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Analysis of the noise emissions of a common-rail pump before and after an endurance test

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Abstract. One of the problems of the modern era that we are facing nowadays, besides the pollution caused by fuel burning, is the level of noise pollution in constant growth in agglomerated cities. The main source of noise is the transport sector where the number of passenger cars had dramatically increased in recent years. Most of the vehicles around the world are powered by internal combustion engines equipped with a fuel injection system and a small percentage with an electric one. Researchers have shown that noise pollution affects human health from a psychological and physical point of view. Due to the manufacturing process of high-pressure pumps, some pumps mounted on the engine and running under certain conditions can produce a higher audible noise than the engine. The paper presents an experimental investigation on a high-pressure pump that provides a comparison between the noise level at the beginning of its lifetime and that resulting after an endurance test performed on a special test bench. It has been found that the greatest contributor to noise emissions is the high-pressure pump outlet valve when it opens. To improve the sound quality of the high-pressure pump, it is essential to further develop the outlet valve design and better control over the manufacturing process.

1. Introduction

Nowadays, endurance testing is the most common form of product validation, especially in the automotive sector. Endurance tests are mainly used in the field of research to observe the behaviour of a product that has just been developed. Also, from the perspective of costs in production plants, there are made process changes, design changes to the products to which a new validation is necessary to meet the minimum quality requirements.

Testing a product under laboratory conditions differs from real-life conditions, such as the presence of external factors that have a meaningful impact on the product. In some cases, before a product is launched, it is also tested under real conditions, aimed at identifying problems that were not detected in the laboratory. Products are becoming more and more reliable and turn into challenges for estimating time of failure or reliability in time over a short period with low costs [1]. Over the last few years, globally, due to stringent pollution and noise regulations, automotive companies have been forced to develop fuel injection systems at a very rapid pace. As automotive systems become more complex, the engine control represents a major part of it and without automatic control, today's performances would never have been achieved [2].



The need for the development of test machines is necessary because of the increasing complexity of new fuel injection systems and their high precision operation. The verification of the emitted noise is a part of the development of laboratory testing of automotive systems. This is required by the new regulations, and until some years ago it was not of major importance. In the future, there will be high transport necessities at the global level, which may lead to road congestion and pollution due to traffic noise [3]. Hence, the noise reduction is an important subject.

The paper provides an overview of the noise emitted by a high-pressure common rail pump before and after an endurance test. The purpose is to study the behaviour of the pump subjected to an endurance test simulating engine operating conditions leading to higher noise emissions. The experimental investigation has shown that the noise occurs when the fuel is compressed, and the outlet valve is opening [4]. Most of the noise emitted by the high-pressure pump assembly is generated by the outlet valve opening. It is said that endurance testing is uneconomical, takes too long and the accelerated life testing is a much more efficient alternative in terms of time and costs [5]. Accelerated Life Testing (ALT) is an aggressive type of test which applies high stresses to the product. Thus, its robustness is analysed, taking into consideration certain stress factors, which can be high levels of temperature, pressure and load [6, 7]. In our study, this test type is not applied because our intention is to simulate the same conditions as on the engine.

2. Overview of experimental hydraulic system configuration

Figure 1 shows the hydraulic configuration of the experimental setup by which the high-pressure pump was tested. This hydraulic configuration has been carried out on a special purpose test bench with electronic sensors connected and controlled by an Electronic Control Unit (ECU).

