OSCILLATION PROBLEMS BY THE USE OF MOOG D633 PROPORTIONAL CONTROL VALVES DUE TO SPOOL OSCILLATION AND AVOIDANCE BY CHANGING HOSE LENGTHS AND CONTROLLER BEHAVIOUR

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The motor is a cyclically controlled hydraulic motor, whereby two cylinders generate a rotary movement from a translatory movement. This is done by shifting two matching screw surfaces to each other. With a weight of 250 kg, a torque of 170 kNm is generated. The two synchronous cylinders are each moved with a Moog D633 proportional control valve in a closed control loop. The exact movement is necessary to be able to precisely adhere to the control times of the cycle-controlled hydraulic motor. After the system had been run in, resonance behavior was observed in several machines, with the pistons and valves vibrating at around 200 to 300 Hz. The valve spools also oscillate at that frequency despite the internally closed control loop. After several measures were carried out, the resonance phenomenon could finally be prevented by changing the hose lengths of the connecting lines and by taking measures on the software side.

Keywords:
hydraulic motor,
oscillation,
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hose

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1 Intruduction

The motor is a cyclically controlled hydraulic motor, whereby two cylinders generate a rotary movement from a translatory movement. This is done by shifting two matching screw surfaces to each other. This hydraulic motor is installed twice in the boom of a concrete pump placing boom, where it is used to move the last two booms. With a weight of 250 kg, the first one produces a torque of 170 kNm, while the second one, weighing 135 kg, produces around 46 kNm.

Figure 1: Concrete Pump Boom with two hydraulic motors.
Source: own

With the cycle-controlled hydraulic motor [1], [2], two synchronous cylinders are actuated, each controlled with a Moog D633 proportional control valve. A rotary movement is derived from a translatory motion, achieved through the specific tooth geometry. The tooth flanks are shaped as helical surfaces, generating rotational motion when the gears mesh. Notably, the helical surfaces facilitate contact across a surface rather than a line.

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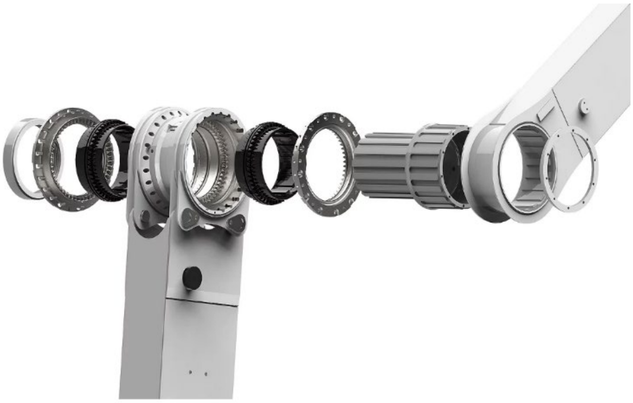

Figure 2: Parts of the hydraulic motor.
Source: own

The two pistons each feature two rows of teeth, with corresponding counter-teeth within the housing. To transmit torque, the pistons are affixed to a shared shaft through splines, preventing relative rotation between the pistons. In the provided Figure 3, one cycle of movement, the pistons are depicted in blue and green, while the housing is shown in red. The four separate images illustrate one of the four cycles through which the load is transferred between the pistons. Within each cycle, the pistons alternate between the two sets of teeth. These teeth are located within the piston chamber, ensuring a continuous flow of pressurized oil for lubrication of the tooth flanks.

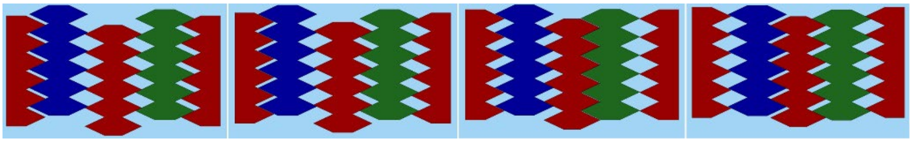

Figure 3: One cycle of movement.
Source: own

The pistons' motion is controlled by two Moog D633 proportional control valves. An LVDT displacement sensor accurately measures the piston's position. This enables closed-loop control, where the valves and displacement sensors work together to move the pistons. Precise movement is essential to maintain strict adherence to the timing of the cycle-controlled hydraulic motor.

The motor receives oil from a constant pressure system at 300 bar. The supply line to the motors spans 30 meters along the boom. A diaphragm accumulator is installed into the supply line to mitigate pressure fluctuations that may arise. The safety-oriented check valves, positioned before the cylinder chambers, are omitted in the provided circuit diagram [Figure 4: hydraulic schematic of the cycle controlled hydraulic motor] to ensure clarity and legibility.

