Experimental analysis of hydraulic discharge line in the frequency domain

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Abstract. The article presents the results of the experimental test of the pressure pulsation propagation across hydraulic line. 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 series of pressure runs were analysed in frequency domain using FFT method. The results confirmed the prediction that the discharge line should be treated as a hydraulic transmission line (similar to the long transmission line) with distributed parameters, which variously attenuates pressure pulses of different frequencies.

1. Introduction
For simple models of hydraulic systems, it is assumed that the hydraulic resistance, capacitance and inerterance are the lumped parameters of pipes and hoses. In this way can be assumed the models of channels connecting block valves. Hydraulic pipes and hoses lengths of several meters should be considered as hydraulic long lines.
Most practitioners tend to think that each hydraulic pipe or, especially, hose acts like low pass filter of pressure pulsations. The aim of the studies presented in this article is checking the veracity assuming that the pressure line with a flexible hose operates as the filter 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.

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                                 |                             |                                    |
3. Test results in frequency domain

The obtained pressure runs have undergone the FFT analysis. For the measurement phase, the following parameters for the configuration of the measuring equipment have been adopted:

- sampling frequency at 1kHz,
- 4096 samples of FFT analysis window,
- FFT window type - rectangular,
- averaging the results from 3 realizations of spectrum.

Selected amplitude-frequency spectrum of pressure variability has been shown in Figures 2÷4.

Figure 2. Amplitude-frequency spectrum of pressure variability (case A01, Table 1).

Figure 3. Amplitude-frequency spectrum of pressure variability (case A01, Table 1) accompanied by the frequency of pump shaft rotation (ca. 12 Hz).
Figure 4. Amplitude-frequency spectrum of pressure variability (case A01, Table 1) accompanied by the frequency of pump teeth at the moment of contact (ok. 145 Hz).

Table 2 presents the overall results of the amplitude-frequency analysis of the conducted experiment.

| Measurement denotation | Frequency of pump shaft rotation | Frequency resulting from pressure pulsation | Subsequent dominant harmonics |
|------------------------|---------------------------------|---------------------------------------------|-------------------------------|
|                        | Frequency [Hz] | Amplitude [bar] | Frequency [Hz] | Amplitude [bar] | Frequency [Hz] | Amplitude [bar] |
| A01                    | 12              | 0.01            | 146            | 0.225           | 292            | 0.015           | 0.005           | 0.006           |
|                        | 12              | 0.009           | 0.08           | 142            | 0.179           | 358            | 0.085           | 0.052           | 0.044           |
| A02                    | 25              | 0.015           | 0.012          | 0.007          | 295            | 0.046           | 0.01            | 0.00            | 0.005           |
|                        | 25              | 0.012           | 0.01           | 0.01           | 142            | 0.179           | 358            | 0.085           | 0.052           | 0.044           |
| A03                    | 25              | 0.016           | 0.014          | 0.014          | 295            | 0.046           | 0.01            | 0.00            | 0.005           |
|                        | 25              | 0.015           | 0.012          | 0.007          | 294            | 0.045           | 0.017           | 0.01            | 0.002           |
| A04                    | 24              | 0.016           | 0.014          | 0.014          | 146            | 0.184           | 0.123           | 0.14            | 0.09            | 0.06            | 0.07            |
| B01                    | 12              | 0.013           | 0.013          | 0.012          | 146            | 0.184           | 0.123           | 0.14            | 354            | 0.09            | 0.06            | 0.07            |
| B02                    | 12              | 0.018           | 0.018          | 0.018          | 146            | 0.184           | 0.123           | 0.14            | 354            | 0.09            | 0.06            | 0.07            |
| B03                    | 25              | 0.016           | 0.014          | 0.014          | 146            | 0.184           | 0.123           | 0.14            | 354            | 0.09            | 0.06            | 0.07            |
| B04                    | 24              | 0.018           | 0.018          | 0.018          | 290            | 0.048           | 0.037           | 0.03            | 210            | 0.062           | 0.047           | 0.032           |
| C01                    | 12              | 0.01            | 0.008          | 0.007          | 146            | 0.206           | 0.123           | 0.02            | 354            | 0.101           | 0.061           | 0.011           |
| C02                    | 12              | 0.011           | 0.01           | 0.01           | 142            | 0.138           | 0.09            | 0.07            | 357            | 0.066           | 0.043           | 0.033           |
| C03                    | 25              | 0.015           | 0.012          | 0.007          | 294            | 0.045           | 0.017           | 0.01            | 205            | 0.06            | 0.022           | 0.004           |
In case of the dominant harmonics in amplitude-frequency spectra at the beginning of the pressure line, also their attenuation has been determined; according to the procedure adopted in relation to the curves in time domain. The obtained results have been presented in Table 3.

