

MODELING, TESTING AND CORRELATION OF INTERLINKED AIR SUSPENSION SYSTEMS FOR PREMIUM VEHICLE PLATFORMS

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ABSTRACT - Since a vehicle is actuated by road irregularities in many different ways the improvement of the passengers driving comfort is a major focus of automotive research and development work especially in the premium vehicle segment. Apart from the acoustic properties of a vehicle generally referred to as NVH (noise vibration harshness), the low-frequency and mechanical kind of vibrations mainly decide on the driving comfort felt by the passengers. Providing sufficient roll stiffness to counteract body roll under the influence of lateral acceleration and achieving a maximum of ride comfort are conflicting targets in terms of the body roll motion of a vehicle. Especially during straight line driving - particularly on uneven roads - high levels of roll stiffness may severely compromise driving comfort due to copy effects and increased body excitation.

A substantial improvement to resolve this conflict is the implementation of controllable interlinked air suspension systems as semi-active suspension systems. An interlinked air suspension system consists of a conventional four corner air suspension system including pneumatic interconnection lines between the two front and the two rear air spring modules. The connection lines can be switched on and off using solenoid valves so that the air flow between the left and right air spring modules can be terminated depending on the current driving condition.

The advantage of this concept lies in facilitating variable body roll stiffness and damping rates without severely increasing complexity or cost of the entire suspension system. Besides an improved ride comfort by means of reduced body roll accelerations during on-road driving conditions the system is also capable to improve the off-road capability of SUV-type vehicles in terms of an improved level of articulation between the two axles reducing the resistance to that articulation and the wheel load differences.

Therefore the system performance in terms of the potential to improve the ride comfort of a vehicle was subjectively and objectively analyzed on vehicle level and different system setups were investigated experimentally on a servo-hydraulic test bench.

The focus of the comprehensive investigations on a servo-hydraulic test bench was the analysis of the dynamic system response and the complex, highly nonlinear behavior for dynamic excitations mainly caused by the turbulent and compressible air flow between the air spring modules. A variety of design parameter variations like pipe and valve geometry variations were carried out and investigated in detail. Different excitation modes, frequencies and amplitudes were studied to cover the complete range of relevant system responses of an interlinked air suspension system.

To support the research and development work a CAE environment including thermodynamic air spring models, pipe models and different models of pneumatic resistors was established in MATLAB/Simulink to enable detailed system analyses and investigations including parameter variation studies of the system based on a CAE approach. Finally, the results of the test bench investigations were used to validate the models.

TECHNICAL PAPER

SERVO-HYDRAULIC TEST BENCH

For the testing of the interlinked air suspension system the servo-hydraulic test bench at the Institute for Automotive Engineering (ika) at the RWTH Aachen University was used. Figure 1 shows the test bench setup for the system. The two air suspension modules were clamped at the servo-hydraulic test bench by custom made adapters to realize a coaxial movement of the rolling pistons in relation to the top of the air spring modules. The top mount adapters are bell-shaped to allow for a suitable fixing of the air springs just above the air spring bellows. Cut-out areas enable the connection of the pipes for the air supply, the pneumatic connection between the air springs as well as the cables to connect the temperature and the pressure sensors. The rolling piston adapters feature an attached cylinder that guides the air spring pistons and seal the gaps between the air springs and the adapters with the aid of two o-rings at each side. Since the air spring modules are utilized in the vehicle within air spring-damper units in combination with continuously variable damper modules, additional volume dummies were bolted onto the top of the guiding cylinders of the air spring piston adapters to displace the air volumes originally captured by the outer geometry of the continuously variable damper modules.

