

MECHATRONICS SYSTEM ENGINEERING FOR CAE/CAD, MOTION CONTROL AND DESIGN OF VANE ACTUATORS FOR WATER ROBOT APPLICATIONS

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ABSTRACT

The paper presents research results using IT-Tools for CAE/CAD and dynamic modelling, simulation, analysis, and design of a water hydraulic vane actuator for motion control of robot manipulator arm. Matlab/Simulink and CATIA are used as IT-Tools. The development and design a novel water hydraulic rotary vane actuator for robot manipulators is presented. The contribution proposes mathematical modelling, control and simulation of a novel water hydraulic rotary vane actuator applied to power and control a three-links manipulator. The results include engineering design and test of the proposed simulation models compared with IHA Tampere University's presentation of research measurements from a similar robot manipulator arm driven by tap water hydraulic components. Experimental and simulation results are compared for evaluation and verification of developed mathematical models of the motion control of the manipulator. Furthermore, presents performance results of to follow trajectories of path motion control.

KEY WORDS

Water hydraulics, Vane Actuator, Motion Control, Robot Manipulator

NOMENCLATURE

b_c	Coulomb friction coefficient	$[\text{m}^3/(\text{s Pa})]$	Q_A	Flow rate - chamber A	$[\text{m}^3/\text{s}]$
b_s	Static friction coefficient	$[\text{m}^3/(\text{s Pa})]$	Q_B	Flow rate - chamber B	$[\text{m}^3/\text{s}]$
b_v	Viscous friction coefficient	$[\text{Nm s/rad}]$	T_{ACT}	Torque – Vane actuator	$[\text{Nm}]$
K	Turbulent flow coefficient	$[\text{m}^3/(\text{s Pa}^{1/2})]$	θ_i	Angle position $i=1,2,3 \dots$	$[\text{rad}]$
ΔP	Pressure load	$[\text{Pa}]$	ω_i	Angle velocity	$[\text{rad/s}]$
P_A	Pressure in chamber A	$[\text{Pa}]$	ε	Parameter	$[\text{rad/s}]$
P_B	Pressure in chamber B	$[\text{Pa}]$	x_v	Servo valve spool position	$[\text{m}]$
P_s	Supply Pressure	$[\text{Pa}]$	T	Torque disturbance	$[\text{Nm}]$
P_{tr}	Transition pressure	$[\text{Pa}]$	D	Inertia - acceleration matrix	$[\text{N m s}^2/\text{rad}]$
Q	Valve orifice flow rate	$[\text{m}^3/\text{s}]$	h	Coriolis - centrifugal vector	$[\text{N m s/rad}]$
			c	Gravity vector	$[\text{N m /rad}]$
			b	Viscous friction vector	$[\text{N m s/rad}]$

INTRODUCTION

Three rotary vane actuators drive the robot manipulator studied in this paper. Water as pressure medium is chosen to drive the actuator. Water is a non-contaminant, fireproof, radiation proof and readily available. Many industrial applications as food processing, steel, mining, pharmaceutical and nuclear industry, require particular cautions that water hydraulics can provide [1]. On the other hand, water has low viscosity relative to mineral oil, and can in general only be recommended applied for supply pressure up to 160 bars. The limited motion range of hydraulic cylinders, confine their use in manipulators with few degrees of freedom. A water hydraulic rotary vane actuator may satisfy most of the requirements necessary to drive a dexterous manipulator and a specific water version could partially solve the problem of high leakage flow. The developed slave robot arm results in a multiply-purpose device suitable for an environmental friendly approach to the industrial processing.

DESCRIPTION OF THE MANIPULATOR

The novel developed robot manipulator with three joints, each driven by a water hydraulic rotary vane actuator, has three links and is able to sustain a maximum load of 85 Kg with 1.9 m of extension, shown in Figure 1, Figure 2, Figure 3 and Figure 4. For a dexterous use, a load of 50 Kg has not to be exceeded. The slave arm weighs around 90 Kg and the actuators generate 2156 Nm, 1056 Nm and 448 Nm, respectively. The robot arms have servovalves to flow rate control. This solution allows the use of rigid connection between the valves and the actuator.