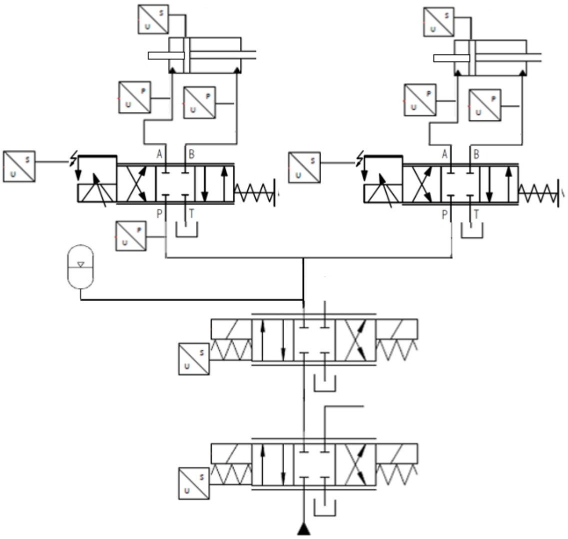

Figure 4: Hydraulic schematic of the cycle controlled hydraulic motor.

Source: own

After the system had undergone a break-in period, resonance behaviour was observed in multiple machines, causing pistons and valves to oscillate at approximately 200 to 300 Hz. This results in highly disagreeable noise and places additional stress on the system's components.

2 The Oscillation of the pistons and valves

2.1 Description of the resonance phenomenon

Under specific operating conditions, a resonance phenomenon arises within the motor. The pistons and proportional control valves oscillate at a frequency of 200 to 300 Hz, displaying a relatively substantial amplitude. This leads to pressure fluctuations that can reach up to 100 bar, even when the load pressure is at 220 bar. The diagram [Figure 5: Plots of the start of oscillation] below illustrates the initiation of an oscillation cycle, depicting the paths and differential pressures of the pistons, along with the supply pressure, valve control value, and the current valve positions.

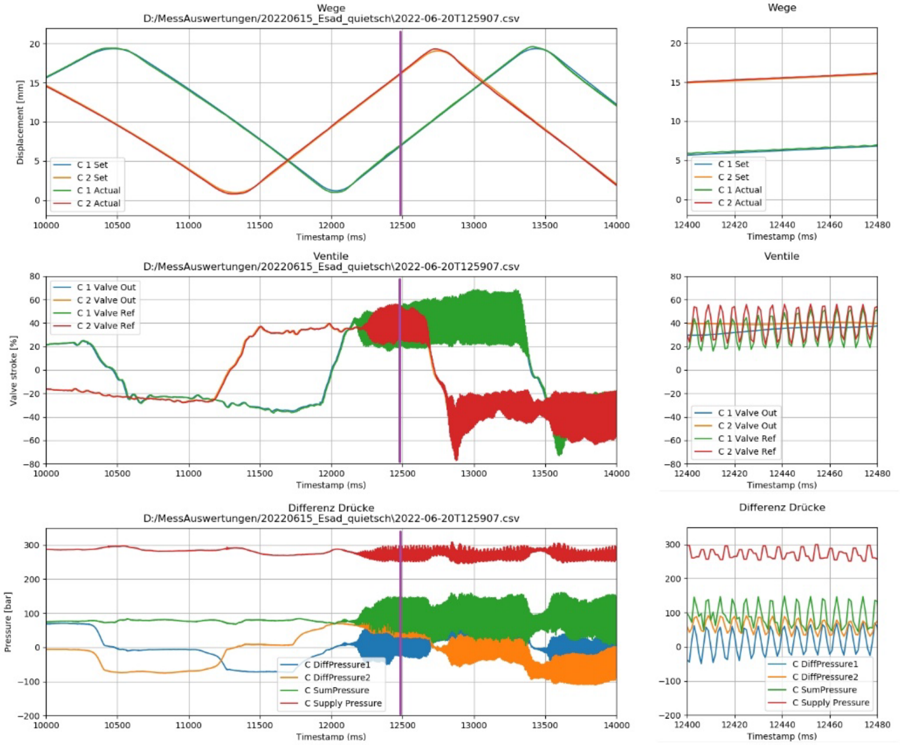

Figure 5: Plots of the start of oscillation.

