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THEORETICAL AND EXPERIMENTAL ANALYSIS OF PNEUMATIC SUSPENSIONS

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ABSTRACT
Nowadays almost all the machines, both stationary and dynamic ones, are linked to some type of suspension in order to reduce and eliminate the vibrations as far as possible. The first applications for air springs were not for pneumatic suspensions but some advantages over classic mechanical suspensions made attractive that choice. In this paper, the authors present a nonlinear model of an air spring suspension that previously they tested. The agreement between the model and tests is quite good. Some different aspects about this results are discussed with the purpose of investigate the possibility of add some active behaviour to this suspension.
Key words:

1. INTRODUCTION
The air spring suspensions were used a few years after the air springs were possible to make. This type of suspension presents some useful advantages about the classic mechanical suspension. The necessity of such systems has been previously justified in [1]. Some other authors talk about the vibrations caused by vehicle cabins and their effect on the human body. They explained the necessity of adding isolation to the vehicle cabins in order to avoid harmful vibrations to their passengers. Other authors' work [2] studied this suspension and they found some benefits over classic systems like the mechanical springs. First of them proved to give better comfort to the passengers. Moreover, it is able to give more attenuation than the second one. An orifice dissipation element has been selected in several works like [3] in order to get enough damping. Nevertheless, this damping element has probed to be not very useful since level of damping is amplitude dependent [4] and is complicated to be analytically determined and do not suits to linear models [5].
In this work, a pneumatic suspension is presented, choosing some different pipes as the dissipation elements together with an auxiliary volume. These all parts make it possible to change the suspension parameters as far as possible. This air suspension is theoretically studied with the purpose of getting information about the system that suggests some different control strategies in order to avoid undesirable vibrations.

2. ANALYTICAL MODEL
The equations that take part in the analytical model are presented below. The equations (1) and (2) represent the effective area and volume variations of the air spring with respect to h, where h is the difference between the response and the excitation plus an initial value of the height h, and is experimentally determined in other work of the same authors [6].

$$A_s = A_s(h) \tag{1}$$

$$V_s = V_s(h) \tag{2}$$

The following equations are developed using the preliminary ones that are included in [1-6]. The expression (3) and (4) show the pressure variation both the air spring and the reservoir with respect to time, where $C_r = (\pi d_p^4)/(128\mu l_p)$ as can be defined by a Poiseuille flow [7].

$$\dot{P}_s = -\dot{m}_f \frac{nRT_{s0}}{V_s(h)}\left(\frac{P_s}{P_{s0}}\right)^{\frac{n-1}{n}} - \dot{V}_s(h)\frac{nP_s}{V_s(h)} \tag{3}$$

$$\dot{P}_r = -\frac{\gamma C_r}{2V_r(h)}\left(P_r^2 - P_s^2\right) \tag{4}$$

The equation (5) represents the time dependency of the exerted force of the air spring with respect to time and the equation (6) the air mass flow rate through the pipe.

$$\dot{F} = \dot{P}_s A_s(h) + (P_s - P_{atm})\dot{A}_s(h) \tag{5}$$

$$\dot{m}_f = \frac{V_r}{nRT_{r0}}\left(\frac{P_{r0}}{P_r}\right)^{\frac{n-1}{n}} \dot{P}_r \tag{6}$$

Finally, the equation (7) corresponds to the Newton's law and takes into account the sprung mass dynamics.

$$M\ddot{z} + Mg = F \tag{7}$$

2.1. Numerical simulation

The equations previously presented are implemented using Matlab's Simulink package as can be seen in the figure 1. The system is divided into three principal blocks that correspond to the three main parts of the suspension. The inputs and outputs of each block are connected so that the model's equations are linked. The model takes the principal input, that is, the excitation *x*, and returns the principal output, that is, the response *z*. The secondary inputs and outputs correspond to the three principal blocks. Three additional inputs are needed to complete the model: the reservoir volume, the pipe's cross section diameter and the pipe's length. All the equations presented above are included into the three blocks. The equations (4) and (6) are enclosed into the pipe-reservoir block, the equation (7) in included into the sprung mass block, and the equation (3) and (5) into the air spring block. Moreover, this last block contains the equations (1) and (2).

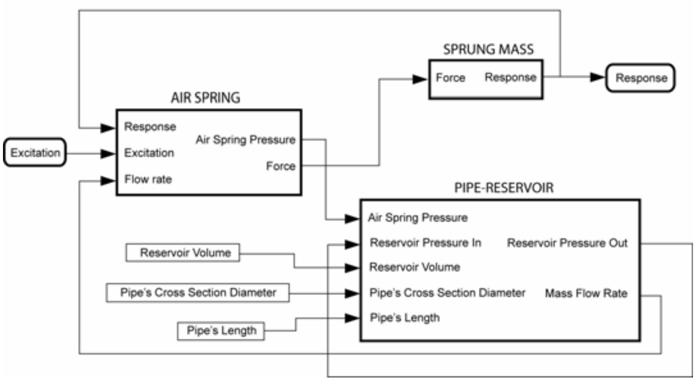

Figure 1. Analytical model of the pneumatic suspension in Simulink environment.

