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ACOUSTIC AND ENERGY EFFICIENCY ANALYSIS OF POLYMER ROTOR APPLICATION IN A GEAR MICROPUMP

Leonid Rodionov, Pavel Rekadze and Salimzhan Gafurov

Samara National Research University, Institute of Engine and Power Plant Engineering, Samara, Russia
email: rodionov@ssau.ru

The previous research shows, that it is possible to replace several parts of gear pumps with plastic ones. This substitution leads to cost saving and noise reduction of the pump. Therefore, the series of acoustic experiments on a test bench were carried out. Sound pressure levels were recorded with a microphone located in a pipe made of a rubber. The conducted experiment shows that acoustic characteristics of the micropump depend on the material of the driven rotor. Experimental result indicates that the proposed measures for replacing a metal rotor with a plastic one reduce micropump noise within the studied modes. The maximum achieved acoustic efficiency on equivalent level is 17 dB.

Keywords: micropump, rotor, plastic material, acoustics

1. Introduction

Engineers pay particular attention to vibroacoustic loads in different technical objects [1,2,3,4,5], caused by constant wear. Moreover, in some industries there exist strict requirements on noise levels [6].

The vital part of any hydraulic systems is its flow sources and pumps. Positive displacement machines are most common in that systems. Among these types of machines, gear pumps are the most popular. Gear pumps have a widespread use because of the simplicity of their design, low sensitivity to mechanical impurities, ease of manufacturing and low cost. Along with the advantages, there are disadvantages: a high noise level [7], high-quality requirements for the production of gears, high-pressure ripples causes the pipeline instability, cavitation processes [8]. These disadvantages are caused by different phenomena. For example, the authors [9] describe measures for pressure pulsations and vibrations loading reduction, which lead to a higher noise level. Kollek [10] shows that the fluid trapped between gears is the main reason for gear pump noise. Other papers were devoted to the instability of the pipeline caused by high-pressure ripples [11,12]. These articles provide numerical models of vibrations in the pipeline due to pressure ripples.

Nomenclature

b	face width (mm)
E	Young's modulus (MPa)
d_{in}	initial diameter (mm)
f	operator
f_{sh}	shaft frequency (Hz)
$f_{teeth1,2}$	first and second teeth frequency (first and second harmonic) (Hz)

k	harmonic number
m	module of the wheel (mm)
n	shaft speed (rpm)
P_{out}	output pressure (bar)
$Q_{act/theor}$	actual and theoretical flow (l/min)
z	number of teeth
ΔL	sound pressure level efficiency (dB)
ΔLeq	equivalent sound pressure level efficiency (dB)
Greek characters	
α	coefficient of linear thermal expansion (1/K at 20 °C)
η	loss factor
η_v	volumetric efficiency
λ	thermal conductivity (W/(m·K))
μ	friction coefficient
σ	strength limit (MPa)

Polymeric materials (PM) are more extensively used in mechanical engineering due to a higher than steel and aluminium loss factor η [13,14]. A strength limit σ of several existing PM is over 500 MPa while Young's modulus E, in comparison with steel, is considerably lower [15]. These properties have been causing inevitable substitution of traditional materials (TM) of mechanical engineering from 70teens [16] till nowadays [17].

The papers show possibility of using PM instead of TM with an appropriate efficiency for hydraulic units [18,19] as well as for different parts of external and internal gear pumps [19,20]. Moreover, PM application leads to pumps noise and vibration reduction [21,22].

The main PM advantages for mechanical engineering are its increased chemical resistance [15,23], the ability to operate under lubrication lack [24], its rather high loss factor η [14,16,25].

In this paper the authors have assessed acoustic efficiency of a plastic rotor implementation in a gear micropump with only the driven rotor was substituted.

2. Experimental study

The PEEK and PPS were chosen as the materials for the driven rotor [15] because of their better properties in contrast to other PMs. The comparison of PEEK/PPS (driven gear) and steel 42Cr4 (driver gear) are shown in [14].

Sound pressure levels emitted by the micropump with a plastic driven rotor were recorded by a microphone and processed by a signal processing module NI usb-4431 and a PC with an installed LabView software. In addition, flow rate, inlet and outlet pressure of the micropump were collected with a flowmeter, a pressure transducer, a vacuum gauge and a portable registration module.

