HYBRID FUZZY ADAPTIVE CONTROL STRATEGIES ON DOUBLE ACTING PNEUMATIC CYLINDER ROD-PISTON POSITIONING

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I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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I hereby declare that the work in this 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 Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Sistem pneumatik digunakan secara meluas dalam industri kerana kelebihannya seperti nisbah berat ke kuasa tinggi, kelajuan perjalanan yang tinggi, medium cecair bersih dan keberkesanan kos. Walau bagaimanapun, agak mencabar untuk mengawal kedudukan rod-omboh pneumatik disebabkan oleh kelakuan tidak bersandar tinggi dan geseran serta ketidakpastian dalam parameter sistem pneumatik. Dari segi sistem kawalan, terdapat dua pendekatan yang bebas model dan kawalan berasaskan model. Untuk kawalan bebas model, sukar untuk mendapatkan prestasi ketepatan kedudukan yang mencukupi dengan menggunakan *Proportional, Integral and Derivative* (PID) konvensional untuk sistem yang sangat tidak linear, manakala bagi kawalan berasaskan model, *Sliding Mode Controller* (SMC) mengalami fenomena perbualan yang mewujudkan oscillasi trajektori keadaan di sekitar permukaan gelongsor. Oleh itu, kajian ini telah mengambil inisiatif untuk mencadangkan strategi sistem kawalan yang mantap menggunakan unsur *Fuzzy Self-Adaptive* (FSA) untuk menangani isu-isu tersebut dengan menggunakan *pneumatic proportional valve with double-acting cylinder* (PPVDC) sebagai platform untuk mencapai ketepatan kedudukan. Untuk pendekatan kawalan bebas model, penambahbaikan telah dilakukan pada sistem kawalan PID dengan mengintegrasikan FSA dan menggunakan kaedah cascade, membentuk *Cascade FSAPID* (CFSAPID). Sementara itu, untuk pendekatan kawalan berasaskan model, *Dual-Stage FSAISMC* (DFSAISMC) dibangunkan dengan mengintegrasikan dua kaedah FSA. Selain itu, DFSAISMC boleh dipertingkatkan dengan mengintegrasikan penukaran hibrid antara DFSAISMC dan *Force FSAISMC* (FFSAISMC), membentuk HPF-FSAISMC. Untuk pendekatan kawalan bebas model, keputusan simulasi secara keseluruhan menunjukkan bahawa pengawal CFSAPID dapat meminimumkan overshoot pada 3.67 mm dan memberikan respon terpantas masa penyelesaian pada 1.4 s pada keadaan beban luar 10 kg. Selain itu, berbanding dengan PID, CPID dan FSAPID, ayunan di kedua-dua ruang tekanan dinaikkan 90% lebih rendah dengan menggunakan CFSAPID. Sementara itu, untuk pendekatan kawalan berasaskan model, kedua-dua DFSAISMC dan HPF-FSAISMC digunakan untuk kilang model PPVDC. Hasil simulasi menunjukkan bahawa pengawal DFSAISMC dapat mengurangkan masa laras dan menetap, masing-masing pada 90% dan 1.25 s, berbanding pengawal ISMC dan FSAISMC. Sebaliknya, keputusan simulasi model tanaman PPVDC dengan HPF-FSAISMC menunjukkan bahawa pengawal yang dicadangkan mampu menghapuskan ayunan pada anjakan rod-omboh, sementara juga melakukan lebih cepat 0.5 dalam masa penyelesaian berbanding pengawal DFSAISMC dan jauh lebih baik berbanding pengendali ISMC dan FSAISMC. Kajian perbandingan dimuktamadkan dengan perbandingan kedua-dua pengawal CFSAPID dan HPF-FSAISMC sebagai kawalan bebas model dan model berasaskan terbaik untuk masing-masing sistem PPVDC. Simulasi dilakukan menggunakan trajektori langkah dengan beban luaran 15-20 kg dan gangguan daya 100N pada tempoh masa 3 s. Pengawal HPF-FSAISMC menunjukkan kekukuhan yang lebih baik berbanding dengan pengawal CFSAPID dari segi tindak balas pantas pada waktu penyelesaian 1.21 s dengan hampir tidak menyala. Selain itu, pengawal HPF-FSAISMC melakukan penolakan gangguan di mana tahap tekanan dikekalkan pada 4.2 Pa dan 3 Pa bagi kedua-dua ruang tekanan. Hasil keseluruhannya menyimpulkan bahawa pengawal HPF-FSAISMC yang dicadangkan dapat menstabilkan tekanan dalaman dan peratusan dalaman bilik silinder pneumatik, yang merupakan parameter utama untuk pemampatan udara pneumatik, yang mengakibatkan kesilapan-kesilapan hampir sifar.

