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Pressure oscillation analysis in low-pressure fuel piping systems

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Pressure oscillations in low-pressure fuel piping systems can cause noise and damage components. Such phenomena impact both function and reliability. Since interdependencies of the components have to be taken into account, an analysis of the pressure oscillations can only be done on a system level. In this article, the cause-effect relationships in low-pressure fuel piping systems and the value of simulation are discussed using a practical example.

Introduction

A low-pressure fuel piping system (Figure 1) consists of three subsystems: the fuel tank/fuel supply unit, fuel pipe, and fuel pump (high pressure pump, HPP). The system is designed for each vehicle individually. In a car line, the fuel pipe and HPP subsystems often differ depending on the chassis used (line run) and the motorization (HPP type and number). The resulting variety of possible component combinations can make an optimal design matching of the system very difficult. Low-pressure fuel piping systems therefore often experience unwanted pressure oscillation phenomena leading to noise emission or component damage, adversely affecting both function and reliability.

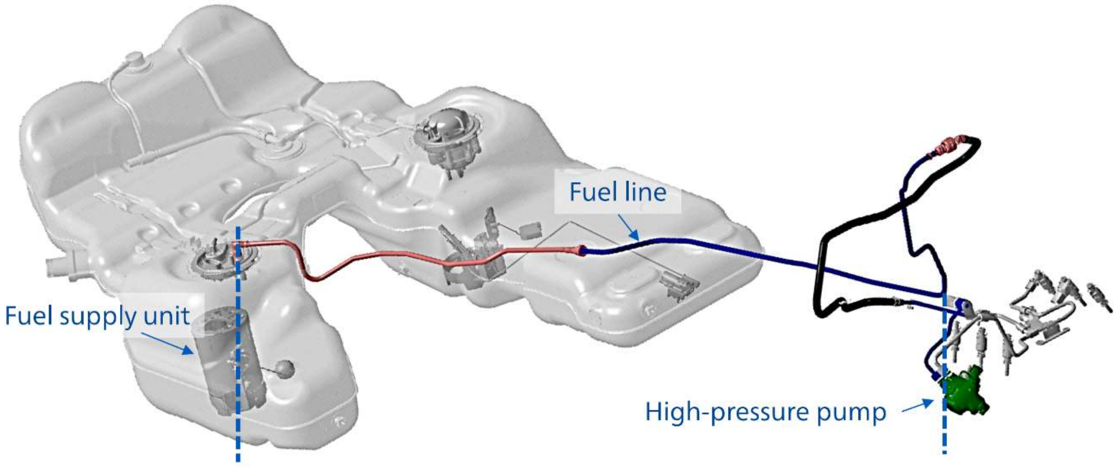

Figure 1: Three subsystems of the low-pressure fuel piping system

Modern 1D fluid power simulation tools [1] are able to predict at which operational points (stationary pressure, dynamic pressure amplitude, oscillation frequency) the hydraulic system is most engaged. Visualisation of the simulated pressure oscillations along the line axis allows for a precise identification of areas with high and low-pressure oscillation – a basic requirement for successful remedial actions. Simulation is ideal for evaluating the dimensions and proper positioning of remedial actions prior to implementing cost-intensive measuring campaigns on the real-world vehicle.

Since the simulation of pressure oscillations is also applied for solving time-critical problem cases, the modelling approaches should not include complex physical approaches which are expensive to validate or require time-consuming calculations.

Problem description

Every hydraulic system, including low-pressure fuel piping systems, features several eigenfrequencies, but this does not automatically mean that resonance problems will occur. First, eigenfrequencies have to be stimulated. In a low-pressure fuel piping system, the excitation comes from the low-pressure volume flow oscillation of the HPP and the resulting compression waves. Due to the variable revolution speed of the combustion engine, flange-mounted to the HPP, the hydraulic system is excited by compression waves in a wide frequency bandwidth. This unfortunately increases the likelihood of “hitting” resonance frequencies of the system.

In the event of a resonance, the system’s damping and the amplitude of the initial pressure pulsation (characteristic pulsation of the HPP) determine whether a pressure oscillation problem occurs or not. Figure 2 illustrates an idealised characteristic pressure pulse of the HPP.

