Noise and vibration studies on pneumatic circuit protection valves

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Abstract

Pneumatic circuit protection valves are frequently used in the air supply systems of commercial vehicles. This paper presents a flexible computational simulation tool being applied in industrial research and development related to complex mechanical and fluid dynamical aspects in such devices. The numerical model has been created with AMESim, a commercial simulation environment, and then validated by simplified experiments. The comparative numerical and experimental study confirmed that the validated numerical model is able to predict the oscillatory behavior appearing in certain setups, and the system parameter alterations suggested by the simulation successfully eliminated the harmful vibration in the experimental setups as well.

Keywords: AMESim, protection valve, numerical and experimental analysis, dynamic simulation

1. Introduction

Pneumatic circuit protection valves (PV) are frequently used in the air supply systems of commercial vehicles [1][2]. According to the ECE R 13 regulation [3] which contains leading principles for the braking system design in Europe, they should supply pressurized air to a number of pneumatic circuits simultaneously, while protecting each of them independently from excessive pressure fluctuations or pressure losses. To prevent damages, these devices must act quickly, closing the PV if becomes necessary. However, this means that these devices can reach a state where certain elements in the valve may start to oscillate. This can compromise the correct operation of the connected pneumatic circuits, and might even reduce the service life of the oscillating elements considerably. This phenomenon can be efficiently analyzed and corrected by means of numerical simulation methods. As illustrated in SZENTE et al., a simplified 1D simulation tool can be effectively used in design, research and development regarding controlled fluid power systems [4]. The PV models must represent reliably the transmission characteristics of the PV, without time-consuming and practically unnecessary resolution of 3D effects.

The case study presented herein comprises an air supply unit, a 4-way pneumatic circuit protection valve, piping, and pneumatic circuit models. The simulation environment that had been used to create the numerical model is AMESim [5], which is a complete modeling and simulation platform that integrates multi-disciplinary (i.e. pneumatic, hydraulic, thermal, electronic, mechanical, etc.) systems into a single environment. This software had already proved its appropriateness in simulation of systems related to automotive industry [6][7][8]. The model has been validated by simplified experiments, reaching a state where the differences between the simulation and the measurement became appropriate for further studies. The comparative numerical and experimental study confirmed that the validated numerical model is able to predict the oscillatory behavior appearing in certain setups, so it can be used to conduct further studies on parameter sensitivity. The parameter sensitivity studies have been used to suggest some system parameter alterations, which have been incorporated into the experimental setup. These alterations successfully eliminated the harmful vibration in the experimental setups as well. Therefore it can be concluded that this simulation tool can be effectively used in design, research and development of pneumatic circuit protection devices.

2. Physical system

The schematic diagram of a PV is shown in **Fig. 1**. It consists of four pressure control valves divided to two stages. Each has one output that can be connected to a separate pneumatic circuit. The PV has one common input (port 1) which is connected to a pressure supply. This common input supplies the pressurized air to the first stage. Here, a bypass valve has been implemented parallel to the pressure control valves in order to speed up the loading process. The inputs of the second stage are connected to the outputs of the first (ports 21 and 22), each through a spring-loaded check valve. In contrast with the first, there isn't any bypass valves in the second stage, only the pressure control valves provide air for the outputs (ports 23 and 24).

