New rotary-actuated proportional valves for humanoid robot

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Abstract

Despite the popularity of electric drives, hydraulic power transmission is used very frequently because it has many advantages. Among the most important are the high-power density and the simple and effective overload protection. Imitating nature and humans often leads to new ideas and better machines, which is why we decided to build a human-like hydraulic leg. We were unable to find suitable, sufficiently small and efficient hydraulic valves on the market for controlling humanoid legs. To control the hydraulic legs of the humanoid robot, we decided to design a hydraulic proportional valve with the smallest possible mass and size. Despite its compactness, it must allow large flows for fast robot movements, and at the same time we want to ensure low internal leakage. Based on the principle of the rotary valve, we designed and dimensioned the proportional valve and optimised it for installation and production. To improve sealing and simplify production, we introduced the use of seals on the spool. We carried out numerical simulations of the basic properties and compared them with measurements on the manufactured prototype. Several specimens of the newly developed valve made of aluminium and brass were produced. At the same time, we tested the use of oxide layers on the aluminium surface, which can be used to increase the surface hardness. The newly developed valve represents a new approach in the control of hydraulic components and is suitable both for controlling humanoid robots and for controlling other devices in industrial and mobile hydraulics.

Keywords: hydraulics, humanoid robots, rotary proportional valves, valve seals, servo motor control

1 Introduction

Hydraulics is an indispensable part of drive technology in many areas. Hydraulic components are categorized into four groups according to their function: primary, secondary or execution, auxiliary and control components. Primary hydraulic components are pumps that convert drive energy into hydraulic energy. Executive components convert the energy of the fluid back into mechanical work in various forms. This group includes hydraulic cylinders and hydraulic motors. Auxiliary hydraulic components include filters, coolers and heaters, tanks, pipes, hydraulic accumulators, sensors, etc. The control components include hydraulic valves for controlling the direction, speed and power of the executing units. Valves are categorized into different groups depending on their function. We recognize flow, check, pressure and directional control valves. They are used to control the execution components, which in our case are hydraulic cylinders for the movement of a humanoid robot [1]. In the case of humanoid robots, other forms of actuation of execution components can also be used to move individual parts of the robot. These include electrical energy for driving electrical actuators and compressed air energy in combination with pneumatic cylinders, which are developing rapidly in medicine for patient rehabilitation [2]. In this work, we have opted for a hydraulic actuator because it has advantages over an electric actuator. The most important are the higher power density, the protection against overload and the good adaptation to dynamic loads. Hydraulic drives are currently also used by humanoid robots from one of the best-known American robot developers [3]. However, when controlling larger flows, there is a risk of high flow forces in classic sliding and longitudinal slide valves, which are predetermined by the use of two-stage control. This is problematic for humanoid robots, as such valves are larger and heavier, which means that their installation has an impact on the overall size and mass of the robot.

Due to the desire to reduce the size and mass of valves, in this work we wanted to investigate and find a solution in the field of sliding proportional rotary valves, which have a lower influence of the flow forces on the spool and consequently do not require a large control force for the direct control of large flows [4].

2 Theoretical background

Continuously operating directional control valves are hydraulic components for controlling the direction and flow of hydraulic fluid in and out of actuators. They enable the direction and speed of movement of the actuator's drive part, e.g. the piston rod of a cylinder, to be changed. They work according to the principle of generating a pressure difference that arises when the flow gap is reduced. Depending on their geometric shape and mode of operation, directional control valves can be categorized as longitudinally moving and rotary valves. Longitudinal valves are widely used in all areas of hydraulics, while rotary valves are only used for special purposes in hydraulics [6].

2.1 Longitudinally movable slide directional control valves

In general, each hydraulic valve controls at least one fluid line, but in most cases valves are used to control several different lines simultaneously. This need has led to the development of many different designs of proportional, longitudinally movable spool valves, which differ considerably in the number of ports, the number of spool positions and the connections between the individual ports in the individual positions. They also differ in the type of control, as they can be controlled manually or with a proportional solenoid.

The main difference between classic conventional and proportional valves is the desire to control the flow. Conventional valves do not allow this possibility, as their purpose is only to allow full flow or to interrupt it completely. These valves cannot assume intermediate positions. This also leads to a tendency to minimize the pressure difference that occurs when flowing through the valve, as this represents a loss of energy.

With proportional valves, on the other hand, it is precisely the pressure difference created by partially closing the valve that makes it possible to control the flow through the valve. Therefore, the nominal flow rate of proportional valves is specified with a pressure difference of 7 MPa [7] over the entire valve when the valve is fully open, which in most cases can be simplified to the flow rate via a single active port at a pressure difference of 3,5 MPa due to the symmetry of the valve design.

Proportional, longitudinally displaceable directional control valves (Figure 1) have a displaceable spool with notches inside the housing that moves along its axis and connects various combinations of channels in the housing with the notches [8]. Different principles are used to move the spool in the housing. The most commonly used control method is with a solenoid (direct) or indirectly with oil pressure from the control line, but we also know manual control via a control lever and a combination of electromagnetic and indirect (hydraulic) control, which is mostly used for valves with oil flow rates above 70 l/min.