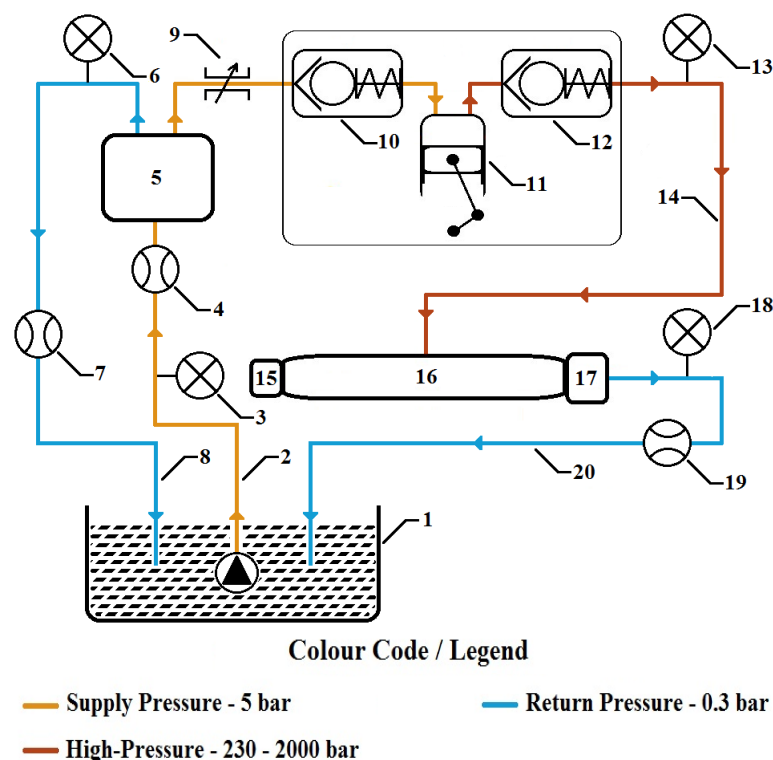


Figure 1. Experimental hydraulic configuration scheme.

On the other hand, on the engine, proper coding of the ECU is required to accurately control the opening and closing of the injectors and the entire common rail system with sensors and valves [8].

The numbered elements from 1 to 20 from figure 1 are described in the following list: 1 - Fuel Tank with Lift Pump; 2 - Supply Line (High-Pressure Pump Inlet); 3 - Supply Line Pressure Sensor; 4 - Supply Line Mass Flow Meter; 5 - High-Pressure Pump Housing; 6 - Backleak Line Pressure Sensor; 7 - Backleak Line Mass Flow Meter; 8 - Backleak Line (High-Pressure Pump Return); 9 - Fuel Metering Valve; 10 - Inlet Valve; 11 - Compression Chamber; 12 - Outlet Valve; 13 - High-Pressure Outlet Pressure Transducer; 14 - High-Pressure Pipe; 15 - High-Pressure Accumulator (Rail) Pressure Sensor; 16 - High-Pressure Accumulator (Rail); 17 - High-Pressure Regulating Valve; 18 - High-Pressure Accumulator (Rail) Return Pressure Sensor; 19 - High-Pressure Accumulator (Rail) Return Mass Flow Meter; 20 - High-Pressure Accumulator (Rail) Return Line;

The elements numbered in figure 1 with 10, 11 and 12, representing the inlet valve, the compression chamber and the outlet valve respectively, constitute the hydraulic head assembly. The most important element in our study is the outlet valve which consists of a spherical seat, ball and spring. The element 13 from figure 1 is an extremely accurate high-pressure transducer connected to a data acquisition board. It records pressure evolution to observe and understand the behaviour of the outlet valve. Before and after the pump housing, the hydraulic head respectively, pressure sensors and flow meters have been mounted. Monitoring the pressure and flow parameters during the test is strictly necessary in order to protect the product or test bench in case if something goes wrong. For instance, it can be said that if there is a difference between the inlet flow rate and the sum of high-pressure pump return flow and the return flow from the rail, somewhere there is a leakage. The leakage may be due to a broken pipe, a deformed gasket or due to the product itself, such as leakage between the driveshaft and fuel seal. In this case, the alarms on the test bench have been configured to stop the test thus avoiding any damage to the high-pressure pump.

The control of the whole system is accomplished by an ECU (Electronic Control Unit) that controls in principle the fuel metering valve, the high-pressure regulating valve and the other sensors and transducers to maintain the proposed test plan. Fuel metering valve regulates the quantity of the fuel to be compressed in the compression chamber, and after delivered to the high-pressure accumulator (rail). The high-pressure regulating valve controls the pressure on the high-pressure accumulator (rail) and would not have worked without the rail pressure sensor that measures the pressure value and sends it to the ECU. The experimental configuration from figure 1 was used to check the pump performance and noise level, before and after the endurance test.

3. Analysis of the hydraulic head assembly with valves

Modern hydraulic systems are using valves in their structure, without which the creating of complex hydraulic systems it would not have been possible. Hydraulic valves, especially spring-loaded ones which often operate small openings and interact with the surrounding flow, are more prone to vibrations and noise [9].