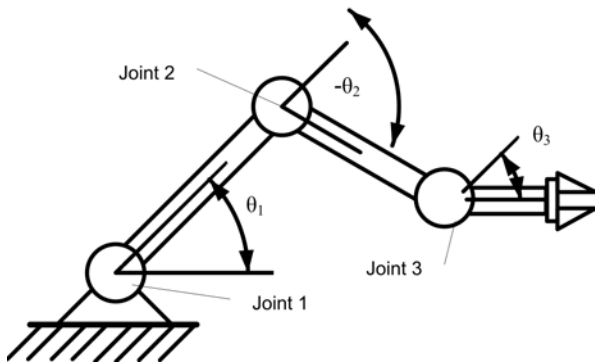


Figure 1 Schematic of the 3 DOF robot manipulator

Approach to the water hydraulic vane actuator

To simplify the model of the water hydraulic vane actuator the pump supply pressure is assumed to be constant at 140 bar to a four-way servovalve to control the flow rate to the vane actuator. A closed loop control system with position feedback is chosen to control the vane actuator movement. Since water hydraulics

components need small clearances, they are more expensive compared to the oil hydraulics mechanism. The servovalve is a Ultra Premier Range 4658 Series with the 9.6 l/min rated flow and a natural frequency of 22 Hz at 70 bar. The small natural frequency of the valve combined with position feedback control system to drive the arm's accuracy.

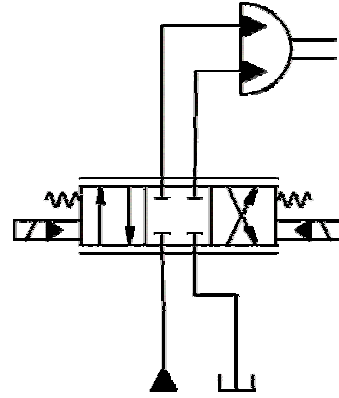


Figure 2 A water hydraulic vane actuator

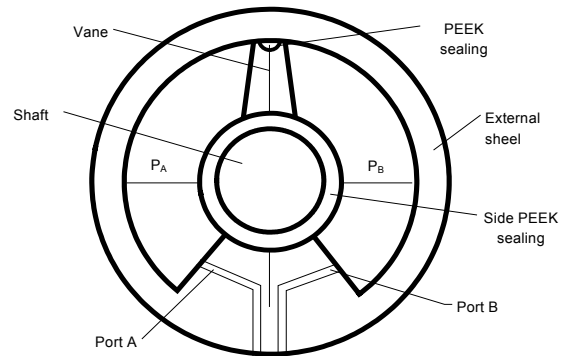


Figure 3 Schematic of the water hydraulic vane actuator

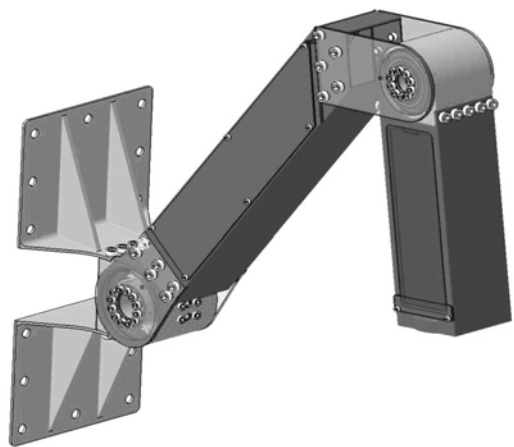


Figure 4 CATIA model of the arm 1 and arm 2 of the 3 DOF robot manipulator

SIMULATION MODEL

To simulate the performance of the slave robot arm a non-linear model was developed by modelling the different components of the water hydraulic rotary actuator system and robot manipulator arm.

The servovalve dynamics, from the input signal to the spool displacement is approximated with a second order transfer function figured out from the servovalve's flow gain and Bode plots from the datasheet.

