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ACOUSTICAL CHARACTERIZATION OF EXTERNAL GEAR PUMPS: COMPARISON OF SPUR AND HELICAL GEARS

Mazzei Pietro
Department of Industrial Engineering, University of Naples Federico II, Italy
Carletti Eleonora, Pedrielli Francesca
STEMS Institute - National Research Council of Italy, Ferrara, Italy
email: eleonora.carletti@stems.cnr.it
Frosina Emma
Department of Engineering, University of Sannio, Italy
Marani Pietro
STEMS Institute - National Research Council of Italy, Ferrara, Italy
Senatore Adolfo
Department of Industrial Engineering, University of Naples Federico II, Italy

The evaluation of the noise performance of hydraulic pumps is a key aspect for manufacturers as the pump often represents one of the main noise sources in hydraulic systems on end users applications. Although sound power tests are the most accurate measurement method for the acoustical characterization of a source, study relies on a more practical and fast approach based on a series of measurements of sound pressure levels at five measurement points around the pump to compare different designs. All tests were performed in the laboratories of the CNR-STEMS research institute in Ferrara, in a quiet environment using a specific test rig which physically isolates the pump from the prime mover. The above approach was employed to acoustically characterize two families of external gear pumps: the “Standard” family with spur gears, and the “Low Noise” one with helical gears, to determine the different noise emissions between spur and helical gears. Subsequently, the methodology was also applied to test a prototype of the Low Noise family: an external gear pump that implements design optimizations aimed to further reduce the emitted noise. The tests were carried out in 36 different working conditions, varying the rotational speed (from 500 to 2200 rev/min) and the working pressure (from 10 to 240 bars), for each pump. The results show that significant differences can be detected among all the tested pumps, with better noise performances for the two versions of the “Low Noise” family with respect to the “Standard” one. Moreover, the pump with an optimized design exhibits further improvements, reducing in a significant way the noise emission levels.

Keywords: Acoustical characterisation, External gear pumps, spur gears, helical gears

1. Introduction

Noise and vibration are becoming a crucial aspect for fluid power systems and more in particular for the positive displacement machines (i.e. hydraulic pumps and motors) which are known to contribute to machines’ noise and vibrations. Indeed, the current trend of machines’ electrification, which is affecting both off-road and on-road mobile fields [1,2], is forcing research in the direction of studying and limiting noise emitted by components in the fluid power field. As quiet electric machines are replacing internal combustion engines as prime movers of hydraulic drive systems, the noise emissions from the hydraulic units often become predominant. Therefore, emitted noise and vibration are becoming crucial metrics for the selection of a component in a system. Consequently, nowadays in the data sheets, along with hydraulic efficiencies parameters (i.e., volumetric and mechanical efficiency) more and more often the level of emitted noise and vibration is specified.

The operational mechanism of positive-displacement pumps produces flow ripples, and consequently, noise and vibrations. Those flow oscillations can be evaluated as a function of the displacement, pumping elements number, and the number of the pump revolutions, the so-called kinematic ripple [3]. The ripples are influenced by the compressibility of the oil, backflow, cavitation phenomenon and leakages.

For the pumps, the noise sources in hydraulic applications are two: fluid-borne noise (FBN) and structure-borne noise (SBN). FBN is due to flow ripples while SBN is mainly caused by the vibration of mechanical components as a consequence of force oscillations. These two typologies of noise sources affect the total air-borne noise (ABN) emission. Therefore, in order to study and reduce the ABN the understanding of fluid dynamics which is responsible for FBN generated inside the components is fundamental. Among the most used pumps, External Gear Pumps (EGPs) are simple and robust hydraulic components, suitable to work at a wide range of pressures and rotational speeds. They are also characterized by long life, high reliability and efficiency, compactness, low weight, low cost and minimum maintenance. All these features make EGPs widely used for energy transmission in hydraulic and fluid power systems. Unfortunately, those pumps are generally characterized by high levels of emitted noise and vibrations. Several authors studied the ideal flow behavior of these machines using theoretical models [3, 4, 5]; others adopted numerical modeling both with lumped parameters [6] and Computational Fluid Dynamic (CFD) approaches [7, 8]; others instead adopted experimental techniques. Some researchers [9, 10] developed a numerical tool to understand EGPs also with asymmetric tooth profiles. Zardin et al. [11], developed lumped parameter models to predict both the volumetric and hydro-mechanical efficiencies and all their main losses. Mancò et al. [12] used lumped parameter approach and experimental data for studying EGPs. Mucchi et al. [13] also developed a lumped parameter-based model that also integrates with mechanical models for the evaluation of gear micromotion. Three-dimensional CFD methods are also widely used for studying EGPs [8]. Corvaglia et al. [14] showed a new application of a 3D CFD algorithm to predict the unsteady flow rate in hydraulic pipes placed after the pump's delivery port.

