Researches regarding a pressure pulse generator as a segment of model for a weighing in motion system

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Abstract. There are many types of weighing in motion systems: with strain gauges, piezoelectric type, with optical fibre, capacitive etc. Although one of them proved to be reliable, many research teams all over the world are interested in finding new types or improving the existing ones. In this paper is presented a hydraulic Weigh-In-Motion sensor composed of a metal vessel filled with hydraulic oil connected to an accumulator through a pipe. Vehicle tires press on the deformable upper wall and pressure pulses generated in this way provides information about the load. In this paper are presented: a structure for an experimental model, the block diagram for numerical simulation, experimental model and some experimental results.

1. Introduction

The weighing in motion experimental model, designed and tested by the authors, consists of a metal vessel filled with hydraulic oil which is connected to a pipe on which is mounted an adjustable hydraulic resistance. The circuit contains two pressure transducers to measure pressure upstream and downstream of adjustable hydraulic resistance. The hydraulic weighing system is supposed to be used in environmental conditions. Consequently large temperature variations will appear between seasons and between day and night. In order to compensate pressure variations due to difference between the coefficients of thermal expansion of the mineral oil and the metal, in the circuit was included a pneumo-hydraulic accumulator [1].

The vessel has rigid walls, except the upper wall that is deformable. By applying the load F, volume of the vessel changes with ΔV and a change of pressure in the hydraulic circuit will appear. On basis of the variation of pressure signals recorded in circuit, caused by the variation of volume, one can determine the value of the load.

2. Numerical modelling

Simulation of the weighing in motion hydraulic system includes elements of the experimental model: single-acting cylinder, hydraulic oil vessel, pipes, variable hydraulic resistance, pneumo-hydraulic accumulator and sensors.

From Simscape / SimHydraulics Library and Simscape / Hydraulic Utilities Library were chosen elements for the bloc diagram corresponding to experimental setup: segmented pipe, variable hydraulic resistance, accumulator, single-acting hydraulic cylinder, hydraulic sensors and related scopes. There is a set of simplifying assumptions, mentioned already: rigid walls of the chamber, rigid pipes and materials used for components.
In order to generate pressure pulses, similar as frequency and amplitude with those produced by vehicle tyres, it was designed a cam mounted on the shaft of the electric motor. Through this cam, which acts on the cylinder rod, is produced the stroke of the piston which induces a volume variation $\Delta V$. $\Delta V$ depends on the eccentricity of the cam and the area of the piston. [2].

Block diagram of the entire system contains among others a subsystem for the cylinder considering all forces acting on it [3], illustrated in equation (1).

$$m \frac{d^2 x}{dt^2} + b_m \frac{dx}{dt} + c_{fp} \frac{x}{|x|} A_2 p_0 + F + kx = A_2 p_0$$

in which: $m$ – piston and rod mass, $b_m$ - linearized coefficient of force losses proportional to speed, $c_{fp}$ - friction coefficient, $F$ – load, $A_2$ – area of the piston, $p_0$ - inlet pressure, $k$ - spring constant.

The single-acting hydraulic cylinder in used in this case to produce pressure pulses and not to produce work, as it is usually used. The spring has to maintain contact between the rod and the cam mounted on the shaft of the electric motor. All these are included in the subsystem block diagram in figure 1. Considering equation (1) the ports of the block Single-Acting Hydraulic Cylinder were connected to functional elements: inertia (Mass), friction (Translational Friction), viscous friction (Translational Damper), and the spring force (Translational Spring).

**Figure 1.** Block diagram for the subsystem single-acting hydraulic cylinder.

The force produced as a result of cam acting on the rod is considered in the block diagram in figure 2. The subsystem includes: Sine Wave Block (generating a sinusoidal signal) and Ideal Force Source (source of mechanical energy in the form of force) connected at Translational Reference.

**Figure 2.** Block diagram of the subsystem used for generating pressure pulses.
The frequency of the sinusoidal signal was set according to the frequency that tyres of a long vehicle rolling with a certain speed may act on the hydraulic sensor.

In figure 3 one can see values for pressure upstream and downstream hydraulic resistance. From the point of view of pulse generator, the block diagram analysed in this paper is suited for the final purpose of the research: an experimental model for a hydraulic weigh-in-motion sensor.

3. The experimental model
For the experimental study, the pressure sensor on which the vehicle tyres act was considered as a vessel (figure 4), having all walls rigid except the upper one [4, 5]. Load F, acting on the deformable wall of the vessel filled with hydraulic oil, produces a volume change ΔV. This volume variation induces a pressure variation in the hydraulic circuit.