The acoustic characteristics of the micropump were measured for the following arrangements of the drive and driven rotors: "steel-steel", "steel-PEEK" and "steel-PPS".

These rotors arrangements were studied on a gear micropump. A number of modes were formed as a combination of outlet pressure and shaft speed. The selected modes are presented in the Table 1.

Table 1: Test modes

Value				Unit	Characteristics
2500	2000	1500	1000	(rpm)	Shaft speed, n
12	9	6	3	(bar)	Outlet pressure, P_{out}

The algorithm of the experiment was:

- Set the shaft speed by a frequency drive and outlet micropump pressure by a throttle.
- Register pressure and flow rate.
- Record an acoustic signal.

The experiments were carried out on a hydraulic test bench. This test bench was based on previously designed one [26], the hydraulic system scheme is illustrated in Figure 1.

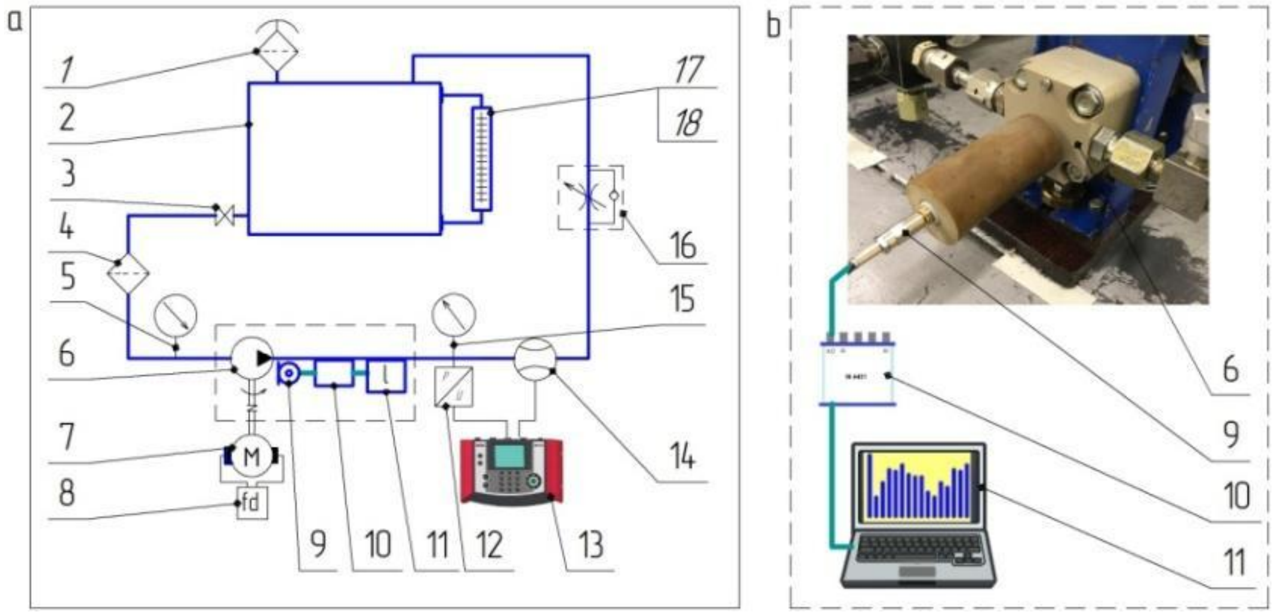

Figure 1:(a) scheme of the test bench: 1 – air filter, 2 – tank, 3 – valve, 4 – preliminary filter, 5 – vacuum gauge, 6 – gear micropump, 7 – motor, 8 – frequency drive, 9 – microphone, 10 – measuring system, 11 – laptop, 12 – pressure transducer, 13 – portable registration module, 14 – flowmeter, 15 – pressure gauge,16 – throttle, 17 – fluid level gauge, 18 – temperature gauge; (b) scheme of the microphone arrangement.

