UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF SLOT-LESS LINEAR OSCILLATORY ACTUATOR

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FK 2009 32

DEVELOPMENT OF SLOT-LESS LINEAR OSCILLATORY ACTUATOR

By

RAJA NOR FIRDAUS KASHFI RAJA OTHMAN

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

June 2009

Dedication

TO RAJA OTHMAN AND CHE RUGAYAH, MY BELOVED PARENTS, MY SISTERS AND BROTHERS.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Master of Science

DEVELOPMENT OF SLOT-LESS LINEAR OSCILLATORY ACTUATOR

By

Raja Nor Firdaus Kashfi Raja Othman

June 2009

Chairman : Dr. Eng. Norhisam Misron, PhD

Faculty : Engineering

Linear Oscillatory Actuator (LOA) is an electromechanical device that can produce short linear stroke motion directly without the use of any mechanical transmission to convert rotary motion into linear motion. Due to this simplicity, the benefits of LOA over conventional actuator are simple structure, better dynamical performance, and higher reliability. It has been extensively used in industry applications especially in power generation, healthcare, factory automation, and household appliances.

Currently, most of the researches are only dealing with designing a slot type of LOA with exact values of thrust, electrical time constant, and mechanical time constant. Some of them studied the control strategy of an existing moving coil type of LOA. But, none of them had disclosed information about the oscillation displacement characteristics based on various sizes of LOA. Such information is useful for the designer. It will provide solutions or guidelines about the thrust constant, spring constant, electrical time constant, and mechanical time constant toward oscillation displacement characteristics of LOA. The analysis of the parameters mentioned

above definitely will help any researchers to know whether the LOA is suitable for the specific application before design the optimized structure for fabrication. Unfortunately, the information as mentioned above is not available to the designers.

This thesis describes the development and analysis on the effect of thrust constant, spring constant, electrical time constant, and mechanical time constant to oscillation displacement characteristic of slot-less linear oscillatory actuator. The analysis is necessary to determine the variation and relationship of these constants to various sizes of LOA. In this research, a prototype of slot-less linear oscillatory actuator is designed using Finite Element Method (FEM). The prototype is fabricated and measured experimentally. Moreover, analytical solution is developed for the same prototype using Permeance Analysis Method (PAM). The two methods were verified through comparison with measurement. The comparison shows the proposed analytical solution using PAM had good agreement with both FEM and the measurement.

As summary, the research found that the constants affect the oscillation displacement to be higher but the thrust would become lower for small size of LOA. In contrary, high thrust can be achieved for bigger size of LOA but the oscillation displacement would become lower. Therefore, in order to design high thrust LOA the lower value of electrical time constant and mechanical time constants should be selected. Meanwhile, for both thrust constant and spring constant higher value should be selected. For designing higher oscillation displacement of LOA, the lower value of electrical time constant, thrust constant, and spring constant should be selected where as for mechanical time constant higher value should be selected.

Abstrak thesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

MEMBANGUNKAN AKTUATOR PENGAYUN LELURUS TANPA SLOT

Oleh

Raja Nor Firdaus Kashfi Raja Othman

June 2009

Pengerusi : Dr. Eng. Norhisam Misron, PhD

Fakulti : Kejuruteraan

Aktuator pengayun lelurus (LOA) ialah alat elektromekanikal yang menghasilkan daya berjarak pendek lelurus tanpa menggunakan sebarang transmisi mekanikal untuk menukarkan gerakan putaran kepada lelurus. Disebabkan oleh keringkasan, kebaikan LOA mengatasi aktuator biasa ialah struktur yang ringkas, prestasi dinamik yang lebih baik, dan kesesuaian yang tinggi. Ia telah digunakan secara meluas sebagai aplikasi industri terutama penjanaan kuasa, kesihatan, automasi kilang, dan peralatan rumah.

