Experimental analysis of hydraulic discharge line in the time domain

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Abstract. The article presents the results of preliminary experimental analyses of damping pressure pulsation by the hydraulic flexible hoses. The tests have been conducted in the form of a complete two-level experiment, having selected the following parameter variables: flexible hose type (1 or 2-wire hose), pressure value in the pressure line, rotational speed of the pump shaft, pressure line length. The acquired curves have been analysed in time domains. Values of pressure line damping in relation to the dominant pressure peaks have also been determined. The aim of the undertaken tests has been to confirm or overthrow the common belief that the pressure line with flexible hose itself is the sufficient damper of pressure pulsation in a hydraulic pump.

1. Introduction
Vibroacoustic phenomena like vibration [1, 3, 6, 15] and noise [5, 9, 14] are considered significant defects of the industrial hydraulic systems. One of the basic reasons for these occurrences is the capacity fluctuation of most types of displacement pumps [4, 9, 11, 12, 13, 16]. The simplest method of minimizing vibration and noise of hydraulic equipment is using zero capacity fluctuation pumps (i.e. special screw pumps used in opera or theatre stage drive units). Yet another method is damping pressure pulsation using dampers [2, 9] or dedicated design solutions. Most practitioners tend to think that it is sufficient to use the flexible hose section in the pressure line in order to isolate the motor-pump unit from the rest of the hydraulic system and magnify the effect of damping the pressure pulsation.

The aim of the studies presented in this article is to challenge the thesis assuming that the pressure line with a flexible hose is the sufficient damper of pressure pulsation for operating medium in the hydraulic units.

2. Description of the measuring station, course and schedule of the experiment
Measuring system (Fig. 1) has been composed of the following elements:

- gear pump with external gear design (series PGP511B0060, manufactured by Parker Hannifin) powered by asynchronous AC motor with a frequency converter (series AC690+, manufactured by Parker Hannifin),
- throttle valve 9N600S (for setting the hydraulic resistance in the pressure line and regulating the pumping pressure),
- flexible hoses (parameters presented in Table 1),
- SCPT-060-C2-05 pressure sensors (manufactured by Parker Hannifin).

During the series of experiments, the temperature of working fluid HLP-46 (according to DIN 51524) was within the range of 30÷40°C. Results of the experiment were saved using Service Master Plus diagnostic tool.

**Figure 1.** Simplified schematic diagram of the measuring station for testing pressure line fluctuation.

The change of the pumping pressure was forced using a throttle valve positioned at the end of the pressure line, selecting its opening in a manner allowing for obtaining two values of pressure (30 or 60 bar). A maximum valve was not used to simulate the system’s load since, as was the result of tests described in [7, 8], it may be the source of extra pressure pulsation.

Laboratory tests were carried out as a complete, two-level experiment adopting the following parameters:
- flexible hose type (1 or 2-wire hose),
- pressure in the pressure line,
- rotational speed of the pump shaft,
- length of the pressure line.

In case of the listed elements, sixteen independent configuration combinations of the experiment bench were achieved and have all been presented in Table 1.
Table 1. Presentation of different configurations of the test bench for the purposes of the experiment.

| Measurement denotation | Flexible hose type                        | Number of wires in a flexible hose | Pressure in the pressure line [bar] | Length of the pressure line [m] | Rotational speed of the motor [rpm] |
|------------------------|------------------------------------------|-----------------------------------|-------------------------------------|---------------------------------|-----------------------------------|
| A01                    | Parker Elite 492 WP 22.5MPa 10mm (3/8") 1SC | 1                                 | 30                                  | 4.8                             | 720                               |
| A02                    |                                          |                                   | 60                                  |                                 |                                   |
| A03                    |                                          |                                   | 30                                  |                                 |                                   |
| A04                    |                                          |                                   | 60                                  |                                 |                                   |
| B01                    | Parker Elite 492 WP 22.5MPa 10mm (3/8") 1SC | 1                                 | 30                                  | 1.6                             | 720                               |
| B02                    |                                          |                                   | 60                                  |                                 |                                   |
| B03                    |                                          |                                   | 30                                  |                                 |                                   |
| B04                    |                                          |                                   | 60                                  |                                 |                                   |
| C01                    | Fluidconnecto WP 28MPa DN10-6 (3/8") 2SN | 2                                 | 30                                  | 4.8                             | 720                               |
| C02                    |                                          |                                   | 60                                  |                                 |                                   |
| C03                    |                                          |                                   | 30                                  |                                 |                                   |
| C04                    |                                          |                                   | 60                                  |                                 |                                   |
| D01                    | Fluidconnecto WP 28MPa DN10-6 (3/8") 2SN | 2                                 | 30                                  | 1.6                             | 720                               |
| D02                    |                                          |                                   | 60                                  |                                 |                                   |
| D03                    |                                          |                                   | 30                                  |                                 |                                   |
| D04                    |                                          |                                   | 60                                  |                                 |                                   |