The flow through the orifices is calculated switching from the laminar to the turbulent equation when the pressure difference became higher than the transition pressure P_{tr} . A second order interpolation, was developed by using the Lagrange method to keep the continuity of the first derivate in the transition point

$$Q = \frac{K(\Delta P - 3P_{tr})}{2P_{tr}^{3/2}} \quad (1)$$

The effects of friction could be modelled as a generalized force applied on the joint of the arm. Friction is a complex non-linear force that is difficult to model accurately, yet in many cases it can have a significant effect on the robot dynamics. A model that includes the viscous, the static and the Coulomb friction from components as proposed by [3]. Comparison between the complete and simplified viscous friction model is shown in Figure 5, and modelled by the following equation (2)

$$b = b_v \cdot \dot{\theta} + \text{sign}(\dot{\theta}) \cdot \left[b_c + (b_s - b_c) \cdot e^{-\frac{|\dot{\theta}|}{\varepsilon}} \right] \quad (2)$$

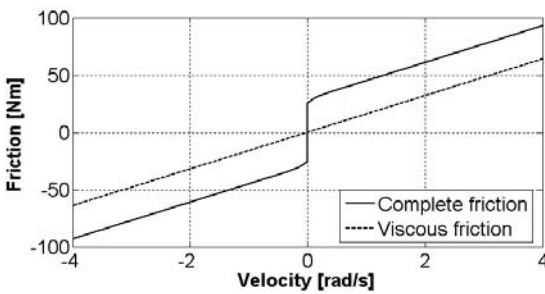


Figure 5 Comparison between the complete and simplified viscous friction model

In the following simulations, the friction model was reduced to only viscous term due to assuming a good engineering design to avoid Coulomb friction and sticktion. To test the water hydraulic rotary vane actuator a non-linear model developed was used to evaluate the performance. Test simulation results were

obtained by using the developed non-linear model shown as an overview diagram of the Simulink model in Figure 6.

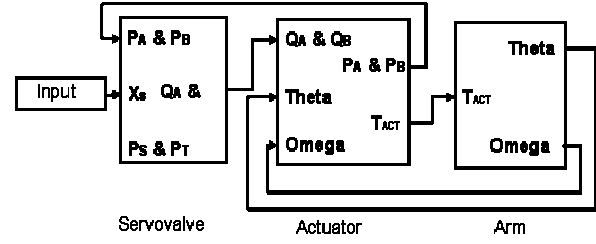


Figure 6 The non-linear model for test simulation

The general motion equations of the manipulator can conveniently be expressed through the direct application of the Lagrange-Euler formulation to non-conservative system. The approach for modelling of the considered test robot manipulator applying the robot model notation by Schilling, 1990, [3]

$$T = D(\theta)\ddot{\theta} + h(\theta, \dot{\theta}) + c(\theta) + b(\dot{\theta}) \quad (10)$$

Model Evaluation and Verification

To validate the developed models of the proposed water hydraulic vane actuator we did compare with experimental results by Rameda, IHA, Tampere University of Technology 2004, [4] of a similar vane actuator designed to work with oil and tested with tap water as fluid. The non-linear models are evaluated and verified against open-loop response of the valve-controlled rotary vane actuator.

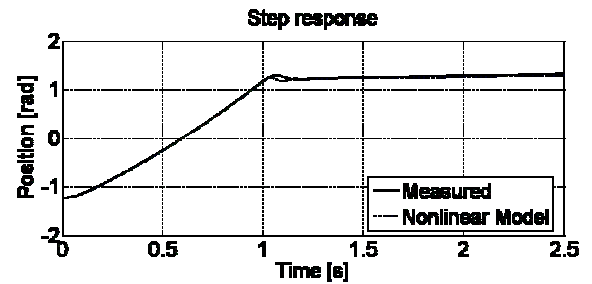


Figure 7 Open loop position response, simulated and experimental results.

The actuator is in vertical position (no gravity load in the zero position) with an inertial load of 31.2 Kg m^2 and weights attached at the end of the boom. The input signal to the servovalve was a step input (the valve was kept open for 1 second) to show the step response in Figure 7. The conclusion was that non-linear model could be used in this analysis because the simulation fit very well to the measured response. Furthermore, validation of the model and verification of the model was needed.

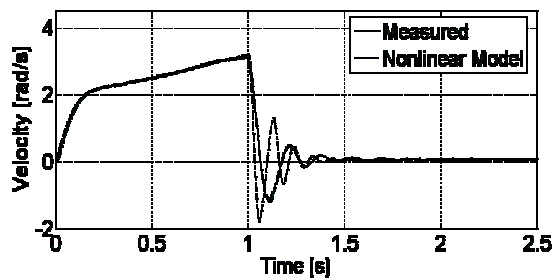


Figure 8 Open loop velocity response, simulated and experimental results

As shown in Figure 7 and Figure 8, during the valve opening, the non-linear model provides, with good accuracy, both the position and the velocity of the measured performance. However, there are errors of damping during the valve closing, probably due to the simplified friction model. In fact the friction force is the first cause of the damping and the operated model is mostly underrate at low velocity.