Results presented in this paper fall within the framework of a larger project aimed at the characterization of several groups of external gear pumps already in production and at the performance optimization of the silenced family equipped with helical gears.

This paper describes the experimental investigation on two families of 11 cm^3/rev EGPs: the "Standard" family (later called SPUR), equipped with spur gears, and the "Low Noise" family (later called HEL), equipped with helical gears. Tests were repeated also on a prototype version of the "Low Noise" family (later called HEL-PROTO) designed using an optimization procedure developed by the authors and already described in [6, 15] aimed at a further reduction of the noise emitted by the pump.

2. Materials and methods

2.1 Sound sources under test and operating conditions

Noise tests, as said, were performed on three different EGPs: one with spur gears (SPUR), a second with helical gears (HEL) and a latter prototype with helical gears (HEL-PROTO). The first two EGPs are "in production" specimens while the third is a prototype of the "Low Noise" family. This prototype implements some optimizations aimed to limit the pressure spikes and the flow ripples, reducing thus the FBN emissions. The optimization procedure was completely developed by the authors and consists of a subroutine included in the tool EgeMATor MP+ (External Gear Machine Multi Tool Simulator) EgeMATor MP+, indeed, is composed of different subroutines developed in different environments, interconnected to each other. The subroutine related to optimization permitted to redesign the pressure relief grooves inside the pump's wear plates; it was based on geometric assumptions to minimize the crossflow between delivery and suction while limiting pressure spikes with a particular focus for the speed of 1500 rev/min and the pressure range between 100 and 200 bar. These working conditions are indeed the most commonly used. Asymmetrical designs of the front and rear pressure relief grooves were also implemented as a result of the optimization procedure to correctly follow the helical profile of both gears.

For each pump (SPUR, HEL, HEL-PROTO), the noise measurements were repeated on two different units to have a more realistic characterization, compensating for the effect of possible production errors.

All the tested pumps had a displacement of 11.3 cm^3/rev and consisted of a die-cast aluminum alloy case with the front and the rear covers made of cast iron. This design permits to reach higher maximum pressures while maintaining a small weight, making these pumps ideal for mobile applications. The exploded view of the HEL design is shown in Figure 1.

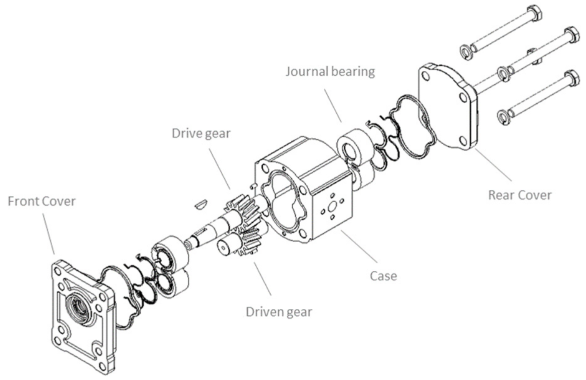

Figure 1: Exploded view of the HEL external gear pump.

The basic technical data of all the tested EGPs are listed in Table 1, while Figure 2 shows the two different kinds of gears.

Table 1: Pump technical data.

Description	**Value**	**Unit**
Nominal displacement	11.3	cm^3/rev
Max. continuous pressure	240	bar
Max. intermitted pressure	270	bar
Max. peak pressure	310	bar
Min. rotational speed	500	rev/min
Max. rotational speed	4000	rev/min

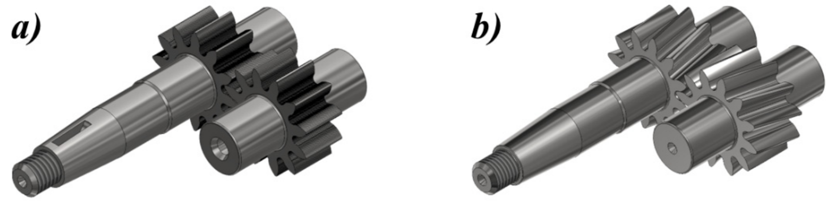

Figure 2: a) Spur gears design (SPUR); b) Helical gears design (HEL).