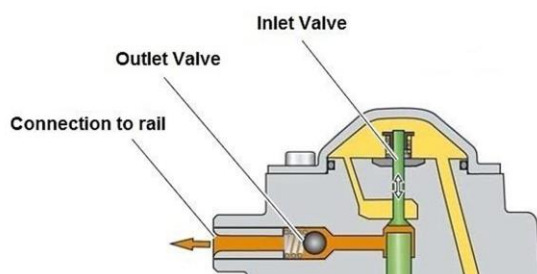


Figure 2. Inlet and outlet valve assembly [3].

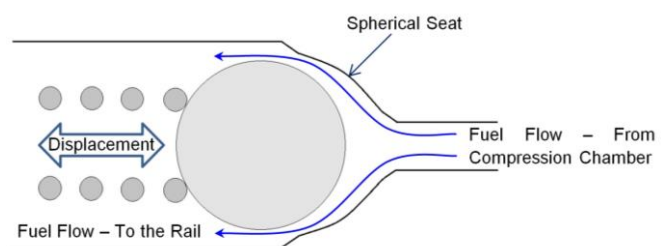


Figure 3. Outlet valve assembly [3].

Figure 2 shows the hydraulic head assembled with an inlet valve and an outlet valve. The outlet valve is a one-way valve designed to open and deliver compressed fuel to the high-pressure accumulator (rail) and to block reverse flow from the high-pressure accumulator (rail) in order to not

return into the pump. This valve is composed of a ball, a spring and a machined spherical seat (see figure 3), where the contact ball-spherical seat is of interest [10].

Figure 4 shows a simulation with Matlab software on a physically measured spherical seat profile with the purpose of analysing the contact points between the ball and the seat. The dark blue line identifies the aligned trace of the spherical seat profile, the green one is representing a ball with a smaller diameter than the nominal one, with the red line is the nominal ball diameter, and the light blue line represents a ball with a diameter bigger than the nominal one. The balls used in the assembly of the outlet valve are made of steel with wear good resistance.

Also, it can be observed that the theoretical position of the nominal diameter ball is seating in the centre of the profile, in the valley. This type of ball settlement can lead to multiple contact points between the ball and spherical seat, and when the outlet valve opens, an abnormal noise of hydraulic nature can occur [4]. The lines shown in figure 4 with green and light blue represent the smaller diameter ball and the bigger ball diameter, respectively. It can be observed that there are few contact points between the ball and the seat and no abnormal noise should be generated.

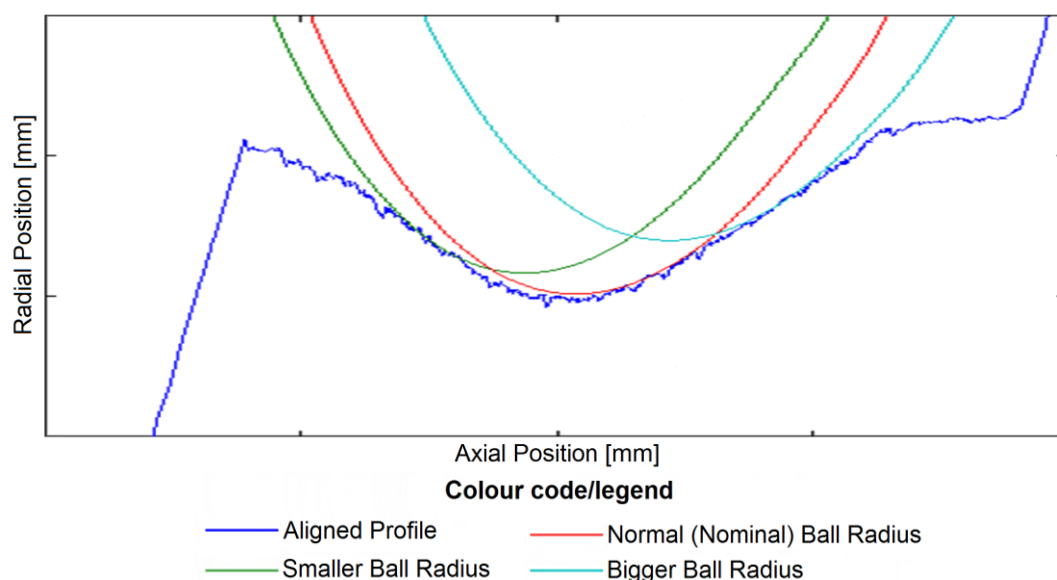


Figure 4. Outlet valve spherical seat profile.

