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The study of the impact of oil type and throttling pressure on the vibrations of a gear pump

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ABSTRACT

The aim of the article is to demonstrate the impact of the type of pumped oil on the values of vibrations expressed by acceleration. Three groups of oils were examined: engine oils, hydraulic oils, and gear oils. The research methodology focused on measuring the average vibrations expressed by acceleration and the dynamics of vibrations expressed by acceleration for a fixed throttling pressure. The analysis of the results showed that the viscosity of the oil (ν) has a significant effect on the average vibrations expressed by acceleration value (avg. R) in the group of oils intended for internal combustion engines, with $p = 0.0285$, while the impact of pressure (p) on avg. R was not statistically significant ($p = 0.0799$). However, for the dynamics of peak-to-peak acceleration (ΔR), pressure had a significant impact ($p = 0.00001$), while viscosity was not significant ($p = 0.9490$). In the groups of hydraulic and gear oils, none of the examined parameters showed a significant effect on avg. R. Pressure changes were significant only concerning ΔR in these groups. The highest ΔR values occurred at 0 bar pressure, indicating the impact of pressure on changes in vibrations expressed by acceleration. It was also analyzed that differences in the chemical composition of oils, although subtle, affect their physicochemical properties, which are important for cavitation occurrence and vibrations in the pump. Ultimately, selecting the appropriate oil, such as H2, significantly improves pump performance, which is crucial in hydraulic applications where operating pressure ranges from 100 to 300 bar. The findings also provide valuable insights for industrial applications, particularly in the diagnostics of oil production installations and the design of pipelines for packaging and transporting oils. By understanding the relationship between oil properties, cavitation, and pump vibrations, engineers can optimize system performance, extend equipment lifespan, and ensure more reliable operation under varying pressure conditions.

Keywords: pump vibrations, hydraulic pumps, kinematic forces, kinematic characteristics of the pump.

INTRODUCTION

Vibration analysis plays a crucial role in assessing the longevity and performance of pumps used in mechanical and hydraulic systems. Monitoring vibrations allows for the evaluation of hydraulic system operation and the selection of optimal operating parameters [1]. Vibrations caused by dynamic loads, imbalance, or improper installation can lead to premature wear of components such as bearings, seals, and rotors [2]. Furthermore, in the case of pumps lubricated by the pumped fluid, the properties of that fluid can also affect the pump's operational characteristics and lead to accelerated wear [3]. Regular vibration monitoring enables the detection of anomalies and the identification of potential issues before they result in failure [4, 5]. However, in production environments, equipping hydraulic systems with monitoring equipment for parameters unrelated to the hydraulic process is often unfeasible [6]. Therefore, access to studies describing how operational factors impact the vibrations expressed by acceleration of the pump during operation is essential. This knowledge will facilitate the selection of hydraulic system operating parameters during the configuration stage of the technological process. Choosing optimal operating parameters helps avoid prolonged exposure to high vibration levels, which also results in reduced pump efficiency, increased energy consumption, and decreased system effectiveness. Through vibration analysis, it is possible to optimize the operating parameters of pumps, contributing to their extended service life, reliability, and reduced maintenance and repair costs.

The appropriate selection of oil plays a key role in reducing vibrations and improving the efficiency of pump operation, especially under challenging conditions of high loads and variable pressures. Oils with suitable viscosity and lubricating properties can effectively dampen vibrations [7], that arise from the operation of mechanical components [8, 9]. Proper viscosity allows for the formation of a stable oil film, which minimizes metal-to-metal contact [10], a critical factor in preventing micro-vibrations and reducing frictional forces. Additionally, oils with special anti-wear [11] and antioxidant additives enhance the pumps' resistance to changing operating conditions [12], allowing for more efficient and stable performance. In the case of high loads, oils with higher viscosity can improve damping and limit micro-vibrations, significantly impacting the device's longevity and reducing maintenance costs. With the appropriate oil selection, it is possible not only to increase the energy efficiency of the system but also to reduce downtime resulting from pump failures and wear during prolonged operation.

The viscosity and the presence of appropriate chemical additives in oils significantly impact their resistance to phenomena such as cavitation and oxidation, as well as the amplitude and dynamics of vibration excitations. The viscosity of the oil is a crucial factor that determines the lubrication ability and the formation of a stable oil film, which protects the working surfaces of pumps from direct contact, thereby preventing the generation of high vibration amplitudes and accelerated wear [13–15]. High-performance antioxidant additives extend the oil's lifespan in demanding conditions by preventing the formation of deposits and stabilizing its properties even at high temperatures [16]. In turn, anti-cavitation additives minimize the risk of cavitation bubble formation, which can lead to violent micro-explosions and increased vibration amplitudes, causing micro-damages to mechanical surfaces [17–19]. Reducing cavitation and stabilizing oil viscosity contribute to smoother and more stable pump operation, which not only enhances their efficiency but also significantly extends their service life. Well-chosen lubricating additives and viscosity modifiers [20] ensure dynamic balance in pump operation, effectively minimizing the impact of variable loads and pressures [21], while also reducing vibration amplitudes, thereby contributing to noise reduction and increasing system reliability [22, 23].

