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FEASIBILITY STYDY OF CHAIN DRIVE IN WATER HYDRAULIC ROTARY JOINT

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ABSTRACT

In hydraulic manipulator applications effective joints movement range of above 180° is often needed. Vane actuator has maximum movement range about 270°. However, water hydraulic vane actuators are quite expensive to manufacture. Thus we investigate a possibility to use so called chain drive instead of vane actuator. Chain drive consists of two cylinders which are connected in series with a chain. Reduced model for chain-drive equals to symmetric cylinder and can be compared with a vane actuator of same size. Concerns with chain drive are the smoothness of sprocket turning around, stiffness of the chain and minimum required back-pressure level for keeping chain tension. In this paper a chain drive is designed, built and tested. We also compare chain drive's and vane actuator's properties mathematically from control point of view. We can conclude that chain drive's characteristics almost equal with vane actuator and it is much more cost effective.

KEY WORDS

Chain drive, vane actuator, dynamic properties

NOMENCLATURE

K_H :hydraulic stiffness
B :bulk modulus
A_2 :cylinder's piston rod side area
V_0 :pressurized volume
R :sprocket's radius
ω_N :natural frequency
d_N :damping factor
J :load's inertia
D :radian volume of vane actuator

INTRODUCTION

Hydraulic manipulator applications often require effective rotary joint movement range over 180 degrees. Most often, however, rotary manipulator joints are driven by cylinder which limits the maximum movement range to about 120 degrees. With the aid of four-bar transmission linear cylinder driven rotary joint can extended from 120 degrees close to 180 degrees. Four-bar transmission is a widely used in elbow joints of heavy-duty hydraulic manipulators. However, as four-bar transmission consists of at least two additional rotary joints and links, the kinematic calibration and tolerance issues in robotic applications requiring high accuracy can easily become a problem.

An alternative for linear actuator driven joints is vane actuator which has maximum movement range is about 270 degrees. In heavy-duty oil hydraulic manipulators, however, vane actuators are seldom used. This is mainly because in these applications a low leakage and low price actuators are required. Low leakage requirement usually makes vane actuator seal friction level relatively high and thus limits the usability of the actuator. Still another drawback of vane actuators is that leakage across vane seal makes e.g. lock-valves ineffective in hydraulic load holding functions. Hydraulic cylinder actuator can be considered zero leakage actuators and thus load holding functions for them have proven to be effective.

However, in smaller scale purpose build hydraulic manipulator applications with a workspace less than 1-2 meters, vane actuators have proven to be effective solution due to robust design, compact size and large joint range. On the other hand, in water hydraulic applications vane actuator has some weaknesses. This is because water's viscosity is about ten times smaller than oil's which led to tight tolerances in manufacturing. This makes manufacturing of water hydraulic vane actuators quite expensive. Also as mentioned above leakage across vane seal makes e.g. lock-valves ineffective in hydraulic load holding functions. On the other hand, as well known, leakage cross actuator seal improves the dampening of the actuator, but it decreases position accuracy.

Because of above mentioned weaknesses vane actuators have, we investigate in this study a possibility to use cost-effective chain drive for rotary joint actuation. Chain drive consists of two hydraulic cylinders which are connected in series with a chain. Reduced model for chain-drive equals to symmetric cylinder and thus can be easily compared with a vane actuator of same size.

HYDRAULIC ROTARY CHAIN DRIVE

The schematic of chain drive actuator is shown in Figure 1. Chain drive consists of two hydraulic cylinders which are connected in series with a chain and rotate a sprocket. Cylinder rodless sides are connected to tank and a servovalve is connected to rodsides of the cylinders. Reduced model of the chain actuator therefore equals to symmetric cylinder, making open-loop gain of the system equal to both directions. As well known, for example with zero load and critically lapped symmetric four way servovalve, the steady state pressures of symmetric cylinder chambers are equal to Ps/2 (supply pressure divided by two). Therefore, adequate chain tension can in some cases always be guaranteed if the application specifications are well known. This could be a case for example in some relatively low speed application. If the application specifications are not known exactly or the application requires for example high accelerations, minimum chain tension has to be provided for example with external pressure reducing valves, as shown in Figure1. Downsides of the back pressure provided by pressure reducing valves is that they limit available torque output range of the actuator and make actuator design less compact. In addition to adequate back pressure function, chain design is of high importance. If the chosen chain stiffness is less or about the same magnitude as the stiffness of hydraulic cylinder, the result is complex 5 th order system that makes controller system design tedious task. Therefore, usual rule of thumb design requires that chain stiffness has to at least a decade higher than corresponding hydraulic stiffness.