With proportional valves, the oil flow is usually controlled via the edge of the notch on the spool. These can have different shapes, which makes it possible to utilize different valve characteristics simply by changing spool with different notches.

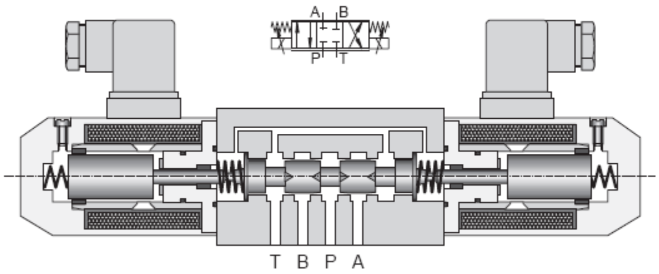

Figure 1: Proportional valve with direct electromagnetic control in cross-section and its symbol [8]

With proportional valves, the oil flow is usually controlled via the edge of the notch on the spool. These can have different shapes, which makes it possible to utilize different valve characteristics simply by changing spool with different notches. By selecting the appropriate shape of the notches and their number, we can ensure very precise changes in the oil flow. To determine the effects of different notches, CFD analyses are now used to simulate the fluid flow through different valve openings, which is detailed in modern research papers comparing different groove shapes [9]. In addition to more precise flow control, the geometric shape of the grooves and their distribution on the spool can also reduce the flow forces of the fluid on them. A reduction in the influence of the flow forces can also be achieved by additional geometric optimization of the entire spool [10].

Reducing the flow forces on the spool has an effect on the control force required to move the spool and also on the stiffness of the return springs that stabilize the valve in the neutral position.

Due to the sharp control edges over which they control the fluid, seals cannot be used with longitudinally moving spools that would ensure a good seal in the case of a closed valve in a spool with blocked ports. In these cases, sealing is only guaranteed by the precision of the spool and the bore in the housing, as the leakage of the valve depends on the radial gap. Leakage also increases with wear during the service life of the valve, so that valve leakage is also one of the indicators of wear [11].

2.2 Rotary slide directional control valves

In rotary valves, a rotational movement is used for control instead of a translational movement. The shape and design of the spool are therefore slightly different. Typical rotary valves have grooves located on different sides of the spool along the circumference, connecting individual ports together at a given rotation. In this case, certain grooves are connected to each other by a bore in the spool so that a cross position can be realized. An example of how a rotary spool works is shown in Figure 2.

Rotary valves are primarily used for special purposes, which is why they are specially developed for individual applications. One such valve is used, for example, to control the movements of a humanoid robot, for which a patent with the designation US4966192A [12] has been granted.

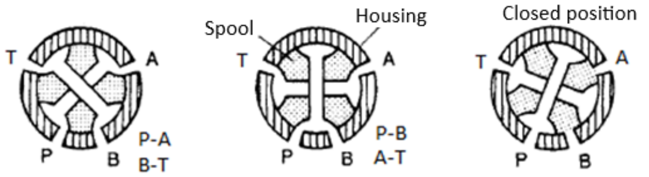

Figure 2: Functionality of a rotary valve [6]

This valve has a large number of control openings on the housing and on the spool, which supply different amounts of fluid to the individual working lines at different rotations of the piston. Among the patents we find a number of different designs of rotary valves that take into account certain advantages of the rotary design. A study was also carried out with a CFD analysis of a 2/2 rotary valve in cartridge design [4]. The aim of this study was to analyze the influence of the flow forces on the control torque and the pressure differences of the valve at flow rates of up to 1000 l/min. By implementing the cartridge design of the valve, they were also able to realize the two control edges in the form of a droplet. With this design, they achieved optimised flow characteristics depending on the angle of rotation of the control spool. They found that the torque of the fluid flow changes with the pressure difference across the valve and the angle of rotation of the control spool. However, under the selected conditions (1 MPa pressure difference when the angle of rotation is changed to full opening, with a flow rate of 1000 l/min), it does not exceed 2 Nm.

Based on the established facts, we decided to develop a new rotary valve to control the leg movements of a humanoid robot.

3 Design of rotary sliding valve

The basic idea of the new valve is based on the angular dependence of the spool position in the housing. A hole is drilled through both components, which runs radially through the center of the spool (Figure 3).

Figure 3: 11 mm diameter spool, with 4 mm diameter holes, 48 mm length and grooves for X-sealing rings

When fully open, such a valve design provides only one channel through the body and the spool without changing the flow cross-section of the channel, which minimizes losses in fluid flow. The inlet opening is located on one side of the housing and the outlet opening on the other. The valve is actuated by the rotation of the piston, which changes the instantaneous flow cross-section of the opening at the junction of the piston and housing. In this case, the rotation of the piston from the fully open position creates a constriction at the circumference of the spool, which generates a greater pressure drop through the valve, as in the case of a diaphragm or a valve with a longitudinally movable piston. In this way, the effects of the flow forces are avoided, which occur in the classic longitudinally moving valves, especially on the flat annular surfaces, where they cause uncontrolled movement of the control spool, which can be compensated for by the control system together with solenoid.

