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Pressure wave generator for developing resonance in a closed pipe, used for an alternant-hydraulic transmission

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Abstract : *To meet the current requirements imposed by the vehicle manufacturers to reduce significantly the fuel consumption and associated CO_2 emissions, it is necessary the research and development of new technical emission and consumption quantity reducing systems. A direction that has emerged in recent years is to develop hybrid-hydraulic propulsion systems which permit to reconsider the research objectives of the engines for an optimal functioning. The scientific approach is based on the fundamental research regarding the pressure waves energy generation - propagation and conversion process, research based on 2D simulations of the flow and on experimental results obtained by waves' piezoelectric measuring. The conclusions from the fundamental study are further used for developing mechano-hydraulic resonant systems designed to be integrated into the vehicle's propulsion system.*
Keywords : *fluid power, pressure wave, CFD, hybrid propulsion system*

1. INTRODUCTION

This paper presents and analyses the physical phenomenon that fundaments the structure of the mechano-hydraulic systems which use the resonance phenomenon and which can be integrated in the propulsion system of auto vehicles, in order to highlight the complexity of the factors which influence the development of the dynamic working mode of the system. The idea of using dynamic phenomenon theory comes from the following reasoning: identifying a point characterized by maximum potential energy is followed by searching for the trajectories of which this point belongs to, and then decide, using technical criteria, the optimal trajectory. After that, the system has to support the transformations suggested by the mathematical trajectory, for the environment to be capable to support the dynamic phenomenon, and to have the necessary parametric sensitivity for the transition between the initial conditions and maximum energy point. Technically, this transition needs to be done with energetic benefit, and to identify the potential transition trajectories through the analysis of the dynamic events

A dynamic oscillatory system has more chance for developing dynamic events if the dissipation in the system is minimal. This feature is favorable for liquids where oscillation damping is very low [1].

2. SYSTEM DESCRIPTION.

Structurally, the technical solution "Hydraulic system for road vehicle propulsion", is a driving system, as it has a hydraulic energy source, transmission which contains the command system and the actuators that converts hydraulic energy into mechanical energy [2]. (**Error! Reference source not found.**1. – upper side).

The hydraulic energy generator is composed of a cam mechanism driving a piston, exerting a force F of speed **v**, and generating the $\mathbf{Q_1}$ flow. The systems continue with a pipe capable of sustaining wave propagation, phenomenon which at the other end of the pipe is characterized by Q_2 flow. The phenomenon is unsteady, and depending on load opposing the piston at the end of the pipe, will generate $\mathbf{p_1}$ and $\mathbf{p_2}$ pressures on both ends of the pipe, due to the system load. Using a piston – lever – one- way clutch system, the hydraulic power is converted into rotational mechanical power described by the torque **M** and angular speed **ω**

Dynamically, the system is made of two mechanical components and a hydraulic component in between them, resulting in a mechano-hydraulic coupled system. The assembly is characterized as a dynamic system with $\mathbf{m_1}$ mass and elastic constant $\mathbf{k_1}$ of the generator, resonant angular frequency $\boldsymbol{\omega_{1p}}$, inertia **L**, capacity C, and the resonant pulsation of the liquid column $\boldsymbol{\omega_{Lp}}$, while representative for the execution element are the mass $\mathbf{m_2}$, the elastic constant **k2**, with the resonant angular frequency of **ω2p.**

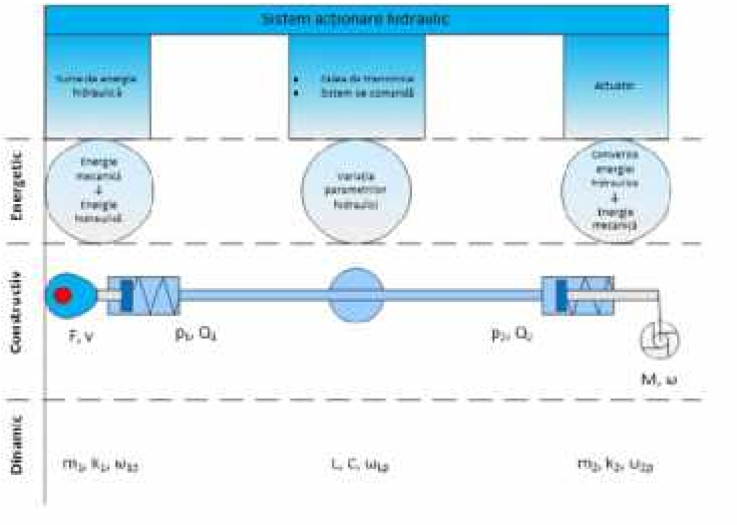

Fig. 1. The conceptual correlations between the propulsion system and the resonant phenomenon.