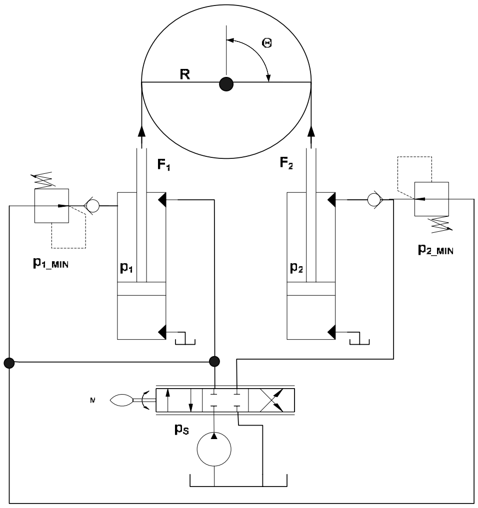

Figure 1 Schematic of chain drive

Prototype chain drive actuator design was based on following design parameters, which allow comparison with the vane actuator of approximately the same torque output.

- Maximum torque output of 525 Nm when maximum available supply pressure of 210 bar and back-pressure is 52 bar
- Maximum velocity of 180 deg/s with QN=6.8 l/min
- Maximum joint motion range of 275 deg.

Based on above specification, the following design was made.

- Two water hydraulic cylinder 32/25 - 550
- Triple chain wheel's with 42 teeth
- Distances between teeth are 15.875mm
- Sprocket radius of 106 mm.

With above design parameters following specification for chain drive actuator were achieved.

- Maximum torque 525Nm
- Maximum velocity of 195 deg/s
- Maximum joint motion range of 298 deg.

ACTUATORS PROPERTIES

The dynamic performance of the any hydraulic actuator is limited by its hydraulic natural frequency that is a function of load mass and actuator hydraulic stiffness. Since the load of the both actuators is the same, the stiffness of the actuator will define the natural frequency of the actuators. Equation for hydraulic torsional stiffness of the vane actuator at its minimum value is [1]:

$$K_{H\_VANE\_1} = \frac{2BD^2}{V_0} \tag{1}$$

For cylinder driven chain actuator, the minimum hydraulic torsional stiffness is obtained:

$$K_{H\_CHAIN}\_1 = \frac{2BA_2^2R^2}{V_0} \tag{2}$$

Vane actuator's and chain drive's natural frequency:

$$\omega_N = \sqrt{\frac{K_H}{J}} \tag{3}$$

A prototype vane actuator was build with following spefication.

Following design was made:

- Ø 57mm axis
- Ø 83mm chamber
- 55 mm width

Following properties were achieved.

- Maximum torque is 525Nm
- $D = 2.503 \times 10^{-5} \frac{m^3}{rad}$.
- Maximum velocity $v = 43 \frac{\deg}{s}$

For vane actuators it is convenient to integrate servovalve directly to vane actuator housing. Water flow paths are inside the chamber with diameter of 4mm and maximum length of 100mm. When vane actuator is at its middle position, its total pressurized volume is $V_0 = 8.0 \times 10^{-5} m^3$. For testbed load mass was 30kg at end of one meter long rod making its inertia about $J = 30 kg \times m^2$. Water bulk modulus is about 1500MPa. These values result minimum natural frequency of $\omega_N = 4.5 Hz$ for vane actuator.

Chain drive characteristics are given above. Servovalve is connected to cylinders with Ø4mm – 200mm pipe making total pressurized volume equal to $V_0 = 8.113 \times 10^{-5} m^3$. These values result minimum natural frequency of $\omega_N = 4.9 Hz$ for chain drive.