The solution used for producing such a signal is presented in figure 5. It consists in a single-acting cylinder with spring return 5, having the rod in contact with the cam 2 under the force exerted by the spring 5 [6].
In this way, each rotation at the electric motor 1 axle changes vessel volume and consequently the pressure in the hydraulic system. Modification of the frequency of the signal can be achieved changing the rotation speed of the electric motor.

Parameters of the experimental equipment must be set as close as possible to those of the WIM hydraulic prototype to be mounted on the road.

As an initial hypothesis, it was considered isothermal system behaviour. In future researches it will be considered also the variation of the temperature.

To estimate the piston stroke and, hence the eccentricity cam, as well as the range fall frequency variation force, it was considered some preliminary calculations:

- The pressure variation if the volume variation is $\Delta V$:
  \[ p_1 = \frac{E \Delta V}{V} \]  
  where: $p_1$ - pressure, $E$ – bulk modulus of the oil, $V$ – oil volume in the vessel, $\Delta V$ – the volume variation.

- The force required on the rod to produce volume variation $\Delta V$:
  \[ F = p_1 \cdot \pi \cdot \frac{D^2}{4} \]  
  where: $p_1$ - pressure, $D$ – the diameter of the piston.

- During the deformation flow is:
  \[ Q = \frac{\Delta V}{\Delta t} \Rightarrow \Delta t = \frac{\Delta V}{Q} \]  
  where: $Q$ – flow, $\Delta V$ - volume variation.

- Frequency of the pulse:
  \[ T = 2 \cdot \Delta t \quad f = \frac{1}{T} \]  
  \[ n = \frac{60}{T} = \frac{60}{2 \cdot \Delta t} \]  
  where: $f$ - the frequency of rotation, $T$ – period, $\Delta t$ - time, $n$ – the number of rotations per minute.

**Figure 6.** The system used to generate pressure pulse. 
1. electric motor, 2. cam, 3. hydraulic cylinder

- The stroke of the piston:
where: $\Delta V$ – the volume variation, $D$ – the diameter of the piston.

- The speed of the piston:

$$v = \frac{C}{\Delta t}$$

where: $C$ – the stroke, $\Delta t$ - the time.

- Hydraulic power:

$$N_h = p_1 \cdot Q$$

where: $p_1$ - pressure, $Q$ – flow.

Figure 6 presents experimental model. On the basis of preliminary estimation was chosen an electric motor (1), with $n=1450$ rpm, and power $N=7 \cdot 10^3$ W. The cam (2) has a profile which determines a stroke of the piston $C=8 \cdot 10^{-3}$ m.

In order to command automatic and/or semi-automatic electric motor speed variation, and data acquisition, booth was equipped with a programmable automation system NI Compact RIO series. It is important to observe that hydraulic damping resistance introduced, determines the differences in behaviour of signals upstream and downstream the hydraulic resistance. The difference between the amplitudes of the two signals is the pressure drop on the hydraulic resistance.

Using hydraulic circuit designed to be tested in laboratory conditions it was obtained some graphic results, corresponding to different cross sections of hydraulic resistance. It was also considered different pre-charge pressure of hydraulic accumulator.

The diagrams have two scales. One of them is pressures scale obtained by using virtual instrument, based on the intrinsic characteristics of the transducer and converts the sensed voltage in pressure values. The other is weight scale.

$$F = \frac{F_p}{\eta} + F_{a0}$$

where: $F_p$ – pressure force, $F_{a0}$ – the elastic force of the spring, $\eta=0.75$ - hydraulic cylinder efficiency.

Figure 7. Signals upstream and downstream hydraulic resistance
The graph in figure 7, is obtained for a pre-charge pressure of hydraulic accumulator $p_0=20\cdot10^5$ Pa, opening of the hydraulic resistance $c=2\cdot10^{-3}$ m, and a frequency of rotation of the electric motor $f=4$ Hz.

4. Conclusions
The proposed structure for the pressure pulse generator proved to be effective and may be used in experimental model in order to simulate the tyres effect on the weigh sensor. The phase difference between pressure signals from the two transducers mounted upstream and downstream hydraulic resistance, and decreased amplitude of downstream signal, seen on the results, are due to variable hydraulic resistance. Measurements at different rotation speeds at the electric motor showed that the signal amplitude decreases with increasing of rotation speed. Other conclusions will result in future researches on the prototype mounted on the road.

5. References
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