Considering the above, conducting a study on the impact of oil type on vibrations expressed by acceleration is essential due to the increasing demands for performance and efficiency related to pumping oils with different properties through a single pump. This issue arises in companies that produce oils where various types of oils are pumped using one hydraulic system. In such cases, it is not feasible to create a dedicated hydraulic system. However, it is possible to prepare tailored pumping parameters for the oil. Understanding how viscosity and pressure affect the dynamics of excitations will enable the optimization of operational parameters for hydraulic systems. The problem presented is a broad issue encompassing a wide range of operational parameters. Therefore, this study focuses on analyzing the impact of oil viscosity and throttling pressure on the dynamics of vibrations expressed by acceleration and the average value of vibrations expressed by acceleration across different groups of oils: engine oils, hydraulic oils, and transmission oils. The research aims to identify statistically significant relationships between these parameters and the type of oil. The results obtained will contribute to a better understanding of the impact of oil and its properties on vibrations expressed by acceleration. Understanding this phenomenon is crucial for correctly developing operational parameters for hydraulic systems.

METHOD AND MATERIALS

The testing setup used for the study (Fig. 1) consisted of an oil reservoir filled with the oil being tested (1). The reservoir was equipped with a

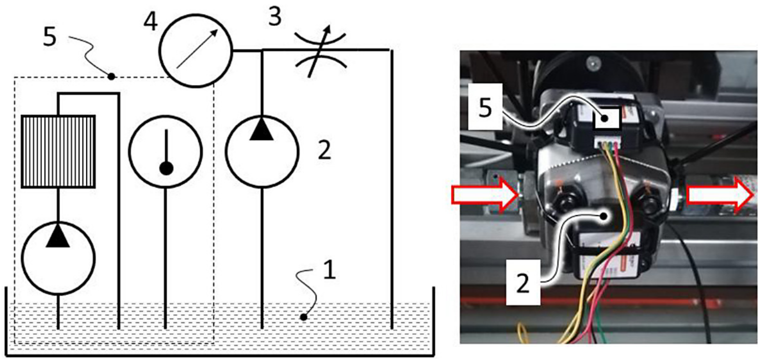

Figure 1. The hydraulic diagram of the measurement setup used and a fragment of its implementation illustrating the position of the accelerometer are shown below. Where: 1 – oil reservoir with the tested oil, 2 – pump for which vibrations expressed by acceleration were analyzed, 3 – throttling valve, 4 – pressure gauge, 5 – oil cooling system (pump, cooler, thermometer)

cooling system (5) that maintained the tested oil at a constant temperature ranging from 293.15 K to 303.15 K. A gear pump (2) model 1.40.09.00.105, manufactured by Agricola Hydraulika Siłowa Sp. z o.o. Sp. k. (Lubień Kujawski, Poland), was used for the study. This pump is characterized by a maximum flow rate of 1.65 l/min (at 1500 rpm). During the tests, it operated at the recommended rotational speed of 2000 rpm. Downstream in the series configuration, a pressure gauge (4) and a throttling valve (3) were installed, allowing for the control of throttling pressure p. An accelerometer (5) used for the study was mounted in accordance with the standard PN-EN ISO 5349-1:2004 "Measurement and Assessment of Human Exposure to Hand-Arm Vibration – Part 1: General Requirements" with its installation location being the upper part of the pump body, between the inlet and outlet pipes.

The tests were conducted using a proprietary vibrations expressed by acceleration measurement system equipped with an inertial accelerometer KIONIX kx023 (with a resolution of 0.009576801 m/s² and a measurement range of 78.4532 m/s²), a data archiving system, and a power supply system. The mass of the measurement system did not exceed 100 g, making it negligibly small compared to the mass of the tested objects. The accelerometer was permanently mounted to the pump body using a thick double-sided tape with a rubber layer, which had a hardness of 40–50 on the Shore A scale. This rubber layer, as part of the tape, allowed the flat base of the accelerometer to conform to the curved surface of the pump. The properties of the tape, including its ability to adapt to irregular surfaces, are comparable to those of wax recommended by the PN-EN ISO 5349-1:2004 standard, ensuring a stable connection and proper vibration transmission. Using the accelerometer, linear accelerations a_x, a_y, and a_z were measured along the three axes of the XYZ coordinate system (Fig. 2a). Since the Y-axis was perpendicular to the surface on which the pump setup was placed, the gravitational acceleration g was subtracted from the a_y signal. Using the signal measured from each measurement trial, the measurement signal lasting from t_0 to t_1 was isolated, with this interval lasting 10 seconds for each tested variant of the independent variable. From the isolated signals, the magnitude of the vibrations expressed by acceleration vector R was calculated (1) (Fig. 2b). Subsequently, for the time sample lasting t = <t_0; t_1>, the average vibrations expressed by acceleration avg R was calculated (2) (Fig. 2c). Additionally, the isolated sample was searched for maximum R_{max} and minimum R_{min} values, based on which the peak-to-peak acceleration value ΔR was computed (3).

$$R(t) = \sqrt{a(t)_x^2 - \left(a(t)_y - g\right)^2 a_z^2} \tag{1}$$

$$avg.R = \frac{\sum_{i=0}^{n} R(t)_n}{n} \tag{2}$$

$$\Delta R = R_{max} - R_{min} \tag{3}$$

where: $R(t)$ – vibrations expressed in acceleration as a function of time, t – time of the signal measurement from the accelerometer, a_x – acceleration on the X-axis, a_y – acceleration on the Y-axis, a_z – acceleration on the Z-axis, g – gravitational acceleration, n – number of samples isolated from the time interval t = <t_0; t_1>, dependent on measurement frequency, ΔR – value of