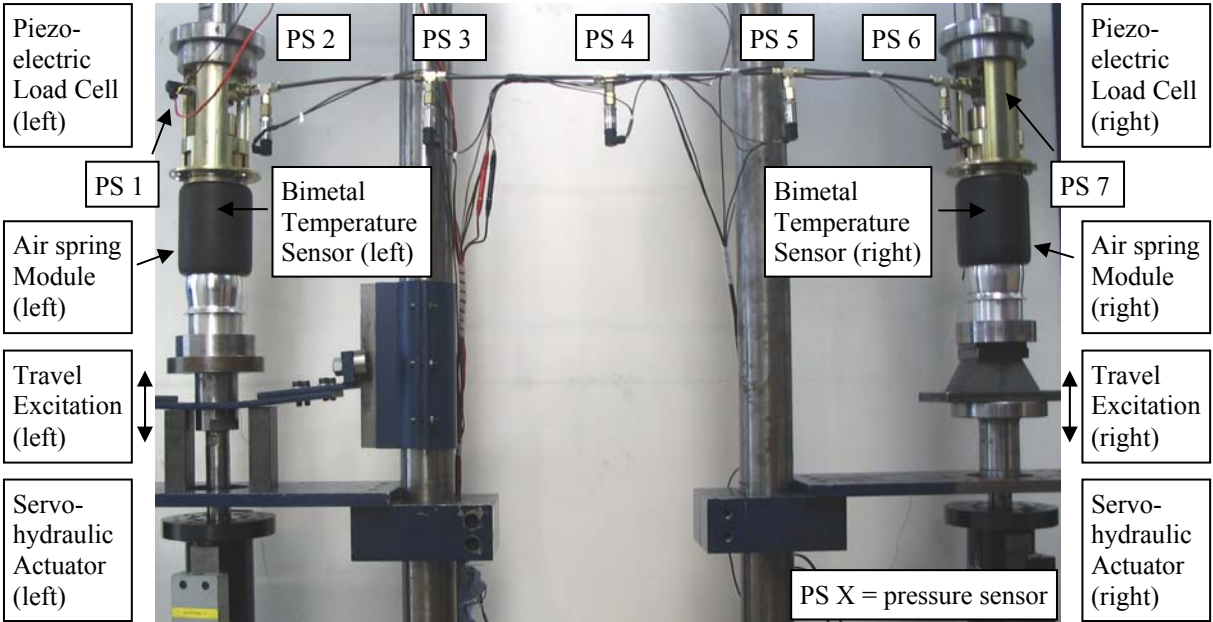


Figure 1: Interlinked air suspension system on the servo-hydraulic test bench at the Institute for Automotive Engineering Aachen (ika) at the RWTH Aachen University

To determine the dynamic behavior of the interlinked air suspension system the test bench was equipped with pressure, force and temperature sensors. All measured signals are collected as time domain signals using a digital data acquisition system. The sample rate of the data acquisition system was adapted to the different excitation frequencies of the tests. The travel

input signals were directly received from the control electronics of the servo-hydraulic actuators. The air spring forces were measured using piezoelectric load cells connected to the top of the air spring modules. The air pressures in the air spring modules and the pneumatic connection line between the air springs were sensed using piezoelectric pressure transducers. The air spring pressure transducers were screwed into the top caps of the air springs. The pipe pressure gradients were measured by means of five to ten pressure transducers (depending on the pipe length) attached via T-fittings evenly distributed over the pipe length. The temperature of the air in the air springs was measured by means of bimetal temperature sensors located in the center of the respective air spring.

SYSTEM TESTING

The test program based on the test guidelines VDA 675480 (1) and DIN 53535 (2) was set up to cover a wide range of excitation frequencies and amplitudes to enable a substantiated correlation of the interconnected air suspension system model. The tests were done for three pressure levels corresponding to 'curb' (empty vehicle weight), 'design' (vehicle plus driver, co-driver and full fuel tank weight) and 'maximum axle weight' loading conditions of the target vehicle. The inner diameter of the pneumatic interconnection line between the two air spring modules was varied between 6 mm and 19 mm according to Figure 2. All variants with a particular inner pipe diameter were tested with a pipe length of 1.5 m and 3 m. To allow for a modular exchangeability of the pressure transducers without disturbing the air flow through the pipe the T-fittings were modulated consistent with the inner pipe diameters.

