Synthetic Esters and Dynamics of Pressure Compensated Proportional Directional Control Valves

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Abstract* – The purpose of this paper is to help reduce the uncertainty in behavior introduced when changing hydraulic oil from mineral oil (HLP) to biodegradable oil (synthetic esters - HEES) by comparing the behavior of proportional valves with HLP and with HEES at various temperatures. The focus of this article is on classic proportional valves used in the industry. The study is based on tests and modelling with characterization of dynamic behavior in mind. The characterization is based on tests of two pressure compensated proportional valves, one with closed loop control of the spool position, and one without. The two ester types tested are one based on a saturated, fully synthetic ester and a regular fully synthetic ester. The tests consist of steps and frequency responses. Both valves are tested at oil temperatures 20°C, 40°C and 60°C. The adopted models are based on a third order linear model with parameters identified using frequency responses from actual valve tests. The variation of amplitude and bias has some influence on the resulting frequency response especially at lower temperatures. But the general tendencies are unaffected by amplitude and bias. As expected a clear tendency for both valves of increasing dampening at decreasing temperatures is seen regardless of oil type, but the increase in dampening is similar for all oil types. The saturated ester leads to less bandwidth at lower temperatures for both valves, but the overall variations between all oil types stay within 1.66Hz of each other when tested with the same test parameters. The investigation indicates that the difference in dynamic characteristics at 20°C caused by the different oil types can not be explained with variations in any single one of the classic liquid properties density and viscosity and more investigations are needed to identify the cause.

Keywords — Dynamics, Hydraulics, Synthetic Esters, Frequency response, Proportional valves, Directional valves.

INTRODUCTION

Legislation and the need for increased environmental sustainability has created a demand for biodegradable oil, in hydraulic systems, but a reluctance hampers this shift towards greener systems. The reluctance stems from conservative thinking, a lack of experience and little detailed information regarding the consequences of introducing biodegradable liquids.

From a system design engineers point of view there are three main problem categories associated with the use of biodegradable oils. Firstly, there is the issue of applying and maintaining the liquid, secondly, there is the issue of compatibility between the system components and the biodegradable liquid and, thirdly, there is the issue of whether the performance characteristics of the system components are altered substantially. Most components are tested with HLP and information on compatibility as well as steady state and dynamic characteristics are, in general, not easily obtained. This paper focuses on the third challenge, namely that of performance. This has been given very little research attention and while the liquids ability to decompose is not directly related to performance, generic fluid parameters such as viscosity, ν, bulk modulus, β, and density, ρ, often are. For a wide range of hydraulic components the performance also depends on tribology because of the fine tolerances between moving parts. Due to the complexity and micro-scale of the lubrication regimes between the moving parts it is expected that difference in performance could be related to chemical composition as well as the above mentioned classic liquid parameters.

For that purpose the dynamic performance of one of the most common components, the electro-hydraulically actuated pressure compensated 4/3 directional control valve, PCPDCV, is investigated.

The research which have been done on valves with biodegradable oil, tends to focus on either system level where the detailed contribution from valves are unclear [1], [2], on oil property level [3], [4], [5], [6], [7], or other components such as pumps [8].

This paper focuses on synthetic esters, HEES. HEES are one of many biodegradable oil types and one of the most popular for high performance hydraulics. They perform well in biodegradebility, eco toxicity [9], and many formulations have a high amount of bio-based content while at the same time having relatively high resistance to oxidation and hydrolysis [10]. The material compatibilities and the general performance are mostly similar to mineral oil, HLP. Viscosity index, VI, [11] and lubrication is better [12], but the cost is higher. It out-performs polyalphaolefins and related hydro carbon hydraulic fluids, HEPR, on biodegradability and bio-based content, vegetable oil, HETG, in resistance to oxidation and hydrolysis [12] and water glycols, HFC, in material compatibility and lubrication [13], [14].

This paper proposes the hypothesis that the typical system engineer does not have to consider new PCPDCV valve dynamics when changing from HLP to HEES. The method below is used to gauge the oil type related differences as evidence for or against the hypothesis.

METHODOLOGY

Figure 1 illustrates the principle of the PCPDCV. The main spool provides directional control by controlling the access from the supply port, P, and the tank port, T, to the A and B port. Load independent flow is achieved using a pressure compensator to keep a constant pressure difference from P_1 to the port receiving flow (A or B). With a constant pressure difference over the restriction from the main spool the flow is then determined by the spool position, Y, and the fluid properties.

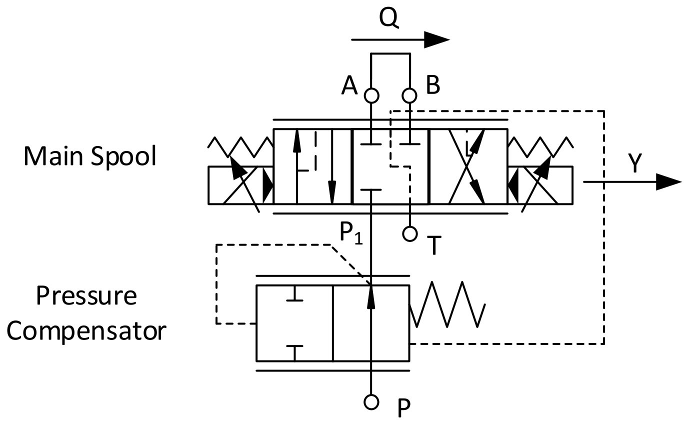

Figure 1. Principle sketch of PCPDCV

While the basic functionality of the PCPDCV is rather simple the actual behavior is complex and nonlinear.

The flow, Q, is a nonlinear function of Y, with a dead band around Y = 0.

The spool position is a function of a pilot pressure, p_p, from the Electro hydraulic module, EH, a friction force from spool contract with fluids and spool bore, f_μ, a spring force, f_{sp}, flow forces, p_{ff}, and the mass of the spool M [15], [16].

$$Y(p_P, f_\mu, f_{sp}, p_{ff}, M) \qquad (1)$$

The pilot pressure is a function of the control signal, U, the bulk modulus, β and some valve dependent dynamics which relate to control algorithms and pilot circuit, G_{sys}, [15], [16], [17].

$$p_p(U, G_{sys}, \beta) \qquad (2)$$

The information and time needed to model the details all of the above mentioned effects are out of scope for most system engineers and a commonly used approach is to use gray or black box modelling of the most dominant effects.