Dynamically, the hydraulic energy generator is a mass suspended by an elastic element, subjected to periodic excitation. Its movement is damped by wall friction. The mass-elastic element assembly has a resonant frequency.

The liquid column, in contact with the hydraulic generator, is characterized by mass, (as an inertial characteristic), and elastic properties which allow accumulation and dissipation effect due to the friction between the fluid and the walls and other local resistances [3]. As a dynamic effect, the liquid column is an oscillatory system with resonant frequency, with external excitation, and, depending on inertial properties, cumulative and dissipative, and also on correlations existent at frequency level with the oscillations source, the output parameters are resulted.

In this paper was analyzed a pressure wave generator, mechanically actuated by a translating piston, observing the formation, propagation, reflection and interference of the pressure waves.

The analysis was made theoretically, through simulations using dedicated software, and also experimentally.

The main objective was to identify the potential of the analyzed solution to be used for automotive propulsion.

3. SCOPE OF THE RESEARCH

The scope of the research is to determine the conditions in which the resonance is reached in a pipe with a mechanical check valve comprised of a sealing element and a spring. It was followed:

- Analysis of the pressure waves generated in a resonant regime, establishment of the oscillation parameters and the average pressure in the pipe;
- Analysis of the slowly generated pressure wave, using a sinusoidal or pseudo sinusoidal law;
- Analysis of the propagation of the wave;
- Analysis of the wave reflection at the closed end of the pipe.

It was also intended to determine the aspect of the wave, the pressure rise and fall periods, and also the duration of the high pressure period.

4. DESCRIPTION OF THE TECHNICAL SOLUTION

The studied system is presented in the principle scheme in Fig.2. Comprising: a pipe (1) closed at one end by a mechanical check valve (2), and at the other end by a piston (8) actuated by a harmonic cam (9). On the pipe, there are piezo-resistive transducers (4) at both ends, manometers (5) and flowmeter (6). Experimental data are recorded on the computer (7). The pipe is supplied with liquid from a stationary steady-pressure source. The perturbation in induced by rotating the cam using an electric motor.

For the maximum speed of the system, 11.000 l/min, the optimum pipe length was calculated so that when the wave runs through the end of the pipe and back, the reflected wave confronts a new impulse. A series of taps (3) was mounted to compensate the eventual unidentified perturbation sources, allowing for the pipe to be lengthened or shortened by 100mm.

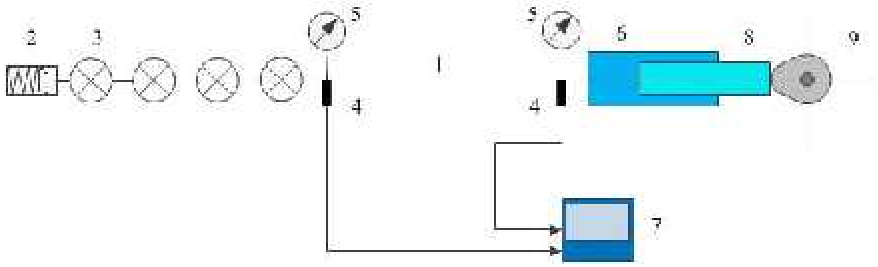

Fig.2. The system used for the slow generation of the wave

5. THE MATHEMATICAL MODEL USED

In order to analyze the mechanism which forms the pressure wave, the mode in which the wave propagates, and its stability analysis, CFDesign, finite element method software was used.

Like all the numerical methods applied on all problems with no analytical solution, it was necessary to reduce the problem of a number of infinite freedom degrees (DOF) to a finite number of DOF.

The finite volume method allows solving complex, three-dimensional, aninsentrope, and unsteady equations. Equations systems do not admit exact solutions, thus, it is necessary to apply numerical methods. Applying the numerical methods requires special calculation resources [4].