The factor analysis of attenuation has been carried out for the selected frequency. The obtained results have been shown in Table 4. Also in this case, there has been a strong dependency between attenuation, hydraulic line length and pump shaft rotational speed, whereas pressure has turned out to be a statistically less significant factor. The influence of number of wires in hydraulic hoses on the line attenuation has been in this case completely rejected.

### Table 3. The results of the amplitude-frequency analysis.

| Measurement denotation | Frequency of pressure dominant harmonics $f_{p,\text{in max}}$ [Hz] | Amplitude of pressure dominant harmonics [bar] | Amplitude of pressure harmonics at the end of the line [bar] | Attenuation [dB] | Theoretical frequency of pump capacity fluctuation [Hz] |
|------------------------|-------------------------------------------------|----------------------------------|----------------------------------|-----------------|-----------------------------------------------|
| A01                    | 145.8                                           | 0.226                            | 0.072                            | 9.843           | 148                                           |
| A02                    | 141.8                                           | 0.18                             | 0.09                             | 5.788           | 141                                           |
| A03                    | 205.3                                           | 0.062                            | 0.01                             | 17.8            | 148                                           |
| B01                    | 145.8                                           | 0.185                            | 0.142                            | 2.27            | 148                                           |
| B02                    | 141.8                                           | 0.157                            | 0.142                            | 0.874           | 143                                           |
| B03                    | 205.3                                           | 0.081                            | 0.030                            | 8.536           | 295                                           |
| B04                    | 210                                              | 0.062                            | 0.032                            | 5.651           | 291                                           |
| C01                    | 146                                              | 0.207                            | 0.023                            | 16.839          | 148                                           |
| C02                    | 142.3                                           | 0.138                            | 0.07                             | 6.019           | 142                                           |
| C03                    | 205.1                                           | 0.06                             | 0.027                            | 6.978           | 294                                           |
| C04                    | 209.5                                           | 0.075                            | 0.015                            | 13.976          | 289                                           |
| D01                    | 146                                              | 0.196                            | 0.132                            | 3.403           | 145                                           |
| D02                    | 142.1                                           | 0.228                            | 0.207                            | 0.825           | 144                                           |
| D03                    | 205.1                                           | 0.082                            | 0.027                            | 9.521           | 291                                           |
| D04                    | 209.5                                           | 0.076                            | 0.041                            | 5.243           | 290                                           |
Table 4. The results of factor analysis of attenuation of the selected stripe of pressure adopted for the test plan.

|                        | Coefficient value | Coefficient standard error | Coefficient t-value (9 degrees of freedom) | Coefficient relevance level |
|------------------------|-------------------|-----------------------------|------------------------------------------|-----------------------------|
| Free term              | -0.365            | 5.122                       | -0.071                                   | 0.945                       |
| Number of wires        | 0.057             | 1.850                       | 0.031                                    | 0.976                       |
| Pumping pressure       | -0.105            | 0.062                       | -1.704                                   | 0.119                       |
| Pressure line length   | 2.051             | 0.578                       | 3.548                                    | 0.005                       |
| Pump shaft rotational speed | 0.006          | 0.003                       | 2.259                                    | 0.047                       |

The frequency analysis has revealed a dependency that is capable of more than one interpretation. Setting the pump shaft rotational speed at circa 1440 rpm (which corresponds to the frequency of capacity fluctuation of a 12-tooth gear pump - 288 Hz), in the spectra of pressure variability at the beginning of the pressure line there is no dominant harmonics corresponding to the frequency of the pump capacity fluctuation. One may observe an extra, dominant stripe in the spectrum that appears in the frequency range 205÷210 Hz (Fig. 5). It is also worth mentioning that the mentioned harmonics appears in all of the results recorded for the pump shaft rotational speed of 1440 rpm. Therefore, such factors as pumping pressure or pressure line length can be ruled out as its cause.

