

# **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**

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Signature of Student: *Seyedeh Marzieh Hosseini*

Date: 29/12/2018

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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 suppress 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
$b_i$	Threshold for the $i$ th 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
$G_a$	Feedback control gain
$G_s$	Amplifier gain
$G_T$	Control gain
$g$	Gravitational constant
$g(x)$	Activation function of the hidden node
$H$	Hidden layer output matrix
$H^*$	Moore–Penrose generalized inverse of the matrix $\mathbf{G}$
$H(x)$	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
$\bar{l}$	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
$N_j$	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
$\bar{v}$	Normalized muscle velocity
$W$	Work
$w_b$	Beam width
$w_a$	Piezoelectric actuator width
$w_s$	Piezoelectric sensor width
$w_i = [w_{i1}, w_{i2}, \dots, w_{im}]^T$	Vector of the weight for the $i$ th hidden and input neurons
$w_n$	Weighted window function
$w_p$	Piezoelectric width
$X = (x_1, \dots, x_N)$	Feature set matrix with $t$ -dimensional space
$x_i^j$	The $i$ th sample of class $j$
$x_j = [x_{j1}, x_{j2}, \dots, x_{jm}]^T$	Input for SLFN
$Y$	Vertical deflection in Euler-Bernoulli beam
$Y(x)$	Fundamental vibration mode shape for Euler-Bernoulli beam
$y$	Lateral displacement in Euler-Bernoulli beam
$y_j = [y_{j1}, y_{j2}, \dots, y_{jn}]^T$	Target for SLFN
$z$	Electrical Pulse width
$Z(x)$	Fundamental vibration mode shape in Timoshenko beam
$\beta_j = [\beta_1, \dots, \beta_n]$	Output weight linking the hidden layer and the $j$ th output node
$\beta_{jL} = [\beta_{j1}, \beta_{j2}, \dots, \beta_{jL}]^T$	Weight vector of $j$ th hidden and output neuron
$\beta_s$	Shaping factor



$\beta_{33}$	Impermittivity coefficients
$\gamma_{xy}$	Shear strain for Timoshenko beam
$\varepsilon$	Strain vector
$\zeta_i^T = [\zeta_{i,1}, \zeta_{i,2}, \dots, \zeta_{i,n}]^T$	Output vector error
$\theta$	Joint angle
$\ddot{\theta}$	Angular acceleration
$\lambda$	Frequency factor on fatigue
$\lambda_i$	Eigenvalue associated with the eigenvector $e_i$
$\mu_j$	Mean of the class j
$\xi_{33}$	Dielectric constant
$\rho$	Density
$\rho_a$	Density of piezoelectric actuator
$\rho_b$	Density of beam
$\rho_s$	Density of piezoelectric sensor
$\sigma$	Stress vector
$\tau$	Processing time of pattern-recognition system
$\tau_{ac}$	Activation time constant
$\tau_{da}$	De-activation time constant
$\tau_{fat}$	Fatigue time constant
$\tau_{rec}$	Recovery time constant
$\tau_{xy}$	Shear stress for Timoshenko
$\tau'_d$	Estimated disturbance torque
$\emptyset$	Angle of rotation of the cross section due to bending
$\varphi(x)$	Fundamental vibration mode shapes

$\psi$	Bending slope of the beam
$\omega$	Natural frequency
$\epsilon_z$	Electric intensity in the z-direction
$\chi$	Lateral displacement in Timoshenko beam

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