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VIBRATION BEHAVIOR IN HYDRAULIC DRIVE SYSTEMS: AN EXPERIMENTAL STUDY OF RIGID AND FLEXIBLE PIPE DYNAMICS

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Abstract: *The specialized literature in the field of hydraulic power drives reserves a generous space for the characteristic vibrations of these systems regardless of the application served by the hydraulic drives system. The present paper aims to make a comparative discussion between the vibrations measured on rigid pipes and those measured on flexible pipes of hydraulic drive systems. The vibration spectrum is highlighted over a range of 5000 Hz for rigid pipes and up to 2000 Hz for flexible pipes. The vibration spectrum is also accompanied by cepstrum representation with the help of which the defects in the analysed system can be highlighted.*

Keywords: *Cepstrum, hydraulic power drive, measurements, spectrum, vibration*

1. Introduction

A large debate in the scientifical and industrial community is the subject of vibrations in hydraulic systems [1-3]. Every component of a hydraulic drive system is a source of vibration and has its proper frequency. During operation the hydraulic power drive systems develop a wide frequency spectrum, from low frequencies (infrasonic frequencies [1]) to high frequencies (more than 1 kHz). In the technical literature is highlighted the influence of mechanical vibration on pressure pulsation spectrum of hydraulic systems, but there are some other papers with good practice examples of vibrations induced by the pulsation of pressure in the hydraulic systems known as flow-induced vibrations [1,2]. The sources of pressure fluctuations in the hydraulic system are: (a) transient states; (b) movement of the cinematic mechanism of positive displacements pumps, (c) mechanical vibrations of the mechanical parts in rotation (as gear box, bearings, rotors) and the waves in long hydraulic lines [4-6].

In the topic of vibrations in hydraulic power drive systems theoretical analysis, experimental and numerical simulation research were conducted to explain the vibration mechanism as Fluid-Structure Interaction (FSI) [1,3], to confirm the coincidence between pressure pulsation spectrum and vibration spectrum of hydraulic components [1,2], to minimize the impact of external vibrations on hydraulic valves [1,4], to demonstrate using Discrete Fourier Transformation (DFT) that non-synchronous vibration components dominate the dynamic behaviour of hydraulic system and have a significantly variation with flow rate [1,5], to find solutions to control and reduce vibrations in the hydraulic systems [1,3,4,6]. Also, it is well known that vibrations can cause operational instability of hydraulic components, reduce durability and seal failures, generate noise emissions in low-frequency range which affect human health [1-6].

This is the reason that we put a legitim question: what is the difference between vibration spectrum of a rigid pipe vs a flexible pipe in a hydraulic power drive system. The purpose of the work is to compare the spectrum of vibrations measured on rigid pipes with those measured on flexible pipes in hydraulic drive installations. With the measured vibrations, spectral representation is made to highlight the harmonic sidebands. The periodicities of harmonic sidebands are transformed into quefrency peaks obtained with cepstrum (the result of applying an inverse Fourier transform to the log magnitude spectrum) [7,8]. Usually, harmonic sidebands highlight certain faults in mechanical systems with rotating parts. In the case of hydraulic drive systems, the harmonic sidebands do not indicate necessarily a fault but seem to be a characteristic behavior of these systems.

2. Experimental setup

Two test stands were considered.

The shock absorber test stand, Figure 1, has the entire hydraulic drive system made with rigid pipes. The stand includes an electrohydraulic servomechanism supplied by a gear pump driven by an asynchronous electric motor with a speed of 1500 rpm.

The hydraulic equipment test stand, Figure 2, has flexible pipes in the system. The stand is intended for testing various types of hydraulic devices and equipment. Depending on the equipment being tested, different hydraulic circuits can be created. In this case, an axial piston pump and a swash plate were used and the load in the hydraulic circuit was created with a throttle valve.