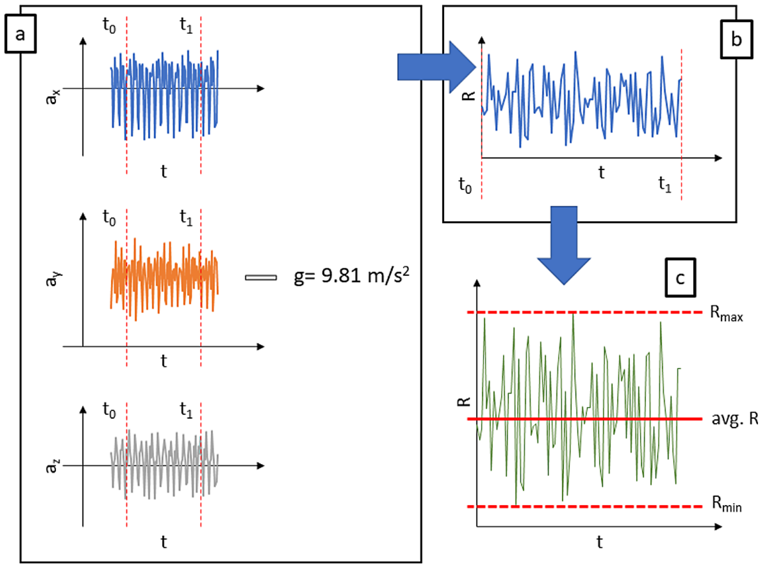

Figure 2. Signal processing diagram used in the study, where: a – raw data collected from the accelerometer, b – function of vibrations expressed in acceleration magnitude over time t, c – indication of physical values used in the analysis

the peak-to-peak acceleration value, R_{max} – maximum value of vibrations expressed in acceleration for the time interval $t = <t_0; t_1>$, R_{min} – minimum value of vibrations expressed in acceleration for the time interval $t = <t_0; t_1>$.

The study analyzed the effect of oil type (defined by oil group and kinematic viscosity) and throttling pressure on the value of vibrations expressed in acceleration variation, defined as the peak-to-peak acceleration value ΔR, and the average vibrations expressed in acceleration avg R. Throttling pressure was varied from 0 to 200 bar at 50-bar intervals, adjusted using a throttling valve. Thus, even with the valve fully open, residual throttling occurred due to fluid flow resistance through the pump and hydraulic channels, though this pressure was negligibly small.

Three oil groups were used in the study: engine oils (C) (Table 1), hydraulic oils (H) (Table 2), and gear oils (G) (Table 3). Each tested oil was described by its kinematic viscosity ν at a temperature of 298.15 K.

RESULTS AND DISCUSSION

The statistical significance analysis based on collected data (Tables 4–6) showed that, within the group of engine oils (Group C), oil viscosity (ν) significantly impacts the mean value of average vibrations expressed in acceleration (avg. R) [24–26], with a statistical significance level of $p = 0.0285$. In contrast, the impact of pressure (p) on this mean value is not statistically significant ($p = 0.0799$). Regarding the parameter evaluating

Table 1. Summary of the engine oil group (Group C) used in the study, along with their designations and viscosity parameters

Sample no.	Kinematic viscosity at 25 °C	SAE Viscosity Grade/ trade designation	Manufacturing company	Trade name	City, Country
C1	65.02	5W/20	Mannol (SCT-Vertriebs GmbH)	Energy Ultra JP	Wedel, Niemcy
C2	99.39	0W/30	Mannol (SCT-Vertriebs GmbH)	Legend Extra	Wedel, Niemcy
C3	229.82	15W/40	Mannol (SCT-Vertriebs GmbH)	Universal	Wedel, Niemcy
C4	280.50	20W/50	Orlen Oil (Orlen Group)	Lubro	Trzebinia, Polska
C5	320.75	10W/60	Liqui Moly	Synthoil Race Tech GT1	Ulm, Niemcy

Table 2. Summary of the hydraulic oil group (Group H) used in the study, along with their designations and viscosity parameters

Sample no.	Kinematic viscosity at 25 °C	SAE Viscosity Grade/ trade designation	Manufacturing company	Trade name	City, Country
H1	58.73	L-HL 32	Orlen Oil (Orlen Group)	Hydrol	Trzebinia, Polska
H2	87.79	HL 46	Flukar sp. z o.o.	Revline	Katowice, Polska
H3	118.65	PAO 68	Airstal sp. z o o.	Hart	Koluszki, Polska

Table 3. Summary of the gear oil group (Group G) used in the study, along with their designations and viscosity parameters

Sample no.	Kinematic viscosity at 25 °C	SAE Viscosity Grade/ trade designation	Manufacturing company	Trade name	City, Country
G1	269.68	GL-4	Orlen Oil (Orlen Group)	Hydrol	Trzebinia, Polska
G2	295.70	80W/90	Flukar sp. z o.o.	Revline	Katowice, Polska
G3	784.50	GL-5	Airstal sp. z o o.	Hart	Koluszki, Polska

Table 4. Summary of measurement Results for average vibrations expressed in acceleration (avg. R) and dynamics of peak-to-peak acceleration value (ΔR) for the group of engine oils