4. Initial experimental test results

The initial investigation consists of testing a new high-pressure pump that was assembled with the hydraulic head having the spherical seat profile shown in figure 4 and the outlet valve assembly with the nominal diameter ball. Theoretically, this configuration should generate noise. During the test, two important parameters are monitored and recorded, such as pressure on the high-pressure circuit and pump noise level.

The test was performed on the special purpose test bench, which configuration is depicted in figure 1, where engine idle conditions are 800 rpm speed and 300 bar on the high-pressure accumulator. These conditions were chosen based on the many tests carried out at various speeds and pressures, and it has been found that, in engine idle conditions, the noise emitted by the outlet valve opening can be easily distinguished from the other high-pressure pump components. Also, the microphone acquiring the sound is unidirectional, and it is positioned at 500 mm distance from the high-pressure pump.

The fluid used for the experimental test is synthetic oil that has specific characteristics as a diesel fuel complying with EN590 standard [11]. EN590 is a European Fuel Standard applying to marketed diesel fuel for use in internal combustion engines in countries belonging to European Union [12].

Diesel fuel used for propulsion of the vehicle by burning it in the internal combustion engines has not been used for testing because it is flammable and the risk of fire is very high.

Figure 5 presents two parameters recorded during the test, and it is observed that when the pressure increases and the outlet valve opens, a pressure spike that is correlated with an increased noise signal appears. The noise level when the outlet valve is opening reaches a value of 0.0875 Pa which is equivalent to 72.81 dB. Moreover, two pressure pulsations are represented by one complete rotation of the pump driveshaft which means that the design of the driveshaft is with two lobes.