These errors are probably due to the simplified friction model, in fact, the friction force is the first cause of the damping and in our model is mostly underrate at low velocity. Since we did check the system stability by applying this model because it has a lower value of the damping rate compared to the measured velocity response (Figure 8) for the implemented robot manipulator arm by IHA, Tampere University of Technology [2].

THE NOVEL VANE ACTUATOR

A Mechatronic System Engineering approach was applied to develop and design the three links water hydraulic robot driven by rotary water hydraulic actuators.

The Figure 9 as illustrated the proposed IT-Tool controller design concept that integrates the development and design phases into a single design platform. It uses the Matlab Real-Time Workshop to generate C-code automatically from a Simulink block diagram, and then compile it, and download it to the real-time hardware. It can perform all steps of the control design process in one development environment. In a dSPACE system, input/output (I/O) can easily be specified and connected within the Simulink environment.

A view of the 3D CAD model of the proposed novel water hydraulic vane actuator is shown in Figure 10. The main materials used are stainless steel and PEEK. The fundamental components of the actuator are: the housing, the vane and the shaft. The rotor vane is fixed on the shaft and slides on the internal face of the

housing. To perform the sealing system the vane is composed of two pieces coupled together by bolts. This solution allows inserting different layer of sealing material for the two parts of the vane. The housing is made of three parts; a cylinder for the rotary vane, and two-side cover entrusted to close the pressure chambers and sustain the shaft. To secure the sealing between the vane and the side cover, two rings are applied with a rounded shape, to avoid corners in the contact surface.

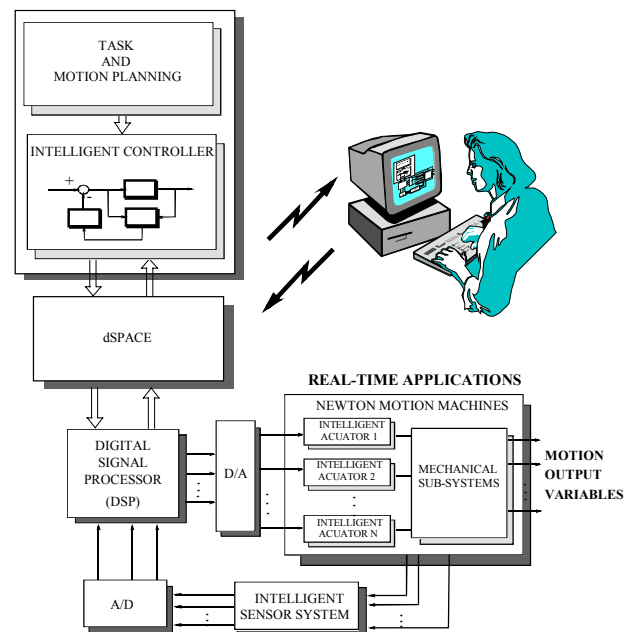


Figure 9 IT-Tools controller design concept

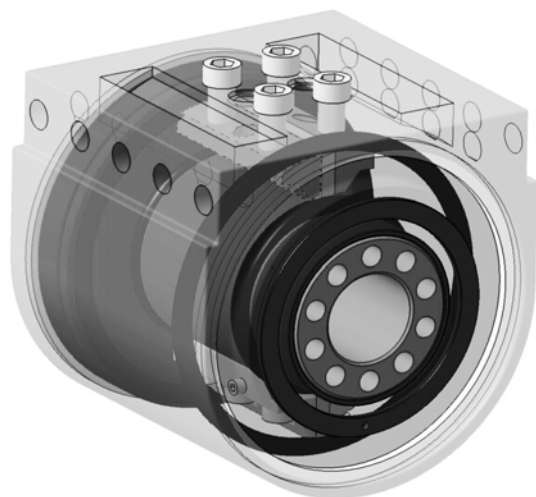


Figure 10 Shows a 3D CAD model of the novel water hydraulic vane actuator

The rings are fixed on the grooves machined in the shaft and in the housing. To sustain the shaft thrust bearings are used and fixed by pins and sleeve bearings forced on the lateral covers. Holes are machined in the housing, to perform the coupling of the arm and the stator vane. The side covers are ensured on the housing by spiral retaining ring, which thwart the pressure. Two flats coupled to the shaft close the actuator and the connection to the second robot arm.