3. Verification of the pressure hose length
Papers [10, 18, 19, 20] present the method of categorizing the hydraulic hoses into groups of elements with concentrated parameters and long hydraulic lines. Determining whether the hydraulic line (electric or other) belongs to the class of long lines depends on the ratio of hose’s geometric length to the length of the wave propagating along the line. In turn, the wave’s length depends on the nature of the considered phenomenon (wave type, characteristics of the medium where it propagates) and its frequency.

The first resonance frequency of the hydraulic line is observed when the following relation occurs:

\[
\frac{L}{\lambda_f} = \frac{1}{4}
\]  \hspace{1cm} (1)

where:
- \( L \) - length of a hydraulic hose [m],
- \( \lambda_f \) – length of the hydraulic medium pressure wave in the hose [m].

The pressure wave length may be determined following the formula:

\[
\lambda_f = \frac{c}{f}
\]  \hspace{1cm} (2)
where:
- $c$ – speed of pressure wave propagation (phase velocity) in the hose [m/s],
- $f$ – pressure pulsation frequency [Hz].

In order to determine the phase velocity $c$, the formulae given in this paper were used [18]. For the purposes of the experiment, it has been necessary to determine the kinematic viscosity and velocity of sound propagation in the hydraulic fluid.

On the basis of the data included in this paper [9], the velocity of oil sound propagation in flexible hoses was 800 m/s. The kinematic viscosity of oil, over the course of tests, was set at 50 mm$^2$/s.

As a result of the tests, it has been shown that with pump shaft rotational speed of 720 rpm, the pressure hose shall be treated as a long line starting with 1.25 m (analogically, with rotational speed of $n=1440$ rpm, the pressure hose is characterized as a long line with its minimal length of 0.71 m).

4. Verification of the pressure hose length

The result of the conducted experiment has been pressure curves in the selected sections of the pressure line, as a function of flow rate and rotational speed of a pump shaft. The last two quantities have been registered in order to precisely determine the conditions of the experiment execution. They have not been, however, further processed because the configuration parameters of the used measurement tracks had not made it possible to register the variability of curves with frequencies higher than a few Hz.

The obtained curves of pumping pressure pulsation have been analysed in time and frequency domains.

![Figure 2. Curves of pressure fluctuation at the beginning ($p_3$), in the middle ($p_2$) and at the end ($p_1$) of the pressure line (case A01 acc. to Table 1).](image-url)
Figure 3. Curves of pressure fluctuation at the beginning ($p_3$), in the middle ($p_2$) and at the end ($p_1$) of the pressure line (case B01 acc. to Table 1).

In relation to the obtained pressure curves, pulsation has been defined as the difference between the highest and the lowest pressure in the period $T=0.1$s (the obtained results have been presented in Table 2). No analysis of pressure fluctuation in the longer period of parameter recording results from the observed tendency of average pressures to drop (Fig. 4), which is caused by the warming of medium during measurements, which results in the change of viscosity and throttle of the stream.

Figure 4. Declining tendency in the curves of the recorded pressures (case A01, Table 1).
The following two main conclusions may be drawn from the obtained results of experimental tests:

- the amplitude of pressure pulsation depends on the chosen measurement spot on the pressure line,
- the amplitude of pressure pulsation at the beginning of pressure line, which is the result of periodical changes of temporary capacity of a gear pump, depends on the rotational speed of the shaft.