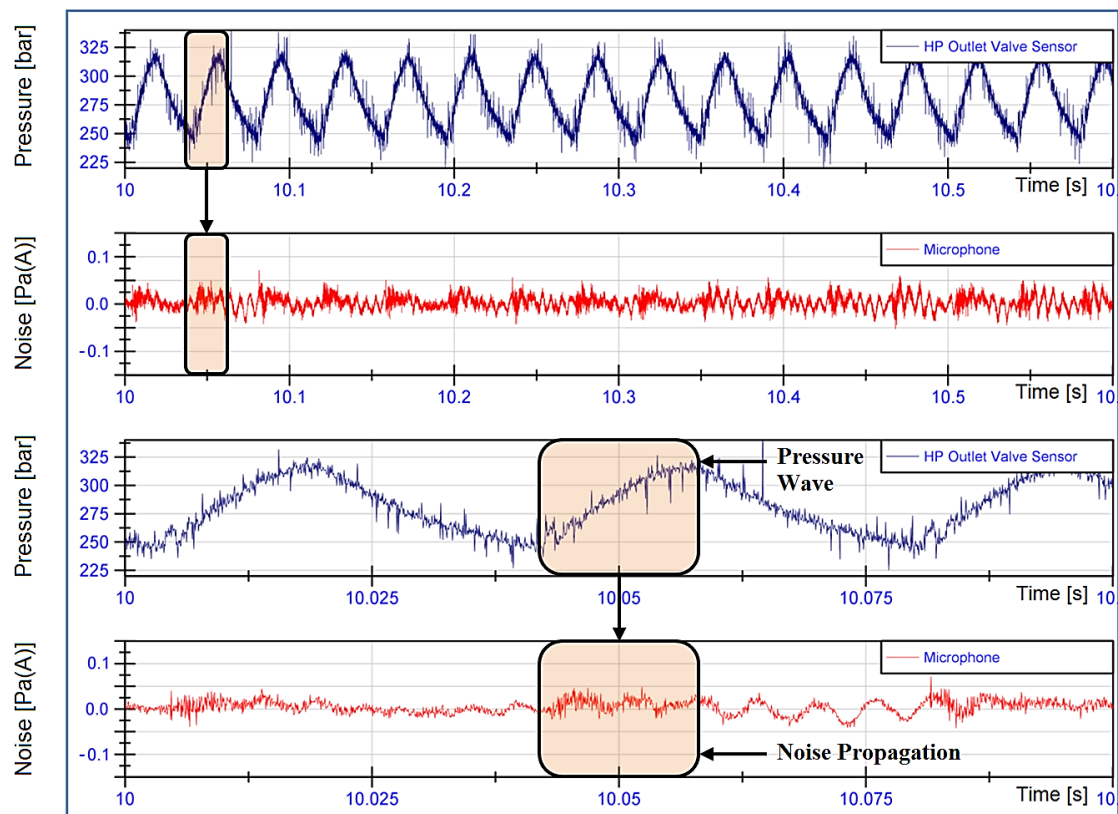


Figure 5. Initial experimental test results.

5. Experimental results after the endurance test

An example of an endurance test cycle is shown in figure 6 where it can be seen that the speed and pressure fluctuate and gradually increase compared to real running conditions.

The endurance test bench has been specially developed for long tests and to have the ability to simulate the same conditions as the engine in terms of speed, pressure, pump load and fuel temperature. Moreover, the testing apparatus can perform accelerated tests to estimate the lifetime of the product [13].

The endurance test presented in our paper is a test with cycles simulating the engine regime, such as gear shifting and pump load according to the position of the throttle. During a test cycle, the pump load varies between 0% and 90%. In fact, if the pump is mounted on an engine, by reducing the pump load when power is not needed, the engine consumption is improved due to reduced drive torque.

Also, a high pump load causes high stress on the pump drivetrain components and shortens the lifetime of the pump while a low pump load enhances it.

The test period is 100 hours, and in case if some of the pump parameters during the test are going outside of the alarms limits, the ECU stops the test, and the pump is inspected in detail. In our investigation, the pump had successfully finished the endurance test.