This system provides an opportunity to measure the flow under different operating conditions, a shaft speed and output pressure, while the oil temperature is kept constant. Sound pressure levels were recorded with a microphone located in a pipe made of a rubber. A thickness of the pipe is 9 mm (Fig. 1).

3. Results and discussion

The collected data were carefully processed. Then we calculated acoustic efficiency caused by the implementation of a plastic rotor which replaced the steel one were thoroughly analyzed and presented:

- For shaft and teeth frequencies depend on the micropump outlet pressure (Fig. 2).
- For equivalent efficiency depended on the shaft speed (Fig. 3).
- For equivalent efficiency depended on the micropump outlet pressure (Fig. 4).

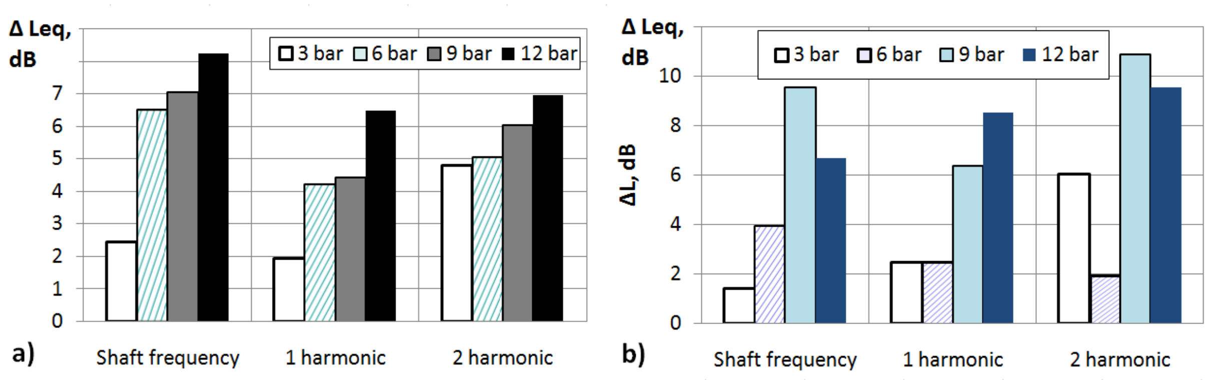

Figure 2: Acoustic efficiency $\Delta L = f(f_{sh}, f_{teeth1}, f_{teeth2})$ at the main working process frequencies at n=2000 rpm for arrangement with (a) PEEK and (b) PPS driven rotors.

The teeth frequency is determined as:

$$f_{teeth} = kzf_{sh} = k\frac{n \cdot z}{60} \tag{1}$$

Figure 2 shows that acoustic efficiency at shaft frequency is slightly higher. The efficiency strictly depends on the outlet pressure of the micropump. This tendency is observed at other shaft speeds. The maximum efficiency of the pair "steel-PEEK" and "steel-PPS" is 8 and 11 dB and is achieved at high pressures: 12 and 9 bar.

Figure 3 demonstrates the results of equivalent acoustic efficiency like shaft speed $\Delta Leq = f(n)$ function as a difference between a noise emitted from "steel-steel" and "steel-PEEK", "steel-steel" and "steel-PPS" packages.