Applying the method also involves integration of the equations characteristic to finite space called finite volume or control volume. Each finite volume is associated with one or more points (nodes) in which the unknown variables are calculated. The geometric property of the finite volume is the fact that they are in contact through nodes which are placed at the boundaries of the finite volume. It is useful that the finite volume limits to exist at the boundary of the calculation domain, and in the areas where sudden property variations appear. Thus, for applying the method, it is necessary to replace the geometrical model with a set of finite volumes which geometrically approximates the studied domain. The finite volumes are tied through nodes, and these form the mesh network. The eulerian formulation of the flow equations is applied to these geometrical conditions. The solution for the problem is calculated at node level, while for the boundaries, the interpolation is used.

The base of the numerical method consists of converting the generalized equation with partial derivatives into an algebraic equation which relates the value of Φ variable in a random point P, belonging to the meshed domain, with the values in its neighborhood. This is done through integration of the general equation on a typical control volume, approximating different terms of the integral so that they will be expressed according to the values of the mesh nodes.

6. VALIDATION OF THE SIMULATION MODELS

The experimental research objective was to validate the simulation models.

The experimental study is done on functional models using piezo-electric transducers to measure instantaneous pressure, and with conventional manometers to measure the average pressure. The pressure variations are measured near the end of the pipe to observe the influence of the reflection at the closed end, and the way the waves propagate in time, in the straight, and curved pipe respectively.

The experimental results consisted of generating the wave at the speeds indicated in Table 1, for the 12.5mm diameter pipe. For this condition, the instantaneous pressures at the ends of the pipe have been recorded, according to Fig. 2.

System overview

Piston actuation components

Fig 3 Images of the experimental system

The fact that, experimentally, the induced pressure stagnated at 3 bar is due to the limitation of inducing oscillations in permanently high value compressed environment, having the same energetic efficiency.
In Fig. 4 are shown the instantaneous pressure evolution corresponding to 1000 l/min and 11000 l/min respectively. It shows that for high frequencies, the wave front is strongly distorted, the liquid properties being covered, influence-wise, by the externally induced perturbation. At low frequencies, the oscillation is freely manifested according to the properties and the flow conditions.

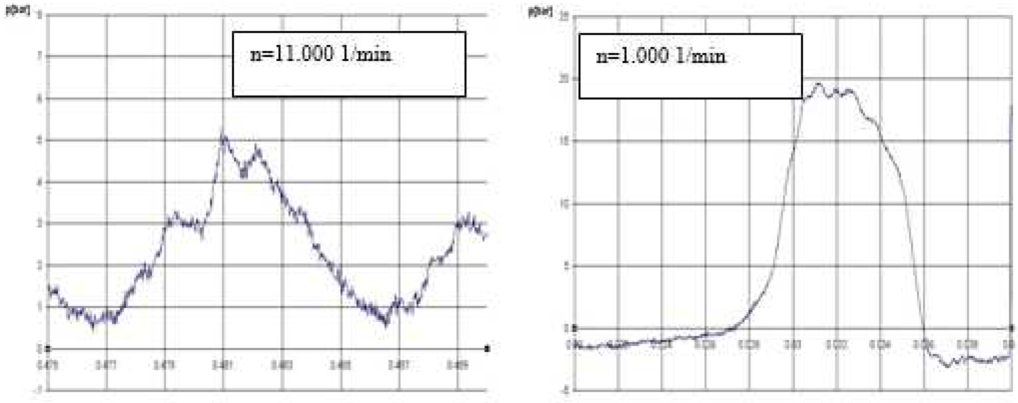

Fig. 4 The comparison of the elementary waves for different excitation frequencies

7. PRESENTING THE SIMULATION RESULTS

In order achieve the determinations; the electric motor spins the camshaft, which transforms the rotational movement into translational movement of a piston which pushes the liquid in the pipe. The studied versions and their characteristic dimensions are identical with the ones in Table 1.

Table 1. The constructive parameters of the studied system

Parameter	**Measuring unit**	**Value**
Pipe length	[m]	0,5; 1,0; 3.8
Pipe diameter	[mm]	2,0; 9,0; 12.5
Generation speed	[1/min]	1000; 2500; 11000
Cam number	[-]	1

The goal of the simulations was to find the way the waves form in pipes of different diameters, different lengths and using different frequencies. In the analysis, it was considered the amplification mechanism in a resonant regime by sinusoidal function.