Fig. 1. Shock absorbers test stand with rigid pipes

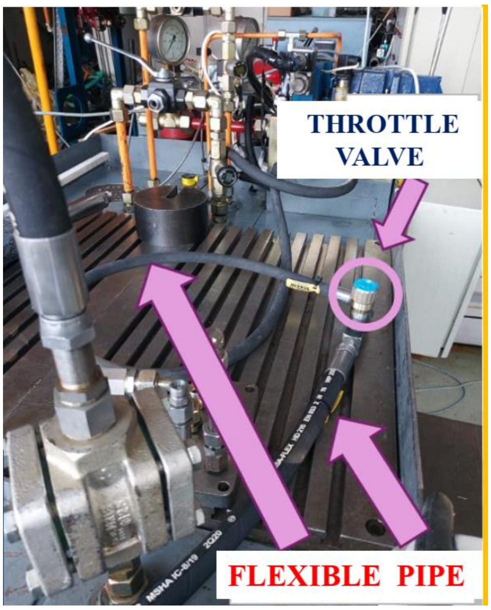

Fig. 2. Hydraulic equipment test stand having flexible pipes

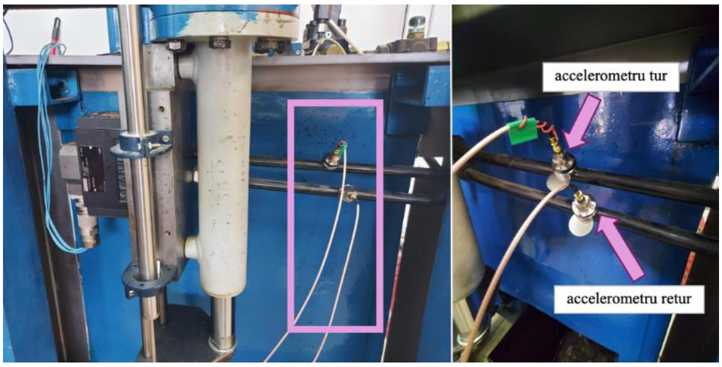

Fig. 3. Mounting accelerometers on the supply and return pipes (rigid pipes)

Fig. 4. Mounting accelerometers on the supply and return pipes (flexible pipes)

In the experiments, two CCLD piezoelectric accelerometers, type B&K 4507-B-001 with TEDS, sensitivity 10 mV/g, with a dynamic frequency range of 0.1 ÷ 6000 Hz, with operating temperatures

$(-54 \div 121)$℃ , which were fixed on the pipes, were used. Acquisition rate was 50,000data/s (50 kHz).

The two accelerometers were mounted on the supply and return pipes. Thus, in the rigid pipe stand, an accelerometer was mounted on the inlet pipe into the actuator, respectively on the outlet pipe from the actuator, Figure 3. In the flexible pipe stand, the accelerometers were mounted on the upstream and downstream pipe of the throttle valve, Figure 4.

The accelerometers were connected to a computerized data acquisition system, the measurement chain consisting of:

- ❑ accelerometers,
- ❑ an NI-DAQ 9233 acquisition board (National Instruments) and
- ❑ specialized software for signal acquisition and processing dBFA Suite 4.8.1, developed by 01dB-METRAVIB (Areva Group).

The measurements were made for different operating conditions. Thus, for the stand with rigid pipes, the measurements were made for: (i) zero flow ($Q = 0$) when the electro-hydraulic servovalve has no control signal; (ii) flow $Q \neq 0$ for control the servovalve with a sinusoidal control signal with 1 Hz frequency; (iii) flow $Q \neq 0$ for control the servovalve with a sinusoidal control signal with 2 Hz frequency. For the stand with flexible pipes, the measurements were made at pressures of (j) 50 bar; (jj) 70 bar.

3. Measurements and results

With the two accelerometers mounted perpendicular to the pipe walls, therefore perpendicular to the flow direction in the pipes, the accelerations were measured. The signals were filtered and integrated, determining the velocities, respectively the displacements. From a physical point of view, the displacements are displacements (deformations) in the radial direction of the pipe.

Figure 5 shows the displacement spectrum for the rigid supply and return pipes in the case of zero flow at the actuator, when the servovalve does not receive a command signal. The harmonic sidebands that form at different frequencies are observed on 2,000 Hz frequency range. The result was obtained using the subroutines of the dBFA Suite 4.8.1 program.