Group of oils	Sample numberl	p	v	avg. R	ΔR
-	-	*bar*	*m2/s*	*m/s2*	*m/s2*
C	C1	0	65.02	0.707803	1.546946
C	C1	50	65.02	0.649722	1.366195
C	C1	100	65.02	0.597885	1.002945
C	C1	150	65.02	0.671553	0.743593
C	C1	200	65.02	0.667677	0.631065
C	C2	0	99.39	0.795443	1.652051
C	C2	50	99.39	0.853666	1.657449
C	C2	100	99.39	0.790481	1.146464
C	C2	150	99.39	0.750909	0.545612
C	C2	200	99.39	0.684429	0.729953
C	C3	0	229.82	0.884775	1.250701
C	C3	50	229.82	0.585991	1.210904
C	C3	100	229.82	0.770225	1.254199
C	C3	150	229.82	0.674881	1.19722
C	C3	200	229.82	0.682634	0.517635
C	C4	0	280.5	0.6919	1.617906
C	C4	50	280.5	0.632478	1.107282
C	C4	100	280.5	0.770225	1.254199
C	C4	150	280.5	0.651043	0.785301
C	C4	200	280.5	0.621175	0.608122
C	C5	0	320.75	0.80261	1.718705
C	C5	50	320.75	0.479997	1.089384
C	C5	100	320.75	0.526186	1.088523
C	C5	150	320.75	0.612717	0.722532
C	C5	200	320.75	0.60963	0.659473

Table 5. Summary of measurement results for average vibrations expressed in acceleration (avg. R) and peak-to-peak acceleration value (ΔR) for the group of gear oils

Group of oils	Sample number	p	v	avg. R	ΔR
-	-	*bar*	*m2/s*	*m/s2*	*m/s2*
G	G1	0	269.68	0.492749	1.190071
G	G1	50	269.68	0.655067	1.125212
G	G1	100	269.68	0.877559	0.564051
G	G1	150	269.68	0.62265	0.620263
G	G1	200	269.68	0.569657	0.704219
G	G2	0	295.7	0.553624	1.508042
G	G2	50	295.7	0.706355	1.008048
G	G2	100	295.7	0.676032	0.925241
G	G2	150	295.7	0.624124	0.597107
G	G2	200	295.7	0.576629	0.584564
G	G3	0	784.5	0.566813	1.543006
G	G3	50	784.5	1.027328	0.87563
G	G3	100	784.5	0.72245	0.733461
G	G3	150	784.5	0.597058	0.593973
G	G3	200	784.5	0.567227	0.598936

Table 6. Summary of measurement results for average vibrations expressed in acceleration (avg. R) and peak-to-peak acceleration value (ΔR) for the group of hydraulic oils

Group of oils	Sample numberl	p	v	avg. R	ΔR
-	-	*bar*	*m2/s*	*m/s2*	*m/s2*
H	H1	0	58.73	0.807573	1.499218
H	H1	50	58.73	0.689531	1.473353
H	H1	100	58.73	0.829786	0.767734
H	H1	150	58.73	0.619506	0.836423
H	H1	200	58.73	0.618389	0.461278
H	H2	0	87.79	0.586244	1.079496
H	H2	50	87.79	0.941261	1.507539
H	H2	100	87.79	0.359793	1.188513
H	H2	150	87.79	0.314715	0.562596
H	H2	200	87.79	0.273828	0.629562
H	H3	0	118.65	0.668571	1.595581
H	H3	50	118.65	0.618477	1.392514
H	H3	100	118.65	0.758761	0.796071
H	H3	150	118.65	0.537533	0.792182
H	H3	200	118.65	0.494972	0.637077

the dynamics of peak-to-peak acceleration value (ΔR), statistical analysis revealed [27], that pressure (p) has the greatest impact, with a statistical significance of p = 0.00001, an observation supported by other researchers' findings [28]. However, viscosity (ν) does not significantly impact the value of ΔR (p = 0.9490). In the case of hydraulic oils (Group H), neither viscosity (ν) (p = 0.2094) nor pressure (p = 0.1575) had a statistically significant effect on the mean average vibrations expressed in acceleration (avg. R). The analysis of the impact on the dynamics of peak-to-peak acceleration value (ΔR) for this group showed that only pressure (p) has a statistically significant effect on the peak-to-peak acceleration value (p = 0.0022). Viscosity (ν) does not significantly affect changes in ΔR for Group H oils ($p = 0.9248$) [29]. For the gear oils group (Group G), no statistically significant impact of any of the tested parameters on the average vibrations expressed in acceleration (avg. R) was observed. The statistical significance for pressure was $p = 0.0672$, which is close to the significant threshold (< 0.05). Analyzing the peak-to-peak acceleration value (ΔR) for Group G oils revealed the same dependency as in the other groups, i.e., a change in pressure (p) significantly affects this parameter ($p = 0.005$). In the case of Group G oils, as with the other groups, viscosity (ν) does not significantly affect the value of ΔR ($p = 0.6546$). The statistical analysis conducted demonstrates that, across all oil groups (C, G, H), pressure (p) changes are significant in peak-to-peak acceleration value.