As an example, it is a common approach to apply a linear dynamics model to the spool-valve position and signal input relationship [15]. Using simple models allows for easy comparison between models and, thus, the effect of different oil types.

Test setup

The test setup is shown in **Figure 2** and the components are listed in **Table 1**. Only one set of components have been used with flushing between each exchange of oil. The flushing was done according to ISO 15380.

Table 1. List of components used for test

Component name	**Type**
Container refrigeration unit (CRU)	Thermoking Reefer MP4000
Ambient Thermometer (TA)	MBT 5252
Danfoss PCPDCV	PVG 32
Danfoss EH	PVES-SP
Hawe PCPDCV + EH	PSVF-EAWA
Inline Thermometer (T_I)	N/A
Bosch Rexroth Hydraulic pressure unit (HPU)	ABKAG-60ST9

The HPU delivers supply pressure using a gear pump running at a fixed speed 15.5L/min with a relief based pressure control unit set at 100bar.

Cooling of the oil is achieved by placing the entire setup in a refrigeration unit and cooling down the ambient temperature to 30-35°C less than the oil and letting the HPU air to oil heat exchanger cool the oil. The air temperature is monitored via a PT100 sensor, T_A.

The oil temperature is measured at the valve inlet by an inline thermometer made with a type K thermocouple with a thin coat of epoxy with enhanced thermal conductive properties, T_I. The thermometer is designed for high pressure and low response time (6-10s) and has an accuracy of < 1°C.

This setup led to a slowly increasing oil temperature during testing but all data is collected within ±2°C of the target inlet temperature.

The Danfoss valve is a pressure compensated 4-3 valve with closed neutral position and a maximum flow of 25L/min. The Danfoss EH-module has a pulse-width-modulation, PWM based pilot circuit with closed loop position control and outputs a spool position signal produced by a LVDT with <2% uncertainty [17]. The Hawe valve is also a pressure compensated 4-3 valve with closed neutral position, but has a maximum flow of 10L/min. The Hawe EH module does not provide closed loop position control, but it does produce a hall sensor based position signal at <9% uncertainty [18].

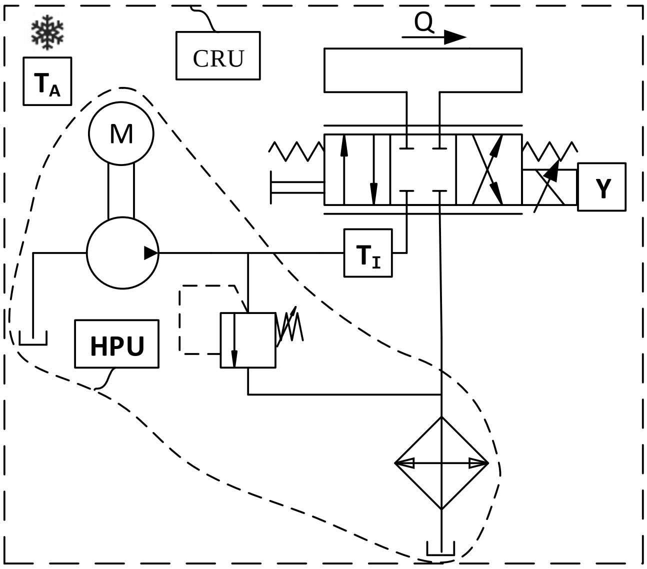

Figure 2. Test setup

Table 2. lists the tested oils along with their density and viscosity index. HEES is a regular synthetic ester and HEES+ is a fully saturated ester. **Table 3** lists oil viscosities at temperatures available in data sheets and an estimate at the test temperatures not covered by the data sheets.

Table 2. Oil used for testing. $\rho_{15}[kg/m^3]$ (ρ at 15°C) VI[-], [19] [20] [10].

Type	Product	ρ	VI
HLP	Shell Tellus S2 V46	872	143
HEES	Statoil Hydraway SE 46	921	190
HEES+	Statoil Hydraway SE 46 HP	923	148

Table 3. Oil used for testing. $\nu_x[cSt]$ (ν at x°C). Values at -20, 40 and 100°C are from data sheets. 20 and 60°C are calculated using the Uddebuhle-Walther equation and the two nearest datasheet values, [19] [20] [10].

Type	ν_{-20}	ν_{40}	ν_{100}	$\nu_{20}{}^*$	$\nu_{60}{}^*$
HLP	2350	46	7.9	116	19.3
HEES	1450	47	9.5	108	21.3
HEES+	2179	45.3	8.0	113	19.3

Frequency-response

The frequency response is found by applying sinusoidal signals with increasing frequencies to the input signal while analyzing the corresponding sinusoidal spool position response.

$$U = A_U sin(\omega t) + B_U \qquad (3)$$

$$Y = A_Y sin(\omega t + \varphi) + B_Y \qquad (4)$$

Figure 3 demonstrates phase shift and amplitude identified by matching a sinusoidal curve, Y*, with known amplitude, phase, frequency and bias to the spool position data Y.

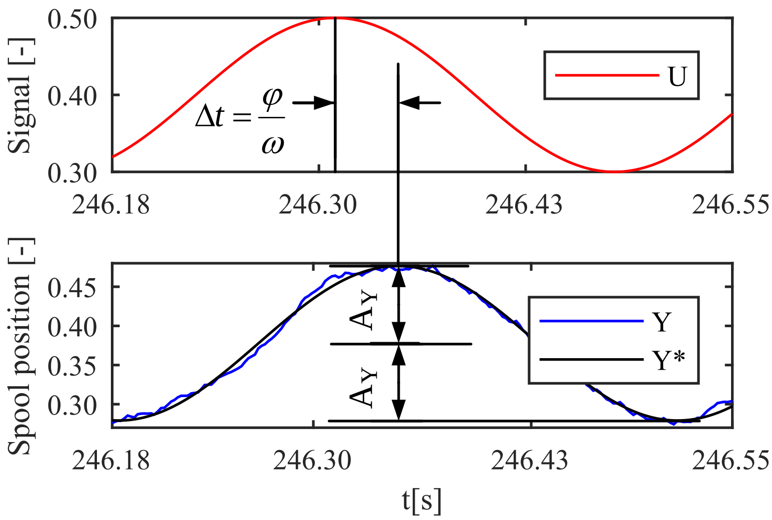

Figure 3. Gain and phase identification

This matching has been done using an optimization algorithm to minimize the RMS error, e, between Y and Y* over at least 3 periods with A_Y, φ and B_Y as decision variables (ω is given by the input signal).

$$e = RMS(Y(t) - A_Y sin(\omega t + \varphi) + B_Y) \qquad (5)$$

The sine parameters of the signal sent to the two valve types were different due to the different nature of the two valves, **Table 4**.