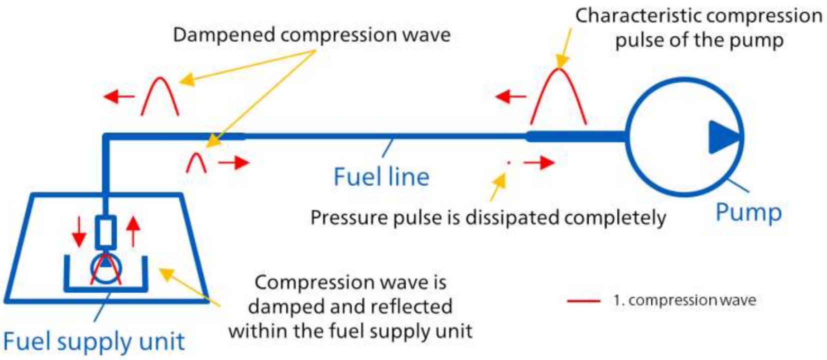

Figure 2: Low-pressure fuel piping system with sufficient system damping

The pressure pulse initially runs as a compression wave through the fuel pipe toward the fuel tank/fuel supply unit. Damping is induced due to the internal friction of the fluid, reflection at quick-connectors or changes to the cross section, and especially the viscoelastic behaviour of the employed plastic material [3] interacting with the compression wave.

The compression wave energy is dissipated into heat. When reaching the fuel tank flange, the compression wave enters the fuel supply unit where it experiences further damping in the corrugated pipes and the overall volume. The remaining part of the compression wave is reflected in the fuel supply unit and runs back through the fuel pipe toward the HPP where energy is again dissipated. Ideally, the compression wave induced into the system by the HPP is completely dissipated on its way from the HPP and back. Even if the resonance is hit, no pressure pulsation problem occurs. This is why it is worthwhile to aim for a HPP with a characteristic pulsation as low as possible.

In most cases, however, the characteristic HPP pulsation is too strong to be completely dissipated. In addition, the damping effect of the plastic materials is reduced with higher operating temperatures. This means that the remaining compression wave is still strong enough to reach back to the HPP (Figure 3). In case of a resonance, the returning compression wave hits the HPP at exactly the point in time (and in the right phase) when a new compression wave is produced. In this instance, both compression waves will superimpose.

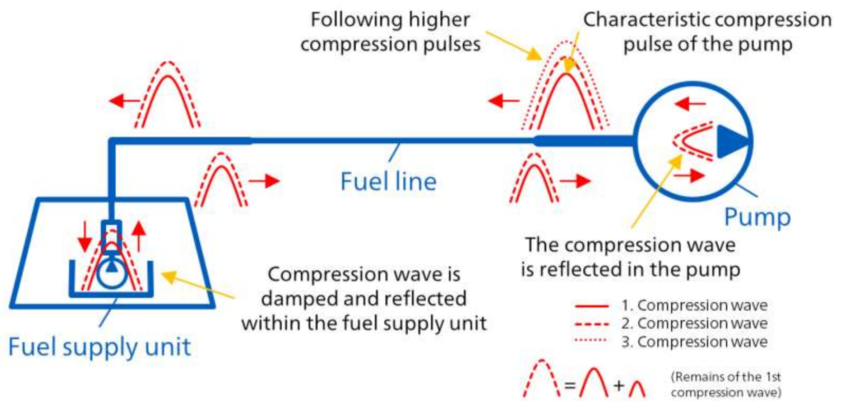

Figure 3: Low-pressure fuel piping system with beginning pressure oscillation issue

This results in a new compression wave with slightly higher amplitude. When returning to the HPP, the remainder of this wave will be bigger than the first one, resulting in a third compression wave with even higher amplitude, and so on. This is the birth of the pressure pulsation problem.

Simply identifying the eigenfrequencies and pressure pulsation amplitudes via measurement is not sufficient to determine remedial measures. The following example illustrates the essential need for a deeper understanding of the interactions of the subsystems.

Pressure oscillation situation in the low-pressure fuel piping system

Modern HPPs feature a significantly lower characteristic pulsation compared to older pump type series. This means, for example, that the number of damping elements in the HPP cover plate can be reduced without increasing the characteristic pressure pulsation. However, as shown in Figure 3, small pressure pulsations are already sufficient to excite a system resonance. To avoid pressure oscillation issues in a low-pressure fuel piping system, it is not enough to just reduce the pressure pulsation amplitude, although this is certainly helpful.

The design of an HPP also has a major impact on its vibration behaviour. For example, waiving one damping element considerably increases the first eigenfrequency. On the other hand, the eigenfrequency gets lower if with a different motorisation or through a pump manufacturer change more or bigger damping elements are used. In both cases the first eigenfrequency of the system can be shifted toward the excitation frequency at idle speed.

The same line of argument applies for the fuel supply unit. If the vibration behaviour of the fuel supply unit changes, the eigenfrequencies will be shifted as well. This applies in particular if, for the sake of component safety, subsystems are disconnected at specific operating conditions. In this case, the vibration behaviour of the fuel supply unit changes immediately.