For the simulation analysis of the resonant regime, standard conditions are considered to be able to compare solutions. A 1 meter long pipe, 1 m/s speed oscillation amplitude have been considered and the pulsations are induced without reflections at the mobile end (at each return, the oscillation is subjected to a new impulse).
The simulation process is done for the liquid that is in a straight pipe, having the diameters from Table 1. The simulation results from CFDesign will be presented only for the 12.5mm pipe diameter. The main parameters of the simulation are synthesized in Table 2.
In all the parameter representations got by simulation analysis, on the horizontal axis is represented the time for a certain number of oscillations (as requested by the simulation program).

Table 2 The main simulation parameters

Parameter	**Measuring unit**	**Value**	
No. of nodes	[-]	4334	
No. of elements	[-]	3930	
Initial speed	[m/s]	0	
Oscillation pulsation	[1/s]	4398	
Time step	[s]	10^{-4}	
No. of time steps Corresponding to a number of oscillations:	[-]	100 *7*	500 *35*

The velocity is calculated in 7 points along the pipe and is illustrated in Fig. 5.

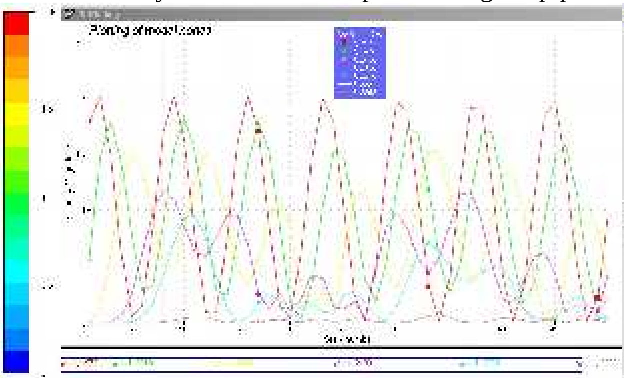

Fig. 5. The time evolution of the velocity induced by a sinus law in a resonant regime

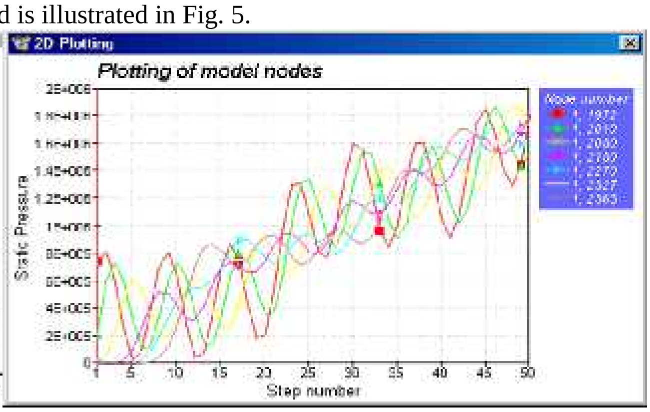

Fig. 6 Pressure evolution induced by a sinusoidal law (1 time step = 2 x 10-4 s)