![Figure 5](image-url)  
**Figure 5.** Amplitude-frequency spectra of pressure variability (case D04, Table 1).

The influence of a maximum valve (i.e. the valve securing the pressure line) can also be ruled out as the cause of the extra, dominant harmonics in pressure spectra, since it has been closed for the time of the measurements (measurements were carried out with pressure of the maximum valve opening set at 115 bar).

In the spectra of pressure variability at the end of the pressure line extra stripes around dominant harmonics can be observed (Fig. 6). If the observed stripes had been the effect of sidebands resulting from the adopted in FFT method (DFT) rectangular window with width N equal to 4096 samples, then for sampling the signal with frequency fs of 1000 Hz, they should have appeared with intervals of 0.244 Hz (fs/N). The analysis results allow drawing a conclusion that differences in frequency of the subsequent stripes are much bigger.
In order to definitely overrule the influence of a rectangular window adopted for the FFT analysis, the recorded variability spectra have been further analysed in terms of frequency (with no changes in the number of samples), using Hanning window. The relevant analysis results have been shown in Fig. 7. Overall results regarding extra side stripes of frequency corresponding to the pump capacity fluctuation have been presented in Table 8.

![Amplitude-frequency spectrum of pressure variability at the end of the pressure line (case A01, Tab. 1).](image1)

**Figure 6.** Amplitude-frequency spectrum of pressure variability at the end of the pressure line (case A01, Tab. 1).

![Amplitude-frequency spectrum of pressure variability at the end of the pressure line (case A01, Table 1, Hanning window).](image2)

**Figure 7.** Amplitude-frequency spectrum of pressure variability at the end of the pressure line (case A01, Table 1, Hanning window).

The comparison of the obtained results of rectangular and Hanning window FFT analysis has shown that the phenomenon of frequency blurring had occurred. Similar phenomenon may be observed in the spectra of pressure variability measured at the beginning of the pressure line (in this case there is a smaller difference of frequencies between the stripes, $\Delta f = 0.98$ Hz; Fig. 8a). However, no extra stripes in the spectra of pressure variability in the middle of the pressure line have been observed (Fig. 8b).

Resonance frequencies of the analysed pressure lines

The hoses used in tests may be used in the function of cylinders closed on one side with a throttle valve. In this case, resonance frequencies of the hose may be determined with the following formula:

$$f_n = \frac{(2n - 1)v}{4L}$$

(1)

where:
\[ f_n \] – value \( n \) of the resonance frequency (\( n \epsilon N \)) [Hz],
\[ v \] - speed of sound in the medium filling the cylinder [m/s],
\[ L \] - cylinder length [m].

On the basis of this work \([x]\), it was possible to determine the speed of sound of the medium filling flexible hoses, taking into consideration the relationship between the number of wires in a hose and pumping pressure. The values for the first resonance frequency have been presented in table 6 (subsequent resonance frequencies are odd multiples of the basic frequency).

