

PERPUSTAKAAN UMP



0000113719

**Developmen** **ow-cost**  
**Wearable Servo valve Using Buckled Tubes**  
**and Embedded Controller**

**2016**

Okayama University of Science  
Graduate School of Engineering  
Systems Science

**Abdul Nasir bin Abd Ghafar**

# TABLE OF CONTENTS

<b>CHAPTER 1 INTRODUCTION</b>	1
1.1 Research background and objectives	1
1.2 Previous studies and basic concept	8
1.3 Thesis overview	13
<b>CHAPTER 2 TWISTING TYPE SERVO VALVE</b>	15
2.1 Introduction	15
2.2 Construction and operating principle	15
2.3 Basic characteristics	20
2.4 Position control of artificial muscle using tested valve	24
2.5 Pressure controlled type servo valve	29
2.6 Summary	36
<b>CHAPTER 3 IMPROVEMENT OF THE VALVE – BENDING TYPE SERVO VALVE-</b>	37
3.1 Introduction	37
3.2 Construction and operating principle	37
3.3 Basic characteristics	43
3.4 Position control of artificial muscle using improved valve	45
3.5 Pressure controlled type servo valve	48
3.6 Summary	53
<b>CHAPTER 4 ANALYTICAL MODEL OF BENDING TYPE SERVO VALVE</b>	54
4.1 Introduction	54
4.2 Analytical model	54
4.3 Parameter identification	61
4.4 Summary	68

<b>CHAPTER 5</b>	<b>CALCULATED RESULT OF VALVE PERFORMANCE.....</b>	<b>69</b>
5.1	Introduction .....	69
5.2	Calculated static characteristics of the valve .....	69
5.3	Calculated dynamic characteristics of the valve .....	71
5.4	Optimal arrangement of buckled tubes .....	77
5.5	Summary .....	82
<b>CHAPTER 6</b>	<b>CONCLUSIONS.....</b>	<b>84</b>
<b>ACKNOWLEDGEMENT</b>	.....	<b>88</b>
<b>REFERENCES</b>	.....	<b>89</b>
<b>PUBLICATIONS</b> .....		<b>95</b>

## NOTATION

- $A_i$  : Sectional area of buckled tube [ $\text{m}^2$ ]
- $b_T$  : Damping coefficient of disc with buckled tubes [ $\text{Nm}/(\text{rad}/\text{s})$ ]
- $D_Z$  : Duty ratio corresponding to the dead zone of the valve [%]
- $duty(i)$  : Input duty ratio to the RC servo motor [%]
- $e(i)$  : Deviation of the displacement from the desired position [mm]
- $e_p(i)$  : Pressure deviation from the desired pressure [Pa]
- $i$  : Motor current [A]
- $J_M$  : Servo motor inertia moment [ $\text{kg}\cdot\text{m}^2$ ]
- $k_e$  : Reverse electromotive force constant [ $\text{Vs}/\text{rad}$ ]
- $K_D$  : Differential gain for positioning control of rubber artificial muscle [ $\% \cdot \text{s}/\text{mm}$ ]
- $K_{DP}$  : Differential gain for pressure control [ $\% \cdot \text{s}/\text{kPa}$ ]
- $K_p$  : Proportional gain for positioning control of rubber artificial muscle [ $\%/\text{mm}$ ]
- $K_{pp}$  : Proportional gain for pressure control [ $\%/\text{kPa}$ ]
- $L$  : Dead time of servo motor [s]
- $L_M$  : Internal inductance of servo motor [H]
- $P_a$  : Atmosphere pressure [Pa]
- $P_o$  : Output pressure of the valve [Pa]
- $P_s$  : Supply pressure of the valve [Pa]
- $Q_a$  : Exhaust flow rate of the valve [kg/s]
- $Q_s$  : Supply flow rate of the valve [kg/s]
- $R$  : Gas constant [ $\text{J}/(\text{kg}\cdot\text{K})$ ]
- $R_M$  : Internal resistance of servo motor [ $\Omega$ ]

- $r_T$  : Distance from the central axis of the motor to the fixed point of the right/left tube [m]
- $r_{Ti}$  : Distance from the tube buckling point to the tube holding point [m]
- $T$  : Absolute temperature [K]
- $u(i)$  : Control input [%]
- $V_{cc}$  : Supply voltage to servo motor [V]
- $V_M$  : Applied voltage to servo motor [V]
- $V_o$  : Volume of the tank [m<sup>3</sup>]
- $W_T$  : Distance from the motor axis to the buckling point of left/right tube [m]
- $\theta$  : Motor rotational angle [rad]
- $\theta_{i0}$  : Initial angle of buckled tube from motor shaft [rad],
- $\theta_r$  : Target angle of motor [rad]
- $\theta_{Ti}$  : Buckling angle of buckled tube [rad]
- $\kappa$  : Air specific heat ratio [-]
- $\rho$  : Atmospheric density [kg/m<sup>3</sup>]
- $\tau_M$  : Generated torque of the motor [Nm]
- $\tau_{Mi}$  : Restoration torque at motor shaft given by restoration torque of buckled tube [Nm]
- $\tau_{MV}$  : Motor torque corresponding of  $K_M \cdot V_M/R_M$  [Nm]
- $\tau_{Ti}$  : Torque generated by the restoration force from the buckled tube [Nm]
- $\Delta_T$  : Sampling period [s]

Here, suffix "i" in certain equations will indicate "L" and "R" that mean left and right, respectively. Then, 0 indicates the initial value.