In the case of the newly designed valve, we avoid flat surfaces, from which we conclude that the required control performance of the entire valve is somewhat lower, even at higher flow rates. To control the legs of the humanoid robot, we opted for a 4/3-way valve with blocked outlets in the neutral position. Based on this decision, the basic concept was developed into a rough model of a 4/3-way valve that requires four connections for operation, namely the fluid supply P, the working connections A and B and the return connection T. For the desired valve, we need to ensure a simultaneously open connection between the oil supply P and the working line A and simultaneously between the working line B and the return T. The pressure supply and return lines must be open at the same time. As the pressure supply and return cannot be interchanged without an additional valve, the number of channels is increased to four so that each working line has one channel leading from the pressure supply and the other to the return. Each of the openings opens crosswise, so that a simultaneous connection of the P-A and B-T lines is achieved in the parallel position or in the crosswise P-B and A-T line connection, which corresponds to the classic 4/3 directional control valves.

When developing the rough model, we also followed the recommendations for the design of hydraulic components. One of these is that the fluid supply is directed to the central part of the valve so that it is surrounded on both sides by areas with lower pressure ratios. We have also considered the use of symmetry in the loading of the components and modelled the rough model of the valve based on these recommendations. The choice of the diameter of the spool valve is also related to the size of the bore through the spool, taking into account the overlap at the same time. In order to achieve the blocked spool in the neutral stable position, we must ensure complete closure or interruption of all connections between the individual ports. This means that there must be at least one additional hole of solid material on the circumference of the spool between the individual holes, which closes the inlets of all holes in the housing in the neutral position.

From these findings and correlations, a mathematical relationship can be defined between the spool diameter, the diameter of the individual bore on the spool, and the size of the overlap. In this case, we also assume that the holes are offset by 90 degrees along the circumference, resulting in a neutral position at an angle of 45 degrees, which we assume to be the starting point or neutral position. Therefore, the control angle of the valve from the neutral position to the parallel position corresponds to a rotation of 45 degrees and the rotation angle to the transverse position corresponds to -45 degrees from the neutral position. In order to achieve the described function of the valve, we must therefore divide the entire circumference of the control spool into 8 equal parts. However, since the bore is located on a curved surface, its diameter is not equal to the length of the arc of the circle it occupies. Therefore, we can connect the diameter of the spool hole with the side length of a regular octagon inscribed in a circle, if we take into account the zero overlap. Taking into account the desired overlap, we can calculate the diameter of the holes from the knowledge of the other dimensions. Figure 4 shows the cross-section of the rotary valve.

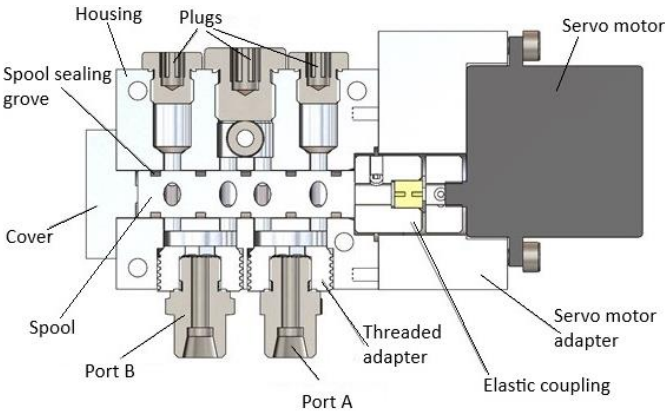

Figure 4: Cross-section of the entire rotary valve

By changing the movement of the spool valve from a back and forth movement along its axis to a rotation around the same axis, we achieved that the spool does not move longitudinally over sharp edges. Based on this realization, we can add grooves for seals on the spool to better seal the entire valve. As the spool rotates, it is advisable to use dynamic seals, which is why we opted for X-sealing rings. In order to achieve a good seal, the individual chambers (areas of the spool and the housing) must be separated from each other, which is why we need five seals in our case. When using seals, there is a problem with the initial assembly of the spool into the housing, although the seals do not run over sharp edges during valve operation. To solve this problem, we decided to further optimize the shape of the valve so that all the control edges of the housing are accessible. Figure 5 shows the final block design with three rotary valves for controlling a humanoid leg.

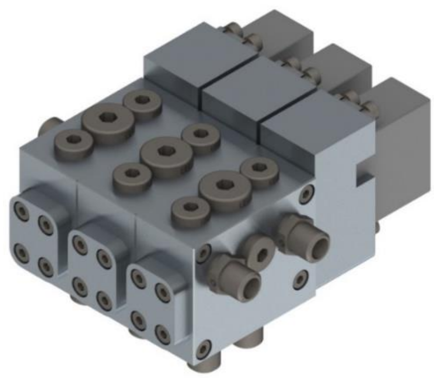

Figure 5: Final model of a valve in a block design for controlling one leg of a humanoid

Technical parameters of the rotary valve: Maximum operating pressure: 350 bar, maximum flow rate 60 l/min at pressure difference of 100 bar.