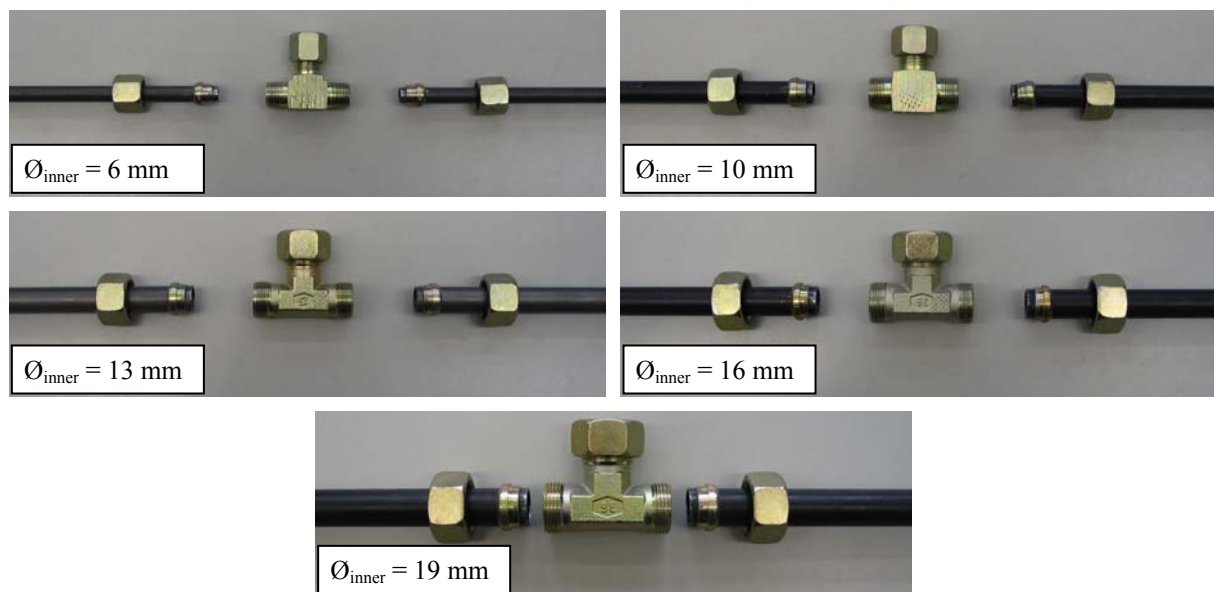


Figure 2: Investigated pipe diameters and corresponding T-fittings for pressure transducers

The first part of the tests consists of sinusoidal excitations with constant amplitudes and different discrete frequencies from 0.001 Hz to 90 Hz (amplitudes: 77.2 mm, 30 mm, 5 mm, 1 mm and 0.5 mm). The second group of measurements include frequency sweeps within the frequency range from 0.5 Hz to 70 Hz for discrete amplitudes from 1 mm to 77.2 mm. These tests are used to derive continuous curve progressions of the transfer functions between different measured signals in the frequency domain. Finally, step input tests starting from the design position of one or both of the air spring modules are conducted to determine and correlate the time constants of the pressure equalization between the two air spring modules.

Idealizing real driving conditions the measurements were grouped into three categories for one-sided, two-sided in-phase and two-sided anti-phase travel excitations. The sinusoidal two-sided in-phase excitations over the full travel range of the air spring modules were used to determine the fundamental isothermal (excitation frequency: 0.001 Hz) and adiabatic (excitation frequency: 3 Hz) pressure and force progressions of the air spring modules. The one-sided as well as the two-sided anti-phase tests were done to derive the transfer functions of the pressure equalization between the two air spring modules.

SYSTEM MODELING

Figure 3 shows the model of the interlinked air suspension system consisting of two thermodynamic air spring models and a model of the interconnecting pipe. The state variables of the air spring models are the air pressure (p), the air volume (V), the air temperature (T) and the air mass (m). The air volumes are nonlinear functions of the air spring excitations. The air spring forces (F) are calculated out of the air spring pressures and the effective areas ($A_{\text{effective}}$), whereas the effective areas are nonlinear functions of the air spring travels. Heat ($\dot{Q}_{\text{air spring}}$) can be exchanged through the surface areas ($S_{\text{air spring}}$) of the air springs depending on the heat transfer coefficients of the air springs ($\alpha_{\text{air spring}}$). The mass flow through the pipe (\dot{m}) is a function of the left and right air pressures and temperatures. Heat (\dot{Q}_{pipe}) can also be transferred through the surface area of the pipe (S_{pipe}) between the air volume in the pipe and the environmental air as a function of the heat transfer coefficient of the pipe (α_{pipe}).