Source: own

This resonance phenomenon frequently emerges under specific operating conditions. These conditions encompass factors such as oil temperature, torque, speed, and the positioning of the booms relative to one another. The oil temperature must be at least 35 °C; beyond 55 °C, occurrences of this phenomenon are almost negligible. The motor must be subjected to a torque load of no less than 30 %, and the speed must attain 80 % of the maximum speed. The boom's position and torque are somewhat interrelated, with the phenomenon being more prone to manifest in certain boom positions.

Another requirement pertains to the motors' service life. During the initial four months following production, the vibration does not manifest. Subsequently, this behaviour can arise sporadically. It gradually becomes more frequent as the usage duration progresses, eventually occurring regularly after an additional 3 months. This pattern initially hints at running-in and wear-related behaviour. Seal replacements offer temporary relief for approximately 2 months, after which the vibration resurfaces. Interestingly, the dismantling and reassembly process, even without altering components, leads to changes in the behaviour. A certain period elapses before the phenomenon recurs.

2.2 Possible causes

This is obviously a hydraulically oscillating system, with a spring-mass system consisting of a piston and an oil column coming into consideration first. Due to the low mass and the short oil column, however, the natural frequency is many times higher. The seals and the mechanical contacts also have an influence due to possible stick-slip effects, unlockable check valves that may close, resonance of the steel structure or possible excitation from the oil supply.

2.2.1 Excitation through oil supply

The system is powered by an axial piston pump connected to a diesel engine. Despite having 9 pistons and operating at speeds ranging from 1440 to 2100 rpm, the excitation frequency might seemingly match; however, the fluctuations are likely attenuated by the 30-meter hose line and the presence of an accumulator. Various speed tests have failed to reveal any discernible impact on the resonance occurrence.

2.2.2 Closing check valves

The pistons are secured against unintentional movement with hydraulically unlockable check valves. There was a suspicion that these could possibly close in operation. Measurements of the control pressure at the valves have shown that they are constantly open when driving.

2.2.3 Stick-slip effects on the mechanical friction contacts and the seals

The pistons are in mechanical contact with other components, both within the gearing in the oil chamber and on the output shaft featuring splines. Relative movements occur at these junctures, with hydraulic oil serving as lubrication within the oil chamber and grease on the shaft. These contacts exhibit a run-in behaviour, leading to an enhancement of surface smoothness over time. This phenomenon could account for shifts in resonance behaviour over the system's lifespan. However, attempts involving various lubricants on the splined shaft failed to yield any discernible alterations.

The alteration in behaviour subsequent to seal replacement implies that the seal has undergone a run-in process. However, the feasibility of replacing the seal every six months is limited. Modifying the material is equally challenging, as the required testing period would be considerably protracted, and changing materials after several years is not a viable solution either.

2.2.4 Geometric influence

It is striking that it only affects the large motor in the two sizes. The valve block is the same, but the mechanical components have significantly different dimensions. So, there must be a connection here, which unfortunately could not be deduced up to now. The different masses and oil volumes will probably play a role. Due to the circular shape, there are also different ratios between oil volume, ring area, mass and seal lengths compared to the large series.

2.2.5 Accumulator

The size of the accumulator is specified for reasons of space and weight. Although changing the preload pressure and volume did not change anything.

2.2.6 Proportional control valve

Lastly, attention turns to the proportional control valve, which, as evident from the illustration [Figure 6: Bode-diagram Moog D633 with -9dB line], vibrates with notable amplitude and/or potentially triggers the vibration. The Moog D633 valves feature an internal closed-loop control system designed to regulate valve movement, theoretically capable of damping vibrations. Measurements indicate that the control signal remains vibration-free. The Bode diagram aids in determining the valve's natural frequency, which, at f_e= 30 to 50 Hz, remains distant from the vibration range of 200 to 300 Hz. The natural frequency fluctuates based on oil parameters and valve opening. Vibration-related effects can potentially arise due to electronic control mechanisms.

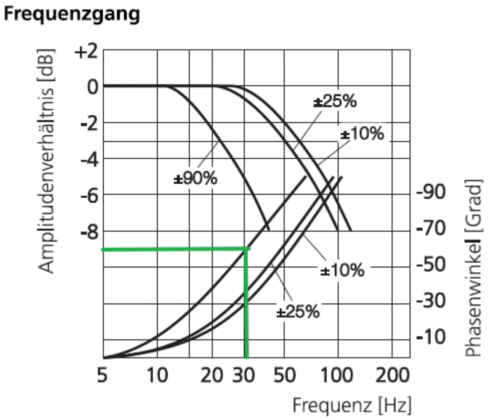

Figure 6: Bode-diagramm Moog D633 with -9dB line.