4 Numerical simulations

With the help of CFD simulations, we can simulate the flow of a fluid through the desired openings. In this case, we need to divide the free volume into small particles generated by volume meshing. As the number of particles increases, the result usually approaches the true value. However, as the number of analyzed particles increases, the number of nodes in which the values are calculated using the finite element method also increases. This leads to a tendency to have as few particles as possible, which is why a minimum number of particles in a line at a single cross-section is recommended for flow analyses. The simulation assumes that ideal conditions prevail. The system is in a stationary state, the fluid used is incompressible, the properties of the fluid do not change with time, the system is thermally insulated and has a constant temperature. The simulation also does not take surface roughness into account, as the surfaces are assumed to be ideally smooth. For all simulations, the hydraulic oil ISO VG46 was used, which has a density of 876 kg/m^3 at 40 °C and a kinematic viscosity of 46 mm^2/s [5]. In order to speed up the CFD simulations and reduce the number of calculations required, we carried out a geometric simplification of the model. This removed geometric details that could affect the need for denser meshing in places where the results are not crucial and could also cause larger errors in the results. The analyzed area is then determined and the entire area is meshed.

Figure 6 shows the numerically calculated pressure difference across the cross-section of the control channel at an oil flow rate of 5 l/min and a spool rotation angle of 15°.

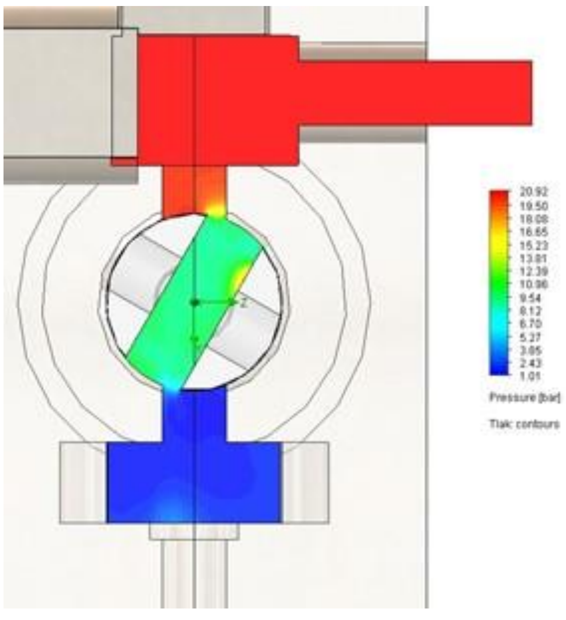

Figure 6: Numerically calculated pressure profile in cross-section with partially open valve

We wanted to use numerical simulations to obtain useful data on the theoretical values of the valve characteristics. These include the Δp/Q and Q/θ characteristics. With the Δp/Q characteristic curve, we determined the maximum flow capacity of the valve at a certain pressure difference across the valve, which is also used to determine the nominal flow rates of hydraulic valves. With the flow characteristic as a function of the angle of rotation of the control spool, we were able to determine the fluid flow through the valve at different angles of rotation of the control spool or different degrees of valve opening from the data at the same pressure difference.

The pressure difference through the valve as a function of the flow rate was performed when the spool was rotated at an angle (θ) of 45° (full valve opening at port P-A and B-T). On the inlet side of the P and B port, we set the flow rates in the range from 0 to 80 l/min with a step of 5 l/min. On the outlet side, we set the ambient pressure as a boundary condition.

5 Experimental work

The designed rotary directional valve consists of standardised and non-standardised parts. All non-standardised parts were manufactured on a CNC milling machine and a CNC lathe. Machine reamers were used to precisely produce the bore for the control piston in the housing. This ensured the cylindricity of the entire bore, which together with the piston must ensure the lowest possible leakage, as the valve can leak not only via the sealing rings but also via the circumference of the control spool if the gap between the spool and housing is too large. A machine reamer was also used to produce the bores with control edges on the spool and housing, with which we wanted to ensure the best possible precision in the production of the control edges. We produced several prototypes of the valve, two with a brass housing and spool and two made of aluminium, which were surface-protected with an oxide layer [13, 14]. Figure 7 shows the rotary valve in a disassembled state.

Two types of tests were carried out with the newly developed rotary valve. The first measurements were short-term and mainly related to the properties of the valve in the steady state, while the second tests related to the permanent testing of the valve.