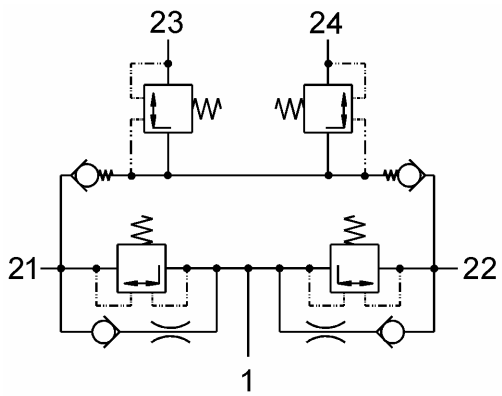

Fig. 1.: Schematic diagram of a pneumatic circuit protection valve

This PV had been connected to a simplified pneumatic circuit setup in order to separate the transmission characteristics of the PV from the pneumatic elements that are usually connected to it in real-world situations. Port 1 had been connected to a constant-pressure air supply P_{in} through an orifice D_{in}, ports 21, 22 and 23 had been closed while port 24 had been connected to the atmosphere through an orifice D_{out} as it can be seen on **Fig. 2**.
The aim of the study was to investigate a specific behavior which occurs only when certain conditions have been met. During the load process, when the empty pneumatic circuits are to be filled with pressurized air, it is possible for certain setups to reach a state where the pressure of one or more outputs on the PV starts to oscillate. This phenomenon can cause disturbances in the connected pneumatic circuits; therefore the investigation has been concentrated on eliminating this oscillation.

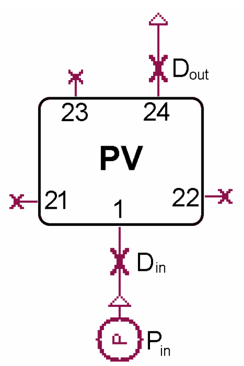

Fig. 2.: Simplified circuit setup

3. Modelling of the system

As it has been mentioned previously, the simulation environment that has been used to create the numerical model is called AMESim, which is a graphical environment for modeling, simulation and analysis of dynamic engineering systems. AMESim is based on a large set of validated model libraries issued from different physical domains. The basic element concept, which lies behind each model, provides basic engineering elements that can be combined to describe all functions of the component or system in the model.

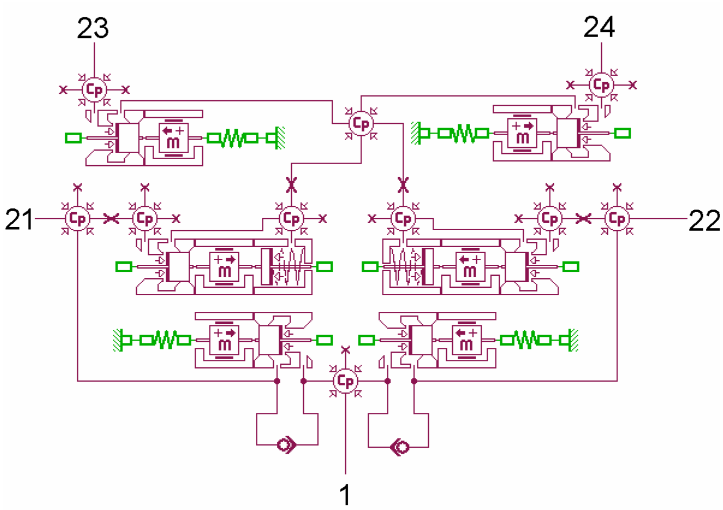

Fig. 3.: AMESim circuit diagram of the protection valve

Although AMESim is a multi-domain simulation environment, in this case the pneumatic library had been quite sufficient [9] as almost all sub-element models had been built up using the commercially available submodels taken from this model library, with a few models from the mechanical library as well. Although the pneumatic library already includes some models for e.g. check valves and relief valves, but, due to the complex oscillatory phenomenon, it was necessary to build up the simulation from much more detailed subcomponents. Later on, it turned out that the detailed modeling of the bypass check valve is not necessary, so it had been replaced by the simple check valve model provided in the library. **Fig. 3**. shows the AMESim circuit diagram of the PV.

4. Validation of the model by experiments

In order to conduct meaningful sensitivity studies, the numerical model had to be validated experimentally. For the first series of measurements the simplified setup, which can be seen on **Fig. 2**., had been used with a slight modification. Port 24 had been connected to a 2 m long pipe equipped with a silencer towards the atmosphere, located farther from the test bench, in order to reduce the disturbing effect of outflow noise on the acoustic studies of the protection valves. All ports had been fitted by pressure sensors capable of 1 kHz sampling frequency. Furthermore, three acceleration sensors had been installed on the housing of the PV, the first one on the supply port 1, the second on port 24 on which the D_{out} orifice had been installed, and the third one is on the valve housing in the vicinity of the check valve related to port 24. Furthermore, for acoustic studies, a sound pressure measurement device had been mounted at a distance of 0.1 m from the valve housing.