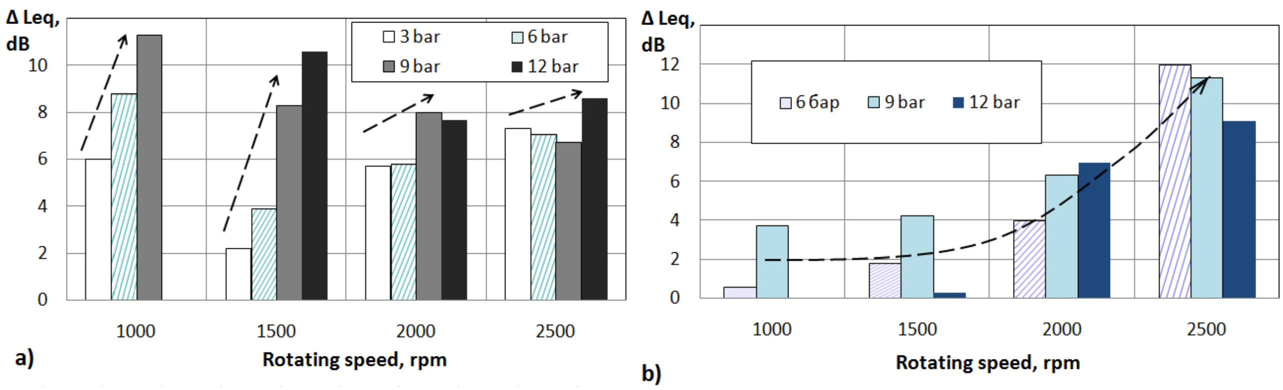

Figure 3: An acoustic efficiency $\Delta Leq = f(n)$ for (a) PEEK driven rotor and (b) PPS driven rotor.

The equivalent acoustic efficiency at low shaft speeds (1000 and 1500 rev/min) rises sharply for arrangement "steel-PEEK" (Fig. 3 (a)), at 2000 and 2500 rev/min the efficiency increased slightly. For the "steel-PPS" arrangement the acoustic efficiency rises evenly with increased frequency (Fig.3 (b)). This divergence of the results can be explained by the different rubbing degree of the plastic rotors and housing, as well as the fluctuations of the rotor shaft in the pump housing.

Figure 4 depicts the results of equivalent acoustic efficiency like output pressure $\Delta Leq = f(P_{out})$ function as a difference between a noise emitted from "steel-steel" and "steel-PEEK", "steel-steel" and "steel-PPS" packages.

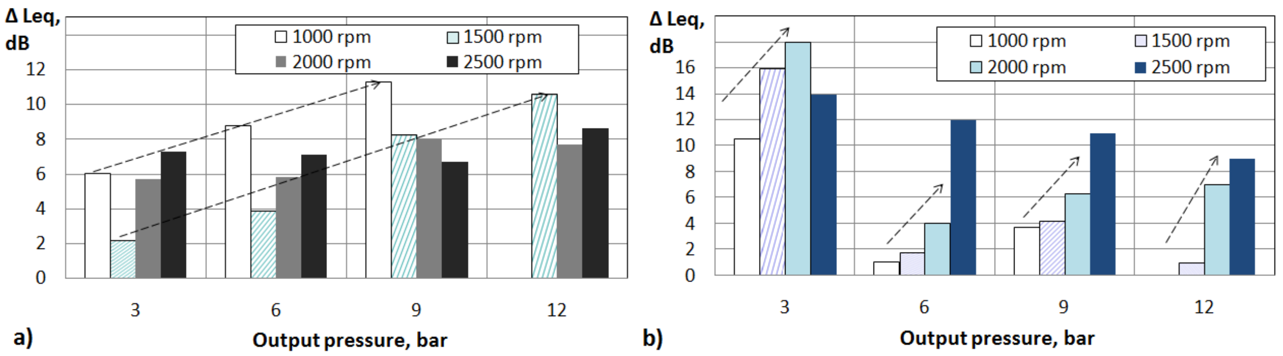

Figure 4: An acoustic efficiency $\Delta Leq=f(P_{out})$ for (a) PEEK driven rotor and (b) PPS driven rotor.

As we observed in the course of the experiment (Fig. 4(a)) there was a strong correlation between acoustic efficiency and outlet pressure of the micropump at 1000 rpm and 1500 rpm. Apart from that, there is no strict dependence between acoustic efficiency and outlet pressure of the micropump at 2000 rpm and 2500 rpm. For the "steel-PPS" arrangement, the acoustic efficiency is proportional to the increase in the rotational speed (Fig. 4 (b)). The greatest repetition frequency of measurement is observed at low rotational speeds of the motor shaft (1000 rpm and 1500 rpm).The sound pressure level was not registered at operating mode with n=1000 rpm and P_{out} =12 bar due to low micropump delivery.

The volumetric efficiency and the theoretical delivery [27] for pumps with teeth number z=8…16 should be determined as:

$$\eta_v = \frac{Q_{act}}{Q_{theor}} = \frac{Q_{act}}{6{,}5 d_{in} mbn} \tag{2}$$

Figure 5 shows the volumetric efficiency of the gear micropump versus the output pressure for three configurations.