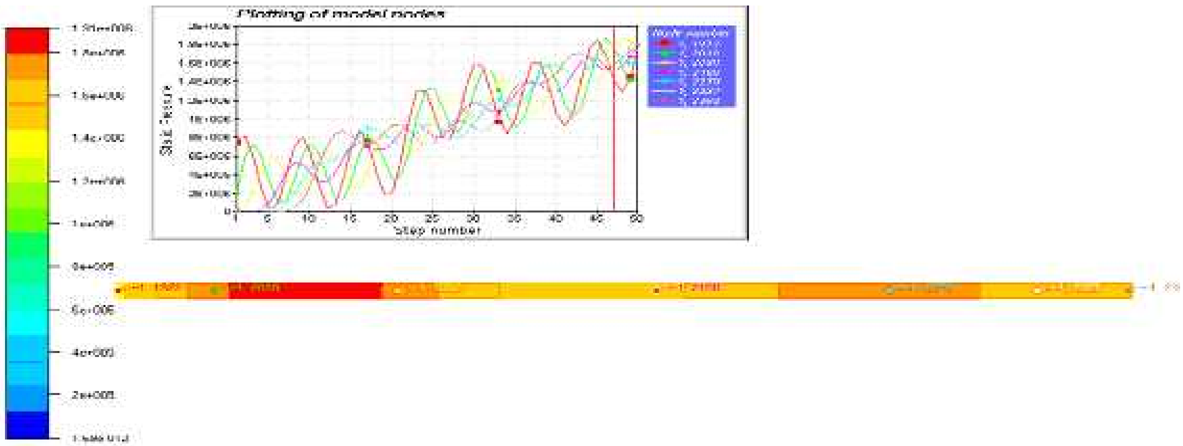

Fig. 7 The degree of uniformity of the pressure in the pipe

The pressure is induced by a sinusoidal law in resonant regime, and its temporal evolution is represented in Fig. 6.
It is noticeable that on seven sinusoidal oscillations induced in a resonant regime for 10^{-2} seconds, for an velocity amplitude of 2m/s, a 20 bar pressure is reached. The influence of the reflections on the amplification mechanism, through the fact that it has an oscillating evolution around a general linear evolution, marked separately on the

chart, is also noticed. Through the pressure rise in the resonant regime, there is a unification of the total pressure variations, which leads to an improvement on the pipe pressure uniformity. (Fig. 7)
The described mechanism illustrates an 18 bar / (2 x 10^{-4}) s amplification. Extrapolating this result, the 360 bar target pressures could be reached in 4 x 10^{-2} s. The simulated amplification mechanism considers the liquid compressibility, and the propagation conditions are considered if other perturbation sources don't exist. In Fig. 8, the wave fronts deform spatially, being unstable under the interference action.

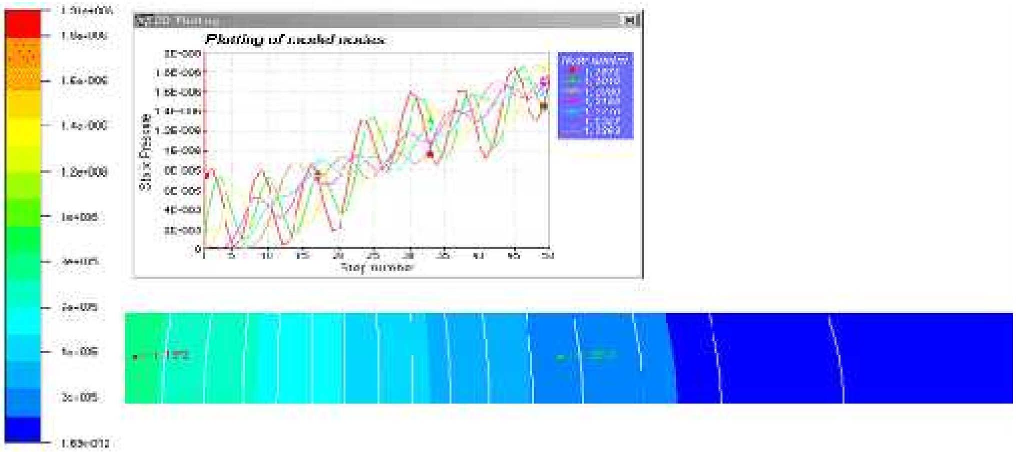

Fig. 8 Wave front evolution for pressure

8. CONCLUSIONS

- The analysis of the simulation results shows that the pressure generator for resonant regime in a closed pipe, with a mechanically coupled oscillating system generates a linear rise of the average pressure in the system;
- The studies regarding the possibility of inducing resonance illustrated the wave formation mechanism in the permanent perturbation regime.
- It was noted that although the oscillations are more distorted, when the frequencies are high, the sustained oscillations amplitude is higher and it induces a remnant pressure in the system, three times higher than the initial pressure. The process is revealed both theoretically and experimentally. The extrapolation of the results, demonstrated by simulation, shows a slight rise in the remnant pressure, induced by resonance.
- Experimentally, the amplification mechanism was identified to be less efficient, with local perturbation sources in the transducers zones and in the variable section area between the piston and the pipe, and also 4 reflections on the closed wall between successive impulse generations.
- The resonance generation mechanism is a continuous process if the generation conditions are maintained. Through impulse generation, the theoretical potential has an exponential evolution in regard to the energy induced to the system by impulse. Numerical simulation showed a linear evolution, while the experiment showed a fast evolution in the resonant regime, followed by stagnation.
- The resulted conclusion shows that it is necessary to have a new system design for the oscillatory system so that it is functionally closer to the impulse perturbed oscillator.

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