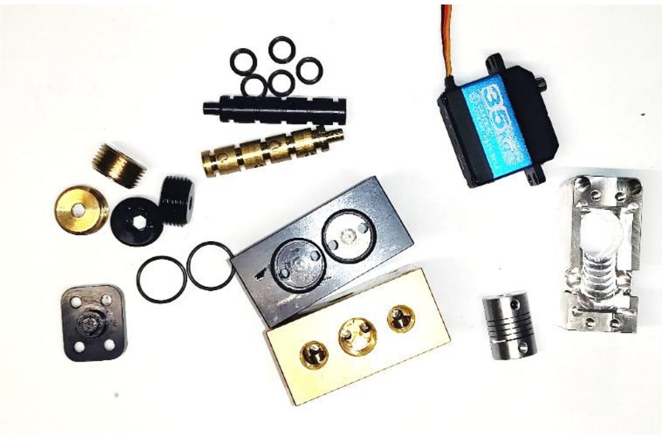

Figure 7: Manufactured non-standardized valve components with servomotor, seals and flexible coupling

Figure 8 shows the hydraulic schematic of the test rig for testing the new rotary 4/3 proportional directional control valve. The hydraulic pump with a variable displacement of up to 100 cm^3/rev (6) is driven by a 20 kW electric motor. The system pressure is set to 300 bar via a pressure relief valve (7). The flow rate can be preset with a manually adjustable flow valve (5) and measured with a flow sensor (4). This is followed by a temperature (3) and pressure sensor (2.1) and the newly developed valve – the test item (1). A pressure sensor (2.2) and a return filter (8) are also located on the A connection of the test item.

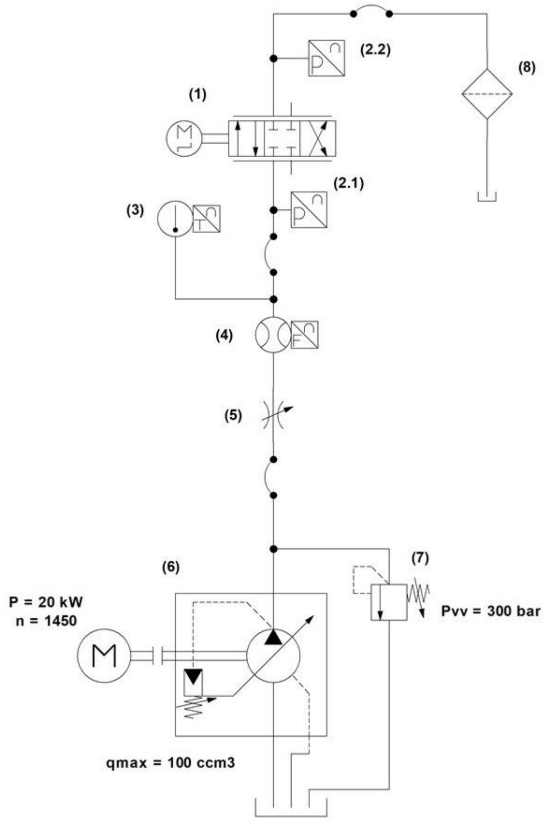

Figure 8: Hydraulic diagram of the valve connection for measuring its properties

With the long-term testing of a 4/3-way rotary valve, we wanted to find out what happens after a long period of operation in which the valve constantly switches between one extreme position and the other. To do this, we monitored the leakage of the valve in the closed position after specified time intervals. To carry out the tests, the rotary valve was connected to a new test station according to the diagram in Figure 9. The tested rotary valve (1) was connected to a hydraulic power pack with a gear pump (7) with a displacement of 8 cm3 and an electric motor with an output of 4 kW at a nominal speed of 1450 rpm. The hydraulic power pack (7) generated an oil flow of 12 l/min. A pressure relief valve (4) was installed between the pump (7) and the valve (1) to ensure that the pressure of the entire system did not exceed 200 bar. The working ports of the tested valve (1) were connected to a flexible hose into which we inserted a nozzle with a bore diameter of 0.6 mm (2), replacing the execution unit that would generate the working pressure on the working line. Both return connections were connected with flexible hoses and a T-port and passed through a water heat exchanger (6), which we used to cool the oil. From the heat exchanger, the oil travelled through another flexible line to the return filter on the power pack (7). Due to the choice of small connections, all flexible pipes had a size of 1/4". A pressure gauge (5) was connected upstream of the valve inlet connection to check the system pressure at the P connection of the tested valve (1).

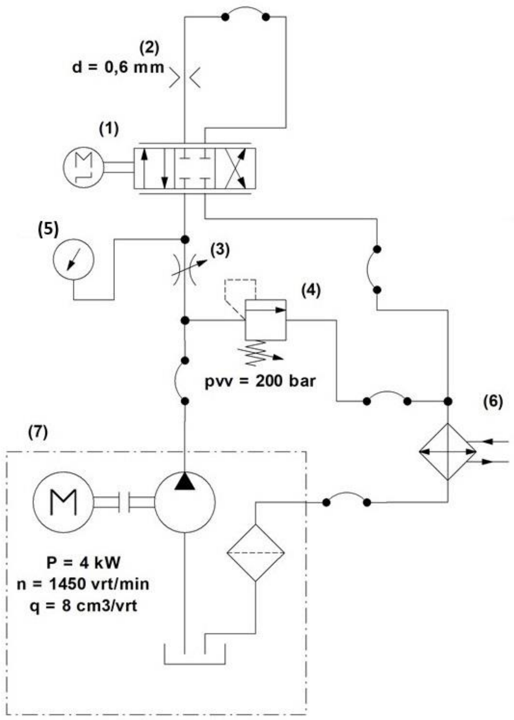

Figure 9: Hydraulic diagram of the valve connection for long-term test

During the endurance test of the valve, the main pressure relief valve was set to 200 bar on the test site. Using a nozzle with a hole diameter of 0.6 mm, we achieved a working pressure of 180 bar by setting the manual flow valve with the valve fully open. We interrupted the flexible line connecting the working lines for a certain time or the number of cycles performed and measured the internal leakage at working ports A and B with the valve closed. The amount of leaked oil was measured using measuring syringes with a measuring range of up to 20 ml. At the same time, we monitored the events and possible leaks at other points on the valve. The entire test was carried out at an oil temperature of 60 ºC, which was ensured by a heat exchanger.

