Understanding interactions

Part II – Sensor Positioning in the Piping System

Abstract

Pressure oscillations in piping systems have to be identified by the process control in order to initiate suitable countermeasures in due time. Much depends on the correct positioning of the sensors. The following example of a piping system illustrates the effect diameter and/or material changes have on the resonance frequencies in the piping system. Visualization of the resonance frequencies and mode shapes with so-called pressure vector plots provides graphic support for the correct positioning of the sensors.

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Introduction

To optimize the quality of a system's operation, the process control must be able to react to changes in a timely manner. In piping systems, pressure oscillations are always a disturbing occurrence for the process control, especially if high-pressure amplitudes in resonance damage components and lead to system failure.

Even if the pulsation amplitudes in resonance are at an acceptable level, the pulsation may adversely affect the process control. To make sure that the process control receives the correct measurement data, the positioning of the pressure sensors is of utmost importance and cannot be left to chance. Sensor positioning has to be adjusted for each system. To that aim, Simulative Pressure Oscillation Analysis is a suitable tool to support the project engineer in the correct positioning of the sensors.

The Challenge

Pressure oscillations are primarily caused by the volume flow pulsation of the displacement pumps. A comprehensive overview of the various interactions is provided by *Vetter* [1]. Pressure oscillations always lead to a pressure oscillation problem if an excitation frequency occurs simultaneously with a resonance frequency in the piping system. If, as described in part I [2] of this article, the pump operates at a constant revolution speed, the excitation frequencies are defined. It is then possible to build the piping system in such a way that during the steady-state operation of the pump, no frequency would "hit" a resonance frequency of the piping system.

The design of a piping system is more complicated if the system is equipped with variable-speed displacement pumps. For example, changing the revolution speed to control the flow rate would change the excitation frequency respectively. Hence, using variable-speed pumps increases the risk of exciting the resonance of the piping system.

Hydrodynamic pumps, whether constant or variable-speed revolution, can cause pressure oscillations. *Karassik et al.* [3] describes some of the possible sources. In addition, defective or worn hydrodynamic pumps excite frequencies that could not have been measured in the system when new. A further complication is that the excitation frequencies of a hydrodynamic pump are not only coupled to the rotation speed of the pump but, as shown by *Jungowski* [4], also vary with regard to the pump operating point.

Even an intermittent process control – such as in big filling plants or dosage systems, where control and adjusting devices open and close fast with regard to the eigenfrequencies of the piping system – causes pressure oscillations.

In order to be able to intervene and control the process, two requirements have to be met: First, the pulsation has to be measured. This may sound trivial, but for reasons of cost, only a limited number of sensors can be installed in a process plant. Sensor placement must ensure that the available sensors will measure the significant pulsations. Second, one should know how to interpret the measured pressure oscillation: Is it just a process-related pressure oscillation, or are the pressure oscillations part of an upcoming resonance oscillation?

Resonances in the Piping System

Numerical pressure oscillation analysis meets both requirements by simulating the pressure oscillation problem. The standard procedure of this analysis method is described below by means of an exemplary piping system. The pipes consist of three steel pipe segments and two hose lines, with an overall length of 8.1 m (image 1). It is assumed that a pump start in the system would linearly increase the rotation speed of the pump, which causes excitations in the piping system in a broad frequency range.

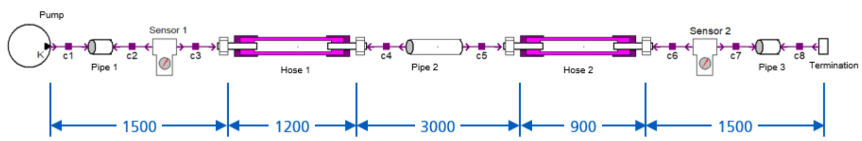

Image 1: Exemplary piping system consisting of steel pipes and hose lines.

If resonances now occur in the piping system, at the physical plant only the signals of both pressure sensors are available for investigating the oscillation behavior. The resonances of the pressure oscillation are already visible in the time signals of the pressures (image 2, upper part of image). As pressure sensors only capture the total of the pulsations at the measurement point, a deeper understanding of the oscillation behavior cannot be achieved by analyzing the time signals alone.