In order to compare the test results in time domain, the attenuation parameter of pressure line \( T \) has been introduced. It has been determined according to the formula:

\[
T = -20 \log \left( \frac{A_{p1}}{A_{p0}} \right)
\]

where:
- \( T \) – attenuation [dB],
- \( A_{p0} \) – amplitude of pressure pulsation at the beginning of the pressure line [bar],
- \( A_{p1} \) – amplitude of pressure pulsation at the end of the pressure line [bar].

In order to determine explicitly which of the factors adopted in the test program (i.e. number of wires in a hose, pumping pressure, pressure line length or rotational speed of the pump shaft) have significant impact on damping the pressure pulsation by the pressure line, the analysis of
correlation between the above factors and attenuation of the line have been performed and defined by the formula (3). The obtained results have been shown in Table 3.

**Table 3. Coefficients of correlation between the identified factors of the test program.**

|                      | Number of wires | Pumping pressure | Pressure line length | Rotational speed of the pump shaft | Attenuation |
|----------------------|-----------------|------------------|----------------------|-----------------------------------|-------------|
| Number of wires      | 1.000           | 0.071            | 0.071                | 0.071                             | 0.182       |
| Pumping pressure     | 0.071           | 1.000            | -0.071               | -0.071                            | -0.452      |
| Pressure line length | 0.071           | -0.071           | 1.000                | -0.071                            | 0.714       |
| Rotational speed of the pump shaft | 0.071 | -0.071 | -0.071          | 1.000                 | 0.369       |
| Attenuation          | **0.182**       | **-0.452**       | **0.714**            | **0.369**                        | 1.000       |

Analysing the obtained results (Table 3), it has been observed that attenuation has the smallest correlation coefficient with the number of wires in a pressure line hose. It is highly likely that there is a significant correlation between the pressure line length and its attenuation. Determining the significance of such factors as pumping pressure or rotational speed of a pump shaft is difficult to achieve. Negative value of correlation coefficient between pumping pressure and attenuation means that larger attenuation of pressure fluctuation occurs with lower values of pumping pressure. For the final identification of factors directly influencing the pressure line attenuation, the factor analysis based on multiple regression method has been performed. The obtained results, relating to the significance of the adopted independent factors, have been presented in Table 4.

**Table 4. Results of factor analysis for the adopted test program.**

|                      | Coefficient value | Coefficient standard error | Coefficient t-value (9 degrees of freedom) | Coefficient relevance level |
|----------------------|-------------------|---------------------------|-------------------------------------------|---------------------------|
| Free term            | -1.637            | 3.149                     | -0.520                                    | 0.614                     |
| Number of wires      | 1.179             | 1.137                     | 1.037                                     | 0.324                     |
| Pumping pressure     | -0.115            | 0.038                     | -3.024                                    | **0.013**                 |
| Pressure line length | 1.969             | 0.355                     | 5.541                                     | **0.0002**                |
| Rotational speed of the pump shaft | 0.005 | 0.002 | 3.010        | **0.013**                  |

Factor analysis results confirm that the values of pressure line attenuation do not change significantly with different number of wires in hoses used in the tests. At the same time, it has turned out that it is impossible to overlook the influence of pumping pressure and rotational speed of the pump shaft on damping pressure pulsation. Whereas one might intuitively assume that rotational speed of the pump shaft (thus pressure pulsation frequency) influences its damping by the pressure line, the relationship between pumping pressure and damping pulsation has not been expected.
5. Conclusions
To a certain extent, the obtained results prove the previous assumptions. The following relevant facts may be stated on the basis of the tests:
to a certain extent, the pressure line influences damping the pulsation of pressure generated by the pulse nature of displacement pump operation,
attenuation of the pressure line depends on its length and frequency of pressure pulsation,
the experiment did not prove the dependency between attenuation of flexible hoses and the number of wires (it is, however, worth mentioning that it is a conclusion resulting from the statistical analysis with insufficiently large number of samples),
categorical overthrow of the dependency between attenuation of flexible hoses and number of wires would require further tests.
Pressure values are of great significance for the attenuation of pressure pulsation. One of the hypotheses underlying the fact that lower damping was observed with higher pressure may be the reduction in hose vulnerability to changes of capacity resulting from the deformation of the external layer of the flexible hose made from elastomer.
The described phenomenon requires additional model and experimental tests of influence of the hydraulic line on the propagation of pressure pulsation.

6. Bibliography
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