6 Results

The numerically calculated Q-φ characteristic curve of the new rotary valve, which corresponds to the Q-s characteristic curve of other longitudinally moving valves, with the difference that it takes into account the angle of rotation φ instead of the axial movement of the spool, is shown in Figure 10. The result of the flow measurement as a function of the angle of rotation and the pressure difference is shown in Figure 11. Due to the limited performance of the hydraulic power pack at a pressure difference of 200 bar and 150 bar, not all results were achieved. We also measured the maximum torque required to overdrive the valve (Figure 12). In the tests, the greatest resistance occurred when the spool was moved from the fully closed position.

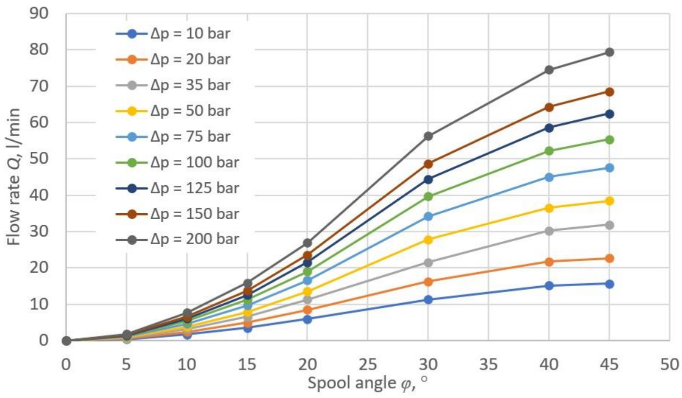

Figure 10: Numerically calculated *Q*- *φ* characteristics of the rotary-controlled valve

From the graph (Figure 11), we can see the similarity with the graph of the Q-φ characteristic curve obtained by numerical simulations (Figure 10). However, we also note some deviations due to the inaccuracy of the desired and actual position of the spool rotation. We found this anomaly in the measurements, but to eliminate this problem, we would need a servomotor with a better position reader that allows for higher accuracy.

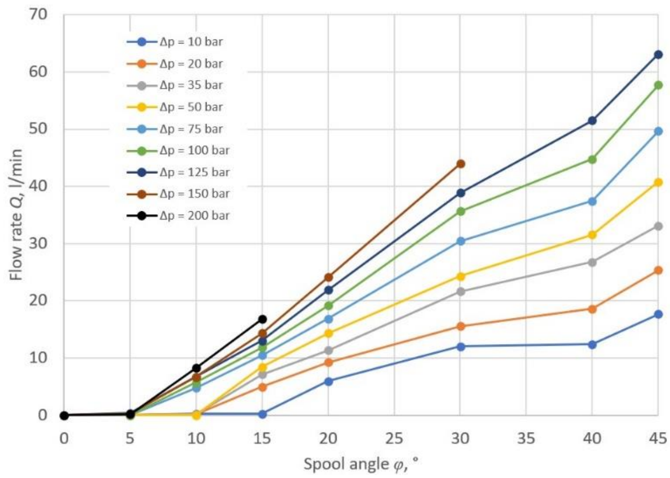

Figure 11: Measured Q-φ curves of the rotary-controlled valve

The graph (Figure 12) shows an almost linear increase in the required torque, which reaches a value of 0.1 Nm at a pressure difference of 0 bar. The result (Figure 12) also shows that a servomotor with a torque of 1.6 Nm is required to control the valve at a pressure difference of 300 bar. From this it can be concluded that this torque is a result of the friction of the seals on the housing and the spool, as no flow forces occur in the valve when it is fully closed and therefore cannot cause any torque. Part of this torque when the valve is fully closed can also be caused by the force that acts on the spool via the two P control edges in the housing and presses it against the opposite wall, as there is a certain amount of leakage between the spool and the housing.

We wanted to determine the service life of the valve by carrying out durability tests. The results showed that the newly developed valve completed 733,000 switching cycles before failing. The tests also showed that the time for each complete (100 %) switching cycle was around 0.6 s, which means that the valve can switch at a frequency of 1.6 Hz. The measured switching time of the existing valve design (0.6 s) allows the robot to run slowly.

During the durability tests, we encountered some unexpected problems as some purchased components failed.

