Understanding interactions

Part III – Dynamic Load Cases in the Piping System

Abstract

Pressure oscillations can cause permanent mechanical loads and fatigue in the piping system. Ultimately, this will result in plant downtimes if leakages and fatigue failure occur. The Simulative Pressure Oscillation Analysis takes into account the interaction between fluid and piping system, known as fluid-structure interaction, meeting the needs of the dynamic loads of the piping system.

Introduction

When pipe breaks and leakages on joints and flanges occur, the first thing that comes to mind are damages caused by pressure oscillation problems and pressure impacts. These operating states usually can be avoided with careful plant planning and a proper plant operation management. This, however, quite often ignores the fact that pressure pulsations, which initially are not critical for the plant's operation or for the strength of the piping system, will induce mechanical stress in the piping system.

Pressure oscillations can cause permanent mechanical loads in the components and brackets of the piping system or plant components, which can result in component damage and a negative impact on the function and the reliability of the plant. Using the simulative pressure oscillation analysis, the

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engineer is provided with a tool that enables him to quickly and easily analyze the pressure oscillation situation in the branched piping system.

The first part of this paper (see CITplus 12/2017, pp 14) describes the evaluation of the pressure situation by means of so-called pressure vector plots, visualizing the fluid eigenfrequencies of the piping system. The second part (see CITplus 5/2018, pp 42) covers the identification of piping segments with high-pressure amplitudes, which is a prerequisite for the correct positioning of remedial measures (dampers, resonators, etc.) and sensors. The third part will show that the simulative pressure oscillation analysis is also able to analyze the dynamic load cases which are important for a durable piping system design.

The Challenge

The numerical analysis of forces and torques in piping systems is nothing new but is standard for the design of these systems. This is explained by *WOSSOG* [1] in his methodical overview in the manual for pipeline construction, which also includes fluid dynamic analysis. The guideline VDI 3842 [2] explicitly addresses the frequencies in the piping system. Both sources recommend the consideration of the fluid-structure interaction (FSI) if dynamic load cases are to be considered.

But why is the consideration of dynamic load cases for durable design of the piping system so important? VDI 3842 provides a clear answer to this question:

> "Dynamic loads – together with the static operating loads occurring at the same time – and depending on the type of load case – can result in
>
> - Violent rupture (strength failure),
>
> - Failure due to reaching the plastic fatigue strength limit,
>
> - Failure due to reaching the time or fatigue limit (fatigue)"

Although oscillation problems and corresponding damage in fact frequently occurs, usually only the static loads are designed. What makes taking the dynamic load cases into account such a difficult and costly task?

During plant configuration, this is simply due to not knowing the pressure oscillation situation which prevents the suitable consideration of the dynamic load. However, the pressure oscillation situation also changes in existing plants where the production process is being adapted or machine components are being replaced.

This sets the stage for the numerical pressure oscillation analysis. This is because a realistic depiction of the pressure oscillation situation, from which the required dynamic loads and torques can be derived, can only be analyzed within the context of the overall system by simulating representative operating cycles. As shown in the first and the second part of this paper, advanced fluid power systems are able to determine the dynamic pressure pulsation for any position within the branched piping system. The only thing that has to be integrated into the numerical model description is the fluid-structure integration (FSI).

Basic principles of the fluid-structure interaction

FSI must always be taken into account when, due to pipe bends or pipe elbows, a pipe's direction is being changed. During operation, a dynamic force impact on pipe bends or elbows is caused by intermittent pressure and pulse forces. As a result, the pipe is excited and oscillations can be transmitted first to the mounting points and then to the plant structure. **Image 1** shows the fractions the dynamic load is composed of when a compression wave runs through a pipe bend.

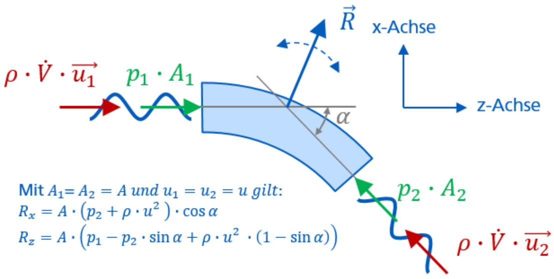

Image 1: Map of forces on the pipe bend

In order to consider FSI in the simulative pressure oscillation analysis, the existing equation system of the piping models is extended; in addition to the momentum and continuity equations for the fluid media, now twelve additional equations for the six degrees of freedom (each with one flow and potential variable) are being solved. As the axial movement of the pipe wall is coupled with the pipe flow through lateral contraction and friction, the momentum and continuity equations of the fluid media have to be complemented by additional terms.