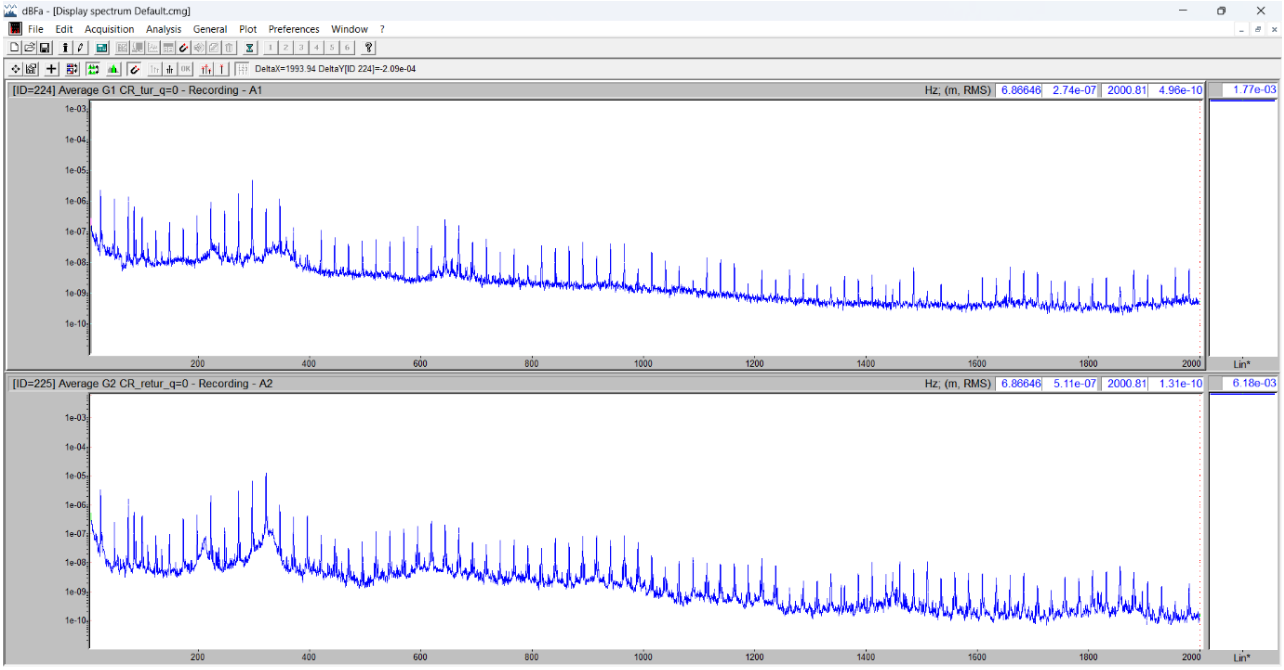

Fig. 5. Displacements spectrum and harmonics of the rigid supply and return pipes, $Q = 0$.

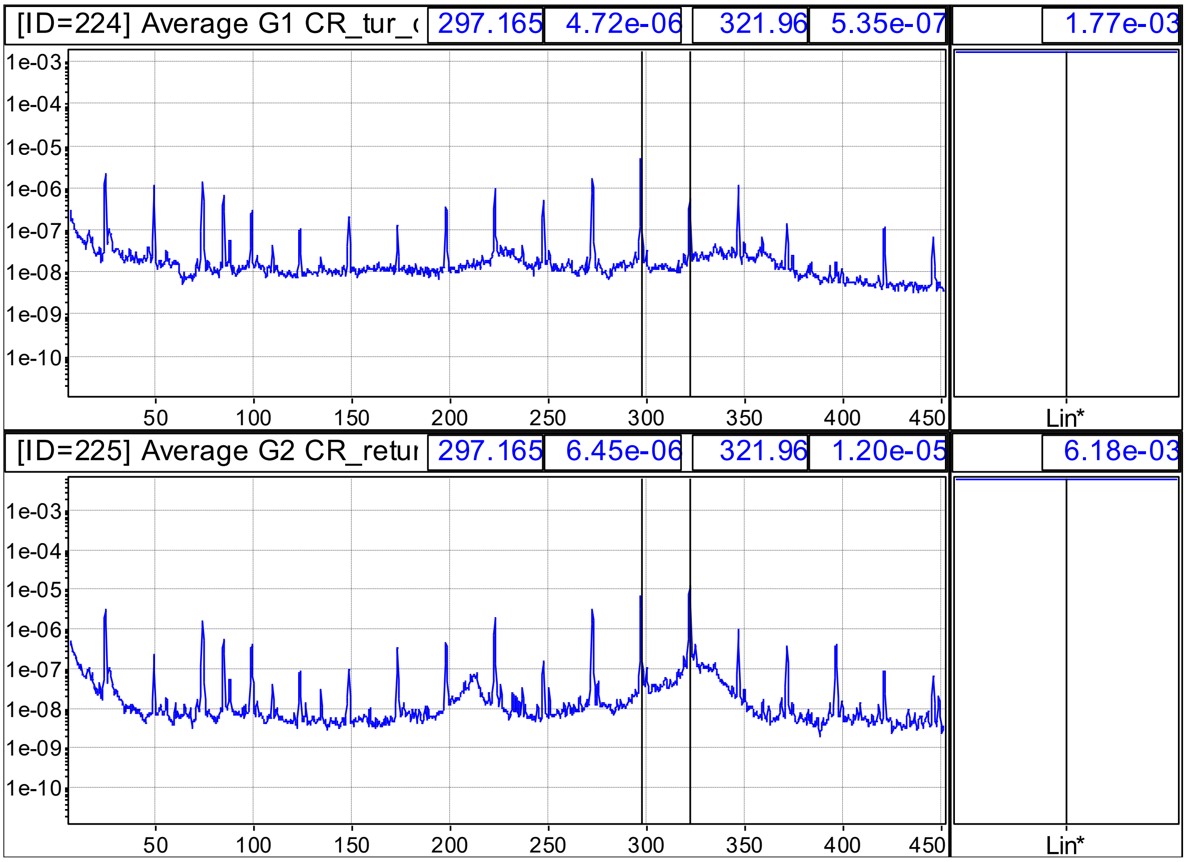

Fig. 6. Displacements spectrum of the rigid supply (top image) and return pipe, $Q = 0$, on first 450 Hz

Table 1: Displacement values for the first harmonics of the rigid pipes, supply and return, $Q = 0$

Harmonics	Frequency (Hz)	Rigid pipe radial displacement (μm)	
		Supply pipe	Return pipe
f_1	24.8	2,2	3,21
f_2	49.6	1,17	0,236
f_3	74,4	1,38	1,57
f_4	99,2	0,296	0,413
f_5	124	0,1	0,084
f_{6-11}	…	…	…
f_{12}	297,2	**4,72**	6,45
f_{13}	321,96	0,54	**12,0**

In Figure 6 the displacement spectrum is plotted on first 450 Hz from the frequency range plotted in Figure 5 and the harmonics of the fundamental frequency f_1 are given in Tabel 1 together with the radial displacements on the supply and return rigid pipes.