ABSTRACT

The pneumatic system is widely used in the industry due to its advantages such as high weight to power ratio, high travel speed, clean fluid medium and cost-effectiveness. However, it is quite challenging to control the position of the pneumatic rod-piston due to the high nonlinearity behavior and friction as well as uncertainties in the parameters of the pneumatic systems. In terms of the control system, there are two approaches which are model-free and model-based control. For the model-free control, it is difficult to obtain adequate position accuracy performance by using the conventional Proportional, Integral and Derivative (PID) for the highly nonlinear system, while, for the model-based control, the conventional Sliding Mode Controller (SMC) suffers from chattering phenomenon creating the state trajectory oscillations around the sliding surface. Therefore, this study has taken the initiative to propose a robust control system strategy using the Fuzzy Self-Adaptive (FSA) element to tackle the aforementioned issues using a pneumatic proportional valve with double-acting cylinder (PPVDC) system model as a platform to achieve the positioning precision. For the model-free control approach, an improvement has been done on the PID control system by integrating the FSA and applying the cascade method, forming the Cascade FSAPID (CFSAPID). Meanwhile, for the model-based control approach, the Dual-Stage FSAISMC (DFSAISMC) is developed by integrating two FSA methods. Furthermore, the DFSAISMC can be improved further by integrating the hybrid switching between the DFSAISMC and Force FSAISMC (FFSAISMC), forming the HPF-FSAISMC. For the model-free control approach, overall simulation results showed that the CFSAPID controller is able to minimize the overshoot at 3.67 mm and provide the fastest response of settling time at 1.4 s at 10 kg external load condition. Moreover, compared to PID, CPID and FSAPID, the oscillation in both pressure chambers is improved at 90% lower by using CFSAPID. Meanwhile, for the model-based control approach, both DFSAISMC and HPF-FSAISMC are applied to the PPVDC model plant. Simulation results showed that the DFSAISMC controller was able to reduce the overshoot and settling time, at 90% and 1.25 s, respectively, compared to ISMC and FSAISMC controllers. On the other hand, simulation results of the PPVDC model plant with HPF-FSAISMC showed that the proposed controller is capable of eliminating the oscillation on the rod-piston displacement, while also performing 0.5 s faster in settling time compared to DFSAISMC controller and far better compared to ISMC and FSAISMC controllers. The comparison study is finalized with the comparison of both CFSAPID and HPF-FSAISMC controllers as the best model-free and model-based control designed, respectively, for the PPVDC system. The simulation was done using the step trajectory with 15-20 kg external load and 100N force disturbance at the time period of 3 s. HPF-FSAISMC controller showed better robustness compared to the CFSAPID controller in terms of fast response at 1.21 s settling time with almost zero overshoot. Moreover, the HPF-FSAISMC controller performs disturbance rejection where the pressure levels were sustained at 4.2 Pa and 3 Pa for both pressure chambers, respectively. The overall results conclude that the proposed HPF-FSAISMC controller is able to stabilize the internal pressure and internal frictions of the pneumatic cylinder chambers, which are the main parameters for the pneumatic air compression, resulting in almost zero steady-state-error.

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LIST OF SYMBOLS

x_{pv}	Valve Orifice Spool Position
A_1, A_2	Cross-Sectional Area of the Rod-Piston
A_v	Effective Area of Valve Orifice
$A_{v,eq}$	Equivalent Control Component
$A_{v,ro}$	Robust Control Component
$b(\cdot)$	Function Describing System's Control Gain
c	Speed of Sound
C_d	Discharge Coefficient of Valve Orifice
c_v	Specifics Heat at Constant Volume
$D_{cti(i=1,2)}$	Inner Diameter of the Connecting Tubes
e	Error
$f(\cdot)$	Function Describing System Dynamic
f_{mf}	Maximum Force
F_{rp}	Force of rod-piston
F_C	Coulomb Friction
F_f	Internal Friction Force
F_L	External Friction Force
F_S	Static Friction
f_{op}, f_{oi}, f_{od}	fuzzy output gain for PID
$g(\cdot)$	Function Describing Stribeck Effect in LuGre Friction Model
G_r	Gain of Robust Control
k	Ratio of Specific Heats of Air
k_e	Fuzzy Input of Error
$k_{\Delta e}$	Fuzzy Input of Rate of Error
k_{pv}	Simple Valve Gain
K_p	Proportional Control Gain
K_i	Integral Control Gain
K_d	Derivative Control Gain
L	Length of the Rod-Piston Cylinder
$L_{cti(i=1,2)}$	Length of the Connecting Tubes
L_{sf}	Scaling Factor of the Magnitude of the Transition
m	Mass of Air Inside the Cylinder Chamber
$\dot{m}_{i(i=1,2)}$	Mass Flow Rate