Table 4. Sine parameters for signal input to the two valves during frequency response test.

Danfoss PCPDCV		Hawe PCPDCV	
A_U	B_U	A_U	B_U
0.10	0.4	0.10	0.7
0.20	0.4	0.15	0.7

The analysis is used to create a bode plot where spool position amplitude (gain), A_Y, and phase shift, φ, is presented as a function of frequency. **Figure 4** shows a bode plot of analyzed test data for the Danfoss PCPDCV with HLP at 40°C, using a signal amplitude of A_U= 0.10.

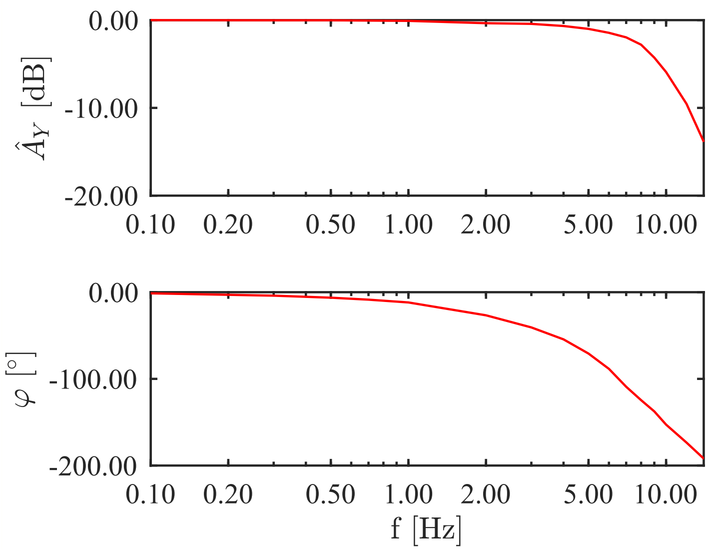

Figure 4. Bode plot of the Danfoss PCPDCV with HLP at 40°C and $A_U = 0.10$.

The first subplot shows A_Y(f) normalized with $A_Y(f = 0.1Hz)$ to get $\hat{A}_Y$(f) and is shown in dB as it is customary. The frequency unit has been changed to Hz for a more intuitive interpretation. The second subplot shows $\varphi(f)$.

Linear model

Assuming our system is close to linear for U near B_U means that a linear model with a similar frequency response to that of the data in that region exists. Thus parameters of a linear system can be found by adapting the model response to the curves of the frequency response data. **Figure 5** shows the frequency response data with a 2nd order and a 3rd order model adapted to the data by minimization of error on the amplitude. Doing the optimization on phase error and a combination of phase and amplitude error was also tried but the best results were achieved by adapting to amplitude.

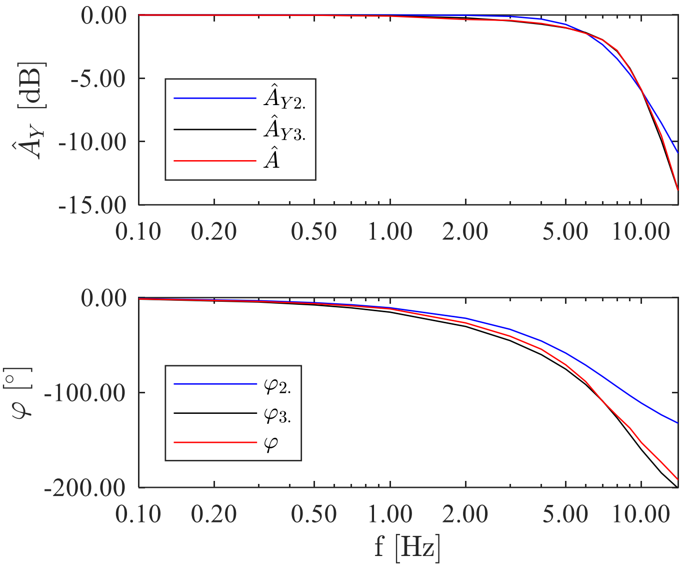

Figure 5. Frequency response data of the Danfoss PCPDCV with HLP at 40°C with $\boldsymbol{A_U = 0.10}$ including the response of the adapted 2nd and 3rd order model.

The 2nd order model fits reasonable well on amplitude with less than 1dB gain deviation before 11Hz but differ on phase from about 5Hz and onwards with 12° to 70° difference from the data.

The 3rd order model fits significantly better especially at higher frequencies with less than 0.5dB amplitude difference and 11° phase difference over the entire test spectrum. Little is gained by expanding the order of the model beyond 3 and the 3rd Order model is therefore used to compare Danfoss PCPDCV behavior with different oil types.