**Table 5.** Analysis results for the I side stripe in the spectra of pressure variability at the end of pressure line.

| Measurement denotation | Frequency of pump capacity fluctuation \( f_p \) [Hz] | Amplitude of pressure pulsation \( A_p \) [bar] | Frequency of the I-st sideband \( f_{1st} \) [Hz] | Amplitude of pressure pulsation of the I-st sideband \( A_{1st} \) [Hz] | \( \Delta f \) [Hz] | Pressure amplitude ratio | Attenuation pulsation of the I-st sideband [dB] |
|------------------------|-----------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|----------------|-------------------------------|--------------------------------------|
| A01                    | 145.75                                        | 0.073                                | 148.44                                | 0.005                                | 2.69           | 0.07                          | 22.8                                 |
| A02                    | 141.85                                        | 0.092                                | 144.53                                | 0.007                                | 2.68           | 0.08                          | 21.9                                 |
| A03                    | 294.68                                        | 0.002                                | 297.6                                 | 0.0001                               | 2.92           | 0.166                         | 15.6                                 |
| B01                    | 145.75                                        | 0.142                                | 148.44                                | 0.011                                | 2.69           | 0.08                          | 22.0                                 |
| B02                    | 141.85                                        | 0.142                                | 144.29                                | 0.01                                 | 2.44           | 0.07                          | 23.2                                 |
| B03                    | 294.68                                        | 0.023                                | 297.36                                | 0.004                                | 2.68           | 0.159                         | 15.9                                 |
| B04                    | 290.04                                        | 0.0251                               | 292.73                                | 0.004                                | 2.69           | 0.174                         | 15.2                                 |
| C01                    | 146                                           | 0.022                                | 148.68                                | 0.002                                | 2.68           | 0.082                         | 21.7                                 |
| C02                    | 142.33                                        | 0.07                                | 145.02                                | 0.009                                | 2.69           | 0.126                         | 18.0                                 |
| C03                    | 294.92                                        | 0.003                                | 297.61                                | 0.0006                               | 2.69           | 0.178                         | 15.0                                 |
| C04                    | 290.53                                        | 0.009                                | 293.21                                | 0.001                                | 2.68           | 0.16                          | 16.0                                 |
| D01                    | 146                                           | 0.132                                | 148.68                                | 0.012                                | 2.68           | 0.088                         | 21.1                                 |
| D02                    | 142.09                                        | 0.207                                | 144.78                                | 0.016                                | 2.69           | 0.077                         | 22.2                                 |
| D03                    | 294.92                                        | 0.02                                | 297.61                                | 0.003                                | 2.69           | 0.154                         | 16.2                                 |
| D04                    | 290.53                                        | 0.032                                | 293.21                                | 0.006                                | 2.68           | 0.177                         | 15.0                                 |
Figure 8. Amplitude-frequency spectrum of pressure variability: a) at the beginning of the pressure line, b) in the middle of the pressure line, c) at the end of the pressure line (case D03, Table 1).

Table 9 includes the case of B03 measurement, where capacity fluctuation frequency is close to the calculated second resonance frequency of the hydraulic line. Nevertheless, pressure pulsation amplitudes in this case do not indicate that the phenomenon of resonance occurred. For the resonance to occur there must be significant increase of the pulsation amplitude at the beginning of the line and their significant reduction at the end of the hydraulic line.
Table 6. The values for the I resonance frequency of the pressure line determined with analytical method.

| Measurement denotation | L [m] | Frequency of pump capacity fluctuation $f_Q$ [Hz] | Amplitude of pulsation $f_Q$ [bar] (beginning of the line) | Amplitude of pulsation $f_Q$ [bar] (end of the line) | $v$ [m/s] | First resonance frequency [Hz] | Second resonance frequency [Hz] |
|------------------------|------|---------------------------------|---------------------------------|---------------------------------|------|-----------------|-----------------|
| A01                    | 4.8  | 146                             | 0.225                           | 0.072                           | 650  | 33.9            | 101.6           |
| A02                    |      | 142                             | 0.179                           | 0.092                           | 700  | 36.5            | 109.4           |
| A03                    |      | 295                             | 0.046                           | 0.002                           | 650  | 33.9            | 101.6           |
| A04                    |      | 290                             | -                               | -                               | 700  | 36.5            | 109.4           |
| B01                    | 1.6  | 148                             | 0.184                           | 0.142                           | 650  | 101.6           | 304.7           |
| B02                    |      | 143                             | 0.157                           | 0.142                           | 700  | 109.4           | 328.1           |
| B03                    |      | 295                             | 0.06                            | 0.023                           | 650  | 101.6           | 304.7           |
| B04                    |      | 291                             | 0.048                           | 0.025                           | 700  | 109.4           | 328.1           |
| C01                    | 4.8  | 148                             | 0.206                           | 0.022                           | 770  | 40.1            | 120.3           |
| C02                    |      | 142                             | 0.138                           | 0.069                           | 820  | 42.7            | 128.1           |
| C03                    |      | 294                             | 0.045                           | 0.003                           | 770  | 40.1            | 120.3           |
| C04                    |      | 289                             | 0.058                           | 0.009                           | 820  | 42.7            | 128.1           |
| D01                    | 1.6  | 145                             | 0.195                           | 0.132                           | 770  | 120.3           | 360.9           |
| D02                    |      | 144                             | 0.228                           | 0.207                           | 820  | 128.1           | 384.4           |
| D03                    |      | 291                             | 0.061                           | 0.02                            | 770  | 120.3           | 360.9           |
| D04                    |      | 290                             | 0.058                           | 0.03                            | 820  | 128.1           | 384.4           |