The results of the peak-to-peak acceleration value (ΔR) as a function of pressure changes (p) for the group of oils intended for internal combustion engines are presented in the graphs in Fig. 3. These characteristics are approximated using a trend line that is a second-degree polynomial described by the parameters a, b, and c (4). The statistical parameters of the characteristics are included in Table 7.

$$\Delta R(p) = a \cdot p^2 + b \cdot p + c \quad (4)$$

The group of oils designed for internal combustion engines (C) exhibited a dependence of the ΔR value on the change in pressure p. The highest values of the dynamics of changes in kinematic forces ΔR were measured for all tested samples at a pressure of p equals 0 bar, which corresponds to an undamped flow. Conversely, the lowest ΔR values were measured for all tested samples at a pressure of p equals 200 bar. The highest ΔR value was obtained for oil C5, which was 1.72 m/s^2 at a pressure of p equals 0 bar. It should be noted that for the same pressure, the lowest value measured was 1.25 m/s^2 for oil C3. Oil C3 was the only one with a different characteristic shape,

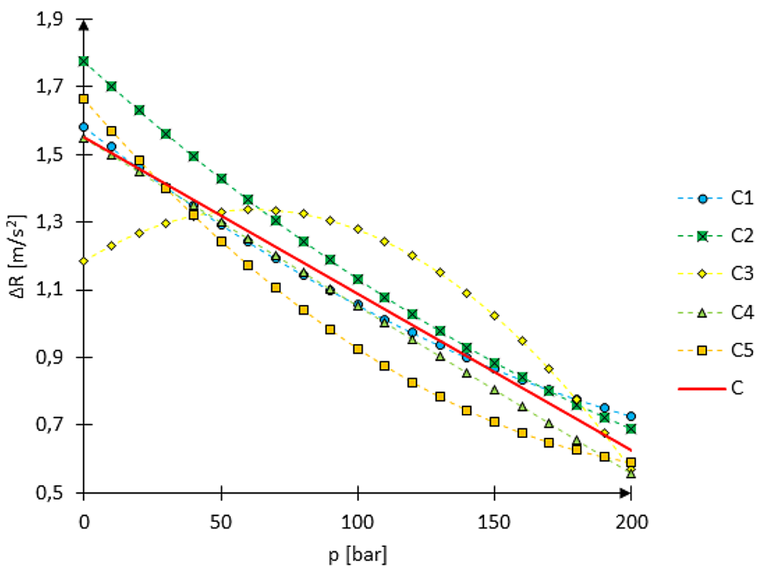

Figure 3. The characteristics of the function ΔR(p) for the entire group of oils C and the different oil samples C1-C5 tested within this group are summarized below

Table 7. Summary of the parameters of the characteristic ΔR(p) for the group of oils C

Parameter	Sample number					
	C1	*C2*	*C3*	*C4*	*C5*	*C*
a	0.00001	0.00001	-0.00004	0.00000	0.00002	0.00000
b	0.00628	0.00744	0.00493	-0.00497	-0.00936	-0.00463
c	1.58336	1.77580	1.18497	1.55017	1.66241	1.55134
p-value (a)	1.95e-05	0.00026	1.49e-05	0.00063	2.61e-05	2.22e-16
p-value (b)	0.00092	0.01141	0.00517	0.00808	0.00265	2.22e-16
p-value (c)	0.00651	0.03738	0.03738	0.04491	0.02613	1.21e-13

which was convex (Fig. 3), in contrast to the others that were concave. In the case of this oil, the ΔR value remained constant up to a pressure of p equals 100 bar, and only above this pressure did it begin to decrease. Referring to the minimum value of ΔR for all tested samples, it was achieved at a pressure of p equals 200 bar. Globally, for the entire group C, the lowest ΔR value was measured for oil C3, which was 0.52 m/s^2. At a pressure of p equals 200 bar, the maximum ΔR value was measured for oil C2, which was 0.73 m/s^2.

The characteristics of ΔR for the group of hydraulic oils are presented in the graphs in Figure 4. These characteristics were approximated by a trend line represented by a second-degree polynomial described by the parameters a, b, and c (5). The statistical parameters of the characteristics are included in Table 8.

$$\Delta R(p) = a \cdot p^2 + b \cdot p + c \quad (5)$$

For the hydraulic oils (H), pressure also causes a decrease in the peak-to-peak acceleration value ΔR. For this group, it was observed that the highest values of ΔR occur for the sample H3, measuring 1.60 m/s^2 at a pressure of p = 0 bar. Notably, the sample H2, which is the oil dedicated for use in the pump tested, recorded the lowest value of ΔR at a pressure of p = 0 bar, which was 1.08 m/s^2. This oil, unlike the others in group H, also maintained a similar level of ΔR within the pressure throttling range from 0 bar to 10 bar. In group H, it was measured that the increase in pressure translates into a reduction of ΔR, which minimally reached 0.46 m/s^2 at a pressure of p = 200 bar for oil H1. In this group, it can be stated that the viscosity of the oil correlates with ΔR at p = 200 bar. This correlation indicates that the lower the viscosity ν, the lower the value of ΔR. The last analyzed group of oils consisted of transmission oils, and their characteristics of ΔR are presented in Figure 5. For these oils, a trend line approximation was applied in the form of an exponential function described by the parameters a and b (6). The statistical parameters of the characteristics are included in Table 9.