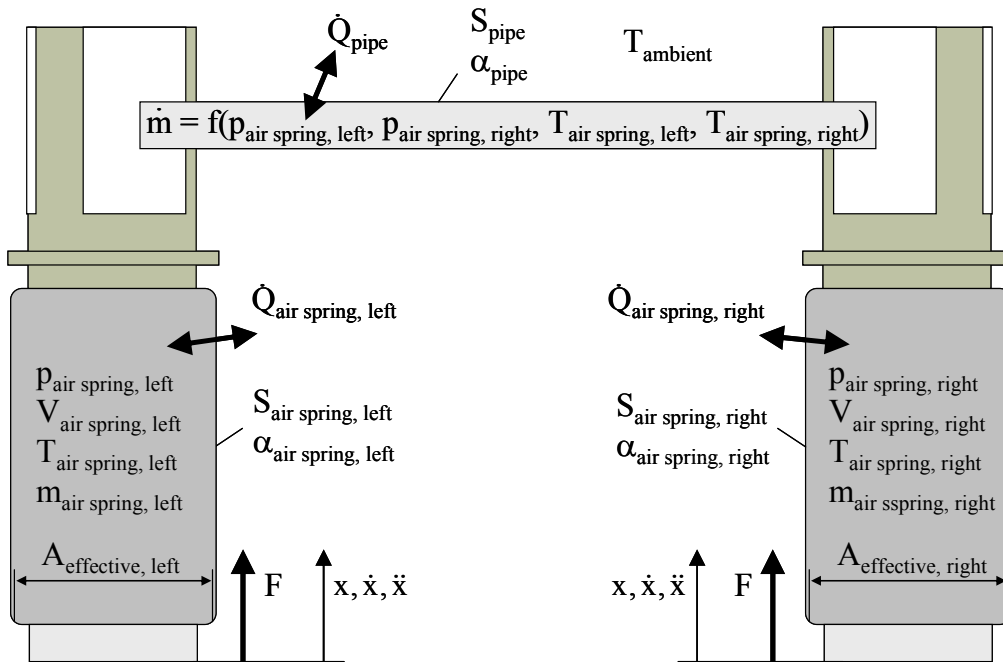


Figure 3: Interlinked air suspension system model

The thermodynamic air spring model used to simulate the left and right air springs was developed in the MATLAB/Simulink environment. It is based on the first law of thermodynamics for open systems. This means that the change in volume caused by the travel excitation of the air spring induces a pressure and a temperature change of the air within the air spring bellows. Additionally, heat can be transferred between the air spring and the surrounding air depending on the temperature difference between the air temperature in the air spring and the environment. By modeling the air spring as an open thermodynamic system an

air mass exchange between the air spring model and other connected air volumes is possible by means of pneumatic resistor models like valve or frictional resistance models. Based on (3), (4) and (5) the change in pressure of the air spring can be calculated according to equation [1] using the first law of thermodynamics for open systems.

$$dp = \frac{\kappa}{V} \cdot \left[R \cdot (dm_{in} \cdot T_{in} - dm_{out} \cdot T_{out}) - p \cdot dV - \frac{\kappa - 1}{\kappa} \cdot \alpha \cdot A \cdot (T - T_a) \cdot dt \right] \quad [1]$$

Symbols

A	air spring surface area
R	specific gas constant for wet air
T	temperature
V	volume
m	mass
p	pressure
t	time

α	heat transfer coefficient
κ	specific heat capacity ratio

Indices

a	ambient
in	system input
out	system output

Thus it appears that the first contributor to the change in air pressure within the air spring is the change in air mass in combination with the temperature in the air spring and the temperature of the surrounding air $[dm_{in} \cdot T_{in} - dm_{out} \cdot T_{out}]$. The second contributor to the pressure change in the air spring is the displacement work due to change in volume $[-p \cdot dV]$. Finally, the heat transfer from and into the air spring also make a contribution to the change in air pressure $[\alpha \cdot A \cdot (T - T_a) \cdot dt]$. The differential terms dp , dm_{in} , dm_{out} and dV indicate the change of state during an infinitesimal time step dt . Therefore equation [1] was converted into MATLAB/Simulink (6) by means of numerical integration algorithms and used as the pressure integration subsystem of the thermodynamic air spring model.