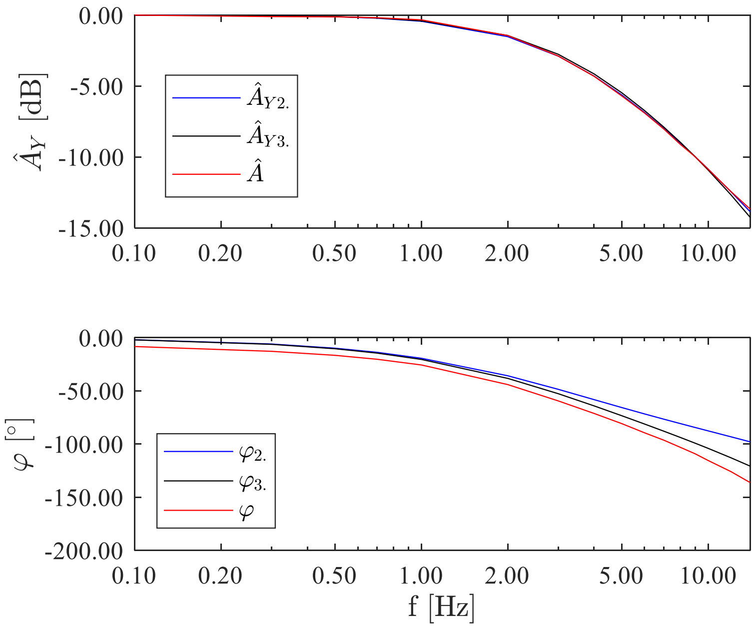

Figure 6. Frequency response data of the Hawe PCPDCV with HLP at 40°C with $A_U = 0.10$ including the response of the adapted 2nd and 3rd order model.

In **Figure 6** both the 2nd order and the 3rd order models is seen to match well with Hawe PCPDCV data with less than 0.8dB amplitude error over the entire test spectrum. The 3rd order model does perform better on phaseshift for higher frequencies, but with a low amplitude at these frequencies this effect on the dynamics is expected to be small. By prioritizing accuracy over complexity and for consistency with the Danfoss model, the 3rd order model is therefore used to compare PCPDCV behavior with different oil types.

The Laplace transform of models used is presented in equations (6) and (7).

$$G_2(s) = \frac{\omega_o^2}{s^2 + 2\zeta w_0 s + \omega_0^2} \tag{6}$$

$$G_3(s) = \frac{\omega_o^2}{s^2 + 2\zeta w_0 s + \omega_0^2} \frac{1}{\frac{1}{\omega_1} s + 1} \tag{7}$$

The parameters obtained are presented in **Table** 5.

Table 5. 2nd and 3rd order model parameters for Figure 5 and Figure 6. Frequencies are in [rad/s].

	Danfoss PCPDCV			Hawe PCPDCV		
	ω_0	ζ	ω_1	ω_0	ζ	ω_1
$G_2(s)$	47.9	0.71		61.1	1.72	
$G_3(s)$	57.6	0.45	37.3	66.7	1.79	219

Step response

The step response is obtained by applying a step signal to U and recording Y as a function of time. The step response much like the frequency response gives information about the dynamics of the valves with typical characteristics such as rise time, T_r, settling time, T_S, and overshoot, M. The step response also allows for an evaluation of the dynamics described by the linear models obtained above. **Figure 7** shows the step response for the Danfoss PCPDCV, with HLP at 40°C when stepping from U=0.25 to U=0.50 three times Y_1, Y_2 and Y_3. Y_x is the spool position during test number x. G_3 is the corresponding response of the linear model.

The step response shows an actual $T_r \in$ [0.050;0.058]s. M is so small that both M and T_S is hard to determine with the disturbance from dither and signal noise. The response from the linear model is similar to the actual response with similar rate of change and a similar overshoot but it does have 30ms larger response time.

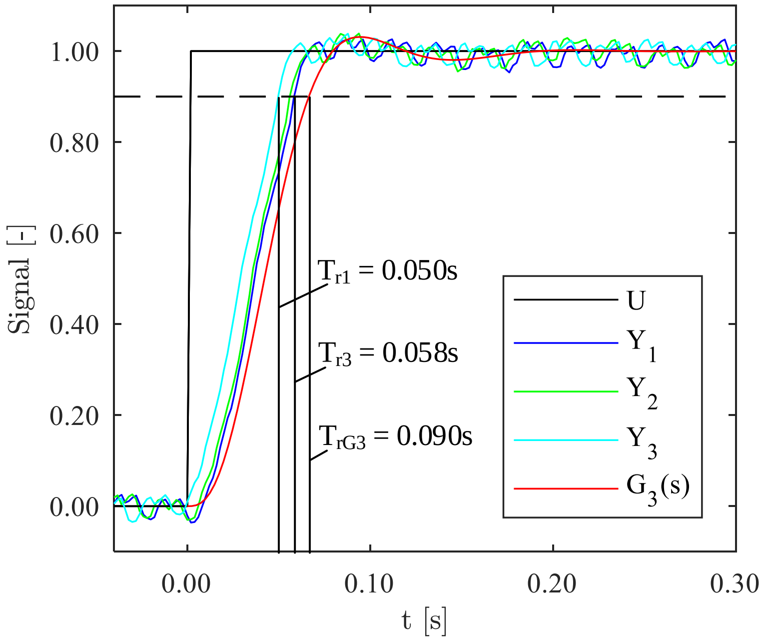

Figure 7. Normalized step response of Danfoss PCPDCV with HLP at 40°C when stepping from U=0.25 to U=0.50.

Figure 8 shows the step response for the Hawe PCPDCV, with HLP at 40°C when stepping from U=0.25 to U=0.50 three times.

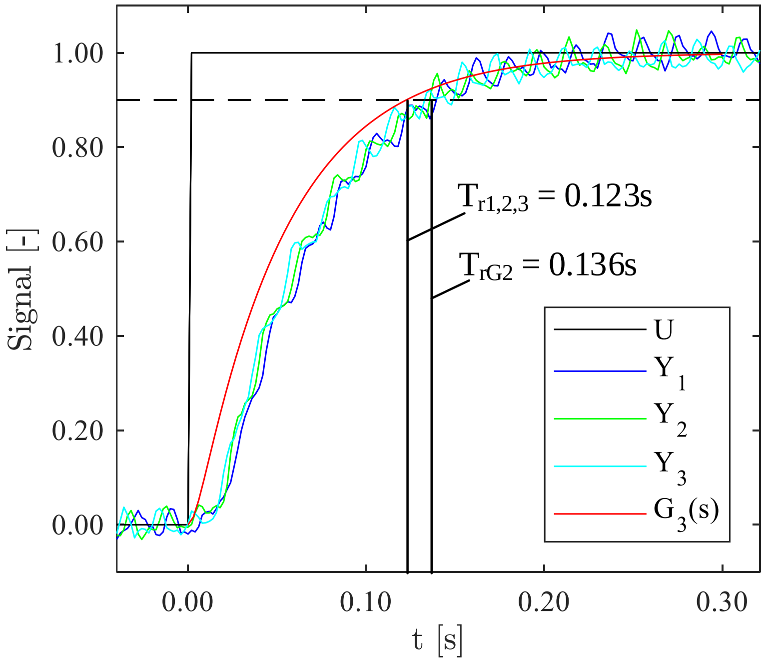

Figure 8. Normalized step response of Hawe PCPDCV with HLP at 40°C when stepping from U=0.60 to U=0.80.