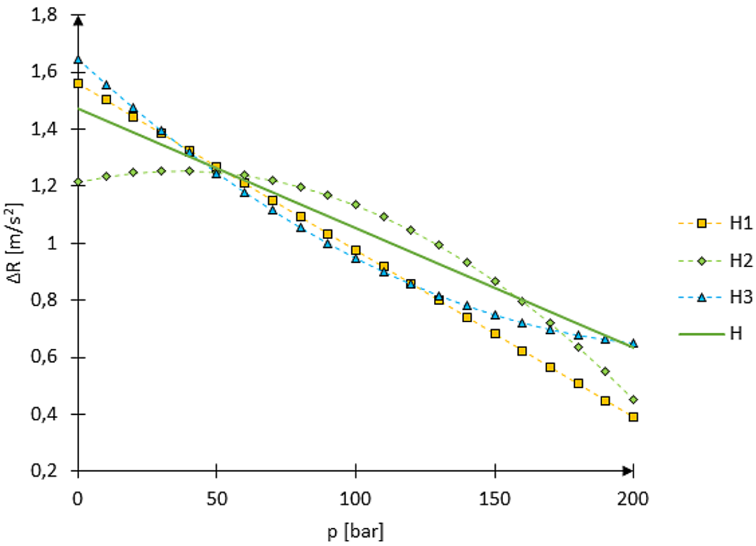

Figure 4. Summary of the characteristics of the function ΔR(p) for the entire group of hydraulic oils (H) and the various samples of oils H1-H3 tested within this group

Table 8. Summary of the parameters of the characteristic ΔR(p) for the group of hydraulic oils (H)

Sample number				
	H1	H2	H3	H
a	0.00000	-0.00003	0.00002	0.00000
b	-0.00586	-0.00219	-0.00897	-0.00421
c	1.56098	1.21550	1.64451	1.47366
p-value (a)	0.00057	8.23e-05	2.82e-05	2.22e-16
p-value (b)	0.00907	0.04640	0.00269	3.09e-11
p-value (c)	0.05838	0.13851	0.02568	3.47e-07

$\Delta R(p) = a \cdot e^{(b \cdot p)}$

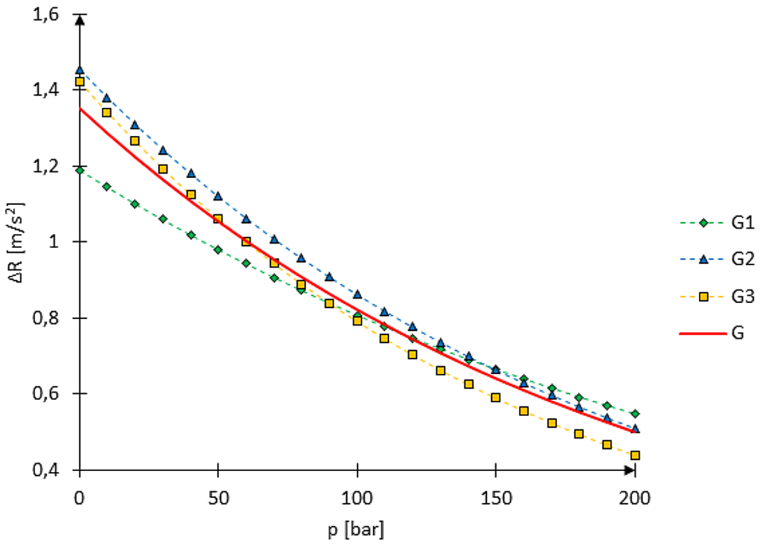

Figure 5. Summary of the characteristics of the function ΔR(p) for the entire group of oils G and the various samples of oil G1-G3 studied within this group

$$\Delta R(p) = a \cdot e^{(b \cdot p)} \quad (6)$$

Similar to the other groups, the transmission oils (G) also show a reduction in dynamic forcing ΔR [30]. In this group, oil G3 exhibited the highest kinematic forcing dynamics ΔR, measured at 1.54 m/s^2 at a throttling pressure of 0 bar. At the same pressure, oil G1 displayed a ΔR of 1.19 m/s^2. Compared to the other groups, transmission oils showed the least variation. This is further confirmed by analyzing the upper throttling pressure limit of 200 bar, where ΔR values were: 0.70 m/s^2 for G1, 0.58 m/s^2 for G2, and 0.60 m/s^2 for G3. Examining the characteristics of oils from group G revealed that the decrease in ΔR is closely related to the throttling pressure. The characteristics follow a concave trend, with a noticeable inflection point at 100 bar, beyond which the change in ΔR as a function of p becomes more gradual.

Despite being categorized into different groups, the tested oils also varied within each group. These differences were due to chemical composition [31, 32], which is protected as a trade secret. Variations in chemical composition affected the physico-mechanical properties, influencing the occurrence of cavitation at different

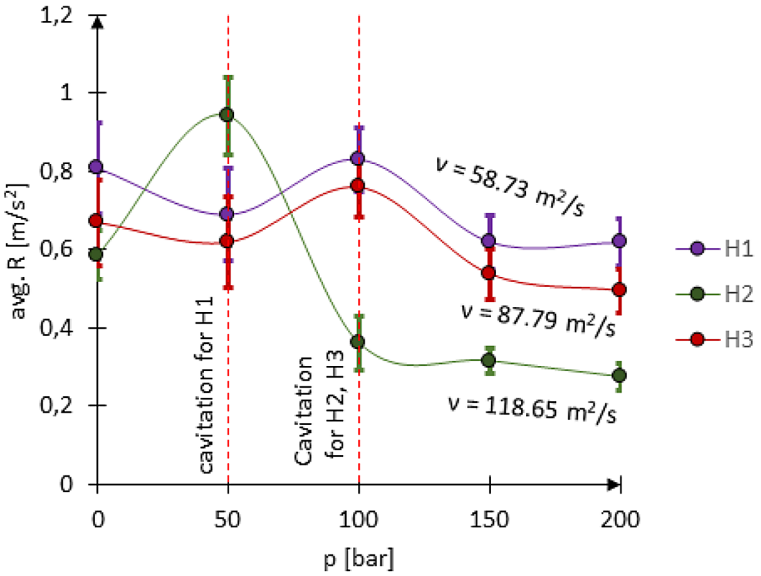

Figure 6. Summary of the change in average vibrations expressed in acceleration avg. R as a function of pressure change for hydraulic oils