The change in volume is modeled as a nonlinear function of the air spring travel and the air mass in the air spring using a three-dimensional lookup table to account for the pressure-dependent elastic expansion of the air spring bellow. Thereby it is possible to determine the exact air volume within the air spring depending on the enclosed air mass and the current air pressure for any air spring travel position. In an analogous manner also the effective area of the air spring is represented as a three-dimensional characteristic diagram. This allows for the involvement of the influence of the rolling piston contour in the effective diameter calculation on the one hand as well as the impact of the pressure- and travel-dependent elastic expansion of the air spring bellow on the effective diameter during the simulation on the other hand. The masses and inertias of the air spring components are not taken into account in the air spring model. The input signals of the thermodynamic air spring model are the air spring travel as well as the air mass flow from and into the air spring. The output signals are the pressure and the temperature of the air within the air spring bellow as well as air spring force.

The pneumatic interconnection pipe model is based on a concentrated parameter approach consisting of two volume elements and three pneumatic resistor models. Two pneumatic resistor models are located between the pipe and the air spring volumes. The third resistor model connects the two pipe volume models. The pipe volumes are modeled in a similar way as the volumes of the air springs [1] including the heat transfer model $[\alpha \cdot A \cdot (T - T_a) \cdot dt]$ and the pressure change due to change in air mass model $[dm_{in} \cdot T_{in} - dm_{out} \cdot T_{out}]$ but excluding a change in volume by omitting the term for the displacement work due to change in volume

[-p·dV]. The input signals of the pipe model are the pressures and temperatures of the two air spring models. The pipe model outputs are the air mass flows between pipe and air springs. The pneumatic resistor models calculate the air mass flow between the air spring and the pipe volume models according to (7). Based on the technical standard reference condition for air according to ISO 6358 (8) with a reference temperature of $T_0 = 293.15$ K, a reference pressure of $p_0 = 1$ bar and the specific gas constant for wet air of $R_{air,0} = 288$ J/kg/K (relative air humidity: 65 %) equation [2] was used to model the supercritical air mass flow and equation [3] to model the subcritical air mass flow. The air pressure (p_1), the air temperature (T_1) and the air density (ρ_1) characterize the state variables of the air entering the resistor. The counter pressure of the resistor is named p_2 . For pressure ratios of the counter pressure and the air pressure of the entering air (p_2/p_1) between zero and the critical pressure ratio (b) equation [2] is valid. For pressure ratios between the critical pressure ratio (b) and one equation [3] is used. The calculation of the conductances (C) of the pneumatic resistors is given in equation [4].

$$\dot{m} = C \cdot p_1 \cdot \rho_1 \cdot \sqrt{\frac{T_0}{T_1}} \quad \text{for} \quad 0 \leq \frac{p_2}{p_1} \leq b \quad [2]$$

$$\dot{m} = C \cdot p_1 \cdot \rho_1 \cdot \sqrt{\frac{T_0}{T_1}} \cdot \sqrt{1 - \left(\frac{\frac{p_2}{p_1} - b}{1 - b} \right)^2} \quad \text{for} \quad b \leq \frac{p_2}{p_1} \leq 1 \quad [3]$$

$$C = \frac{\beta_{a,b,c} \cdot A \cdot \psi_{\max} \sqrt{2 \cdot R_{air,0} \cdot T_0}}{p_0} \quad [4]$$

Symbols

A	cross sectional area
C	conductance
R	specific gas constant for wet air
T	temperature
b	critical pressure ratio
\dot{m}	mass flow
p	pressure
β	correlation factor

ρ	density
ψ	outflow function

Indices

0	related to the technical standard reference condition for air
1, 2	upstream, downstream
a, b, c	resistor model a, b, c
max	maximum

The conductance (C) is a measure for the maximum possible air mass flow rate through the cross sectional area (A) at the air flow velocity $\psi_{\max} \cdot \sqrt{2 \cdot R_{air,0} \cdot T_0}$ based on the technical standard reference condition for air. In this context ψ_{\max} is the maximum of the outflow function ψ (7). To correlate the simulated air spring and pipe volume pressure signals to the measured signals from the test bench individual correlation factors (β_a , β_b and β_c) were used for the three pneumatic resistor models varying with the pipe diameter.