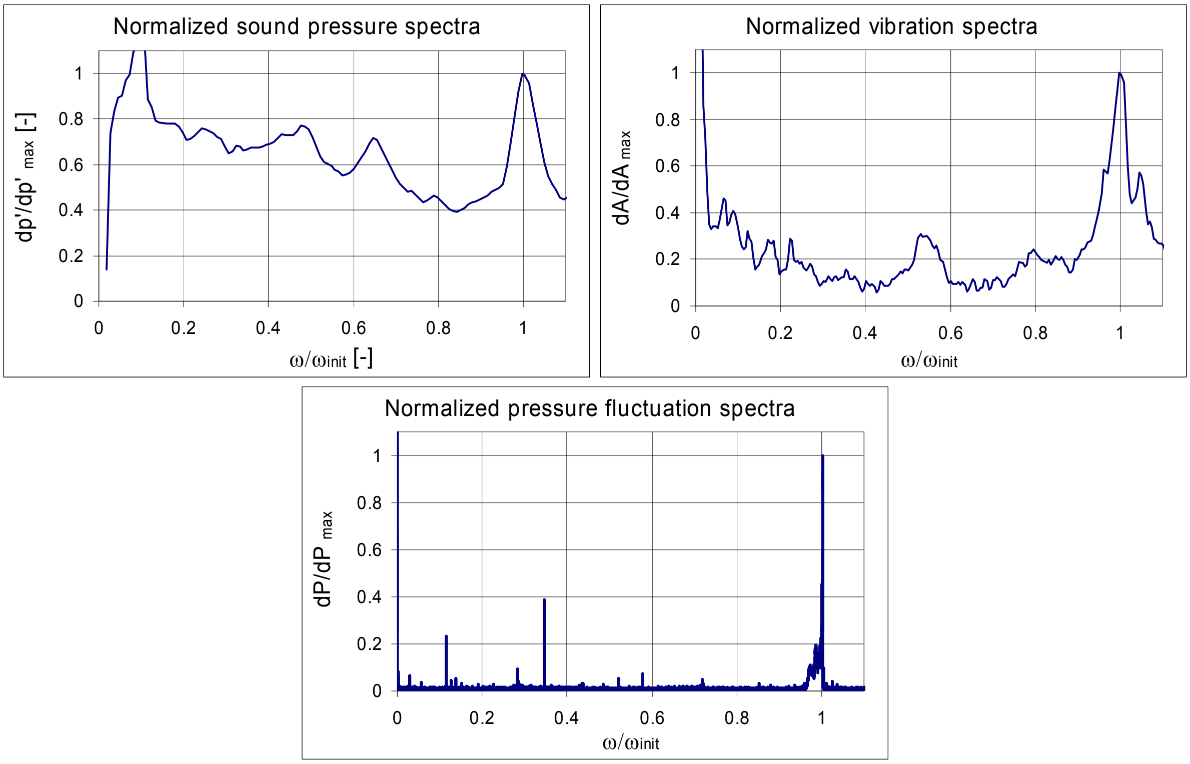

Fig. 4.: Fourier spectra of noise, vibration and pressure fluctuation

During the measurement series, the effect of the supply pressure, inlet and outlet diameter variation has been investigated. In all cases, the dominant frequencies of measured pressure fluctuation and vibration agreed very well with the dominant frequency of noise. **Fig. 4**. shows the normalized Fourier spectra of the noise, vibration and pressure fluctuation at port 24 of a representative test case. No characteristic fluctuation frequencies appeared on the other ports. Lower dominant frequencies also appeared in the noise spectra, but they are not related to the noise generation effects investigated herein. This is proven by the fact that such dominant frequencies appeared in the spectra even in the absence of noise of dominant frequency. Reducing the supply pressure resulted in slight reduction of characteristic frequencies as it can be seen on **Fig. 5**. Increasing the cross-section of the orifice on port 1 caused no considerable changes in the noise phenomenon from dominant frequency point of view. Increasing the orifice cross-section on port 24 initiated a more intense outflow with a minor change in the dominant frequency, stronger noise and vibration, and more intense pressure fluctuation.