Noise tests were performed at six different rotational speeds: 500 rev/min; 1000 rev/min; 1500 rev/min and 1800 rev/min; 2000 rev/min; 2200 rev/min. For each speed, six different delivery pressures were investigated, from no-load condition to maximum continuous pressure, in subsequent ascending and descending runs; namely, 10 bar, 50 bar, 100 bar, 150 bar, 200 bar, 240 bar.

2.2 Test rig

The test rig, specifically built for testing gear pumps, included the prime mover, the oil reservoir and the hydraulic circuit. In order to isolate and measure only the noise radiated from the pump under test, the pump and part of the inlet and the outlet pipes were located inside a large shed, while the rig and the other components were placed outside this shed and separated from the flange-mounted pump by a concrete wall. Both the inlet and the outlet pipes were routed to minimise the influence of the noise emitted from extraneous sources and passed through the wall.

Oil pressure and temperature transducers, integrated in the hydraulic circuit, permitted a continuous monitoring of both these variables during the acquisition. This check ensured the repeatability of the operating conditions for all the pumps under test. As the oil temperature varies during the measurements due to the heating generated by the work of the pump, each time it reached 43 ± 0.5 °C it was brought back to its initial value, set at 37 ± 0.5 °C.

The environmental conditions were almost constant throughout the tests, with an air temperature ranging from 4 °C to 9 °C, and a humidity value ranging from 80 to 94 %. The background noise was stationary, with Sound Pressure Levels (SPLs) at the measurement points always more than 15 dB lower than the corresponding SPLs of the noise sources under test.

2.3 Acoustic measurements

Although sound power tests are the most accurate measurement method for the acoustical characterization of a source, this study relies on a more practical and faster approach based on a series of measurements of SPLs. The main reasons of this choice were that: a) the purpose of this study was the evaluation of the differences in the pump noise emission by varying the type of gears rather than an absolute characterization of each pump configuration; b) the number of measurements necessary to pursue this objective was very high and then sound power tests based on sound intensity measurements would have been excessively costly and time-consuming.

In order to take account of the directivity pattern of the noise emitted by each tested pump and obtain reliable noise data, sound pressure measurements were simultaneously performed in 5 different points around the pump under test, at a 30 cm distance from the source in each direction (front, right, left, top and bottom), as shown in Figure 3.

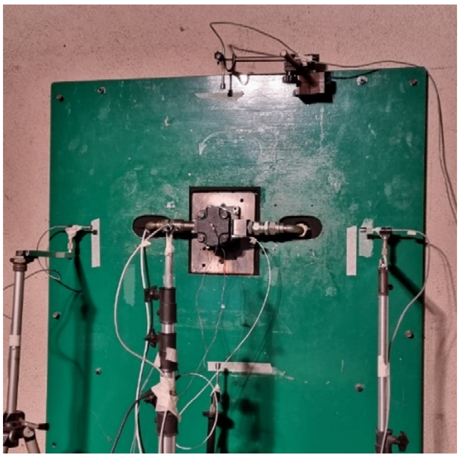

Figure 3: Position of the five microphones around the pump.

The acoustic data acquisitions were performed using an 8-channels Siemens SCADAS analyser (SCM-VM8-E module) and the Simcenter LMS Test.Lab software. Sound pressure measurements were performed in 1/3 octave bands in the range 20÷10000 Hz. The measurement chain was calibrated several times during the tests with a pistonphone (Brüel&Kjær 4220). The measurement instrumentation met the requirements of class 1 instruments.

3. Results and discussion

Taking into account that the main purpose of this investigation was the comparison between the pumps in different operating conditions, for each pump (SPUR, HEL, HEL-PROTO), the noise measurements were repeated on two different units. For each unit, the noise measurements were repeated twice in each of the 36 operating conditions (6 rotational speeds and 6 delivery pressures), during ascending and descending runs with a total number of 720 spectra of SPL for each pump. Therefore, for all the 36 operating conditions an average SPL value was taken for the 2 runs, the 2 units and the 5 measurement points.

