UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A STATE-SPACE OBSERVER FOR ACTIVE NOISE CONTROL SYSTEMS

MAZIN T. MUHSSIN

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By

MAZIN T. MUHSSIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

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Dedicated to

My dearest Parents, Brothers and Sisters

For their extraordinary love and their endless care

Thank You

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Faculty : Engineering

Active noise control (ANC) is a method of reducing the unwanted sound. This is realized by artificially generating canceling (secondary) source(s) of sound through detecting the unwanted (primary) noise and processing it by an electronic controller, so that when the secondary wave is superimposed on the primary wave the two destructively interfere and cancellation occurs at the observation point. ANC system is an active research area for its high demand especially in the acoustic noise and vibration control systems. A lot of work in modeling an ANC system involves the transfer function approach, but unfortunately this method allows observation at a single point or mode. It is of interest to measure the level of cancellation not only at the observer but also around it. Therefore, a state space approach would allow observation at multi modes simultaneously and became the subject of this research.

This thesis is concerned with the study and development of a state-space model (SSM) for ANC system in on dimensional free-field medium instead of Finite Impulse Response (FIR) Models. In this work, the derivation of the SSM of each propagation

path of ANC system is presented and hence the system is termed Feedforward state space control system with feedback inclusion single input single output (SISO) architecture. The criterions of success considered the evaluation process are the length of the propagation path, level of cancellation, convergence rate, number of modes of each path, and destructive interferences occur at the cancellation path. The secondary path of the ANC system is modeled by using the LMS algorithm to complete the design of the Filtered-X Least Mean Square (FXLMS) controller. Then the adaptive FXLMS controller is presented and incorporated with the proposed model for both Feedforward with / without the acoustic Feedback cases. As a result, the comparisons between the two cases are presented by mean of level of cancellation and convergence rate. The simulation results of the proposed model show that the level of the disturbance signal at ten modes along the primary path is decreasing as much as the modes go away from the source indicating that this model is suitable to build the mechanism of the ANC system which satisfies the relation between the wave dissipation against the number of modes which are distributed along the length of path.

The derivation of the SSM gives the opportunity to extend the work furthermore to involve the derivation of a state-space optimal observer which is named State Space Least Mean Square (SSLMS) observer. This observer is employed to observe and monitor the pressure modes along the propagation path through simulating it in an off-line structure i.e. without controller, or to observe the modes at the cancellation path through simulating the SSLMS in an on-line structure i.e. while the controller is converging. The comparison results between the real and observed modes of the secondary propagation show an accurate observing. Finally, the comparisons of the observed pressures of three modes along the cancellation path while the controller is converging (on-line structure) are shown with the mode which is located at the observer achieving the best cancellation.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sians

PEMBANGUNAN SISTEM KAWALAN AKTIF HINGAR MENGGUNAKAN FORMULA RUANG KEADAAN

Oleh

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Kawalan Hingar Aktif (ANC) adalah satu kaedah bagi mengurangkan hingar yang tidak diingini. Dengan menghasilkan kesan tiruan bagi menyingkirkan bunyi dari sumber kedua dengan cara mengesan hingar yang tidak diingini daripada sumber pertama dan diproses oleh pengawal elektronik supaya apabila berlakunya pertindihan antara gelombang kedua dan pertama, ANC yang akan melenyapkan kedua-dua gelombang. Sistem ANC merupakan satu kajian yang mendapat perhatian terutamanya dalam bidang sistem kawalan getar dan akustik hingar. Lazimnya ANC melibatkan kaedah Sambutan Dedenyut Terhingga, tetapi malangnya kaedah ini hanya membenarkan pemerhatian pada mod tunggal. Adalah menjadi untuk mengukur tahap pembatalan, bukan sahaja di pemerhati tetapi di sekitarnya juga. Oleh yang demikian, kaedah keadaan ruang menjadi tajuk utama kajian ini kerana kaedah ini membenarkan pemerhatian untuk pelbagai mod secara serentak.