3. EXPERIMENTAL ANALYSIS

The scheme of the experimental tests is shown in the figure 2. These tests were carried out in a hydraulic unit with displacement control. The reservoir volume was 2 dm^3 whereas four different pipes, with different cross section and length, were chosen. The input excitation was set to a sinusoidal signal of 1.5 mm amplitude and the frequency was changing from 0.5 to 7 Hz. All the tests began with an initial pressure of 2 absolute bar. The displacement data acquisition was developed with three IR cameras and two reflecting points for the excitation and response points respectively. Some others details are explained in [6].

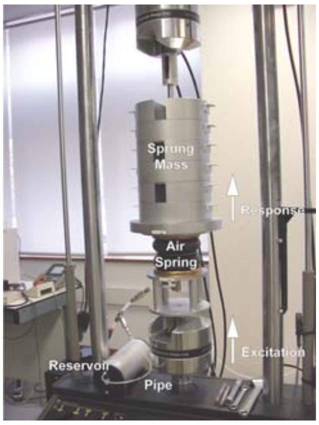

Figure 2. Experimental assembly for the pneumatic suspension.

4. RESULTS

The result presented in this section tries to fit the result previously obtained experimentally. The selected parameter to compare is the frequency response of the pneumatic suspension. The selected restriction coefficients C_r for analytical model are chosen the same that for empirical tests so that the transmissibility curves can be compared.

4.1. Analytical and experimental results

The results for both the analytical model and the experimental tests are shown in the figure 3. Both figures show their curves with a variation of the resonant frequency. This is due to the behaviour of the suspension with high frequencies (the system is close to be like the air spring alone) and low frequencies (the system is close to be like an air spring with the sum of volume of both the air spring and the reservoir). When the pneumatic suspension is subjected to high frequencies, there are hardly connection between the air spring and the reservoir because the air has no time to travel from the spring to the reservoir or vice versa [6].

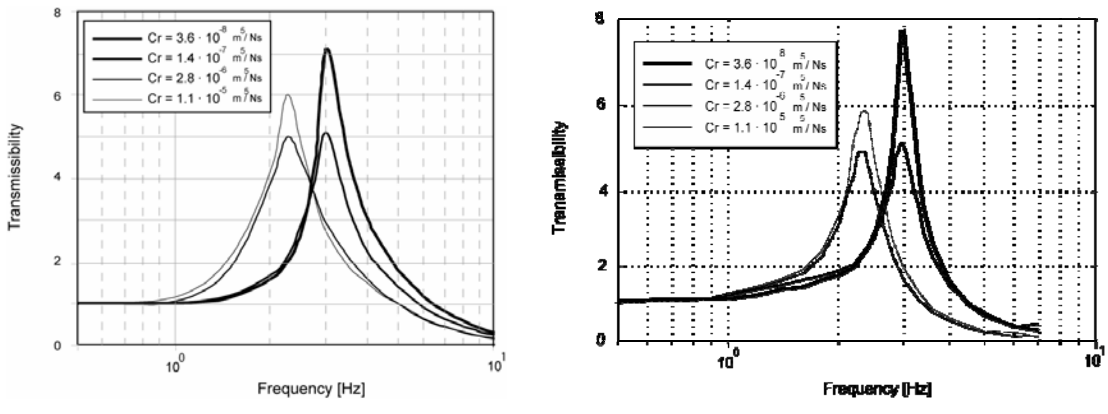

Figure 3. Modulus of the transmissibility function for the nonlinear model (left), and the experimental tests (right).

5. CONCLUSIONS

An analytical model has been presented in this work in order to predict the behaviour of an air spring suspension. There is a good agreement between the analytical results and the experimental results when resonant frequencies or amplification values are compared. Changes in the restriction coefficient affect not only the damping coefficient but also the resonant frequency. The high resonant frequency value is determined by the natural frequency of the air spring alone whereas the low resonant frequency value depends mainly on the reservoir volume. The bigger the reservoir volume is, the lower the resonant frequency value is. It is important to notice that all curves, regardless of the restriction coefficient selected, cross at a common point within the limits of experimental accuracy. This crossing point marks the limit between two different frequency zones that can be defined in order to get reasonable response attenuation. This affirmation is full of sense if the frequency value of this point is used to select the pipe type that makes possible getting the most attenuated response. For this reason, it is very important to research about the parameters that have influence on this point since it must be known if those two zones want to be divided. This is part of the future work that the authors are taking into account in order to add an active behaviour to the pneumatic suspension. Furthermore, in order to obtain more information about the model, the nonlinear model will be fitted into linear one and compared with both the preliminary nonlinear model and the experimental tests.

6. NOTATION

A_s	Spring effective area [m^2]	P_{atm}	Absolute pressure [Pa]
γ	Specific heat ratio	P_s	Air spring absolute pressure [bar]
C_r	Pipe restriction coefficient [m^5/Ns]	P_r	Reservoir absolute pressure [bar]
$\mathrm{d_p}$	Pipe's cross section [m]	R	Gas constant for air [J/kgK]
F	Exerted force in the air spring	T_s	Air spring temperature [K]
g	Gravity acceleration [m/s^2]	T_r	Reservoir temperature [K]
M	Sprung mass [kg]	V_s	Spring volume [m^3]
l_p	Pipe's length [m]	V_r	Reservoir volume [m^3]
m_f	Mass flow rate [kg/s]	x	Excitation [m]
n	Polytropic coefficient	z	Response [m]

7. REFERENCES

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