The fundamental frequency $f_1 = 24{,}8$ Hz is given on the electric motor of the gear pump used in the shock absorbers test stand. The maximum radial displacement of the supply pipe is on harmonics f_{12} and on return pipe on harmonics f_{13}. Note that the displacements on the return pipe are greater than the displacements on the supply pipe for the mentioned harmonics.

Figures 7 and 8 show the displacement spectrum for the rigid supply and return pipes over the first 450 Hz of the frequency range when the actuator is supplied with a flow rate Q≠0 for controlling the servovalve with a sinusoidal control signal with a frequency of 1 Hz (Figure 6) and in the case of a sinusoidal control signal with a frequency of 2 Hz (Figure 7).

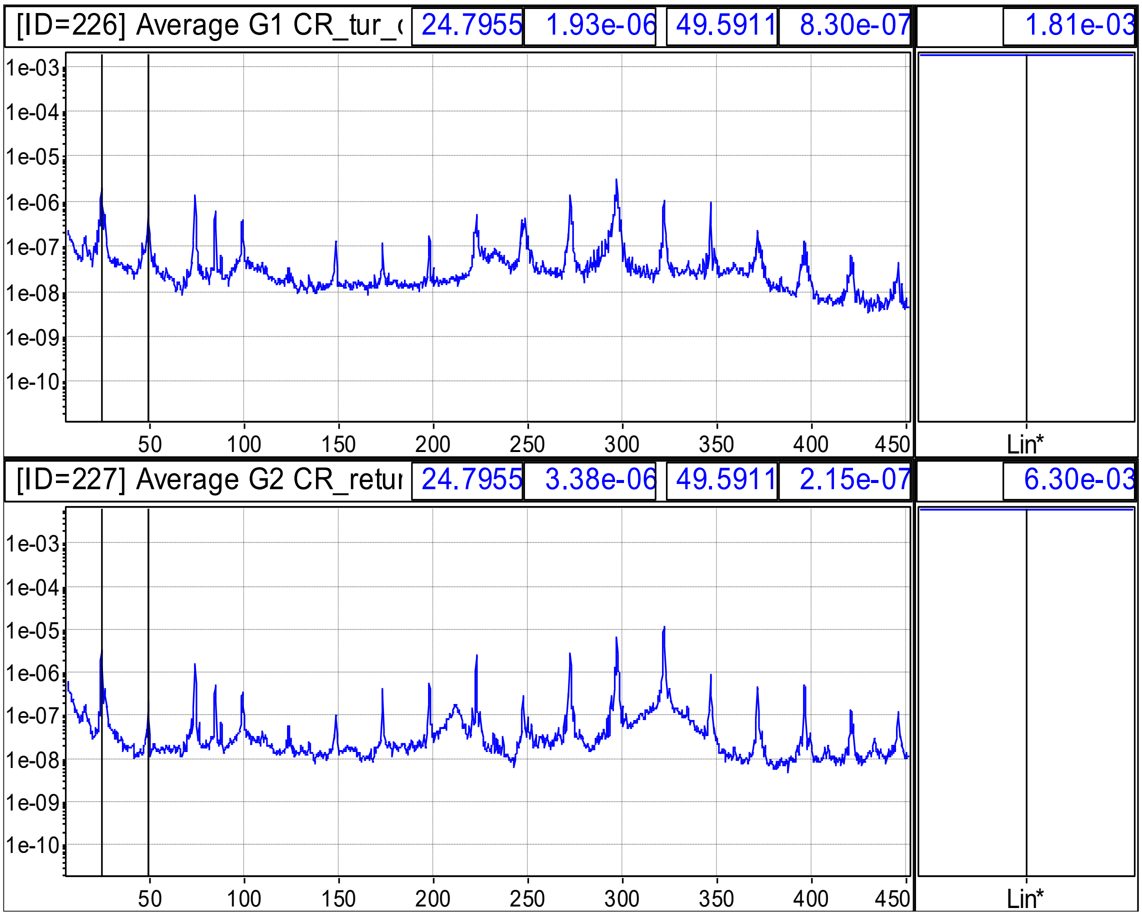

Fig. 7. Displacements spectrum on rigid pipes, supply and return, $Q \neq 0$ and 1 Hz frequency

Table 2: Displacement values of the first harmonics on rigid pipes, $Q \neq 0$ and 1 Hz frequency

Harmonics	Frequency (Hz)	Rigid pipe radial displacement (μm)	
		Supply pipe	Return pipe
f_1	24.8	1,93	3,38
f_2	49.6	0,83	0,215
f_3	74,4	1,4	1,55
f_4	99,2	0,39	0,32
f_5	124	0,03	0,06
$f_{6\text{-}11}$	…	…	…
f_{12}	297,2	**2,9**	6,5
f_{13}	321,96	0,99	**11,5**

The maximum radial displacement of the supply pipe is on harmonics f_{12} and on return pipe on harmonics f_{13}, and the displacements on the return pipe are greater than the displacements on the supply pipe for the mentioned harmonics.