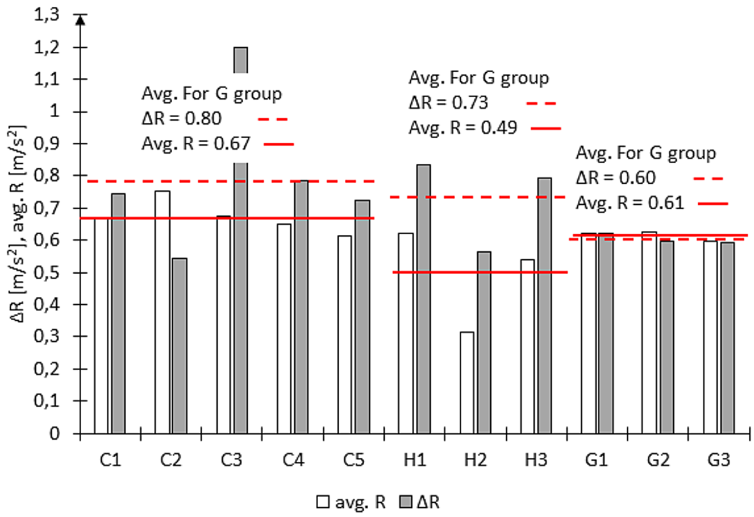

Figure 7. Summary of avg. R and ΔR values for the tested oils, with indication of averaged values for the entire oil groups at throttling with a pressure of p = 150 bar

throttling pressures. An example of this observation is demonstrated with hydraulic oils designed for gear pumps (Fig. 6). In the study, the oil recommended by the manufacturer for the pump used was oil H2. In the context of the described oils and the pump tested, we are not discussing full cavitation but rather localized micro-cavitation [33, 34] associated with turbulent flow or low-pressure cavitation [35, 36].

Analyzing the characteristics of oils in group H reveals that the selection of physicochemical properties of the oil directly impact s the pump's operating characteristics. For hydraulic systems, the typical working pressure ranges from 100 to 300 bar. Within the discussed vibrations expressed in acceleration characteristics for group H oils, only one oil (H2) generates the lowest average vibrations expressed in acceleration avg. R when pumping above 100 bar. Oil H2 is specifically recommended for the pump used in the study; therefore, the internal geometry of the pump was optimized to best accommodate its viscosity and viscous friction [37]. Additionally, cavitation for this oil occurred at a pressure of 50 bar, which falls outside the normal operating range for hydraulic systems. In contrast, for oils H1 and H3, local micro-cavitation was observed around 100 bar, aligning with the operating range of the hydraulic system.

Comparing all the oils tested (Fig. 7) at a pressure of 150 bar, it was observed that hydraulic oils (group H) produced the lowest average vibrations expressed in acceleration avg. R, with an average across the group of 0.49 m/s^2. Notably, oil H2, specifically recommended for the gear pump, significantly lowered this average, and its avg. R and ΔR values deviated markedly from those of oils H1 and H3. Additionally, group H showed the second-highest value for peak-to-peak acceleration value ΔR, which amounted to 0.73 m/s^2. For comparison, for engine oils (group C), the ΔR value was 0.80 m/s^2. An interesting impact on vibrations expressed in acceleration was observed with transmission oils (group G). As a group, these oils generated average vibrations expressed in acceleration avg. R at the level of 0.61 m/s^2, representing the second-highest result among all groups tested. However, the peak-to-peak acceleration value ΔR for these oils was the lowest, at 0.60 m/s^2. This is intriguing since these oils are not specifically intended for the pump used in the study. Furthermore, the average vibrations expressed in acceleration could not be linked to viscosity, as oils in group C (where avg. R was 0.67 m/s^2) had an average viscosity of 199.10 m^2/s, oils in group G (where avg. R was 0.61 m/s^2) had an average viscosity of 88.39 m^2/s, and oils in group H (where avg. R was 0.49 m/s^2) had an average viscosity of 449.96 m^2/s. Consequently, no correlation exists between viscosity and avg. R. The values of avg. R and ΔR are influenced by chemical additives, which are proprietary information.

CONCLUSIONS

The analysis of the impact of engine, hydraulic, and transmission oils on the kinematics of the pump's operation when pumping liquid demonstrates that these physicochemical parameters are crucial for the performance characteristics of hydraulic systems. Their impact on the dynamics of vibrations expressed in acceleration and pump vibrations is significant [38, 39]. In the context of engine oil (Group C), viscosity (ν) was found to significantly impact the average vibrations expressed in acceleration (avg. R), with a p-value of 0.0285. High oil viscosity contributes to smoother flow [40, 41], reducing vibrations within the pump [42, 43]. Good lubricating properties of the oil reduce friction, promoting stable system operation. Conversely, pressure (p) shows a strong impact on the dynamics of peak-to-peak acceleration value (ΔR), with a p-value of 0.00001, suggesting that pressure changes can lead to sudden flow fluctuations, increasing vibration levels [44, 45]. Based on this, it can be concluded that regardless of the oil type, selecting the working pressure is a key factor. Optimizing pressure settings within the hydraulic system minimizes the intensity of vibrations expressed in acceleration and the dynamics of their occurrence, which is essential for the durability and efficiency of the pump.