It is important to specify that in this paper the discussion will be limited to the results in terms of linear overall SPL, leaving the spectral analysis to a further step. Figure 4 shows the SPL differences between the spur gear pump (SPUR) and the helical gear pump (HEL) while Figure 5 shows the SPL comparison between the helical gear pump (HEL) and the optimized prototype (HEL-PROTO). The graphical representation used in both figures reports the result of a comparison and it helps to highlight the operating conditions for which there is an increment of the SPL (negative values) rather than a reduction.

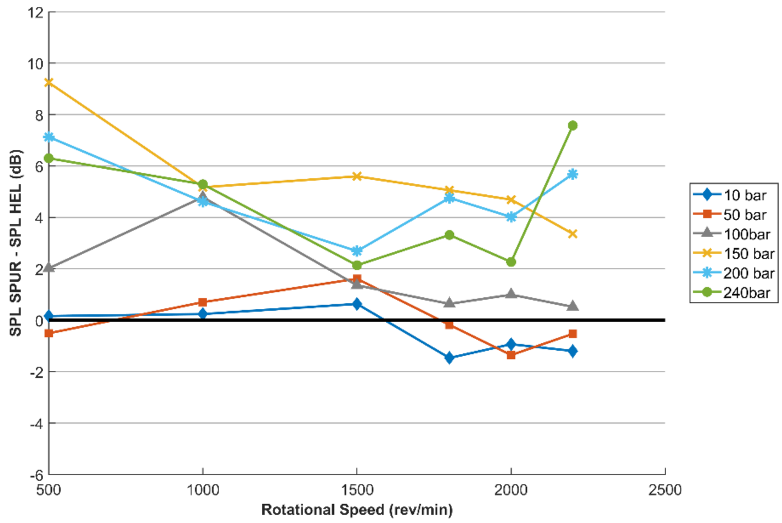

Figure 4: SPL difference between "in production" spur gear pump (SPUR) and "in production" helical gear pump (HEL)

The graph of Figure 4 shows that for all the operating conditions where the differences are positive (above the black thick line), the HEL pump turns out to be less noisy than the SPUR pump. At delivery pressures higher than 50 bar, the HEL is always less noisy than the SPUR, regardless of the rotational speed value. On the contrary, at the low delivery pressures (10 and 50 bar) the acoustic performances decrease; up to 1500 rev/min the emitted noise of the two pumps is almost the same, while HEL is noisier than SPUR at higher rotational speeds (1800 and 2200 rev/min). The best performance of HEL is at 150 bar where the SPL is always significantly lower, ranging from 3.4 dB to 9.2 dB depending on the rotational speed.

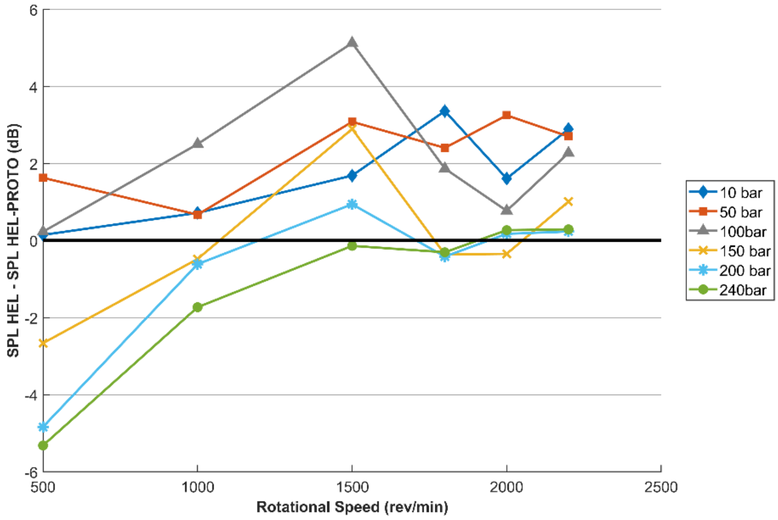

Figure 5: SPL difference between “in production” helical gear pump (HEL) and prototype helical gear pump (HEL-PROTO)