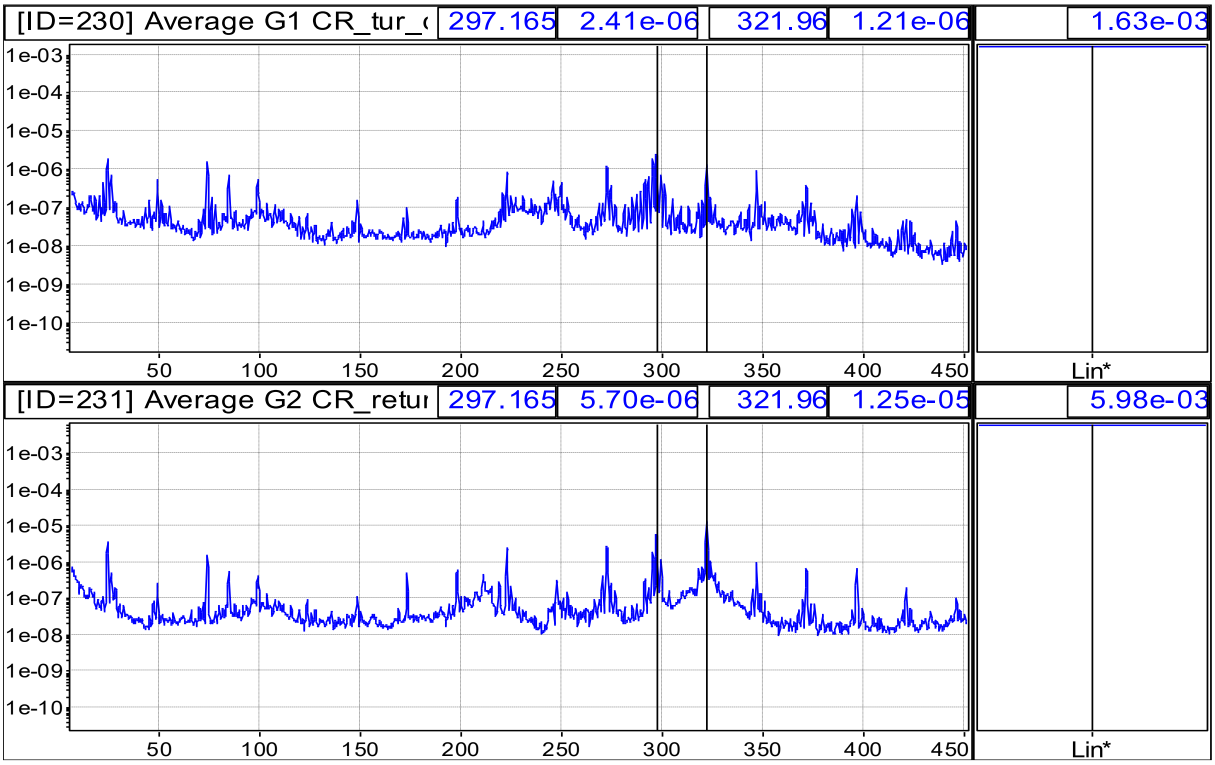

Fig. 8. Displacements spectrum of the rigid pipes, supply and return, $Q \neq 0$ and 2 Hz frequency

Table 3: Displacement values of the first harmonics on rigid pipes, $Q \neq 0$ and 1 Hz frequency

Harmonics	Frequency (Hz)	Rigid pipe radial displacement (µm)	
		Supply pipe	Return pipe
f_1	24.8	1,8	3,46
f_2	49.6	0,52	0,24
f_3	74,4	1,54	1,55
f_4	99,2	0,52	0,41
f_5	124	0,066	0,088
$f_{6\text{-}11}$	…	…	…
f_{12}	297,2	**2,4**	5,7
f_{13}	321,96	1,21	**12,5**

As in the previous case it is observed that the maximum radial displacement of the supply pipe is on harmonics f_{12} and on return pipe on harmonics f_{13}. Also, the displacements on the return pipe are greater than the displacements on the supply pipe.

If we return to Figure 5, we notice that the harmonic sidebands highlight not only the frequency of the electric motor driving the volumetric pump. There are also frequencies of other equipment within the driving scheme that we should identify in the spectrum. For example, the frequency of the electrohydraulic servovalve (if it is known from the catalog data).

Figure 9 is the cepstral representation of the spectrum in Figure 8.