As **Fig. 4**. illustrates, the dominant frequencies of noise, pressure fluctuation and vibration are characterized by well-defined, separate peaks. The measurements of sound pressure spectra showed good agreement with the mechanical and the pressure vibration measurements, as **Fig. 5**. shows. The differences between the dominant frequencies of the different physical domains remained in a ±1% range, which means that all these effects originate from the same phenomenon, which is most likely a regular, periodic motion of an internal element. Unfortunately there are a number of elements in the PV which can be the source of such an oscillation, and to identify that element by measurements is by no means an easy and straightforward task. However, with an appropriate and validated numerical model it is much easier as in a numerical model even those values can be investigated which is practically impossible to measure.

The parameters of the numerical model have been specified on the basis of technical documentation, while some parameters had to be determined by means of basic geometrical, volume, mass and force measurements. It must be emphasized that the pressure is the most important quantity from the viewpoint of a pneumatic system operation. Accordingly, the experimental validation of simulation results was focused on pressure measurements. As it can be seen on **Fig. 5**., the simulation resolves the vibration experienced during the measurements. This is represented by the generally good agreement between the measured and simulated pressure fluctuation. The correlation between check valve oscillation and pressure fluctuation in the numerical model suggests that the check valve plays a major role in the noise generation process.

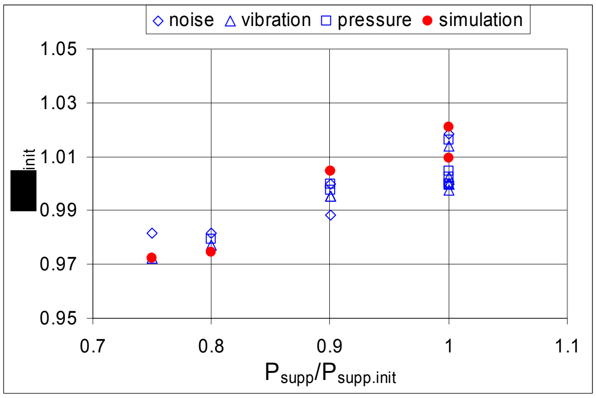

Fig. 5.: Effect of supply pressure reduction

5. Parameter investigations

A number of attempts with different parameters had been made in order to eliminate the vibration. It had been found out that the modification of a single parameter caused only the mistuning of vibration frequency, but the vibration in itself still remained a problem. The modification of two or more appropriate parameters at the same time, however, successfully eliminated the vibration phenomena. The modifications leading to elimination of the vibration were found to be the reduction of check valve spring stiffness with retaining the free and in-built length. This means that the precompression has also been reduced. Furthermore, increasing the friction of the check valve body had also been showed good results, but as this method is controllable only with difficulties in construction, the spring stiffness reduction method had been chosen to implement into the modified PV. The modified PV had been built into the simple measurement setup outlined in Chapter 2. Results with different supply pressures and inlet and outlet diameters showed that the vibration phenomena had been successfully eliminated. After the convincing results of the simple measurement setup the modified PV had been installed into a more realistic measurement system, and the measurements here also confirmed the appropriateness of the modifications.

6. Conclusion

A flexible computational simulation tool has been presented herein, being capable for prediction on dynamic behavior of complex pneumatic systems applied in commercial motor vehicles. The appropriateness of the numerical model has been confirmed through dynamic measurements in an experimental setup with topology identical to that of the simulated case. The simulation results have been showed good agreement with measurements. With the help of the validated numerical model the oscillation phenomena has been successfully eliminated.

It has been concluded that the simulation tool can be favorably used in design, research and development of complex pneumatic systems.

Acknowledgement

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Nomenclature

P	pressure [Pa]
D	orifice diameter [m]
dp'	sound pressure variation [Pa]
dP	pneumatic pressure variation [Pa]
dA	acceleration variation [m/s^2]

Greek letters

ω	frequency [Hz]

Subscripts

in	in-flow values (i.e. the values of the pressurized air flowing into the PV)
out	out-flow values (i.e. the values of the pressurized air flowing out of the PV)
init	values of the original PV at the very first measurement
max	maximum values
supp	supply values

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