Tesis ini akan tertumpu pada kajian dan pembangunan model keadaan ruang (SSM) untuk sistem ANC dalam dimensi yang bebas bagi menggantikan Model Sambutan Dedenyut Terhingga (Finite Impulse Response (FIR) Model). Dalam kajian ini, asalan bagi MKR bagi setiap tindakan penyebaran sistem ANC akan dibahagikan supaya tempoh suap hadapan dan suap balik sistem kawalan tergolong dalam binaan masukan tunggal keluaran tinggal (SISO).

Kriteria bagi menjayakan projek ini adalah bergantung pada tafsiran proses iaitu panjang tindakan penyebaran, tahap pembatalan, kadar pemusatan, bilangan mod pada setiap tindakan dan kemusnahan antaramuka pada setiap tindakan pembatalan. Jalan kedu system ANC akan dimodelkan dengan menggunakan algoritma LMS untuk melengkapi rekabentuk pengawal Filtered-X Least Mean Square (FXLMS). Kemudian FXLMS disajikan dan digabungkan dengan model yang dicadangkan untuk kedua suap hadapan dengan / tanpa kes suap balik akustik. Akibatnya, perbandingan antara dua kes yang akan distunjukkan oleh tahap pembatalan dan kadar penumpuan. Keputusan simulasi model yang dicadangkan menunjukkan bahawa tahap gangguan isyarat di sepuluh mod sepanjang jalan utama menurun sebanyak mana mod pergi daripada sumber yang menunjukkan bahawa model ini sangat desuai untuk membina mekanisma sistem ANC yang memenuhi hubungan antara gelombang disipasi terhadap jumlah mod yang diedarkan di sepanjang jalan.

Hasil perolehan SSM memberi peluang untuk melanjutkan kajian termasuk memperolehi ruang keadaan optimal pada pemerhati yang dipanggil pemerhati Rajah Min Terkecil Keadaan Ruang (SSLMS). Pemerhati ini berfungsi untuk mengamati perambatan dan memantau mod tekanan di sepanjang jalan melalui simulasi perambatan dalam struktur luar talian iaitu tanpa pengawal , atau untuk mengamati mode di jalan pembatalan melalui simulasi SSLMS dalam struktur dalam talian iaitu sementara pengawal itu bertumpu. Keputusan perbandingan antara mod nyata dan mod yang diperhatikan oleh mod perambatan yang kedua menunjukkan pemerhatian yang tepat. Akhirnya, perbandingan tekanan yang diperhatikan daripada tiga mod di sepanjang jalan pembatalan semasa pengawal masih bertumpu (struktur dalam talian) akan dipaparkan dengan mod yang terletak di pemerhati yang mencapai pembatalan yang terbaik.

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I certify that a Thesis Examination Committee has met on **16 October 2009** to conduct the final examination of Mazin T. Muhssin on his thesis entitled "**Development of a State-Space Observer for Active Noise Control Systems**" in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

MAZIN T. MUHSSIN

Date:

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LIST OF ABBREVIATIONS

ANC	Active Noise Control
SSM	State-Space Model
SISO	Single Input Single Output
FXLMS	Filtered-X Least Mean Square
SSLMS	State-Space Least Mean Square
LMS	Least Mean Square
DSP	Digital Signal Processing
ANVC	Active Noise Vibration Control
1D	One Dimension
3D	Three Dimension
ASAC	Active Structural Acoustic Control
FFCS	Feedforward Control Structure
FBPM	Feedback Path Modeling
ADNC	Adaptive Noise Cancellation
FIR	Finite Impulse Response
D/A	Digital to Analog
A/D	Analog to Digital
MSE	Mean Square Error
VSS	Variable Step Size
PRBS	Pseudo Random Binary Sequence
RLS	Recursive Least Square
SPM	Secondary Path Model