The limitation to pipes with a ring-shaped cross section (where no warping occurs) allows analysis of the distortions of the pipe wall around the local z axis according to DE SAINT-VENANT's fundamental theory of torsion [3]. Taking into account the inert mass of fluid, the bending stiffness of the pipes will be modeled with the beam theory of TIMOSHENKO, which, compared to the EULER-BERNOULLI's beam model, also considers additional deformations caused by shear forces [4].

The resulting overall equational system including 14 coupled partial differential equations (PDEqs) represents a synthesis of the works of LAVOOIJ & TIJSSELING (longitudinal waves) and WIGGERT, HATFIELD & STUCKENBRUCK (bending and torsional waves) [5, 6]. To solve the PDEq system, the proven fluid technology method of characteristics is being applied, making use of time interpolation according to GOLDBERG instead of the familiar space interpolation [7].

Pressure oscillation analysis considering fluid-structure interaction

The potential of the pressure oscillation analysis using FSI will be demonstrated by means of an example of a pipe which is open at both ends and has two mounting points and two pipe bends, as shown in image 2. The selected pressure oscillation situation has been chosen so that the first eigenfrequency of the pipe shows its pressure belly in the pipe section between the two pipe bends.

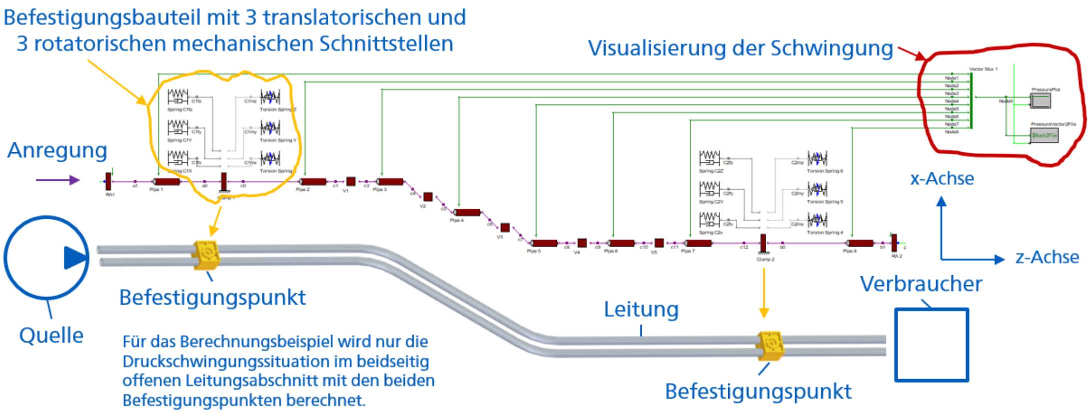

Image 2: Pipe with two mounting points

For the pressure oscillation analysis with FSI, it is important to model the dynamic stiffness (impedance) of the mounting points. If the real stiffnesses are not available in data sheets, they can be determined by measuring or by means of FEA analyses. Image 2 shows the stiffnesses simplified with spring-damper elements and torsional spring-damper elements, which in turn are ideally rigidly connected with the plant.

If the pressure oscillation analysis is used primarily to evaluate component loads, then the pipe forces, speeds, torques, and angular speeds, as well as pressure pulsation, can be visualized by vector plots (see explanation in CITplus 12/2017, 14 pp). As vector plots on the x-axis illustrate the pipe's length before bending, the project engineer gains an overview of whether the fatigue-prone parts of the plant (such as welded joints) are located in the areas with high dynamic load. The frequency of the load can be read off the y-axis.

Image 3 shows this for forces and speeds in the pipe. There is no visualization of the vector plots for pressures, torques and rotational speeds. In image 3, the hydraulic eigenfrequencies of the pipe are marked as dotted lines. Vertical lines mark the positions of the mounting points and pipe bends.