To identify pressure pulsation issues as early as possible in the design of low-pressure fuel piping systems, ideally all combinations of the relevant HPPs and fuel supply units should be evaluated regarding their impact on the system’s eigenfrequencies. Theoretical considerations clearly show that it is necessary to focus on the system level – fuel supply unit, HPP, and fuel pipe. Due to the use of different fuel pipes, the number of combinations is even higher and analytical investigation becomes difficult and time-consuming. Pressure oscillation analyses in the early development phases are therefore best approached by employing simulation.

Analysing pressure oscillation through simulation

Figure 4 shows a simulation model for analysing pressure oscillation. The excitation comes from the experimentally determined characteristic volume flow pulsation of the HPP and is fed into the simulation via the hybrid pump model [2] including a damper element [4].

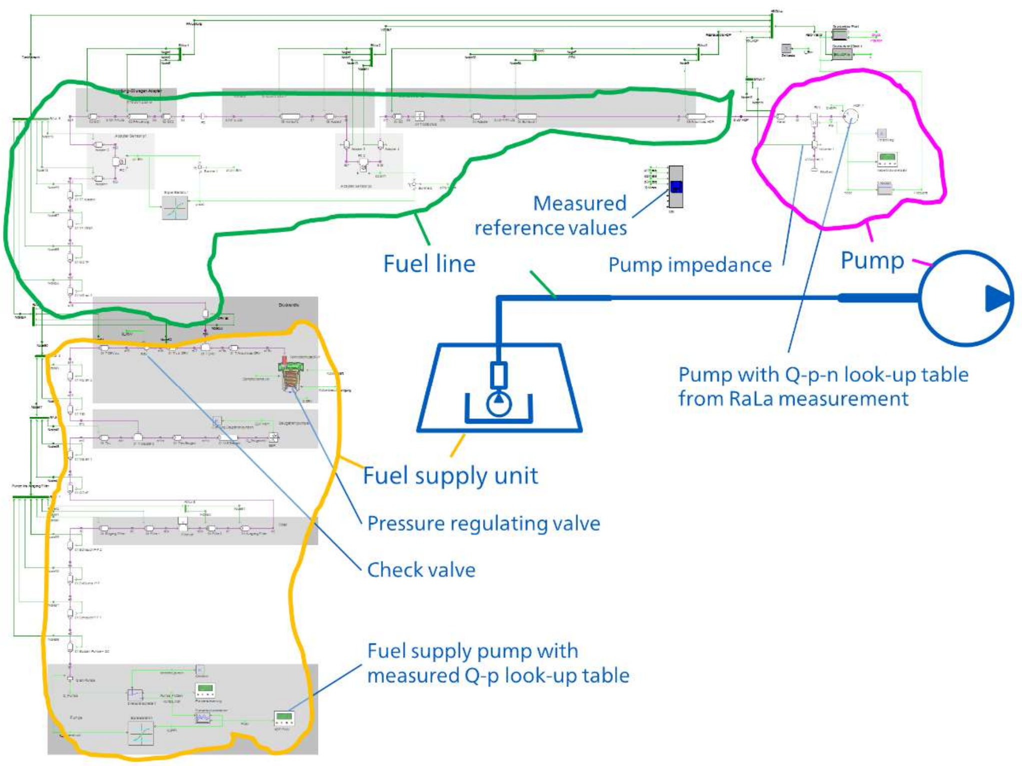

Figure 4: Simulation model of a low-pressure fuel piping system

The fuel pipe consists of aluminium, PA and FPM line sections whose material parameters [3] were determined experimentally. In addition, the fuel pipe includes all quick-connectors and cross section changes. A physically modelled fuel supply unit is used in the simulation model, since the model is also used to effect analysis and for developing remedial measures. The simulation model is validated with experimental data, shown in Figure 5 on the left side. A comparison of experimental and simulated pressure signals for the measurement points “fuel tank flange” and “end of underbody line” is shown. Both the pressure amplitude and pressure pulsation phases are very well reproduced in the simulation.