Source: [3]

In the end, it is likely a blend of valve attributes, piston mass, seal friction, the length of the oil column in the hose, and the presence of the accumulator within the supply line.

2.2.7 Control system

After analysing the measurement data, a reason for the start of the oscillation could be found. A spike can occur when calculating the valve control signal. This comes from a calculation inaccuracy in connection with the control frequency of 1 kHz. The next waypoint of the piston is calculated for the position controller. [4] The current speed is used for the feedforward of the valve controller. The cycles have different calculation methods, which is why the last two waypoints are differentiated according to time to determine the current speed. This can result in a twice as high speed for 1ms and thus a high valve signal. This spike is sufficient as a one-off excitation to start the oscillation.

With the help of a software modification, at least this one-off excitation could be prevented, the calculation basis will be changed later for a better speed calculation. The graphic [Figure 7: spike at valve signal] below shows marked where the spikes occurred.

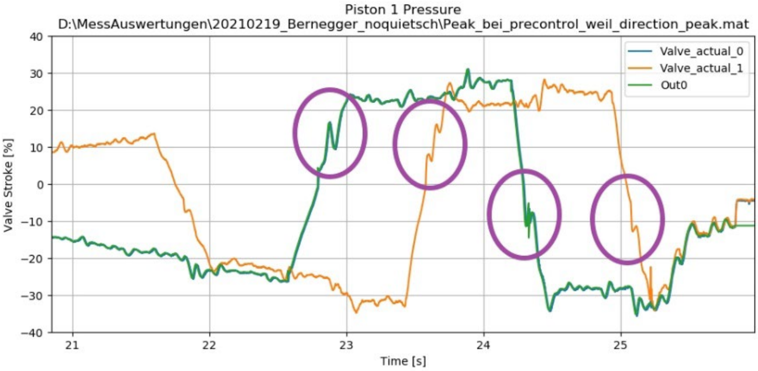

Figure 7: Spike at valve signal.
Source: own

3 Solutions

At the end, two solutions were identified to resolve the issue. Given the dependency on speed, a software adjustment was implemented. Whenever an oscillation surpassing 150 Hz is detected in the present valve position signal, the motor's speed is deliberately reduced. In many cases, initial vibrations generate minimal noise, and a slight speed reduction of 10 % to 15 % often proves adequate. This adjustment remains inconspicuous to users while effectively curbing sustained vibrations. Importantly, this solution could be swiftly executed via remote maintenance across numerous machines worldwide, requiring no physical modifications.

A second solution involved altering the lengths of two hydraulic hoses. After numerous tests, it was discovered that extending one hose per piston effectively detunes the oscillatory system, preventing resonance altogether. Alternate solutions, including mechanical redesign or component replacements, were unfeasible due to the global deployment of approximately 30 machines. Changing the two hoses emerged as a swift and cost-effective resolution. Furthermore, this approach is deemed the most viable and promising solution.

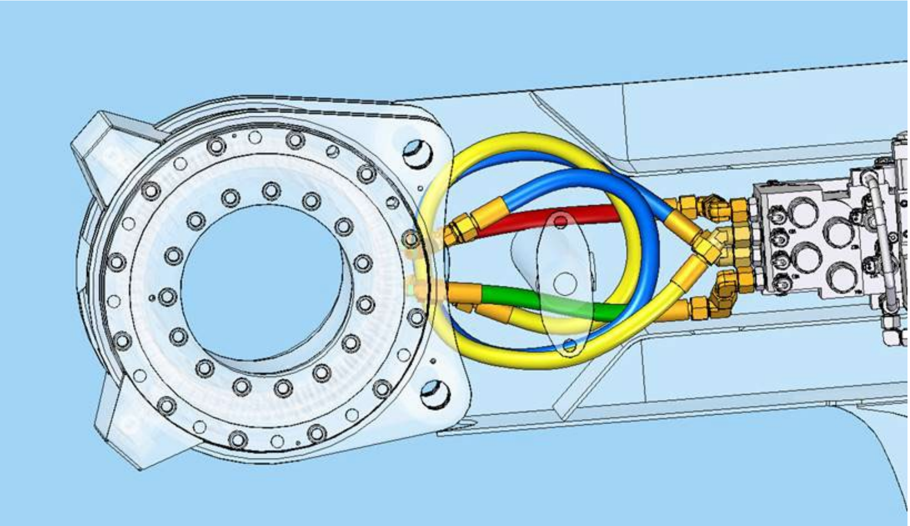

Figure 8: New longer hoses (yellow and blue).
Source: own

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