The graph of Figure 5 shows that for all the operating conditions where the differences are positive (as said, above the black thick line), the HEL-PROTO pump turns out to be less noisy than the HEL pump. At delivery pressures up to 100 bar, the HEL-PROTO is always less noisy than the HEL, regardless of the rotational speed value. On the contrary, at high delivery pressures (≥ 150 bar) the acoustic performance decreases: the HEL-PROTO is generally noisier than the HEL. The difference is very high, especially at low rotational speeds; namely, -4.8 dB at 500 rev/min and 200 bar, and -5.3 dB at 500 rev/min and 240 bar. Therefore, the rotational speed of 1500 rev/min represents an exception. Excluding the condition with the highest delivery pressure (240 bar) the HEL-PROTO is always significantly quieter than the HEL: the level reduction ranges from 1 dB to 5 dB. It is worth noting that this rotational speed is the most used for this kind of pumps and it is the speed which the optimization was focused at.

The overall SPLs at 1500 rev/min are reported in Figure 6 in order to assess the gradual reduction of the noise levels from the SPUR pump to the HEL-PROTO pump at the different delivery pressure values. The SPLs values are normalized against a reference value, N_{ref}, for confidentiality reasons; the space between two grid ticks is 3 dB wide.

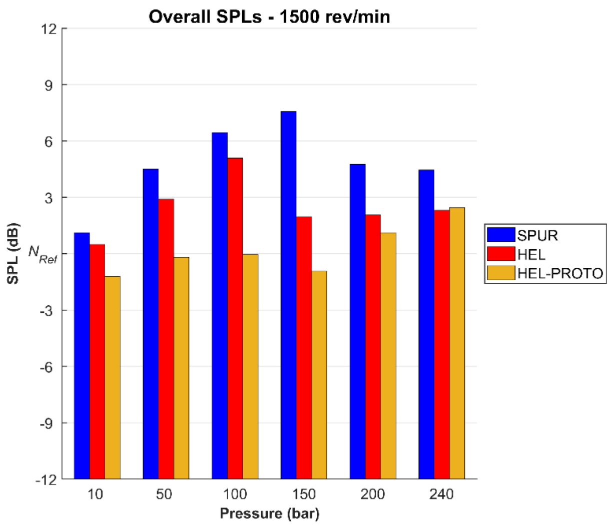

Figure 6: Overall SPLs at 1500 rev/min for SPUR, HEL and HEL-PROTO pumps.

The graph displays a similar behavior between the SPUR pump and the HEL pump: from low pressure until a specific delivery pressure (100 bar for HEL pump and 150 bar for the SPUR pump), the SPLs of the pump increase linearly; after that delivery pressure, the SPLs decrease and remain almost constants. The HEL-PROTO pump instead, exhibits almost constants SPLs from low pressure to the same specific delivery pressure of the SPUR pump (150 bar) while demonstrating a linear SPLs increment for the higher delivery pressure values. This different behavior is very interesting and requires detailed study that will be executed in future works, where the single spectra of the SPL acquired from each microphone will be also analyzed.

4. Conclusions

An experimental noise test campaign was performed on three different external gear pumps: a spur gears pump (SPUR), a helical gears pump (HEL) and a prototype helical gears pump (HEL-PROTO). The noise measurements were performed in 36 different working conditions; for each of them the overall sound pressure levels were averaged against two runs, two units and five measurement positions.

The results showed that the HEL pump is more silent than the SPUR pump, as expected from the use of helical gears. The best performance of HEL is at 150 bar where the overall sound pressure level is always significantly lower, ranging from 3.4 dB to 9.2 dB depending on the rotational speed.

The prototype pump HEL-PROTO implements design variations which were the results of an optimization procedure aimed to further reduce the fluid borne noise. The optimization was carried out by a subroutine included in the tool EgeMATor MP+, completely developed by the authors.

Results showed that the HEL-PROTO pump was quieter than the HEL pump for all the rotational speeds, at delivery pressures up to 100 bar. On the contrary, its acoustic performance decreased at higher delivery pressures and at rotational speeds lower than 1500 rev/min. The best results were obtained for the rotational speed of 1500 rev/min, which was the speed the optimization procedure was focused at.

Further analysis of the data will be performed, looking at the spectra and checking the sound pressure levels in each measuring point, obtaining thus a simplified directivity analysis. In addition, the tests will be repeated on additional displacements and an upgraded optimization procedure will be applied to extend the improvements to a wider range of working conditions.

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