has been of interest to many researchers. Human forearm is modelled as a continuous beam which has a layer of piezoelectric actuator on its top surface and tremor is controlled actively. Also using piezoelectric material as an actuator and sensor in the closed loop control system has a very significant effect on tremor suppression. A closed loop active control system is developed and the human forearm is modeled as a beam which has two layers of piezoelectric on its top and bottom surface as an actuator and sensor respectively. Tremor behaviour of the model is studied in this control system to identify the effect of piezoelectric material on tremor suppression. Hamilton principle is used to obtain the equation of motion of both beam model. Thus, by employing the Galerkin procedure, the governing equation of motion which is a second order ordinary differential equation in time is derived. An external force as a tremor disturbance is applied to the beam by a sinusoidal force to analyse the beam behaviour. The response of the system to the force stimulation gives the analytical relations for natural frequency and amplitude of the vibration. Using the obtained analytical relations, the effects of different factors and piezoelectric properties on the vibration of this beam are examined. The results indicate that the piezoelectric layer as an actuator provides an effective tool for active control of vibration. Also using a piezoelectric layer as a sensor and actuator on the closed loop control system has a significant effect on tremor suppression.

Tremor characteristics help researchers to find the best treatment for its suppression. The frequency and amplitude of tremor have different level in patients. Some patients experience a severe kind of tremor compared to others who have weak tremor. As a result, tremor classification for PD subjects provides beneficial information for the researchers.

Human hand tremor is recorded using electromyography (EMG) from 14 patients who are affected by Parkinson's disease. Different signal-processing including filtering and data segmentation, feature extraction, feature reduction and classification are applied to the raw EMG signal to get accurate and useful information from recorded signals. Extreme learning machine (ELM) was used to classify data into three different classifications; severe, moderate and weak. The results illustrate that the proposed system which consists of the PCA, ELM and the majority vote is successful to recognising the tremor severity in three different classes; weak, moderate and severe.

Abbreviations

AFC	Active Force Control
ANN	Artificial Neural Network
AR	Autoregressive
AVC	Active Vibration Control
BaSTO	Barium Strontium Titanate
CR	Crossing Rate
DBS	Deep Brain Stimulation
DOF	Degree of Freedom
ECG	Electrocardiography
ECRL	Extensor Carpi Radialis Longus
ECU	Extensor carpi ulnaris
EEG	Electroencephalography
ELM	Extreme Learning Machine
EMG	Electromyography
EMG-PR	EMG-based Pattern Recognition
EMG-non-PR	EMG-based non-Pattern Recognition
EOG	Electrooculography
ET	Essential Tremor
EWT	Empirical Wavelet Transform
EWPT	Empirical Wavelet Packet Transform
FCR	Flexor Carpi Radialis
FCU	Flexor Carpi Ulnaris
FD	Frequency Domain
FE	Flexion-Extension
FES	Functional Electrical Stimulation
FGM	Functionally Graded Material

FNN	Feed-Forward Neural Networks
FP	Feature Projection
FS	Feature Selection
HAL	Hybrid Assistive Limb
HMM	Hidden Markov Model
HTD	Hjorth Time Domain
I controller	Integral controller
IEMG	Integrated EMG
IMU	Inertial Measurement Unit
KKT	Karush-Khun-Tucker
KNN	K-Nearest Neighbour
LDA	Linear Discriminant Analysis
LFP	Local Field Potentials
LH	(Biceps) Long Head
LtH	(Triceps) Lateral Head
MAV	Mean Absolute Value
MDF	Median Frequency
MES	Myoelectric Signal
MLP	Multiple Layer Perceptron
MNF	Mean Frequency
MNP	Mean Power
MU	Motor Unit
OFNDA	Orthogonal Fuzzy Neighbourhood Discriminant Analysis
P controller	Proportional controller
PCA	Principle Component Analysis
PD	Parkinson’s Disease
PD controller	Proportional–Derivative controller
PI controller	Proportional –Integral controller