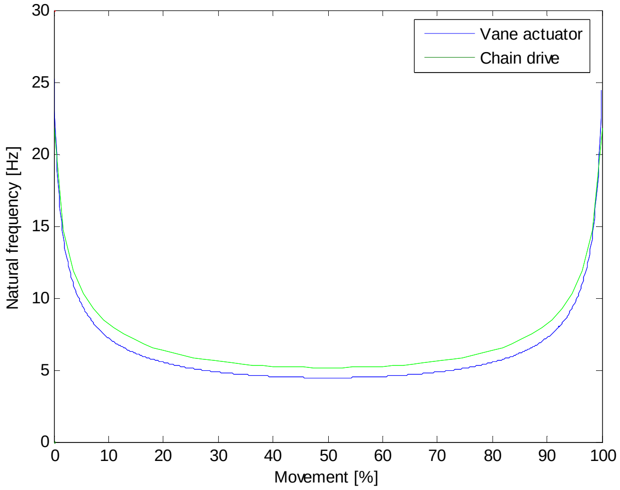

Figure 2 Natural frequencies of two actuators

Natural frequencies of two actuators as a function of actuator movement are plotted in Figure 2. From Figure 2 it can be seen that natural frequencies of the both actuators are about the same. The dampening of the hydraulic actuator is usually in the range of 0.05 - 0.2 and its value is hard to predict by theoretical analysis like given for example in [1]. However, the effective dampening ratio of the chain drive is expected to be lower than it is with vane actuator due to the relatively high cross seal leakage of the vane actuator [2]. Of course the dampening of the chain drive can be increased with leakage orifice across valve ports. However, leakage orifice will then destroy load holding functions that are required in robotic applications.

According to leakage measurements made with previous vane actuator prototype with nominal torque output of 1000Nm, the measured leakage factor across vane was $C_{LEAK} = 1.7 \times 10^{-7} \frac{m^3}{s} MPa$ in 35°C temperature and 210bar pressure difference. If we assume that leakage coefficient is directly proportional to achieved torque, then it will reduce 50% from above value. However, for chain drive there is hardly any leakage. Once available, measurements with lock valves will be performed to verify the load holding functionality of both actuators.

Open loop gain rules the static accuracy of the actuators. Maximum gain for hydraulic drive:

$$K_{\max} = 2 d_n \omega_n \quad (4)$$

According to Fig 2. natural frequency is little bit higher for chain drive. Damping factors are difficult to estimate, but they are about 0.2 for both actuators. Then maximum gain for vane actuator is $K_{\max} = 11.3$ and chain drive $K_{\max} = 12.3$. In theory both actuators static accuracies are almost same.

MEASURED RESULTS

Measurements were carried out with a chain drive testbed shown in figure 3. The testbed specifications were given above. Required nominal torque output of 525 Nm can be obtained with back pressure value of 5.2 MPa and therefore it was used in the experiments. It seems to be enough for this kind solution.

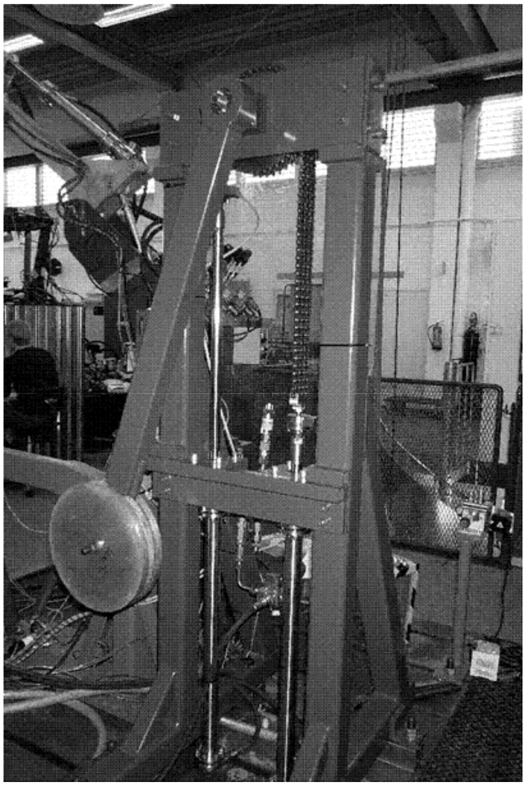

Figure 3 Chain drive testbed

Open loop natural frequency of vane actuator was measured by “hammer test” when load arm was in horizontal position. From Figure 4, it can be seen that approximate natural frequency is about 5Hz making above natural frequency theory presented valid.