In the cepstral representation, the abscissa (x-axis) is represented in seconds and is called the quefrency and the coordinate (y-axis) represents the amplitude of the cepstral components. From the physical point of view, the x-axis indicates the repetition period of the structures in the spectrum (Figure 8), and the y-axis indicates how strong the periodicity detected at a given quefrency is.

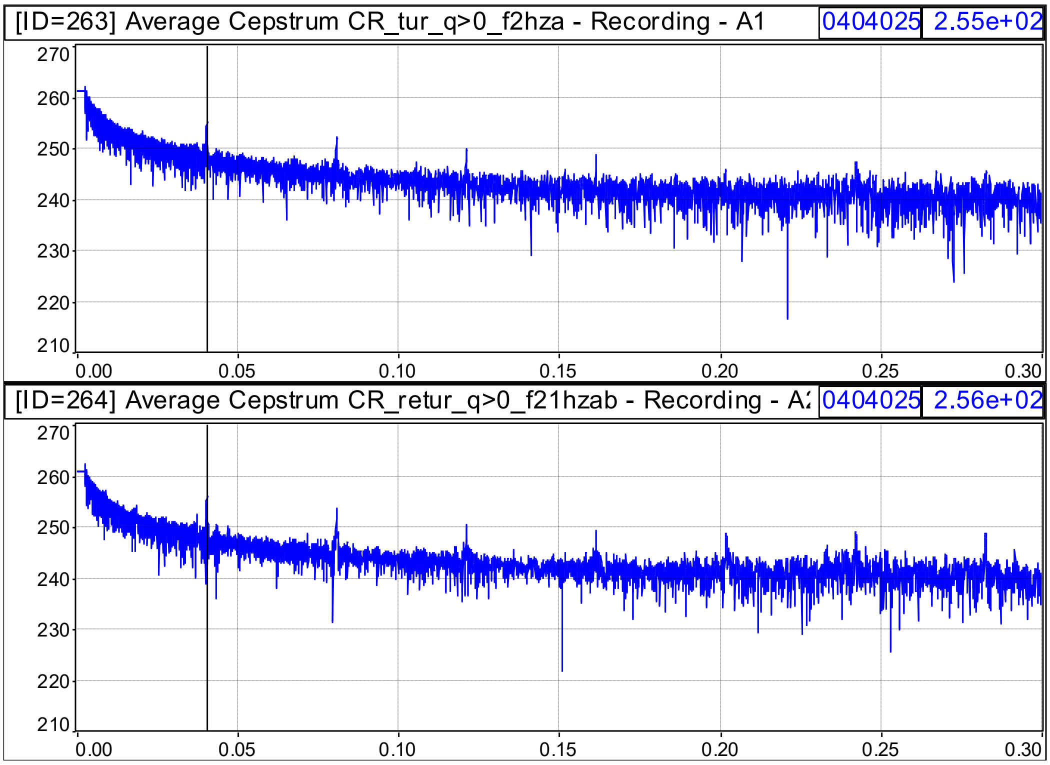

Fig. 9. Displacements cepstrum on rigid pipes, supply and return, $Q \neq 0$ and 2 Hz frequency

Figures 10 and 11 show the displacements spectrum for the installation with flexible pipes (Figure 2). The spectrum shows the frequencies and amplitudes (displacements along the pipe radial direction) in the case of a pressure of 70 bar (Figure 10) and 50 bar (Figure 11) in the adjustable throttle circuit.