MODEL CORRELATION

As an example out of the comprehensive correlation exercises Figure 4 and Figure 5 show the correlation results for tests with a one-sided sinusoidal travel excitation of the left air spring.

The air spring was actuated with an excitation frequency of 3 Hz over the complete usable travel range equivalent to an excitation amplitude of 77.2 mm.

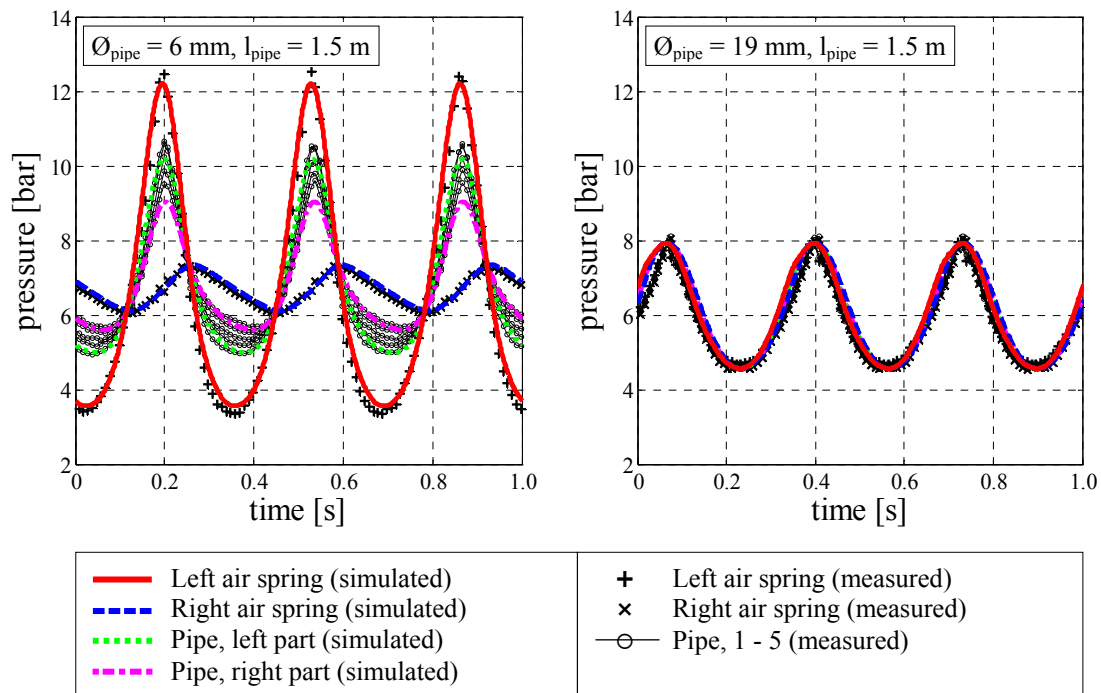


Figure 4: Model correlation in time domain (excitation frequency: 3 Hz, excitation amplitude: 77.2 mm)