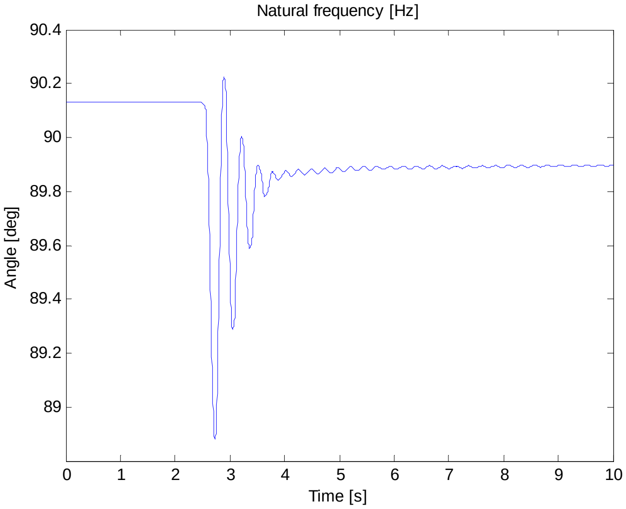

Figure 4 Natural frequency of chain drive actuator

Sprocket turning smoothness measurement test was done. Cylinder position was measured with linear encoder. Sprocket position was measured pulse encoder with 5000 pulse per round and it was interpolated to 25 – fold. As we can see there are some speed variations. Cylinder positions 24mm and 38.5mm and something over 50mm there are higher peaks. This is approximately same as teeth gap. Anyway greatest peak is about 0.6% above mean value.

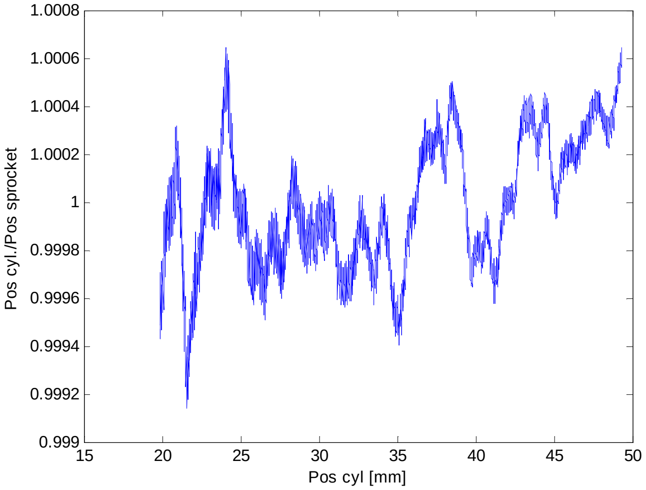

Figure 5 Sprocket turning smoothness

Simple proportional position controller was also tuned and measured in order to verify chain drive actuator dynamic performance under control. Step signal was used as reference. Controller gain was half of the maximum value given by stability criteria.

First measurements were done so that arm was driven to downwards. In next figures 6 and 7 position responses of the chain drive are shown. Static accuracy is 0.025 degrees in first response and -0.05 degrees in second response. So accuracies are relatively good to both directions