4. Conclusions
The results of frequency analysis have not shown significant differences between global attenuation and determined attenuation of the dominant harmonics of pressure frequency. There have, however, appeared two significant matters to be explained:
- the occurrence of strong stripes of pressure pulsation frequency that are not the effect of the operation of the 12-tooth gear pump;
- blurring of pressure stripes which has been illustrated with the occurrence of side-bands around the peaks dominating in the pressure spectrum.

The first explanation of the unidentified stripes in amplitude-frequency spectrum is the phenomenon of aliasing. Since the manufacturer of Service Master Plus and dedicated frequency converters used for the measurement data acquisition does not declare fitting them with anti-aliasing filters, this assumption seems to be a justified approach.

As may be observed (Fig. 5), there are visible harmonics of pump capacity fluctuation frequency of about 146 Hz. Therefore, it has been assumed that the identified dependency shall occur in relation to the pump pulsation with frequency of 295 Hz (Fig. 8) and there will appear harmonics with frequencies of 590 Hz and 885 Hz. Nevertheless, these harmonics do not meet the Nyquist condition; for they are higher than half of the sampling frequency of 1000 Hz.

Due to the fact that the Kotielnikow-Shannon theorem has not been applicable here, the recorded curves feature aliases of pump pulsation harmonics. For that reason, there has been an attempt to
define the most probable aliases of harmonic frequencies with the rotational speed of the pump at 1440 rpm.

The frequencies of the aliases may be determined with the following formula:

\[ f_{An} = |n \cdot f_s - f_o| \]  

(2)

where:

- \( f_{An} \) – frequency of n alias (n \( \in \mathbb{N} \)) [Hz],
- \( f_s \) – sampling frequency [Hz],
- \( f_o \) – frequency of the base signal [Hz].

Assuming that the base signal is the first harmonics of pump capacity fluctuation frequency \( f_o = 590 \) Hz, the frequency of the first alias has been calculated as \( f_{A1H1} = 410 \) Hz. The same calculations have been performed in relation to the second harmonics, whose alias is \( f_{A1H2} = 115 \) Hz. In figures 12 and 13 one may notice stripes in the determined frequencies; they are not, however, dominant. Furthermore, it has turned out that the frequencies of aliases determined in this manner do not comply in any way with the frequency range of 205÷210 Hz, where the dominant stripe has been observed. Hence, it seems reasonable to conclude that the occurrence of the pressure stripe in the frequency range of 205÷210 Hz is not the result of aliasing. The authors come to the hypothesis that this phenomenon may be induced by the low PWM frequency of the frequency converter that has been used to power the pump motor.

Similarly as in the case of the set rotational speed \( n = 720 \) rpm, pressure stripes have been observed in the frequency range of 354÷358 Hz. Also in these cases, it is necessary to reject the theory of the pressure harmonics in the spectra of the recorded curves as caused by the geometric pump capacity fluctuation. The reason for rejecting this assumption is the fact that for this group of measurements pressure stripes have been observed with frequency of the first harmonic of pump capacity fluctuation and their amplitude was several times lower than the harmonics of pulsation frequency.

The results of the undertaken measurements do not also allow explaining definitely the significance of sidebands of the basic harmonics in the spectra of pressure variability at the beginning and at the end of the examined hydraulic line.

Due to the lack of unambiguous interpretation of the obtained results of the under-taken analyses, it seems to be justified to carry out further experimental and model tests of the phenomena connected with the influence of the hydraulic line on the propagation of pressure pulsation in hydraulic pressure lines.

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