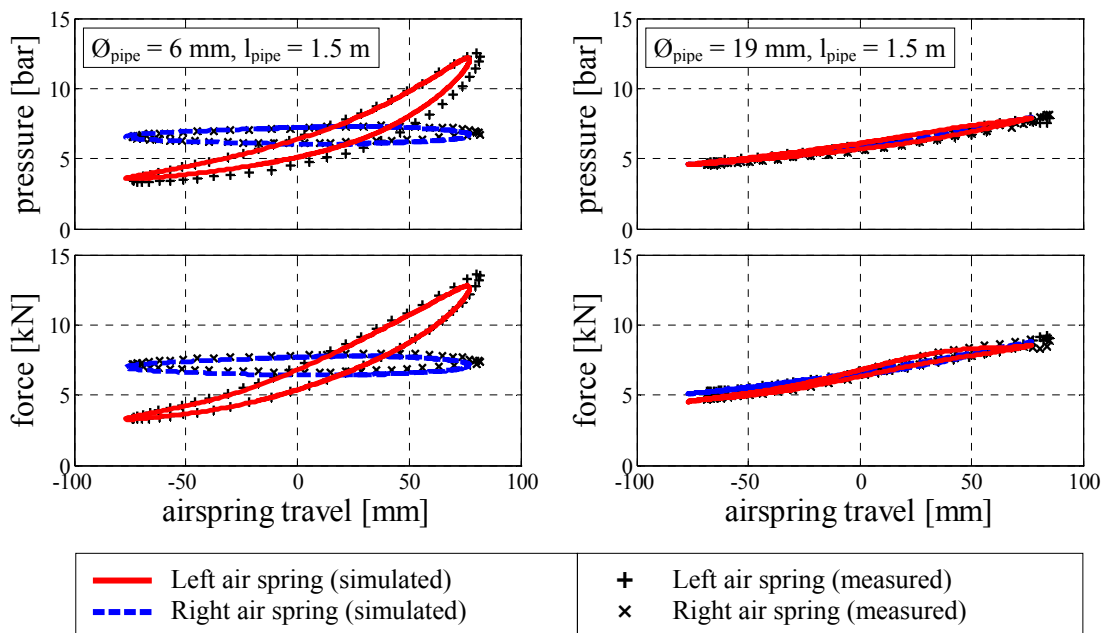


Figure 5: Model correlation in travel domain (excitation frequency: 3 Hz, excitation amplitude: 77.2 mm)

The left hand side diagrams of Figure 4 and Figure 5 show the measurement versus simulation correlation results for a system setup equipped with an interconnecting pipe of 6 mm inner diameter and the right hand side diagrams with a 19 mm inner diameter. All graphs show a good correlation between the measurement results from the test bench and the simulation output of the interlinked air suspension system MATLAB/Simulink model for both the air spring and pipe pressure as well as the air spring force characteristics. The error

analysis for the entire number of measurements and simulations resulted in a maximum relative error of 9.4 % for the worst correlation whereas for more than 90 % of the datasets the relative error was smaller than 5 %. Especially for the setup with a pipe inner diameter of 19 mm it can be seen that the pressure equalization between the left and right air spring is superior compared to the setup with the 6 mm inner diameter pipe resulting in a reduced stiffness of the actuated air spring. A high amplitude damping and a considerable phase delay between the pressure signals of the left and right air springs can be seen in the left graph of Figure 4 for the 6 mm pipe inner diameter variant causing characteristic hysteresis curves in the left hand side pressure and force signal graphs of Figure 5.

SUMMARY

In the paper at hand a modeling, testing and correlation approach of an interlinked air suspension system was presented. After the introduction of the servo-hydraulic test bench setup the measurement instrumentation setup was described including air pressure and temperature as well as air spring force and travel sensors. Additionally, the different investigated system designs as well as the system test plans were outlined. Furthermore, the MATLAB/Simulink model of the interlinked air suspension system composed of two thermodynamic air spring models and a pneumatic pipe model based on a concentrated parameter approach was illustrated. After the parameter evaluation for the air spring and the pipe model the correlation between the simulation results and the measurement data was satisfying and shown exemplarily by means of system designs with different inner pipe diameters. The developed and correlated system model is currently used within a full vehicle simulation environment to predict the performance of interlinked air suspension systems.

REFERENCES

- (1) N. N., "Test procedures for elastomeric components in motor vehicles", Association of German Automobile Manufacturers (VDA), VDA 675480, 1992
- (2) N. N., "Testing of rubber - general requirements for dynamic testing", German Institute for Standardization (DIN), DIN 53535, 1982
- (3) Bošnjaković, F., Knoche, K. F., "Technische Thermodynamik", Steinkopff, 1998
- (4) Hutter, K., "Fluid- und Thermodynamik – Eine Einführung", Springer Berlin Heidelberg New York, 1995
- (5) Ohligschläger, O., "Pneumatische Zylinderantriebe – thermodynamische Grundlagen und digitale Simulation", PhD thesis, RWTH Aachen University, Institute for Hydraulic and Pneumatic Drives and Controls, 1990
- (6) N. N., "MATLAB R2006b reference help", The Mathworks, Inc., 2006
- (7) Backé, W., Murrenhoff, H., "Grundlagen der Pneumatik", RWTH Aachen University, Institute for Fluid Power Drives and Controls, 9th edition, 1994
- (8) N. N., "Pneumatic fluid power – Components using compressible fluids – Determination of flow-rate characteristics", International Organization for Standardization (ISO), Geneva, ISO 6358, 1989