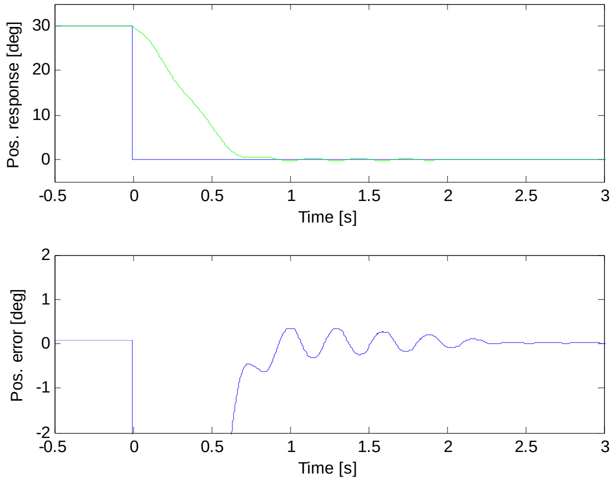

Figure 6 Step response and tracking error from 30 to 0 degrees

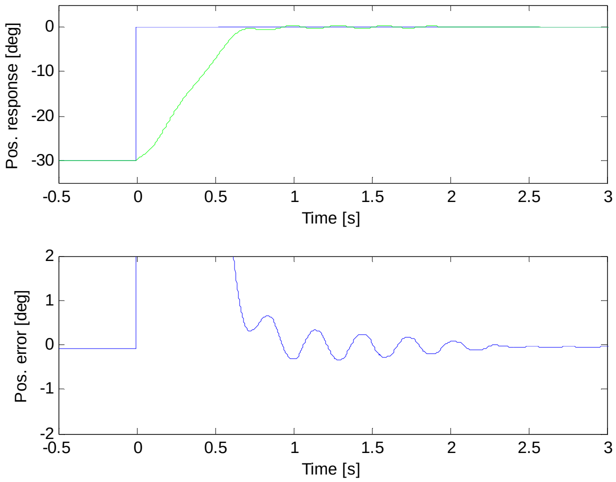

Figure 7 Step response and tracking error from -30 to 0 degrees

In figures 8 9 are shown next measurements. They were done so that arm was driven to horizontal position. Static accuracies are not as good as in previous measurement due to load force caused by gravity. In first response it is 0.25 degrees and second response it is 0.32 degrees. Valve inner leakage can affect worse accuracies. It can be noticed that gravity force causes some oscillation when arm is driven from 120 deg to 90 deg. When arm is driven to other direction oscillation is much less.

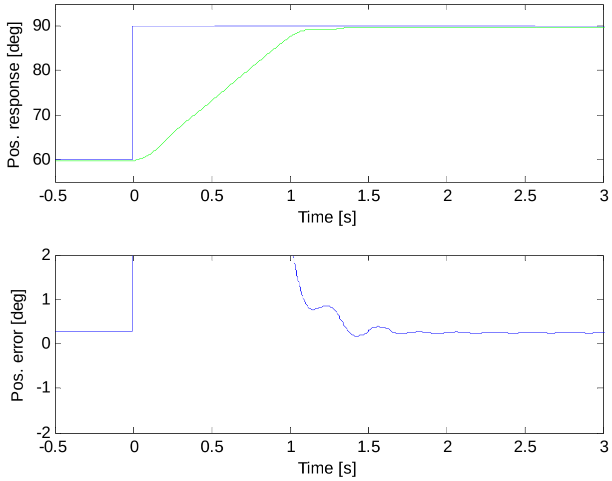

Figure 8 Step response and tracking error from 60 to 90 degrees

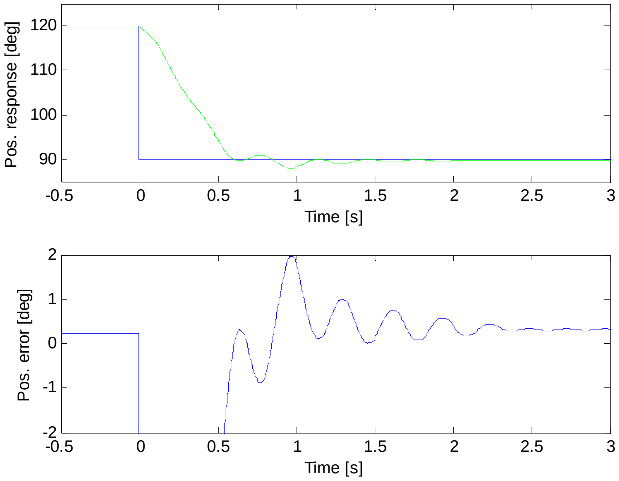

Figure 9 Step response and tracking error from 120 to 90 degrees

Based on measured results it can be assumed that designed chain stiffness seems to be adequate because it is invisible in position control measurements.

CONCLUSIONS

In this study new water hydraulic chain drive actuator was designed and tested. Chain actuator design was compared with vane actuator design of very similar design characteristics. Chain drive is a relatively inexpensive to build and zero-leakage actuator with satisfactory motion range of above 270 degrees. Zero-leakage characteristics are very important for load holding functionality point of view. The down side of the chain drive design is that its size is much bigger than vane actuator with similar maximum torque output and motion range. However, in many cases relatively big size of the actuator is not a problem. For example, sometimes chain drive actuator can be fitted e.g. into manipulator arm link. However, water hydraulic chain drive actuator is proved to very useful new actuator type when rotary motion range above 200 degrees is required at low cost and with zero-leakage characteristics.

This study was our first one concerning water hydraulic chain drive. Our future plan is to test different sprocket and cylinder radius combinations so that natural frequency is always same. Also some different hydraulic connections will be tested.

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