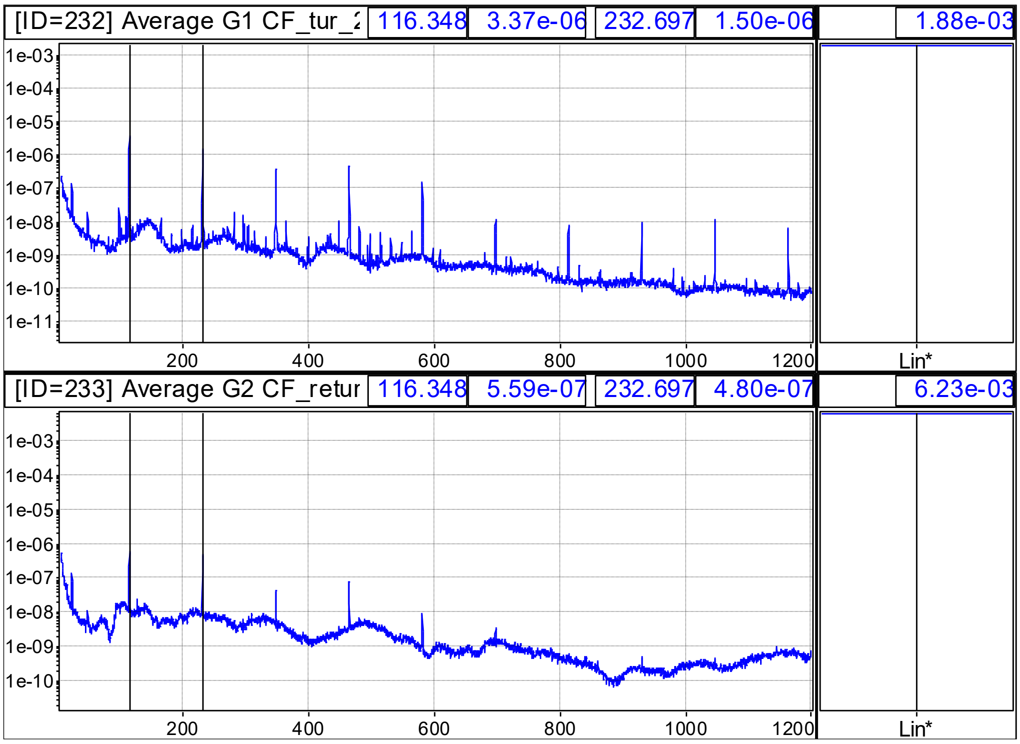

Fig. 10. Displacements spectrum on flexible pipes, supply and return, with 70 bar pressure

Table 4: Displacements values on flexible pipes, supply and return, with 70 bar pressure

Harmonics	Frequency (Hz)	Rigid pipe radial displacement (µm)	
		Supply pipe	Return pipe
f_1	116,35	3,37	0,56
f_2	232,7	1,5	0,48
f_3	349,05	0,36	0,46
f_4	465,8	0,46	0,08
f_5	582,1	0,15	0,009
f_6	698,5	0,012	0,003

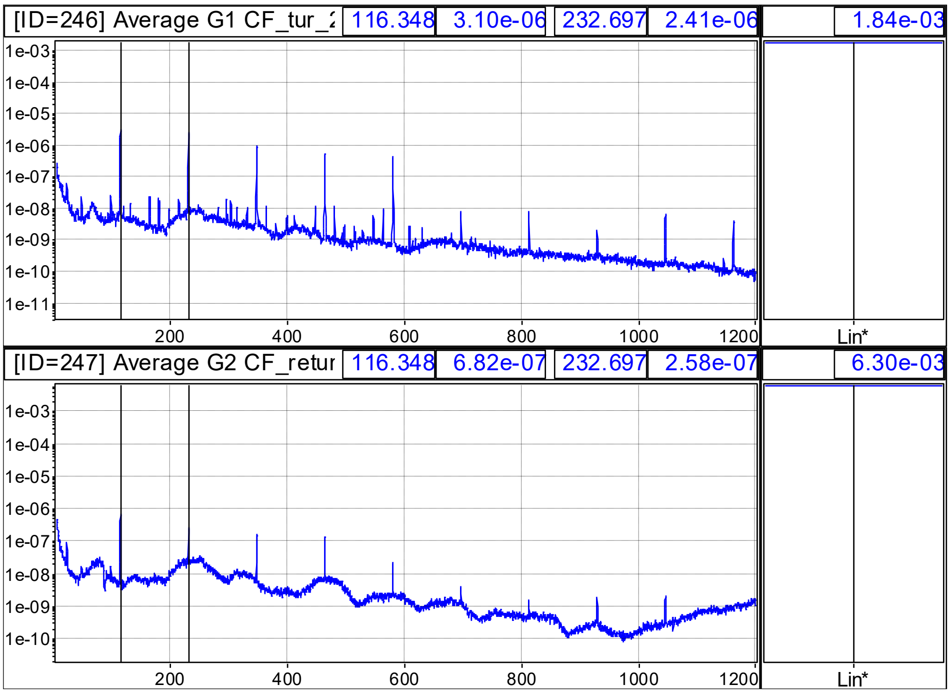

Fig. 11. Displacement spectrum on flexible pipes, supply and return, with 50 bar pressure

Table 5: Displacement values on flexible pipes, supply and return, with 50 bar pressure

Harmonics	Frequency (Hz)	Rigid pipe radial displacement (µm)	
		Supply pipe	Return pipe
f_1	116,35	3,10	0,67
f_2	232,7	2,41	0,26
f_3	349,05	0,95	0,16
f_4	465,01	0,53	0,14
f_5	581,4	0,42	0,002
f_6	697,7	0,004	0,004

In the displacement spectrum it is observed that the harmonics do not have those sidebands highlighted in the case of the hydraulic drive installation with rigid pipes, Figure 5. In the case of the displacement spectrum for flexible pipes, a damping of the vibrations is observed even if harmonics can be highlighted for the fundamental frequency $f_1 = 116.35$ Hz whose amplitude decreases with increasing frequency. Tables 4 and 5 show the values of the displacements at the harmonics in the spectrum characteristic of the hydraulic flow and return circuit in the two operating variants 70 bar and 50 bar. Also, the values of displacement are greater on the flexible supply pipe than on the return pipe.