All three actual step responses show similar $T_r = 0.123$s with no overshoot. The response of the linear model has a 13ms shorter response time but similar rate of change and dampening characteristics.

Both linear models reflect the overall characteristics of the actual step responses indicating that the models and their parameters capture the essence of the valve dynamics.

RESULTS

All test presented in the following have been performed at 20, 40 and 60°C,with both the Danfoss and Hawe valve, and with HLP, HEES and HEES+.

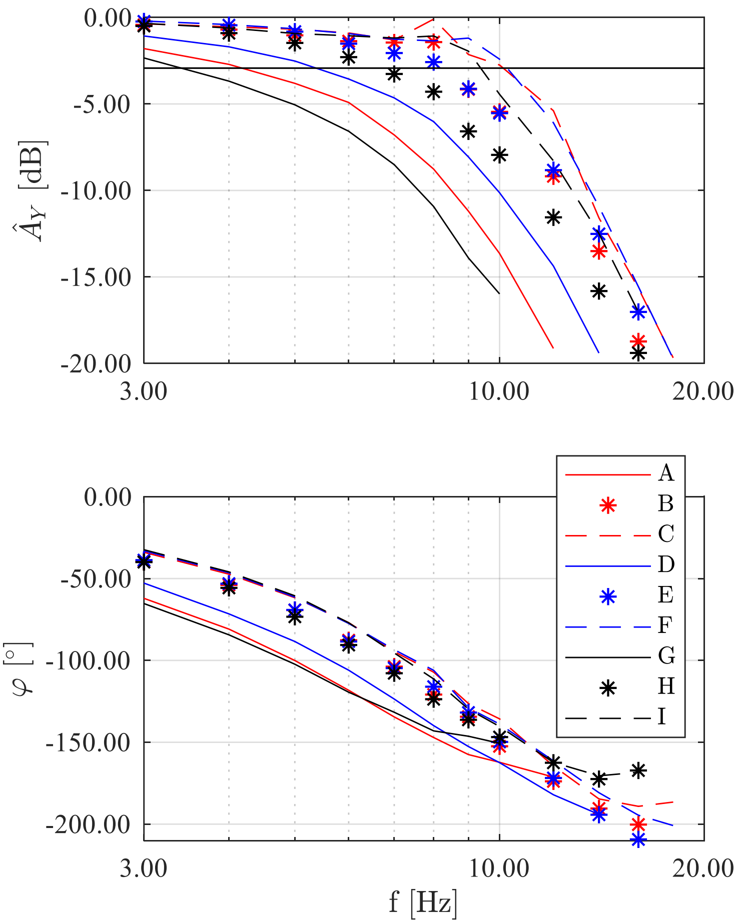

Figure 9. Frequency response for Danfoss PCPDCV at $A_U = 0.10$ with all oil types at 20°C(——), 40°C(*) and 60°C(– – –). Red is HLP, blue is HEES and black is HEES+.

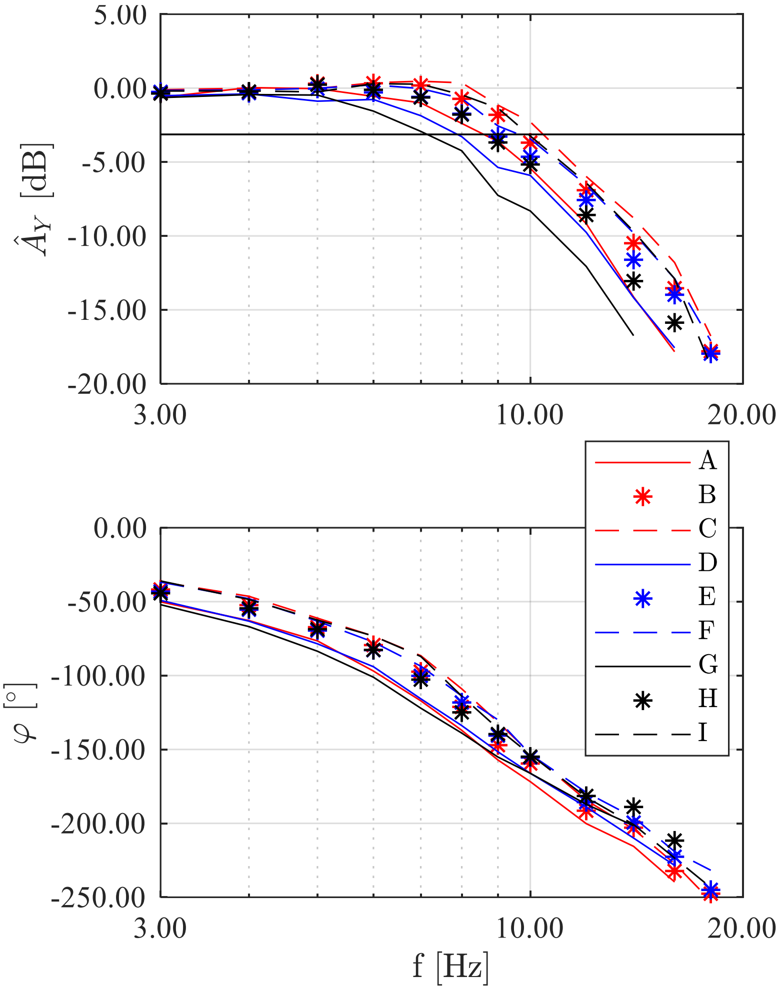

Figure 10. Frequency response for Danfoss PCPDCV at $A_U = 0.20$ with all oil types at 20°C(——), 40°C(*) and 60°C(– – –). Red is HLP, blue is HEES and black is HEES+.