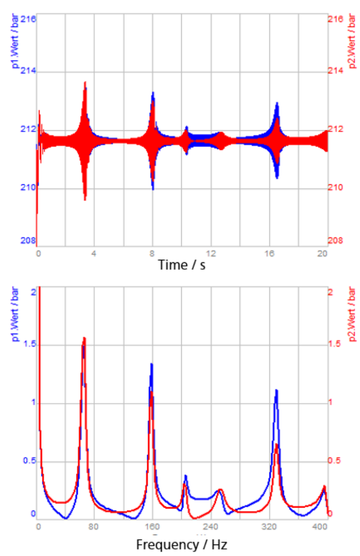

Image 2: time signals and FFT-Spectra of two pressure sensors in the system

With the help of FFT (Fast Fourier Transformation), the critical system resonances can be calculated from the time signals (image 2, lower section). Still, it remains unclear which pump order excites these resonances, and which parts of the piping system are involved in the oscillation. For the exemplary piping system, the FFT spectra show visible resonances at the frequencies 65 Hz, 157 Hz, and 330 Hz. An experienced process manager would now see that the data shows an unusual sequence of resonance frequencies and would initiate further investigations.

Pressure Oscillation Analysis of the Piping System

The simulation of the piping system provides additional information for the oscillation analysis. The visualization of the pressure oscillation in the so-called pressure vector plot gives an overview of the spatial distribution of the pressure pulsation along the central axis of the pipe system. The excitation frequency forms the x-axis and the length of the pipe forms the y-axis (image 3). Positions of high pulsation (pressure belly) and low pulsation (pressure node) are clearly visible through the color highlights.

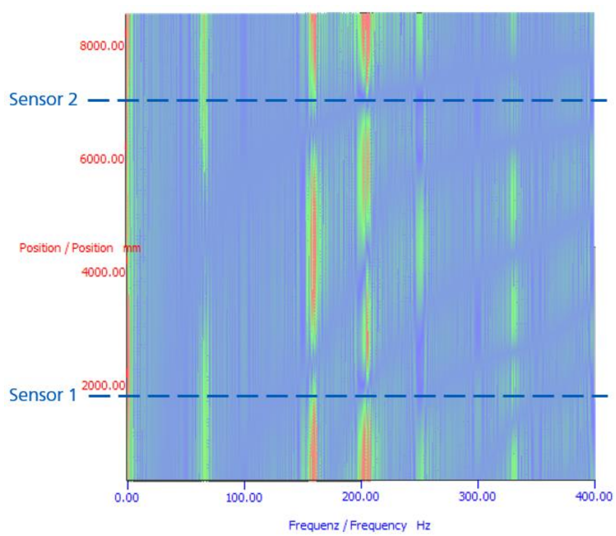

Image 3: Pressure belly position during different excitation frequencies along the center of the pipe

The pressure vector plot reveals a resonance of the system at 205 Hz, which is hardly visible in the time signals due to unfortunate positioning of both pressure sensors in the pressure nodes of this oscillation order. If this resonance frequency was excited by a displaced operating point of the pump, the necessary data to capture the pressure pulsation and take appropriate measures would be missed in the process control.

The further analysis of the oscillation situation is focused on identifying the $\lambda/2$- and $\lambda/4$- resonances in order to narrow down the boundary conditions of the oscillation situation (image 4).