The shaft is axial fixed by the contact between the flanges and the thrust bearing on the side covers. A second sealing system may be operating to isolate the external behaviour and assure that the entire leakage flows through the drain line.

TEST OF THE ROBOT MANIPULATOR ARM

To simulate the behaviour of the tool point centre (TPC) of the slave manipulator arm in a typical motion control application, the slave arm was tested by defining the following complete test path trajectory build up by geometric elements as part of circles, strait lines, corner and ramp as reference input to the robot controller.

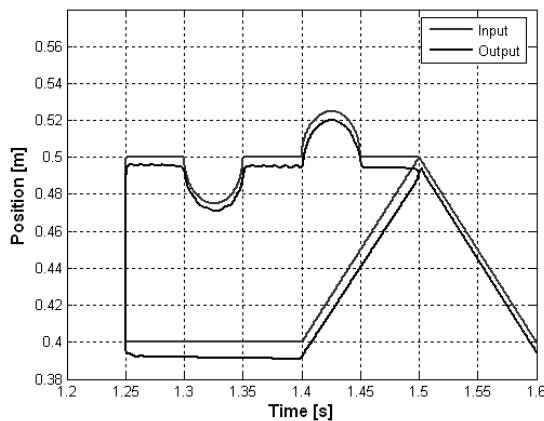


Figure 11 Tool point centre trajectory following a complete reference input path shape

Simulation result for motion control of the robot manipulator arm's TPC trajectory following a complete path trajectory is shown in Figure 12.

Position error following a complete shape is shown in Figure 12. The obtained results shows that even with a simple control system for the proposed novel water hydraulic vane rotary actuator with servovalve, the manipulator perform acceptable accuracy for many applications as long as the required maximum velocity fit to the load and robot manipulator arm design, and is limited.

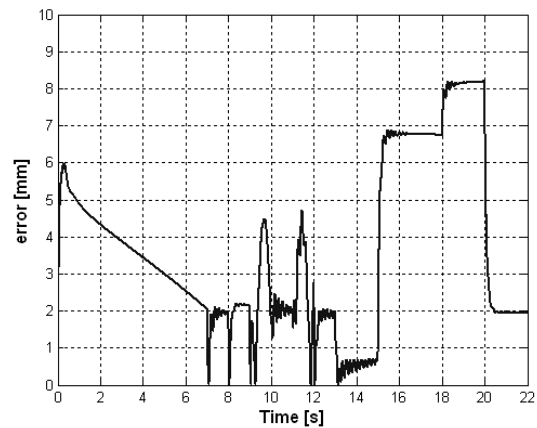


Figure 12 Position error following a complete shape

CONCLUSION AND OUTLOOK

The contributions presents research results using IT-Tools for CAD and dynamic modelling, simulation, analysis and design of water hydraulic actuators for motion control of machines, lifts, cranes and robots. Matlab/Simulink and CATIA were used as IT-Tools for the development and design a novel water hydraulic rotary vane actuator for robot manipulators. Furthermore, presents proposed mathematical modelling, control and simulation of water hydraulic rotary vane actuator applied to power and control a three links manipulator and evaluate the performance. The obtained results shows that even with a simple control system as a position feedback and an internal velocity feedback, the robot manipulator performance a good accuracy following trajectory at slow speed. In general, the simulated response with the linear model agrees well with the non linear model and with the presented measured response, and therefore the linear model can be used to simplify the controller design.

The applied mass located at the TPC of the robot arm decrease the hydraulic frequency benefits the system stability. On the other hand, the position error is approximately proportional to the external load. The control gains cannot be optimized for all the load range and therefore a compromise have to be made. All the control parameters have to be optimized.

The non-linear model can be used for prototype design instead the experimental design, at least for primary set up and provide good possibility to improve the control system. The water hydraulic rotary vane actuators have been developed to be driven by an robot controller, and has been designed to be improved for a 6 DOF water hydraulic robot manipulator arm research and application.

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