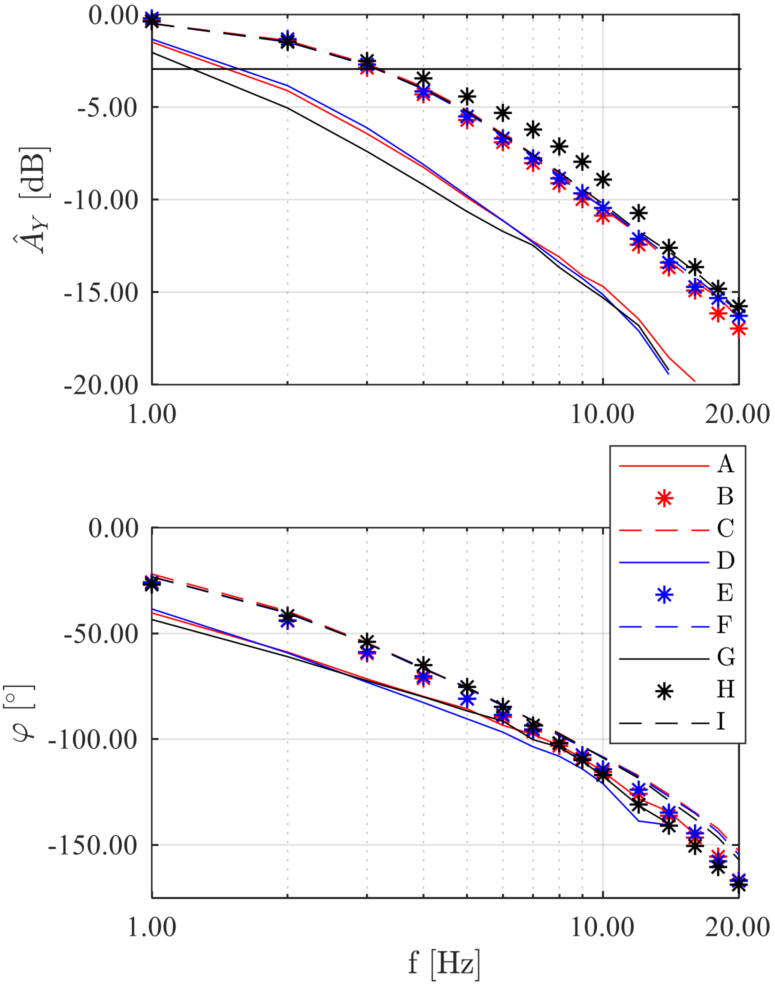

Figure 11. Frequency response for Hawe PCPDCV at $A_U = 0.10$ with all oil types at 20°C(——), 40°C(*) and 60°C(– – –). Red is HLP, blue is HEES and black is HEES+.

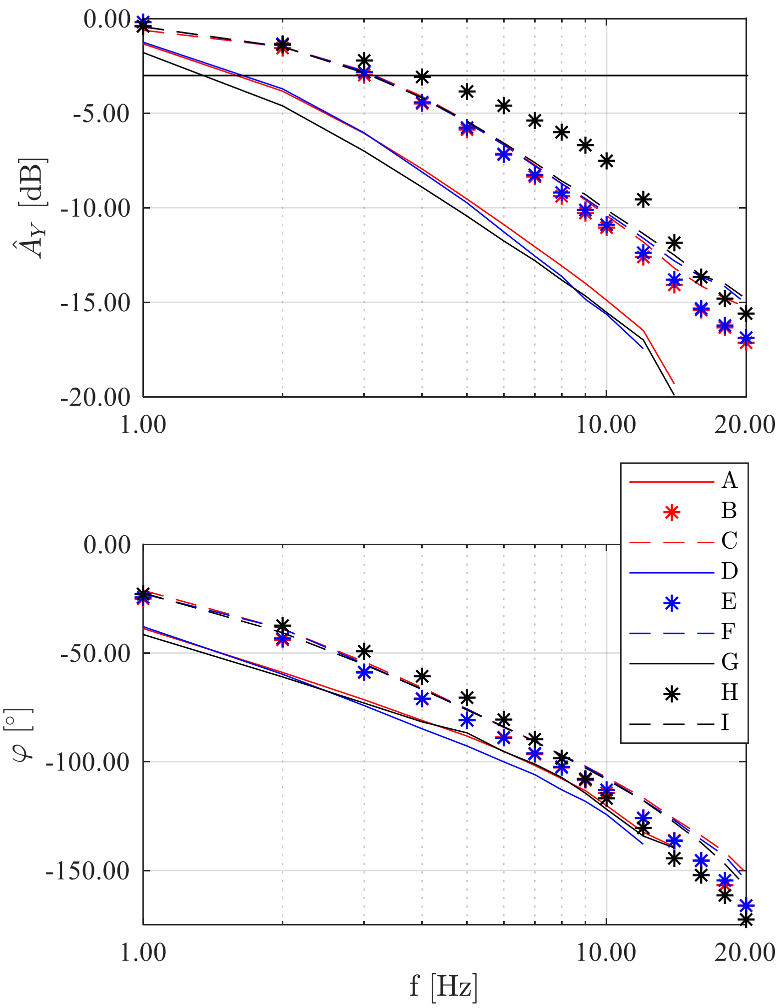

Figure 12. Frequency response for Hawe PCPDCV at $A_U = 0.15$ with all oil types at 20°C(——), 40°C(*) and 60°C(– – –). Red is HLP, blue is HEES and black is HEES+.

The frequency response plots for both valves (**Figure 9**, **Figure 10**, **Figure 11** and **Figure 12**) have been limited to -20dB in order to prevent dither- and noise-disturbances from effecting the presented data. The frequency at which $\hat{A}_Y$ crosses -3dB is called the bandwidth, ω_b. ω_b for the Danfoss and Hawe frequency responses can be found in **Table 6** and **Table 7** respectively.

The four figures show a clear trend of lower temperature leading to less amplitude and phase with 20°C leading to significantly slower responses. Oil types at same temperature have similar responses with the biggest differences at low temperature.