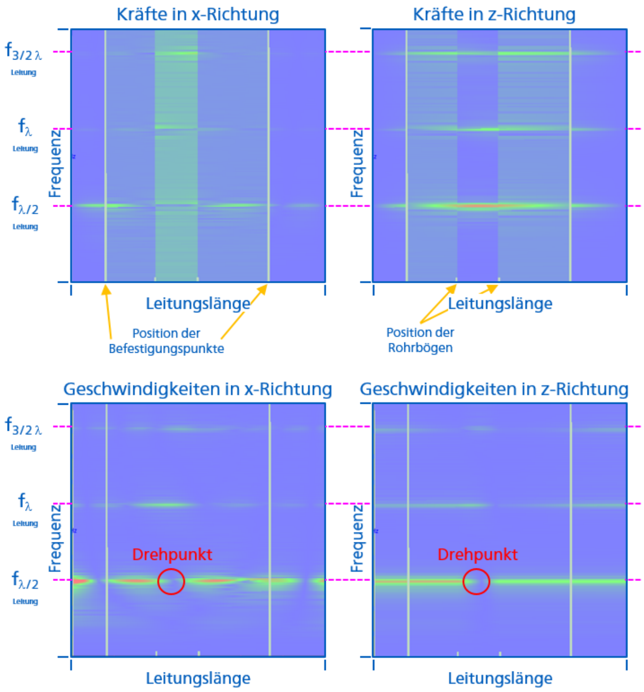

Image 3: Vector plot of forces and speeds in the pipe

The two upper vector plots in image 3 show the forces in the pipe. In the diagrams, the frequencies at which the pipe will be subject to dynamic loads caused by pressure pulsations are clearly visible. The pressure belly of the first eigenfrequency between the mounting points, for example, results in a maximum force in the direction of the z-axis. The vector plots of the speeds (lower row in image 3) illustrate that the pipe is performing a rotational movement. In x-axial direction, the entire pipe additionally oscillates in a higher bending oscillation order – clearly visible in the horizontally distributed sequence of oscillation nodes and bellies. If the project's aim is to minimize the excitation of the mounting points, the 1D simulation will offer additional tools. By means of parameter variation (e. g. the positioning of mounting points) and the subsequent automated analysis of results, the project's workflow can be automated to a great extent.

If the results of the pressure oscillation analysis are meant to be used for the detailed durable design, the time signals will be available at any position within the piping system. In this regard, image 4 displays a set of values of pipe bends and mounting points. The pressure signals from the center of the two pipe bends each show pressure amplitudes from the rim of the pressure belly. While these amplitudes are not the maximum pressure amplitudes – the latter are located in the center of the pipe section between the pipe bends exerting loads in the radial direction of the "pipe breathing" – they are precisely the pressure amplitudes which cause mechanical excitation of the pipe as shown in image 1. Both in the force and in the torque curve, it is clear that the fluctuating force excitation leads to a significant structural excitation of the mounting points. On the right side of the dominant pulsations there are also excitations of the two higher hydraulic eigenfrequencies visible. The excitations on the left of the dominant excitation show the mechanical eigenfrequency of the spring-damper-mass-system consisting of the pipe with two mounting points.

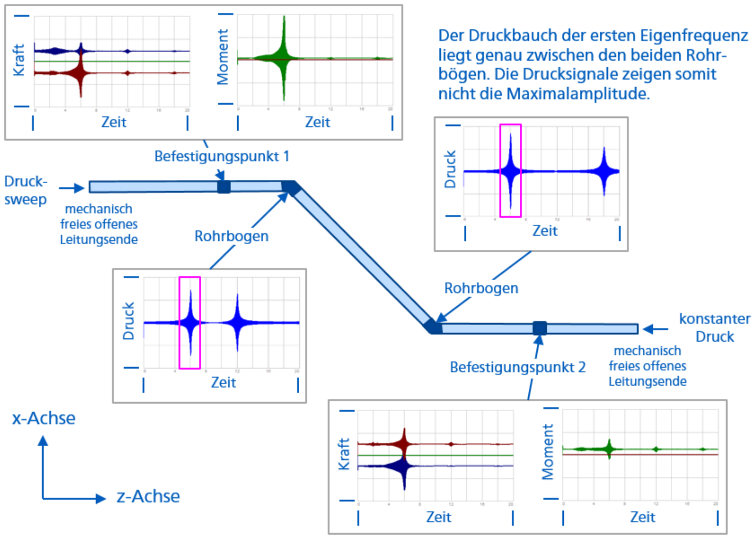

Image 4: Time domain signals of the pressures on the pipe bends as well as of the forces and torques on the mounting points

Depending on the selected sampling rate of the simulative pressure oscillation, the time signals show a resolution in the kHz range. Transformed into Fourier-Spectra, these forces and torques can now be used in the FEM analysis by structural analysis programs as excitation for a transfer path analysis of the plant structure or for predicting the fatigue life of welded joints.

If the project engineer wants to obtain an overview of the existing dynamic loads in the piping system during the pressure oscillation-optimized plant configuration or during a problem analysis, the simulative pressure oscillation analysis, complemented with FSI, provides a suitable tool. When a detailed model of the piping system is already available for the visualization of the pressure oscillation situation, and provided that the stiffnesses of the mountings are available, the fluid-structure interaction can be easily added.

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