Sejak akhir-akhir ini, kebanyakan penyelidik membincangkan tentang merekacipta LOA berjenis slot dengan nilai pemalar daya, pemalar masa elektrik, dan pemalar masa mekanikal yang tertentu. Sesetengah daripada mereka mengkaji strategi kawalan pada LOA berjenis gegelung bergerak yang sedia ada. Tetapi, tiada satu pun daripada mereka yang mendedahkan informasi tentang ciri-ciri jarak ulang alik berdasarkan pelbagai saiz LOA. Informasi sebegini amat berguna untuk perekacipta. Ia menyediakan penyelesaian atau petunjuk tentang pemalar daya, pemalar spring,

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Thesis ini adalah berkisar tentang analisis kesan pemalar daya, pemalar spring, pemalar masa elektrik, dan pemalar masa mekanikal terhadap jarak ulang alik bagi aktuator pengayun lelurus**.** Analisis ini diperlukan untuk menentukan variasi dan hubungan pemalar-pemalar ini terhadap jarak ulang alik untuk pelbagai saiz LOA. Dalam penyelidikan ini, sebuah prototaip aktuator pengayun lelurus tanpa slot direkabentuk menggunakan Finite Element Method (FEM). Prototaip ini difabrikasi dan diukur secara eksperimen. Seterusnya, penyelesaian analitikal terhadap prototaip yang sama dibangunkan menggunakan Permeance Analysis Method (PAM). Kedua-dua cara ini dibuktikan melalui perbandingan dengan pengukuran. Perbandingan ini menunjukkan penyelesaian analitikal menggunakan PAM mempunyai persetujuan yang baik dengan FEM dan pengukuran.

Sebagai ringkasannya, penyelidikan ini menemui pemalar-pemalar mempengaruhi jarak ulang alik kepada lebih tinggi tetapi daya akan menjadi semakin kecil untuk saiz LOA yang kecil. Sebaliknya, daya yang tinggi boleh diperolehi untuk saiz LOA yang lebih besar tetapi jarak ulang alik akan menjadi semakin kecil. Oleh itu, untuk merekabentuk LOA berdaya tinggi, pembolehubah bagi pemalar masa elektrik dan pemalar masa mekanikal yang kecil perlu dipilih. Manakala, bagi pemalar daya dan pemalar spring pembolehubah bagi yang besar perlu dipilih. Untuk merekabentuk LOA berjarak ulang alik yang besar, pemalar masa elektrik, pemalar daya, dan pemalar spring yang kecil perlu dipilih manakala untuk pemalar masa mekanikal pembolehubah yang besar pula perlu dipilih.

ACKNOWLEDGEMENTS

All praise to supreme Almighty Allah swt. the only creator, cherisher, sustainer and efficient assembler of the world and galaxies whose blessings and kindness have enabled the author to accomplish this project successfully.

The author also would like to take this opportunity to gratefully acknowledge the guidance, advice, support, and encouragement he received from his supervisor, Dr. Norhisam Misron who keeps advising and commenting throughout this project until it turns to real success. Great appreciations are expressed to Prof. Ir. Dr. Norman Mariun and Associate Prof. Dr. Ishak Aris for their valuable remarks, help, advice, and encouragement.

Furthermore, the author would like to give special thanks to En Abdul Razak Jelani from Malaysian Palm Oil Berhad for his kindness in sponsoring this project. The author also would like to say deepest thanks to Fairul Azhar, Norafiza Masruni, Ezril Hisham Mat Saat for their kind assistance and guidance. Appreciation also to the Faculty of Engineering for providing the facilities and the components required for undertaking this project.

I certify that a Thesis Examination Committee has met on June, 18 2009 to conduct the final examination of Raja Nor Firdaus Kashfi Raja Othman on his Master of Science thesis entitled "Development of Slot-less Linear Oscillatory Actuator" in accordance with Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the candidate be awarded the Master of Science. Members of the Thesis Examination Committee were as follows:

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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.