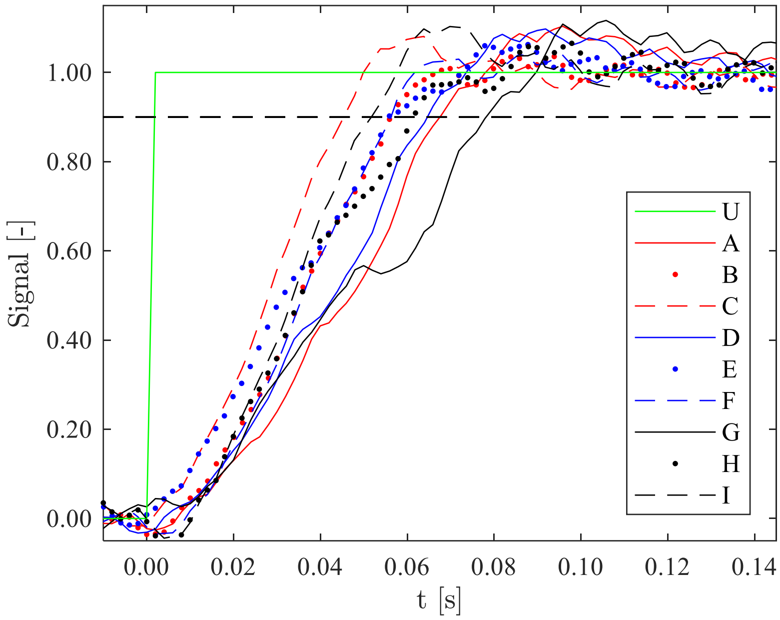

Figure 13. Step response for Danfoss PCPDCV. $\Delta U = 0.25$ with all oil types at 20°C(——), 40°C(*) and 60°C(– – –). Red is HLP, blue is HEES and black is HEES+.

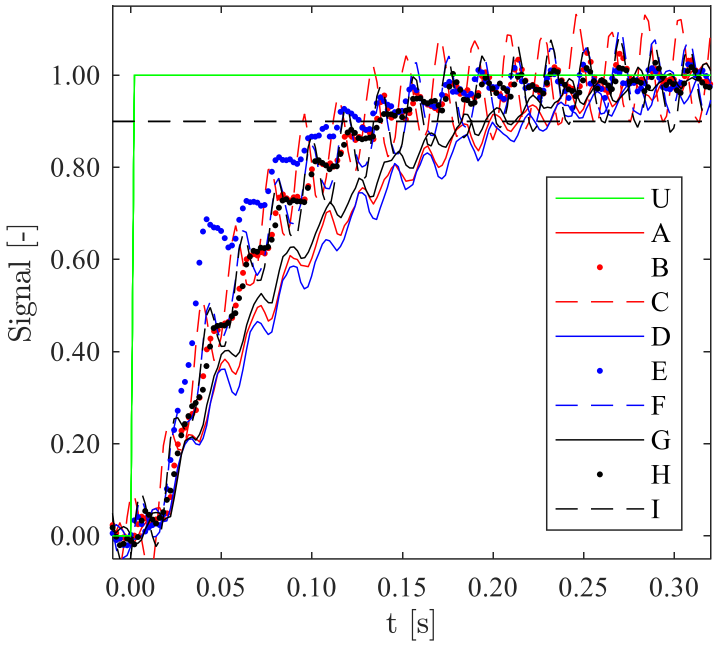

Figure 14. Step response for Hawe PCPDCV.
$\Delta U = 0.25$ with all oil types at 20°C(——), 40°C(*) and 60°C(– – –). Red is HLP, blue is HEES and black is HEES+.

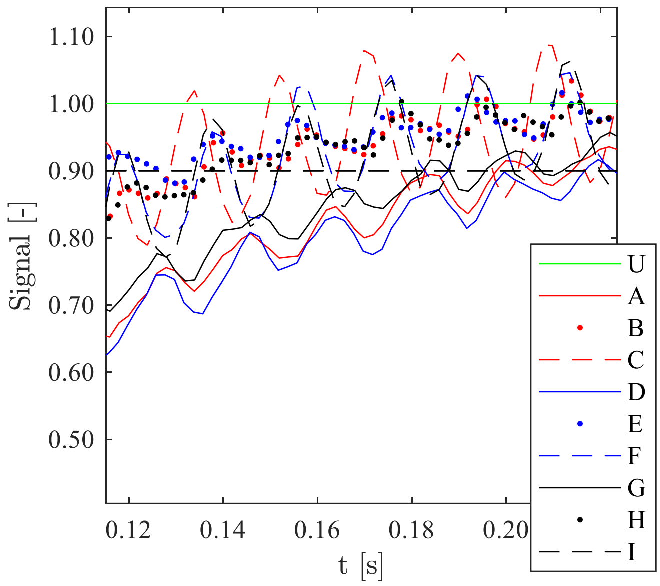

Figure 15. Zoom of Figure 14.

The step responses for both valves (**Figure 13**, **Figure 14** and **Figure 15**) show a significant local fluctuation from dither on the responses, especially the Hawe valve. The general trends do not seem to be affected by the local fluctuations, but the accuracy in reading of the response time is reduced. The response time for the Danfoss and Hawe step responses can be found in **Table 6** and **Table 7** respectively.

The step responses for both valves show slower responses at lower temperature (20°C), but only the Danfoss valve show faster responses at higher temperature (60°C). Oil types at the same temperature show similar responses with similar overshoot and raise time.

Table 6. Danfoss PCPDCV - Dynamic parameters.
ω_0[rad/s], ζ[-], ω_1[rad/s], ω_b[rad/s], f_b[Hz], T_r[s].

Danfoss PCPDCV						
	ω_0	ζ	ω_1	ω_b	f_b	T_r
20°C						
HLP	45.8	0.440	19.2	26.6	4.24	0.066
HEES	52.0	0.487	26.4	34.2	5.44	0.065
HEES+	45.1	0.695	24.0	21.7	3.46	0.078
40°C						
HLP	58.3	0.453	39.8	52.5	8.35	0.056
HEES	60.0	0.523	45.3	52.5	8.36	0.056
HEES+	53.8	0.588	42.7	42.1	6.70	0.061
60°C						
HLP	64.1	0.368	38.9	64.1	10.2	0.045
HEES	64.2	0.348	36.9	64.7	10.3	0.056
HEES+	59.9	0.376	36.5	59.1	9.40	0.052

Table 7. Hawe PCPDCV - Dynamic parameters.
ω_0[rad/s], ζ[-], ω_1[rad/s], ω_b[rad/s], f_b[Hz], T_r[s].