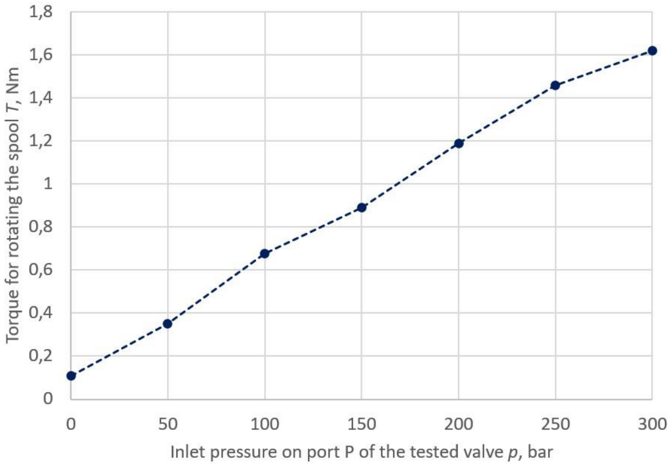

Figure 12: Measured spool torque as a function of the pressure difference

After 296,000 switching cycles, the servomotor failed due to wear of the gearbox in the power transmission. However, as we cannot influence the quality of the servomotors, we replaced the servomotor and continued the tests as we were interested in the lifetime of the main parts of the valve, i.e. the housing and the spool, and their wear. After 544,000 cycles, it turned out that the valve was no longer working due to a break in the flexible coupling between the spool and the servomotor. In this case too, we replaced the broken part and continued the tests. As a result, after the next 3,000 switching cycles, the spool moved axially to a position where the seals reached the control edges on the housing. This resulted in damage to the seals, causing the valve to leak outwards. The problem was solved by replacing the seals and reinstalling them with assembly inserts. After replacing the sealing rings, no new problems occurred until the end of the test. The test was concluded with the failure of the control spool, which broke in the shaft connection with the flexible coupling due to the exceeded dynamic continuous load (Figure 13).

Figure 13: Breakage of the control spool at the contact with the flexible coupling at 733000 switching cycles

During the durability test of the rotary valve, we measured the internal leakage at regular intervals (Figure 14). The last leakage measurement (after the failure) could not be carried out because the valve could no longer be turned.

We were very surprised by the results of the leakage measurements at the beginning of the test, as the measured leakage of the valve is very low. The diagram also shows the point at which the seal was replaced due to the problem described. After replacing the seals, a sudden increase in the leakage value can be seen, which is most likely due to major damage to the seals during reassembly. However, the valve showed no leakage at any other point, which surprised us, as only one sealing ring ensures the seal on both sides between the return zone and the environment.

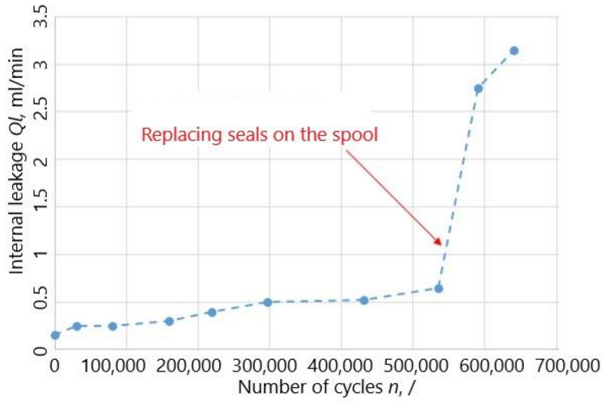

Figure 14: Measured internal leakage of the valve during the durability test

After completing the durability tests, we visually inspected the wear of the control edges on the spool and housing and also noted other areas of wear, which became lighter in colour after wear due to the application of a black oxide layer on the surface of the aluminium parts.

We observed the control edges on the control spool and compared them with the edges on the housing. A change can also be seen on the X-sealing rings. The second seal from the left in Figure 15 shows that only part of the seal has remained in the groove. We conclude that this seal has caused a sudden jump in the values in the diagram. It is interesting to note that the valve achieves a very good seal despite the almost completely damaged seal. Figure 16 shows the wear of the control edge on the spool, which was considerably greater than the wear on the housing.

Figure 15: Spool after 733,000 cycles with visible damage to seals and control edge

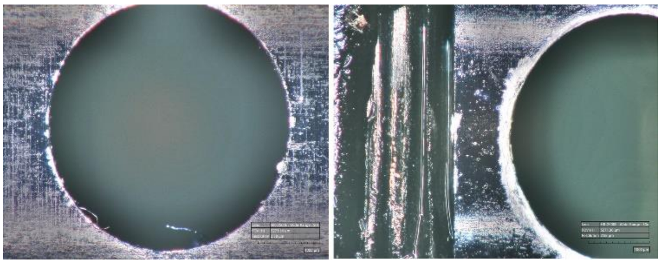

Figure 16: Control edge wear on the housing (left) and on the spool (right).

7 Discussion

From the analysis of the results, we conclude that we have succeeded in developing a new hydraulic rotary valve with a nominal flow rate of 33 l/min according to the criterion of a pressure difference of 35 bar.