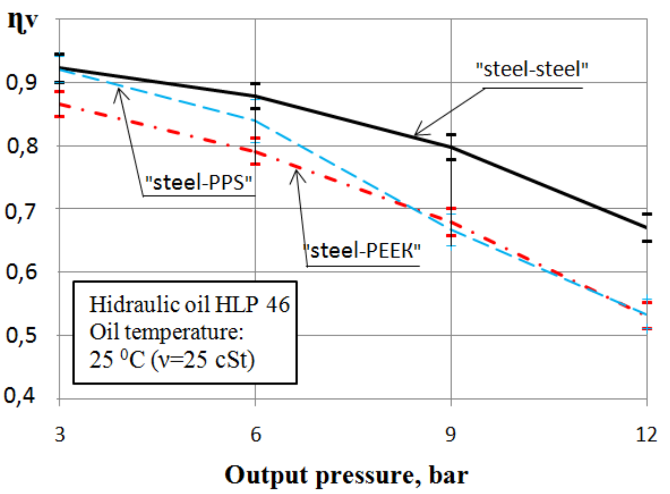

Figure 5: Volumetric efficiency of the gear micropumps at n=2500 rpm.

The inlet micropump pressure was registered by the vacuum gauge. The maximum value was 0.8 bar at n=2500 rpm and P_{out} =3 bar. This value was not taken into account in the equation (2) as additional leakage to a suction area [28]. Thus, theoretical volumetric efficiency, presented in Figure 5 is higher than it is.

It is necessary to emphasize the fact that volumetric efficiency because of the plastic rotor implementation is lower in comparison with steel rotor arrangement [29].

The volumetric efficiency η_v of gear pumps is often expected within the range from 0.8 to 0.95 [30]. In the current research volumetric efficiency was below 0.8 at 6 bars. Nevertheless, these results are suitable for pumps with plastic elements [23,29]. For example, the Tuthill company produces gear pumps with rotors made of PEEK and maximum outlet pressure of P_{out}=16 bar. Therefore, this fact clearly demonstrates importance of outlet pressure increase for pumps made of plastics.

According to Bashta [27], total value of the gaps effects volumetric efficiency of the pump. The declining of the ratio of gaps length to theoretical delivery leads to volumetric coefficient increase. Hence, the low pump delivery leads to the lower volumetric coefficient. Thus, it is recommended to run the pump at a high shaft speeds. This hypothesis is supported by the obtained experimental results: volumetric efficiency η_v=0,53...0,67 was achieved at outlet pressure P_{out}=12 bar, instead expected (η_v=0,8…0,95) [27]. The maximum volumetric efficiency η_v=0,67…0,92 was recorded at highest shaft speed (n=2500 rpm) for "steel-steel" package, the maximum volumetric efficiency for plastic arrangement is η_v=0,53…0,92 (for "steel-PPS" package). The tendency to volumetric efficiency growth is observed within all the studied range of shaft speeds. Starting from n=1000 rpm the volumetric efficiency rose up to 0.075 for each 500 rpm.

4. Conclusion

Fluid power machines are commonly used in the design of hydraulic drives and systems of machines. There are prospects of further development for such units and together with the improvement of their efficiency and outlet pressure limits, it is possible to achieve a significant noise emission reduction.

The carried-out experiment provides the results which clearly establish the relationship between acoustic efficiency and rotor materials in gear pumps. This is specifically refers to plastic materials. The achieved acoustic efficiency of 2...8 dB depends on outlet pressure on the main working process frequencies of the gear micropump at n=2000 rpm, and 2...17 dB on an equivalent level depends on outlet pressure and shaft speeds.

The volumetric efficiency of the gear micropump with a plastic rotor depended on outlet pressure at η_v=0,53…0,92 (for "steel-PPS" package). The principal cause of this wide range was random side gaps in the micropump during its assembly.

To sum up, it can be stated that the experimental results might be more precise in the future studies if researchers take into account natural frequencies of a pump system, increase inlet pump pressure, reduce volumetric leakages, register an emitted noise in an anechoic chamber and conduct a long-duration test.

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