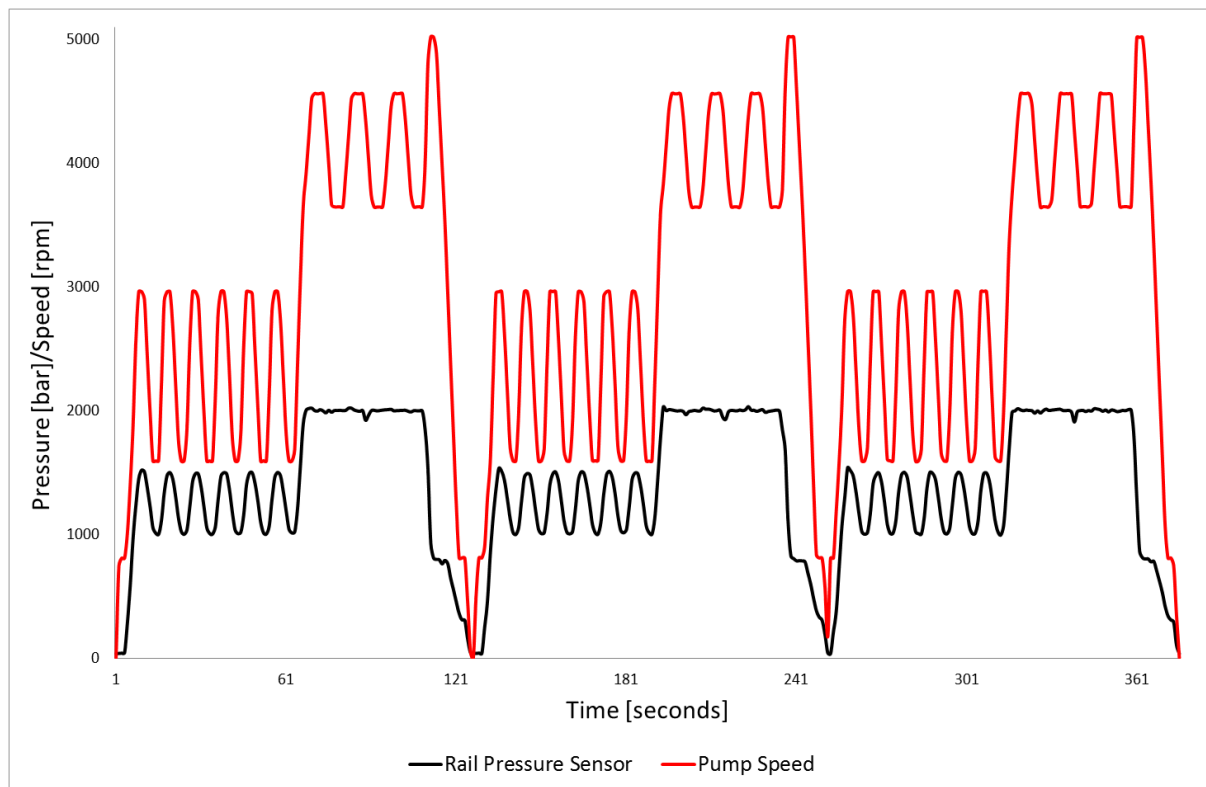


Figure 6. Example of endurance test cycle.

Figure 7 shows the noise test results of the pump after an endurance test. The amplitude of the noise signal is more or less similar to that before the endurance test and reaches a value of 0.09 Pa, which is equivalent to 73.06 dB. The slight increase in noise can be caused by many factors, such as measurement equipment, calibration, microphone or product related, such as component wear, especially the outlet valve spherical seat.

Figures 8 and 9 present the frequency analysis with Fast Fourier Transformation (FFT) of two pump's parameters before and after the endurance test, where the pressure spikes from the outlet valve pressure sensor are correlated with the noise signal and ranges between 4000÷10000 Hz.

It is interesting that there is a slight difference in the noise emitted by the pump with an initial value of 72.81 dB and a value of 73.06 dB after the endurance test.

As a presumption from the product point of view, if the wear of the outlet valve seat from figure 4 is progressing over time, it can lead to high noise emissions. The supposition is sustained by other research concluding that if the ball diameter coincides with the spherical seat diameter, there will be multiple contact points between the ball and the seat and high noise emissions are produced [4].