With a nominal pressure of the hydraulic system for driving the legs of a humanoid robot of 200 bar, a flow rate of almost 60 l/min can be achieved through the valve. To achieve a higher flow rate, one would either have to increase the nominal working pressure of the hydraulic system of the humanoid robot or increase the valve capacity by increasing the diameter of the control edges in the valve. This would also mean increasing the size of the valve, which is not desirable.

The measurement results agree with the results of the numerical simulations. It is surprising that the measured values are very close to the values of the numerical analyses. Only when comparing the Q-φ curves (numerical and measured) is there a partial deviation, which is due to the inaccuracy of the servomotor positioning. To eliminate this anomaly, we would have to use servomotors with very precise positioning, which are more expensive than the motor used. As the control is realised with a feedback loop, we expected better positioning of the completed rotation from the chosen motor.

The durability test of the manufactured valve prototype showed that aluminium performed well as a material for the piston and valve body, contrary to expectations. We are convinced that the applied oxide layer on the surface, which significantly increased the surface hardness, contributed significantly to this.

Even after a fairly large number of cycles, the wear did not lead to excessive and unacceptable internal leakage of the valve. This was significantly lower than the internal leakage of longitudinally moving spool directional control valves [15] at the end of the endurance test. The decision to incorporate seals into the valve assembly itself certainly contributed to the surprising leak tightness results. This required the development of a solution for the valve fastening, which had to be further improved to enable multiple successful seal changes during the service life of the valve.

The durability tests also highlighted the need to be careful when selecting bought-in valve components, as some were found to fail earlier than the main valve components tested, contrary to expectations.

The life of the valve could be extended by optimizing the spool shaft at the point where the failure occurred during the durability test, as we did not pay enough attention to this detail in the spool design and the impact of the notch effect on the dynamic fatigue strength.

In the further development of valves, it would be useful to consider and test the effects of the spool material on the service life of the valve itself. It would also be worth investigating how the choice of seals affects the sealing and also the torque required to control the valve.

After comparing the results of the newly developed proportional rotary valve with the results of existing sliding, longitudinally moving proportional valves at a similar nominal flow rate, we can conclude that the newly developed valve allows the same flow rate with smaller dimensions. We also found that the flow rate of classic valves stabilizes or even decreases with increasing pressure difference across the valve, while the flow rate of the newly developed valve increases continuously at full opening.

If we compare the size of the newly developed 4/3-way rotary proportional valve with that of the classic, longitudinally moving spool valve, we see that the new valve has only 33 % of the volume of the classic valve with similar operating characteristics (flow/pressure) (Figure 17).

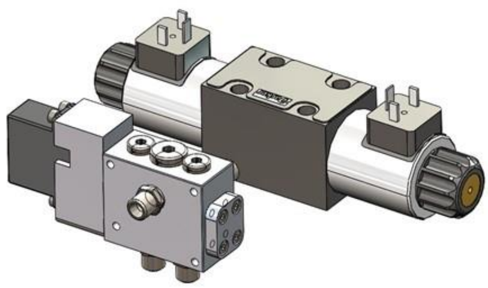

Figure 17: Size comparison between the newly developed valve (front left) and a conventional valve

Figure 18 shows humanoid hydraulic legs, each with three hydraulic cylinders (covered for protection) and three hydraulic rotary valves, each mounted on the support structure of the legs (top).

Figure 18: Humanoid legs with 2x3 rotary valves on top of the structure

8 Conclusions

By researching solutions for proportional spool valves, we have succeeded in developing a new hydraulic proportional spool valve with a rotary design which has significant advantages over conventional proportional valves in terms of internal leakage, size, control and manufacture.

By using seals on the spool, we were able to reduce the internal leakage by almost 100 times compared to conventional valves on the market. To implement the seals, we also had to develop a special device for assembling and disassembling the valve, as the sharp edges otherwise make it impossible to install seals. We also produced a few examples of the newly developed valve from aluminium and brass because it was easier and cheaper to manufacture. We have also tested the use of oxide layers on the aluminium surface, which can increase the surface hardness.

Increasing the surface hardness extends the service life of the entire valve, as the reduced wear, particularly of the control edges, means that critical internal leakage occurs later on, at which point the valve can no longer be used.

The properties of the newly developed valve were calculated numerically using fluid dynamics (CFD) and measurements were carried out on a prototype valve. It was found that the measurements were surprisingly similar to the simulated values, both in terms of the shape of the curves and the values. There were some problems with the measurements of the Q-φ characteristic due to the insufficiently precise servomotor, but despite these problems we were able to achieve acceptable results.

It also turned out that despite the simple design, the new rotary proportional valve completed 733,000 switching cycles before failing the durability test, which could be improved in the future by optimizing the spool shaft.

The newly designed valve represents a new approach to the control of hydraulic components and is useful for controlling humanoid robots and other devices in industrial and mobile hydraulics.

Nomenclature

Variables used in equations are presented in the table below.

Designation	Denotation	Unit
φ	spool rotational angle	°
d	nozzle diameter	mm
n	rotational speed	rpm
n	number of cycles	/
p	pressure	Pa
Δp	pressure difference	Pa
Q	flow rate	l/min
Ql	internal leakage	ml/min
q	pump displacement	cm^3

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