____

RAJA NOR FIRDAUS KASHFI

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LIST OF ABBREVIATIONS

A_c	Cross sectional area of coil (m^2)
A_{m}	Cross sectional area of permanent magnet (m^2)
a	Acceleration of mover in (m/s^2)
a_g	Air gap area (m^2)
$B_{c(n)}$	Magnetic density at coil *n* (end/middle/center) (T)
$B_{\mathrm{c(end)}}$	Magnetic flux density at the end coil of the LOA
$B_{\mathrm{c(middle)}}$	Magnetic flux density at the middle coil of the LOA
$B_{\mathrm{c(center)}}$	Magnetic flux density at the center coil of the LOA
$B_{\mathrm{k(n)}}$	Magnetic flux density of permanent magnet (end/middle) at operating point of (end/middle) (T)
B_{r}	Remanent magnetic flux density (T)
d	Diameter of coil wire in (m)
d_1	Diameter of inner spring (m)
d_2	Diameter of outer spring (m)
$F_{c(n)}$	Thrust at coil *n* (end/middle/center) (N)
$F_{c(end)}$	Thrust at end of LOA (N)
$F_{c(middle)}$	Thrust at middle of LOA (N),
$F_{c(center)}$	Thrust at center of LOA (N),
F_{dyn}	Dynamic force of LOA in (N)
F_m	Force of mover (N)
f_r	Resonant frequency power supply (Hz)
$F_{spring1}$	Force of spring 1 (N)
$F_{spring2}$	Force of spring 2 (N)
F_T	Total thrust of LOA (N)
$F_{T(system)}$	Total force of the system (N)
G	Gain in (dB)
g	Mechanical Clearance of between stator and mover of LOA (m)
H_{c}	Coercive force (kA/m)
h_{f}	Height of oil palm frond

h_c	Height of coil (m)
$I_{c(n)}$	Supplied current at coil *n* (end/middle/center) (A)
i	Current supplied of LOA (A)
k_e	Back emf constant in (V/m/s)
k_f	Thrust constant (N/A)
k_s	Spring constant (kN/m)
$k_{spring1}$	Spring constant for spring 1 (kN/m)
$k_{spring2}$	Spring constant for spring 2 (kN/m)
ℓ_c	Average length of coil per layers (m)
l_{by}	Length of back yoke coil (m)
L_{end}	Self inductance at end coil (mH)
L_{middle}	Self inductance at middle coil (mH)
L_T	Total self inductance (mH)
m	Mass of mover in (kg)
m_T	Total weight of LOA
N	Total number of turns (turns)
$N_{c(n)}$	Number of coil turns at coil *n* (end/middle/center) (turns)
n_1	Number of end coil
n_2	Number of middle coil
P	Input power (W)
ρ	Coil resistivity in (Ω/m)
Þ	Permeance
$Þ_{T(n)}$	Total permeance of (end/middle) (H)
$Þ_{T(end)}$	Total permeance value of the magnetic circuit of end coil (H)
$Þ_{T(middle)}$	Total permeance value of the magnetic circuit of middle coil (H)
R_T	The total resistance (Ω)
r_1	Inner radius of permanent magnet (m)
r_2	Outer radius of permanent magnet(m)
r_3	Inner radius of back yoke (m)
r_4	Outer radius of back yoke (m)

T_e	Electrical time constant (ms)
T_m	Mechanical time constant (ms)
V	Voltage supplied of LOA (V)
w_{cn}	Width of coil *n* (end/middle/center) (m)
w_{c1}	Width of end coil (m)
w_{c2}	Width of middle coil (m)
w_f	Width of oil palm frond
w_m	Width of permanent magnet (m)
w_{my}	Width of moving yoke (m)
ω	Frequency (rad/s)
x	Oscillation displacement of LOA (mm)
α	Displacement coefficient (m)
μ_0	Permeability (H/m)
ε	the coil coefficients
$\Phi_{c(end)}$	Magnetic flux of coil at end coil (Wb)
$\Phi_{c(middle)}$	Magnetic flux of coil at middle coil (Wb)
$\Phi_{c(center)}$	Magnetic flux of coil at end coil (Wb)
$\Phi_{pm(end)}$	Magnetic flux of permanent magnet at magnetic circuit of end coil (Wb)
$\Phi_{pm(middle)}$	Magnetic flux of permanent magnet at magnetic circuit of middle coil (Wb)

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