PID controller	Proportional–Integral–Derivative controller
PKF	Peak Frequency
PLZT	Lead Lanthanum Zirconate Titanate
PNN	Probabilistic Neural Network
PS	Pronation-Supination
PSD	Power Spectral Density
PT	Physical Therapy
PVDF	Polyvinylidene Fluoride
PW	Pulse Width
PZT	Lead Zirconate Titanate
RBN	Radial Basis Function Network
RUD	Radial-Ulnar Deviation
SCI	Spinal Cord Injury
sEMG	Surface Electromyography
SLFNs	Single-Hidden-Layer Feed-Forward Networks
SOM	Self-Organizing Map
SRDA	Spectral Regression Discriminant Analysis
SSC	Slope Sign Changes
SVD	Singular Value Decomposition
SVM	Support Vector Machine
TD	Time Domain
TFD	Time-Frequency Domain
TMS	Transcranial Magnetic Stimulation
WBV	Whole Body Vibration
WL	Waveform Length
WOTAS	Wearable Orthosis for Tremor Assessment and Suppression
ZC	Zero Crossings
2D	Two-Dimensional

Nomenclature

A	Area of cross-section
A_s	Area of the piezoelectric sensor
$A(s)$	Transfer function of the actuator
a	Muscle activation without fatigue
a_r	Normalized muscle recruitment curve
a_m	Muscle activation with fatigue
a_p	Feature vector
b	Dimensionless frequency of the beam
bi	Threshold for the ith hidden neuron
c	User-specified parameter
c_i	Damping coefficients
D	Displacement vector
D_T	Delay time for electromyography control system
d_{31}	Piezoelectric constant that relates the mechanical tension to electrical displacement
E	Modulus of elasticity of the beam /Elasticity coefficient matrix
ei	Eigenvectors
$e(t)$	Error in PD controller
e_{31}	Piezoelectric constant
F_a	Actuator force
F_{Di}	Dissipative force
F_e	Disturbance force
F'_e	Estimated disturbance force

F_i	Muscle force
F_{ki}	Restoring force
$F_{\max}$	Muscle maximum isometric force
F_{Oi}	Excitation force
f	Stimulation frequency
f_l	Normalized factor
f_n	Frequency of EMG signal
f_v	Force -Velocity Factor
$f(x,t)$	External force on the beam
G	Shear modulus
$\mathrm{G_a}$	Feedback control gain
G_s	Amplifier gain
$\mathrm{G_T}$	Control gain
g	Gravitational constant
$\mathrm{g(x)}$	Activation function of the hidden node
H	Hidden layer output matrix
H^*	Moore–Penrose generalized inverse of the matrix **G**
$H(x)$	Heaviside function
h	Coupling coefficients matrix
h_a	Piezoelectric actuator thickness
h_b	Beam thickness
h_p	Piezoelectric thickness
h_s	Piezoelectric sensor thickness
I	Second moment of inertia
I'	Vibratory inertia
$J(x)$	Polar moment of inertia
K	Shear correction factor

K_d	Derivative gain
K_i	Integral gain
K_p	Proportional gain
k_i	Linear stiffness
k_s	Spring stiffness
l	Length
l_a	Piezoelectric actuator length
l_b	Beam length
l_s	Piezoelectric sensor length
$\overline{l}$	Normalized muscle length
M	Bending moment
M'	Estimated Mass
m_a	Mass of the piezoelectric actuator
m_b	Mass of the Euler- Bernoulli beam model
m_i	Mass in 4-DOF palm model
m_s	Mass of the piezoelectric sensor
$m(x)$	Mass of the Timoshenko beam model
Nj	Number of samples in class *j*
P	Order of the AR model
P_l	Linear transformation for features
P_n	Frequency power spectrum
PW_d	Threshold pulse width
PW_s	Saturation pulse width
p	Muscle fatigue factor
p_{min}	Minimum fitness
$p(t)$	Applied voltage to the piezoelectric actuator
Q	Electrical field vector