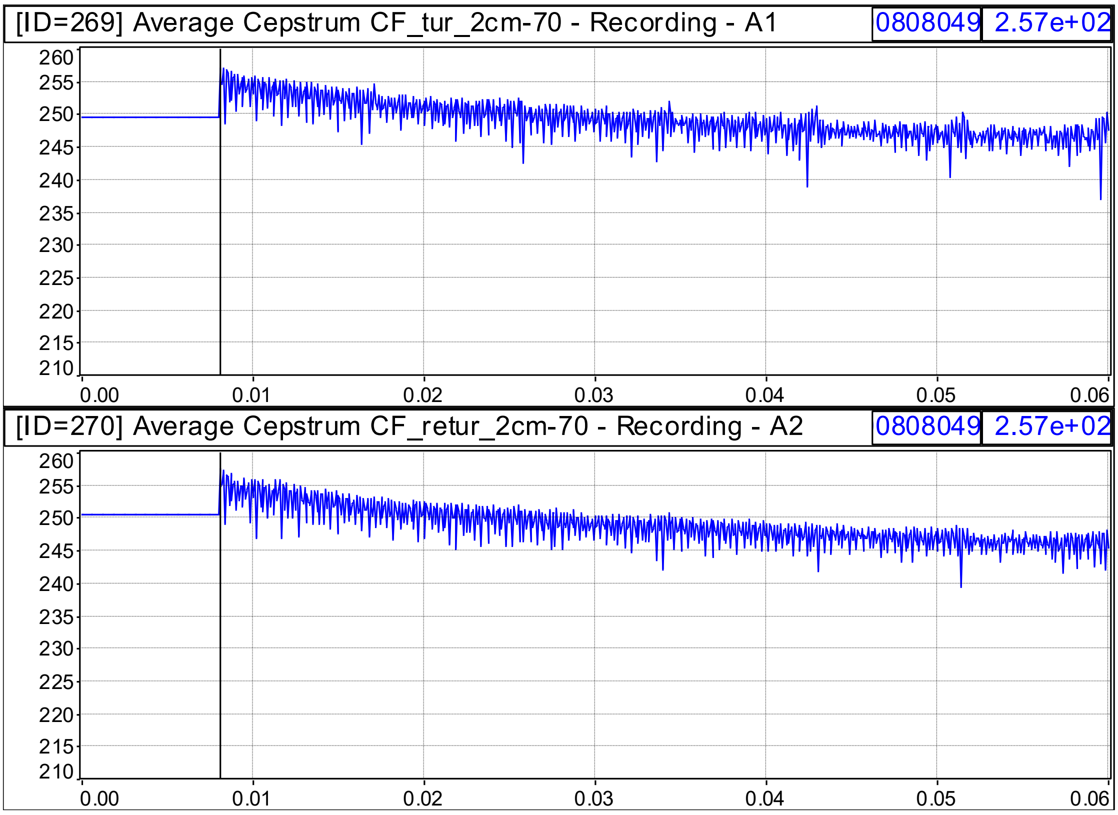

Fig. 12. Cepstrum on flexible pipes, supply and return, with 70 bar pressure

Figure 12 shows the cepstral displacement characteristic for the flexible flow and return pipe for the operation of the adjustable throttle at 70 bar. Even if in the spectral representation the frequency bands do not have the same consistency as the vibrations measured on the rigid pipes, the periodic character of the vibrations in the drive system can be observed from the cepstrum.

4. Conclusions

In this paper vibration measurements were performed on hydraulic drive systems incorporating two pipe configurations: rigid and flexible. The experimental setups differed substantially in the hydraulic structure system designed. One configuration consisted of a shock absorber test stand equipped with an electrohydraulic servomechanism, where measurements were taken on rigid pipes. The second configuration involved a test stand for various hydraulic components, where measurements were conducted on flexible pipes.

Accelerometers were mounted on the supply and return lines associated with specific devices or sections of the hydraulic circuit in each stand. In the rigid-pipe configuration, additional measurements were acquired under zero-flow conditions through the servomechanism, with the servovalve in an inactive state. The recorded vibration spectrum encompassed low-frequency components (<10 Hz) and extended to high-frequency ranges—up to 5000 Hz for rigid pipes and 2000 Hz for flexible pipes. Fundamental frequencies and harmonics up to the 10th order were identified in displacement spectrum.

Frequencies observed in flexible pipes exhibited significant damping relative to those in rigid pipes. The amplitude levels were extremely small (in both cases), in the order of micrometers, corresponding to radial displacements of pipe walls. Accelerometers were oriented perpendicular to the pipe axis and flow direction. The presence of numerous harmonics suggests a potential risk of resonance phenomena.

For flexible pipes, vibration amplitudes were consistently higher on supply lines compared to returned lines, a trend that persisted under elevated pressures (50 bar, 70 bar). The harmonic content on flexible return lines was lower than on supply lines.

Cepstral analysis reveals harmonic periodicity in rigid and flexible pipes; however, graphical cepstrum representations highlighted multiple harmonics and periodic components of modulated signals.

These findings provide a basis for developing methodologies to support predictive maintenance programs for hydraulic drive systems.

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