M_L	Load Mass
M_{rp}	Rod-Piston Mass
n	Number of Rules
P	Pressure
$P_{i(i=1,2)}$	Pressure in Cylinder Chambers
P_{cr}	Critical Pressure
P_S	Supply Pressure
P_u	Upstream Pressure
P_d	Downstream Pressure
P_{atm}	Atmospheric Pressure
$\dot{Q}$	Rate of Heat Transfer Terms
R	Ideal Gas Constant
R_{ct}	Tube Resistance
s	Sliding Surface
$sat(\cdot)$	Saturation Function
$sign(\cdot)$	Signum Function
T	Absolute Temperature of the Air
$t_{hci(i=1...7)}$	Time Period of DS Trajectory Half Cycle
t_{pv}	Proportional Valve Time Constant
t_s	Time Period of Maximum Force of PPVDC Detection
t_{hold}	Time when a change in position is detected
τ_{sf}	Shift Factor of Starting Time of Each Transition
u	Control Signal
$\dot{U}$	Change of Internal Energy
V	Volume of The Cylinder Chamber
$V_{i(i=1,2)}$	Volume of the Cylinder Chambers
$\dot{V}_{i(i=1,2)}$	Change of Volumetric Rate
$V_{0i(i=1,2)}$	Volume of Compressed Air of the Connecting Tubes between the Cylinder Chambers and Valve
v_s	Viscous Coefficient
x	variable of controller
x_d	Desired Displacement
x_{rp}	Rod-Piston Displacement
$\dot{x}_{rp}$	Velocity of the Rod-Piston
$\ddot{x}_{rp}$	Acceleration of the Rod-Piston

$\dddot{x}_{rp}$	Jerk Motion
z	Internal State of Bristles
$\dot{z}$	Average Deflection of Bristles
α	Thermal Expansion Coefficient of Air
β_0	Spring Coefficient of Bristles
β_1	Damping Coefficient of Bristles
β_2	Viscous Friction
ε	Threshold Value of Error
λ	Control Gain Bandwidth of Positive Constant
η	Dynamics Viscosity of Air
ρ	Air Density
φ	Thickness of the Boundary Layer
$\phi_{i(i=1,2)}(\cdot,\cdot)$	Normalized Mass Flow Rate of the Fixed Area of the Valve Orifice
$\tau_{cti(i=1,2)}$	Time Period of Connecting Tube
μ	Fuzzy Membership Function Values
ω	Valve Orifice Gradient Area
ζ	Crisp Output Signal for the Mamdani FLC
ξ	Crisp Output Signal for the T-S FLC
ψ	Order Number of the System
Δe	Change in Position Error

LIST OF ABBREVIATIONS

AESO	Adaptive Extended State Observer
ANNC	Adaptive Neural Network Compensator
ARMA	Auto-Regressive Moving-Average
CFSAPID	Cascade Fuzzy Self-Adaptive Proportional-Integral-Derivative
COG	Centre of Gravity
CPID	Cascade Proportional-Integral-Derivative
DFSAISMC	Dual-Stage Fuzzy Self-Adaptive Integral Sliding Mode Controller
DZC	Dead Zone Compensator
FA	Firefly Algorithm
FASC	Functional Approximation Sliding Mode Controller
FLC	Fuzzy Logic Controller
FPID	Fractional Order Proportional-Integral-Derivative
FSAISMC	Fuzzy Self-Adaptive Integral Sliding Mode Controller
FSAPID	Fuzzy Self-Adaptive Proportional-Integral-Derivative
GA	Genetic Algorithm
GMS	Generalized Maxwellslip
HPF-FSAISMC	Hybrid Position Force Fuzzy Self-Adaptive Integral Sliding Mode Controller
Hz	Hertz
IAE	Integral Absolute Error
IMC-PID	Internal Mode Control Proportional-Integral-Derivative
IPA	Intelligent Pneumatic Actuators
IPID	Integral Order Proportional-Integral-Derivative
ISMC	Integral Sliding Mode Controller
J	Joule
K	Kelvin
kg	Kilogram
L	Large
m	Meter
mm	Milimeter
M	Medium
MIMO	Multiple-input Multiple-output
MISO	Multiple-input Single-output
MMGA	Multi-Variable Multi-Objective Genetic Algorithm
N	Newton
NC	Normally Close
NL	Negative Large
NM	Negative Medium
NO	Normally Open
N-PID	Nonlinear Proportional-Integral-Derivative
NT	Negative Tiny

pa	Pascal
PFASWLT	Pneumatic Force Actuator System with Long Tubes
PI	Proportional-Integral
PI-ANFIS	Proportional-Integral Adaptive Neuro-Fuzzy
PID	Proportional-Integral-Derivative
P-FLC	Proportional Fuzzy Logic Controller
PI-FLC	Proportional-Integral Fuzzy Logic Controller
PL	Positive Large
PM	Positive Medium
PPVDC	Pneumatic Proportional Valve with Double-acting Cylinder
PSO	Particle Swarm Optimization
PT	Positive Tiny
PWM	Pulse Width Modulation
RHC	Receding Horizon position
s	Second
SISO	Single-input Single-output
SMC	Sliding Mode Controller
SN-PID	Self-Regulation Proportional-Integral-Derivative
T	Tiny
TD-MFAC	Model-Free Adaptive Control with Tracking Differentiator
T-S FLC	Takagi-Sugeno Fuzzy Logic Controller
V	Voltage
VGT	Variable Geometry Turbocharger
VL	Very Large
VT	Very Tiny
VVL	Very-Very Large
VVT	Very-Very Tiny
ZE	Zero

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