Q_c	Covariance matrix
Q_n	Non-linear piecewise continuous function
$Q(t)$	Closed circuit charge
q	Actual position in AFC system
$\ddot{q}$	Measured acceleration of the AFC system
$q(f)$	Frequency characteristic factor
q(t)	Time-dependent function
r_i	Moment arm
S_{11}	Elastic constant of piezoelectric material
T	Kinetic energy
TF	Transfer function of piezoelectric actuator
T_g	Gravitational Moment
T_{inc}	Increment of the window
T_P	Internal passive moment
T_t	Muscle generated Moment through active electrical stimulation
Twl	Length of the window
t	Time
t_i	white noise error term
U	Potential energy
U_a	Potential energy piezoelectric actuator
U_b	Potential energy of the beam
U_s	Potential energy of the piezoelectric sensor
U_{spring}	Potential energy of the spring
V	Shear force
V_a	Applied external voltage to piezoelectric actuator
V_s	Applied external voltage to piezoelectric sensor

v_a	Volume of the piezoelectric actuator
v_b	Volume of the beam
$v_{\max}$	Maximum contraction (shortening) velocity
v_s	Volume of the piezoelectric sensor
$\overline{v}$	Normalized muscle velocity
W	Work
w_b	Beam width
w_a	Piezoelectric actuator width
w_s	Piezoelectric sensor width
$w_i = [w_{i1}, w_{i2}, \ldots, w_{im}]^T$	Vector of the weight for the i*th* hidden and input neurons
w_n	Weighted window function
w_p	Piezoelectric width
X= (x1,…, xN)	Feature set matrix with *t*-dimensional space
x_i^j	The *i*th sample of class *j*
$x_j = [x_{j1}, x_{j2}, \ldots, x_{jm}]^T$	Input for SLFN
Y	Vertical deflection in Euler-Bernoulli beam
Y(x)	Fundamental vibration mode shape for Euler-Bernouli beam
y	Lateral displacement in Euler-Bernoulli beam
$y_j = [y_{j1}, y_{j2}, \ldots, y_{jn}]^T$	Target for SLFN
z	Electrical Pulse width
Z(x)	Fundamental vibration mode shape in Timoshenko beam
$\beta_j = [\beta_1, \ldots, \beta_n]$	Output weight linking the hidden layer and the j*th* output node
$\beta_{jL} = [\beta_{j1}, \beta_{j2}, \ldots, \beta_{jL}]^T$	Weight vector of j*th* hidden and output neuron
β_s	Shaping factor

β_{33}	Impermittivity coefficients
γ_{xy}	Shear strain for Timoshenko beam
ε	Strain vector
$\zeta_i^T = [\zeta_{i,1}, \zeta_{i,2}, \ldots, \zeta_{i,n}]^T$	Output vector error
θ	Joint angle
$\ddot{\theta}$	Angular acceleration
λ	Frequency factor on fatigue
λ_i	Eigenvalue associated with the eigenvector e*i*
μ_j	Mean of the class j
ξ_{33}	Dielectric constant
ρ	Density
ρ_a	Density of piezoelectric actuator
ρ_b	Density of beam
ρ_s	Density of piezoelectric sensor
σ	Stress vector
τ	Processing time of pattern-recognition system
τ_{ac}	Activation time constant
τ_{da}	De-activation time constant
τ_{fat}	Fatigue time constant
τ_{rec}	Recovery time constant
τ_{xy}	Shear stress for Timoshenko
τ_d'	Estimated disturbance torque
$\varnothing$	Angle of rotation of the cross section due to bending
$\varphi(x)$	Fundamental vibration mode shapes

ψ	Bending slope of the beam
ω	Natural frequency
$\in_z$	Electric intensity in the z-direction
χ	Lateral displacement in Timoshenko beam

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