In the case of hydraulic oil (Group H), neither viscosity (ν) nor pressure (p) showed a significant effect on avg. R, suggesting that these oils provide a stable flow that does not induce significant vibrations in the pump. Their chemical properties, such as thermal stability and oxidation resistance, may contribute to pump stability [46], thus reducing vibrations expressed in acceleration. It was observed that only pressure had a significant effect on ΔR, with a p-value of 0.0022. This implies that pressure changes in hydraulic systems using this group of oils affect only the peak-to-peak acceleration value ΔR. Therefore, it is advisable to select a working pressure that limits the amplitude between maximum and minimum acceleration (peak-to-peak acceleration value ΔR). Observations indicate that this value depends on pressure and decreases with increasing pressure [47]. Consequently, it is recommended that the system operate at the maximum allowable working pressure. An interesting observation is that the pressure range causing a sudden increase in ΔR varies even within a single group. This phenomenon can be explained by several factors. One is the change in oil viscosity with increasing pressure [48–50], affecting oil flow turbulence. Another phenomenon causing an increase in ΔR at certain throttling pressures p is mechanical resonance, where the frequency of flow vibrations begins to amplify the mechanical vibrations of the pump. Other factors explaining this phenomenon include low-pressure cavitation and cavitation-vibration effects.

Analyzing gear oils (Group G), similar to Groups H and C, no significant effect of viscosity (ν) or pressure (p) on avg. R was observed. This may indicate that gear oils are designed to minimize vibrations in mechanical transmissions [51–53]. Their chemical composition and stability could play an important role in reducing vibrations regardless of viscosity and operating pressure. For ΔR, only pressure shows a statistically significant effect ($p = 0.005$), irrespective of the studied oil group. This effect is achieved through flow stabilization at high pressures and a reduction in local pressure drops [54] leading to low-pressure cavitation.

Comparing the tested oils, it was found that oil H2, dedicated for use in the tested pump, significantly reduced the average kinematic forces (avg. R) and the dynamics of kinematic forces (ΔR) compared to all other tested oils. Oil H2 achieved an avg. R value of 0.49 m/s^2, and the dynamics of kinematic forces (ΔR) amounted to 0.73 m/s^2. The conclusion from this observation is that parameters such as viscosity, thermal stability, and anti-wear and anti-foaming additives should be selected to fit the geometry of the pumping elements in the applied pump. It should be noted that in some cases, a single pump may need to operate with different types of oil. Therefore, controlling the throttling pressure is essential. As studies have shown, this is an independent variable that affects the reduction of vibration dynamics in the same way for all tested oils. Surprisingly, gear oils (G), although not intended for use with the tested hydraulic system, generated the second lowest average kinematic forces (avg. R = 0.61 m/s^2), and their dynamics of forces (ΔR = 0.60 m/s^2) was the lowest among all tested oil groups.

Differences in the chemical composition of the tested oil groups have a significant impact on their performance properties [55]. Hydraulic oils (group H) often contain anti-wear additives and stabilizers that enhance their performance under high-pressure conditions. On the other hand, engine oils (group C) are enriched with detergent and antioxidant additives, which affect their resistance to degradation and deposits in engines. Gear oils (group G) may contain additives that improve lubrication and anti-slip properties, allowing them to operate effectively under mechanical loads. These differences in chemical composition may explain the observed variations in test results, such as the low values of avg. R and ΔR for gear oils (G) and hydraulic oils (H).

The analysis of the results also revealed that there is no direct correlation between viscosity and the kinematic forces generated by the oils (avg. R). For example, oil H2 from the hydraulic oils group, despite its high viscosity (ν = 449.96 m^2/s), generated an avg. R of 0.49 m/s^2. In contrast, engine oils (C) with an average viscosity of ν = 199.10 m^2/s produced a greater avg. R of 0.67 m/s^2, while gear oils (G) with an even lower viscosity (ν = 88.39 m^2/s) generated an avg. R of 0.61 m/s^2. This suggests that the chemical properties of the oils, including the additives used, rather than viscosity, play a crucial role in reducing kinematic forces and the dynamics of the system's operation.

These findings provide valuable insights into the practical implications of oil selection and operational parameters for hydraulic systems. By emphasizing the importance of viscosity, pressure, and chemical composition, this study highlights key factors influencing pump performance and vibration dynamics. For practitioners, the results suggest that carefully selecting oils with tailored chemical properties, such as thermal stability and anti-wear additives, can enhance pump efficiency and durability. Additionally, maintaining the maximum allowable working pressure is crucial for minimizing vibration dynamics across all oil types. Furthermore, the study underscores the significance of controlling throttling pressure as an independent variable that universally affects the reduction of vibration dynamics, regardless of the oil used. For example, the superior performance of oil H2 demonstrates how specific combinations of properties can optimize pump operation. The findings also suggest that even gear oils (Group G), despite not being intended for hydraulic systems, can provide beneficial performance characteristics under specific conditions. Overall, the analysis advances the understanding of how oil properties and operational settings interact to influence hydraulic system performance. This knowledge can guide the development of maintenance strategies, the selection of appropriate oils, and the optimization of operating parameters to achieve improved system reliability and efficiency. These conclusions serve as a foundation for further research and practical applications in the field of hydraulic systems and vibration analysis.

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