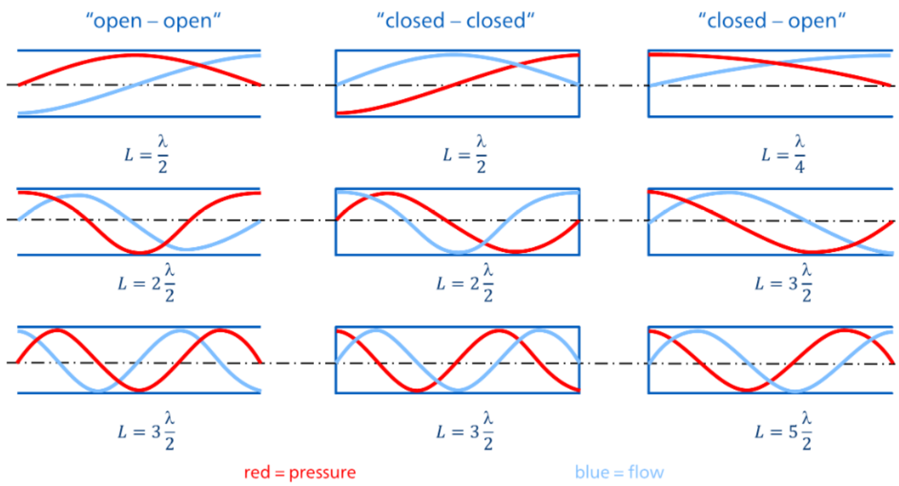

Image 4: Typical oscillation situation in piping systems

A $\lambda/2$ resonance in the piping system is of the type "closed – closed" when a pipe is closed on both ends, while displacement pumps in general and actuators in a closed state are generally regarded as "closures." If actuators are completely or partially open, conclusions can be drawn from the linearization of the flow curve to its effect on the resonance behavior of the system. In the simulative pressure oscillation analysis, this happens automatically during the calculation.

A $\lambda/2$ resonance is of the type "open – open" when a pipe is joining two large vessels. The positions of the pressure belly and pressure node are mirror-inverted to those of the type "closed – closed."

A $\lambda/4$ resonance occurs if the piping system is closed only at one end and if the other end of the pipe leads to a larger volume or to a pipe with a larger diameter. This can be, for instance, a pipe which starts at a vessel or which branches off a main pipe and which then ends in a closed actuator.

The oscillation situation of combined pipes

According to the theory as illustrated in image 4, at a sound velocity of 1320 m/s, the $\lambda/2$ resonance for the 8.1 m long exemplary piping system which is closed at both ends should be approximately 80 Hz, with 160 Hz and 240 Hz for the 2nd and 3rd order. The $\lambda/2$ resonance as shown in image 5 is already visible at 65 Hz.

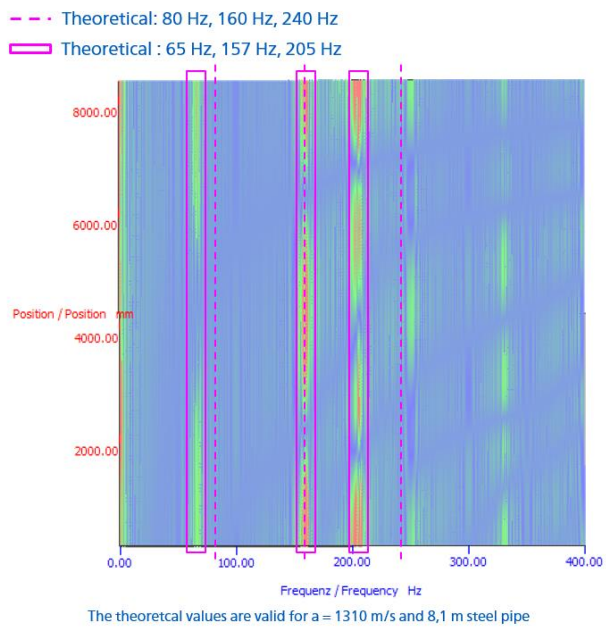

Image 5: $\lambda/2$ resonances in the exemplary piping system

Theoretically, the higher orders of this oscillation should be visible at the integer multiples of the basic frequency each, that is at 130 Hz and 195 Hz. The pressure vector plot shows, however, the 2nd and 3rd oscillation order at 157 Hz and 205 Hz. The reason for this displacement of the sequence of resonance frequencies lies in the subdivision of the pipe in steel pipe and hose line segments. Even with segments of identical diameters, changing the material results in a change of the shock wave propagation velocity in the respective segment. Similar displacement effects of the system resonance ensue also when the piping system is built with segments of different diameters or of parallel pipes.

At this point, if not before, the calculation of the resonance frequencies of the piping system cannot be done any more on the basis of simplified formulas. The comprehensive analysis of the oscillation situation is only possible using the described simulative method. As a result, the critical frequencies and the positions of high and low-pressure pulsation are available. Like this, the project engineer is able to optimize the number and correct positioning of the pressure sensors, allowing the measurement of all critical resonance frequencies. Therefore, the prerequisites have been met to enable the process control to respond in due time to changes in the pressure situation of the system.

Literatur

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