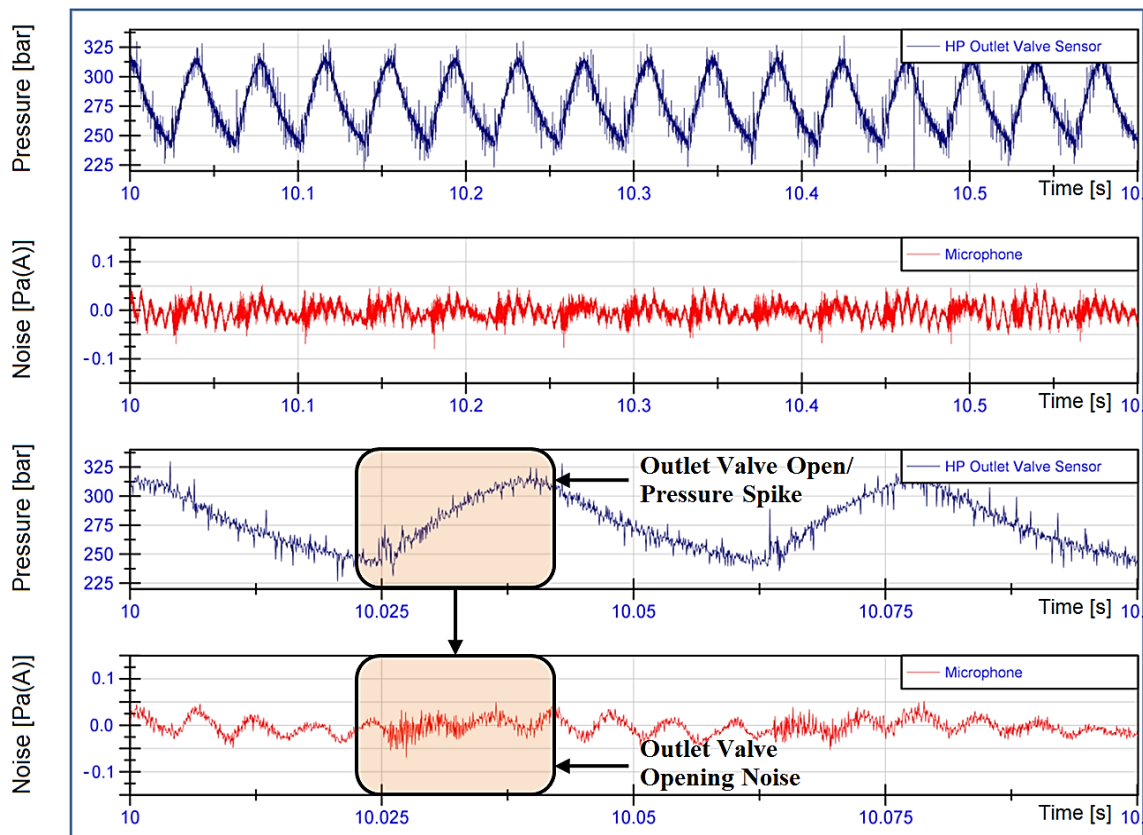


Figure 7. Experimental test results after the endurance test.

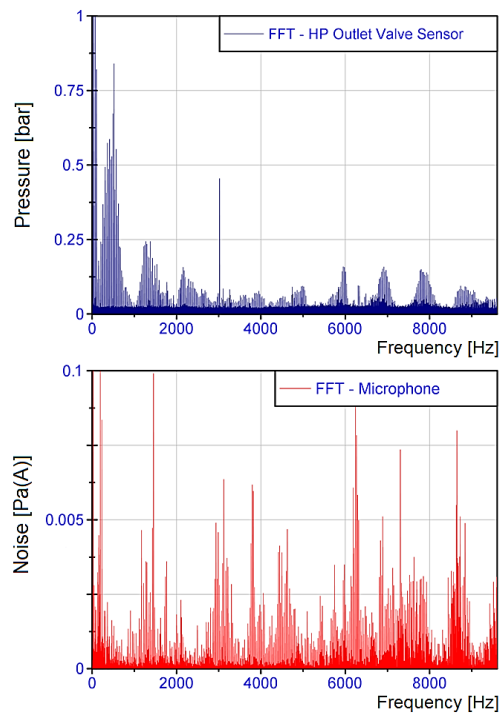


Figure 8. FFT - Before Endurance Test.

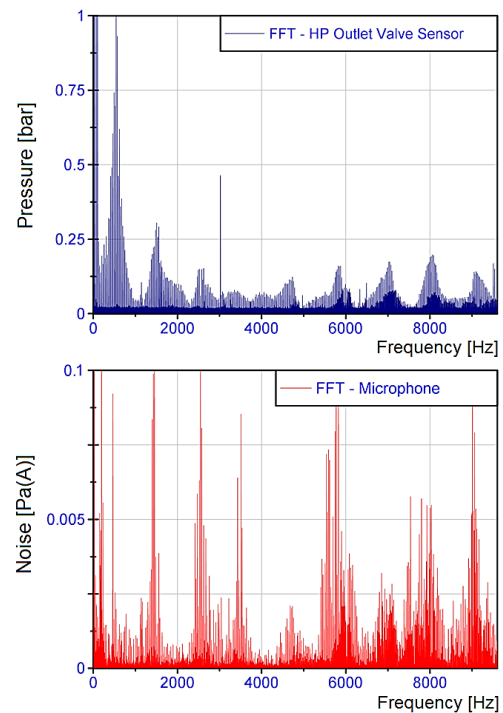


Figure 9. FFT - After Endurance Test.

6. Conclusions

In our study, it turned out that the outlet valve opening represents the most significant contribution to the noise emissions from the high-pressure pump. Before and after the endurance test, performance tests were conducted to verify the appropriate functionality and the emitted noise level. As a comparison of noise emissions before and after the endurance test, we can say that there is a small difference, after the endurance test the noise is higher by 0.25 dB and may be due to various factors. Neglecting the factors related to instrumentation and measuring devices, we conclude that the increased noise level is due to the outlet valve seat wear. Spherical seat wear helps to create more contact points between the seat and the ball due to high pressure and load, and the seat tends to take the shape of the ball. The 100-hour endurance test is equivalent to 11000 km on the engine, so the noise level is unlikely to increase significantly from now on since the ball has deformed the seat. Wear will remain in a stationary condition until the hydraulic head or ball material become defective due to fatigue and most likely will happen after many years of operation at the end of the product's life. A future work will be performed to theoretically base this experimental investigation.

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