ERLS	Extend Recursive Least Square
SSRLS	State-Space Recursive Least Square
SSRLSWAM	State-Space Recursive Least Square Adaptive Memory
FFT	Fast Fourier Transform
MIMO	Multiple Input and Multiple Output
$E(n)$	State-space model of the acoustic path between the primary source and detector through r_e
$E'(n)$	State-space model of the acoustic path between the primary source and detector through r_e coupled with the state-space model of the detector M and the secondary source L.
$F(n)$	State-space model of the acoustic path between the secondary source and the detector through r_f.
$\hat{F}(n)$	Estimate of the of the acoustic path between the secondary source and the detector through r_f.
$F'(n)$	State-space of the acoustic path between the secondary source and the detector through r_f coupled with the state-space model of the detector M.
$G(n)$	State-space model of the acoustic path between the primary source and the observer through r_g.
$G'(n)$	State-space of the acoustic path between the primary source and the observer through r_g coupled with the state-space model of the detector M and the secondary source L.
$H(n)$	State-space model of the acoustic path between the secondary source and the observer through r_h.
$H'(n)$	State-space model of the acoustic path between the secondary Source and the observer through r_h coupled with the transfer functions of the detector M and the secondary source L.

$L(n)$	State-space model of the secondary source
$M(n)$	State-space model of the detector
$M_0(n)$	State-space model of the observer
$U_c(n)$	Control signal generated by the controller
$U_D(n)$	Primary signal at the source
$U_M(n)$	Detector signal at the detector
$Y_{CO}(n)$	Secondary signal at the source point
$Y_{DO}(n)$	Primary signal at the observation point
$Y_0(n)$	Combined primary and secondary signal at the observation point (observed signal)
r	Length of the propagation path
r_e	Distance of the propagation path between the primary source and the detector
r_f	Distance of the propagation path between the secondary source and the detector
r_g	Distance of propagation path between the primary source and the observer
r_h	Distance of propagation path between the secondary source and the observer
w_n	The natural frequency rad / sec
c	Speed of sound in air mm / sec
ρ	Density of air kg / m^3

ζ	Damping coefficient
$n(n)$	Reference signal
$u(n)$	Input signal
A	Dynamic matrix
B	Input vector
C	Output vector
D	Feedforwad vector
A_g	Dynamic matrix of the primary propagation path
B_g	Input vector of the primary propagation path
C_g	Output vector of the primary propagation path
A_h	Dynamic matrix of the secondary propagation path
B_h	Input vector of the secondary propagation path
C_h	Output vector of the secondary propagation path
A_e	Dynamic matrix of the primary propagation E
B_e	Input vector of the primary propagation E
C_e	Output vector of the primary propagation E
A_f	Dynamic matrix of the acoustic feedback path
B_f	Input vector of the acoustic feedback path
C_f	Output vector of the acoustic feedback path
A_m	Dynamic matrix of the mode

B_m	Input vector of the pressure mode
C_m	Output vector of the pressure mode
N_g	No. of modes along the primary path
N_h	No. of modes along the secondary path
N_e	No. of modes along the propagation path E
N_f	No. of modes along the feedback path
$\Psi(x)$	Pressure modes coefficients
$\psi(x,t)$	Time dependent acoustic parameter
$P(x,t)$	Time dependent acoustic pressure
$P(t)$	Pressure wave
$P_n(t)$	Pressure modes
x	Arbitrary point
x_m	Location of observer
x_d	Location of detector
Δ	Laplace operator
s	Lablace function
u_p	Filtered signal vector by $\hat{H}$
d	Disturbance signal
$w(n)$	Weights vector of the filter
y_p	Output of the secondary path

V	Identification signal
K	Observer gain
g_h	The output of the secondary path in off / on- line system identification
e_s	Observer error
ε	Prediction error
X	System state
$\hat{X}[n]$	Observer state
$\bar{X}[n]$	Predicted state
$y(x_m, t)$	Pressure output at the observer
$y(x_d, t)$	Pressure output at the detector
$Z(a, \beta)(z)$	Boundary condition
$\delta[n]$	Error between observer state and predicted state
μ_o	Step size of the SSLMS Observer