Hawe PCPDCV						
	ω_0	ζ	ω_1	ω_b	f_b	T_r
20°C						
HLP	52.8	2.40	243	9.36	1.49	0.206
HEES	47.0	2.15	190	9.99	1.59	0.220
HEES+	42.3	2.45	198	7.85	1.25	0.200
40°C						
HLP	66.7	1.79	219	19.4	3.09	0.136
HEES	67.3	1.74	213	20.0	3.18	0.128
HEES+	66.1	1.42	160	21.7	3.45	0.138
60°C						
HLP	68.3	1.74	216	20.4	3.24	0.138
HEES	69.0	1.76	222	20.0	3.19	0.142
HEES+	66.1	1.42	161	20.0	3.18	0.141

Table 6 and **Table 7** show the linear model parameters adapted to the frequency responses with A_U= 0.1 (**Figure 9** and **Figure 11**), the bandwidth of the same response and the raise times of **Figure 13** and **Figure 14**. The tables quantify the temperature trends observed in the figures.

Valve differences

The linear model parameters of the two valves suggest that the valve dynamics are ruled by slightly different principles. The 3rd order model used can be considered a 2nd and 1st order system in series. The 1st order system plays a much more active role in dampening the 2nd order dynamics for the Danfoss valve with $\omega_1 < \omega_0$ versus $\omega_1 > 2.5\omega_0$ for the Hawe valve. This means that the Hawe valve is mainly dampened by the dampening inherent in the 2nd order system, whereas the 2nd order dynamics of the Danfoss holds less inherent dampening which is seen from the overshoot a 40°C and 60°C in **Figure 13**. The Hawe valve is overall less sensitive to oil type but despite the differences, similar trends are seen when varying oil type for the two valves.

Temperature

The Danfoss and the Hawe valve both become slower and more dampened as the temperature is lowered from 40°C to 20°C. For the Danfoss valve T_r increases 16-27%, ω_b reduces by 34-49% and $\omega_1$reduces by 41-51%. For the Hawe valve T_r increases 45-72%, ω_b reduces by 50-64% and ζ increases by 23-73%.

At 60°C the Danfoss valve becomes faster and less damped, T_r decreases 0-20%, ω_b increases by 22-40% and ζ reduces by 18-36%. The Hawe valve shows little change from 40°C to 60°C e.g. $\Delta\omega_b < 8\%$. Note that for the Danfoss linear parameters it is mainly the 1st order system's parameters that change as the temperature is lowered and mainly the 2nd order system's parameters that change as the temperature is raised which could suggest that the mechanisms causing the change are not the same.

Oil type

The HEES oil types generally perform very similar to HLP with f_b differences of less than 1.66Hz, T_r differences less than 11% and ζ differences less 10% (excluding HEES+ at 20°C) for the Danfoss valve. HEES with the Hawe valve shows f_b, T_r and ζ differences of less than 0.34Hz, 6% and 20%.

HEES+ yields the overall slowest and most dampened responses especially at 20°C but is still within 0.8Hz of the HLP bandwidth and within 18% of the HLP response time.

DISCUSSION

The method of using linear models to describe the dynamic response of the non-linear valves is justified in the sense that the 3rd order transfer function captures the essential dynamics of the valves with a minimal complexity level yet agreeing with both frequency and step responses. Clearly, the valves are nonlinear and it could be argued that not only the bode plot but also other performance characteristics could help describe the valve dynamics. However, the results in this paper support the idea of using the bode plot as the main source for comparison. Adding zeroes could be considered to make the linear model fit more closely to the bode plot at high frequencies see **Figure 9**.

The VI and lubrication of both HEES types are better than HLP (higher ν at low temperature). The dynamic behavior of HEES deviates from HLP especially at low temperature, and the ν and lubrication properties do not explain this. These two properties would be expected to cause higher bandwidth and less dampening than HLP, but HEES+

has significantly lower bandwidth and higher dampening than HLP. Therefore, deviations from HLP at low temperature must be caused by other properties.

This is further supported by the similarity in the behavior of the two valves. The Danfoss valve is closed loop compensated and would be expected to dampen the position disturbance caused by friction, which the Hawe valve should not.

If the deviations originate from tribology related phenomena, more deviation would be expected between oil types used with the Hawe PCPDCV when compared to the deviations between oil types used with the Danfoss PCPDCV. This is not the case, thus also suggesting that lubrication is not the main factor causing the deviations.

HEES and HEES+ have similar ρ and the property can thus by itself not make HEES behave differently from HEES+. This means that neither of the two classic liquid properties ν can ρ can by themselves explain the deviations at 20°C.

CONCLUSION

A method for evaluation of oil type effects on PCPDCV dynamics has been presented. HEES has been evaluated on valves with and without closed loop spool position control, and deviations have been found to be less than 1.66Hz on f_b and 17% on T_r and in most cases a deviation on ζ of less than 20% for both valve types.

It is important to stress that this work puts emphasis on commercially available components and information that is relevant to a system designer. This is reflected in the chosen method and the hypothesis that has been put forward. The variations in performance should therefore be considered in relations to the system in which the valve is applied. For any system with an operator-in-the-loop the observed variations in bandwidth and dampening are of limited importance when at between 40°C and 60°C. The changes to valve dynamics are significantly larger when changing temperature from 40°C to 20°C than when comparing the two HEES types to HLP at constant temperature. This suggests that the HEES dynamics deviations are within an order that would often be absorbed by the robustness in systems designed for variations in temperature.

The reduction in bandwidth experienced with the HEES+ at 20°C suggests more detailed studies should be conducted to identify the cause.

The investigation in this paper indicates that the dynamic characteristics change in a way which cannot be explained with variations in any single of the two classic liquid properties density and viscosity.

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