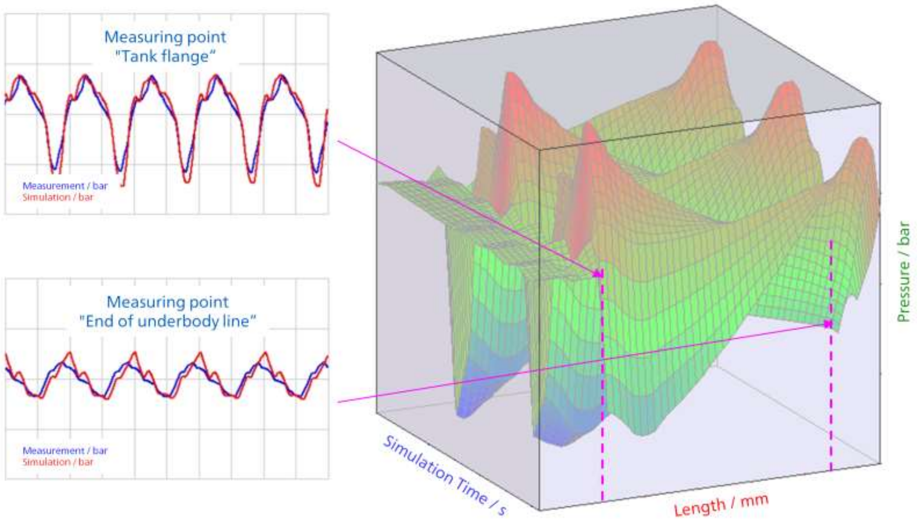

Figure 5: Comparison of experiment and simulation – detailed view on the pressure oscillation

Since there are various pressure values along the middle line of the pipe in the data matrix of the pressure vector plot, and not just two pressures at the measurement points, the pressure vector plot can be used for an accurate vibration analysis. On the right side of Figure 5, some pressure oscillations of the first eigenfrequency are showcased.

Figure 6 provides a top view of the pressure plot, giving an overview of the entire vibration situation.

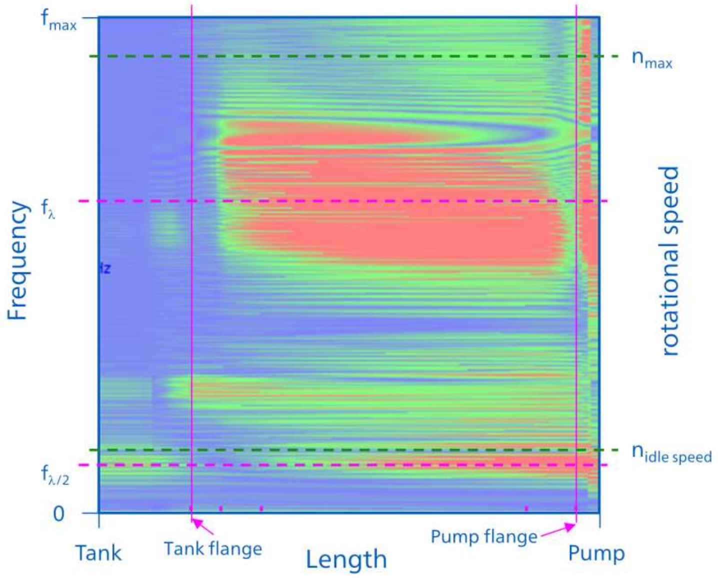

Figure 6: Pressure plot of a low-pressure fuel piping system at ambient temperature

The x-axis represents the length of the fuel pipe. The left y-axis shows the excitation frequency. The first and second eigenfrequency are highlighted with horizontal lines. On the right y-axis, typical revolutions of speed limits are plotted. The results show that the first eigenfrequency of the system is below the idle speed of the engine. Through simulation, it is now possible to investigate whether and to what extent the eigenfrequency is shifted toward the idle speed due to a temperature change which might cause a pressure oscillation issue. The second eigenfrequency covers a relatively large frequency range. The middle of the underbody line is subject to higher pulsation amplitudes over a large rpm range which might impact durability and fluid-structure-interaction in this section of the low-pressure fuel piping system

Conclusion

As long as piston pumps are used as high pressure fuel pumps (HPP), a pressure pulsation excitation might be caused by the kinematic volume flow pulsation of these pumps. In a resonance case, the system damping will determine whether a pressure pulsation issue will or will not occur. Practical experience shows that the damping usually is not sufficient, and pressure pulsation issues have to be treated in the course of the systems application.

With various combination options of HPP, fuel supply unit, and fuel pipe, which change their acoustic behaviour depending on pressure and temperature conditions, an analytical evaluation of the pressure oscillation situation is difficult. 1D system simulation with specific components designed for pressure oscillation analysis provides a feasible development tool. The early knowledge gained through simulation as to which excitation frequencies lead to resonance with disturbing pressure amplitudes helps in the design of low-pressure fuel piping systems and enables an educated assessment of modifications for operational efficiency and performance.

Literature

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