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MODEL OF DYNAMIC OF WAVE PHENOMENON DURING THE FUEL INJECTION IN THE COMMON RAIL SYSTEM

Abstract: In this paper the general equation to calculate the frequency of needle vibrations has been introduced. Also there has been taken under consideration wave phenomenon in the pipe and spring and the influence of loss of pressure wave amplitude in the injection pipe on the frequency of atomizer needle vibrations. Furthermore, on the basis of example pressure measurement in the indicated chamber the course of wave phenomenon in the injector and its source in the hydraulic tank has been presented.

Keywords: vibrations of atomizer needle, wave phenomenon, common rail

1. INTRODUCTION

The question of determining the frequency of vibrations of atomizer needle including wave phenomenon in the pipe and the spring was considered in the number of scientific studies [1 ÷ 4] for various constructional solutions. Researches of atomizer needle have the aim to find such constructional solutions so that the system will work stable. If vibration system losses more energy than receives, the system works stable and vibrations are damped. However, if there is greater energy supply than energy outflow from the atomizer at the time of needle operating, vibrations have the tendency to increase and system works unstable.

2. CALCULATING THE FREQUENCY OF VIBRATION OF NEEDLE

The subject of following consideration is an accumulate system. Its simplified scheme is presented in the Fig. 1. Pump pumps fuel through the hydraulic tank. In the high pressure pipe between the tank and the injector, there is installed a valve, which is used to regulate

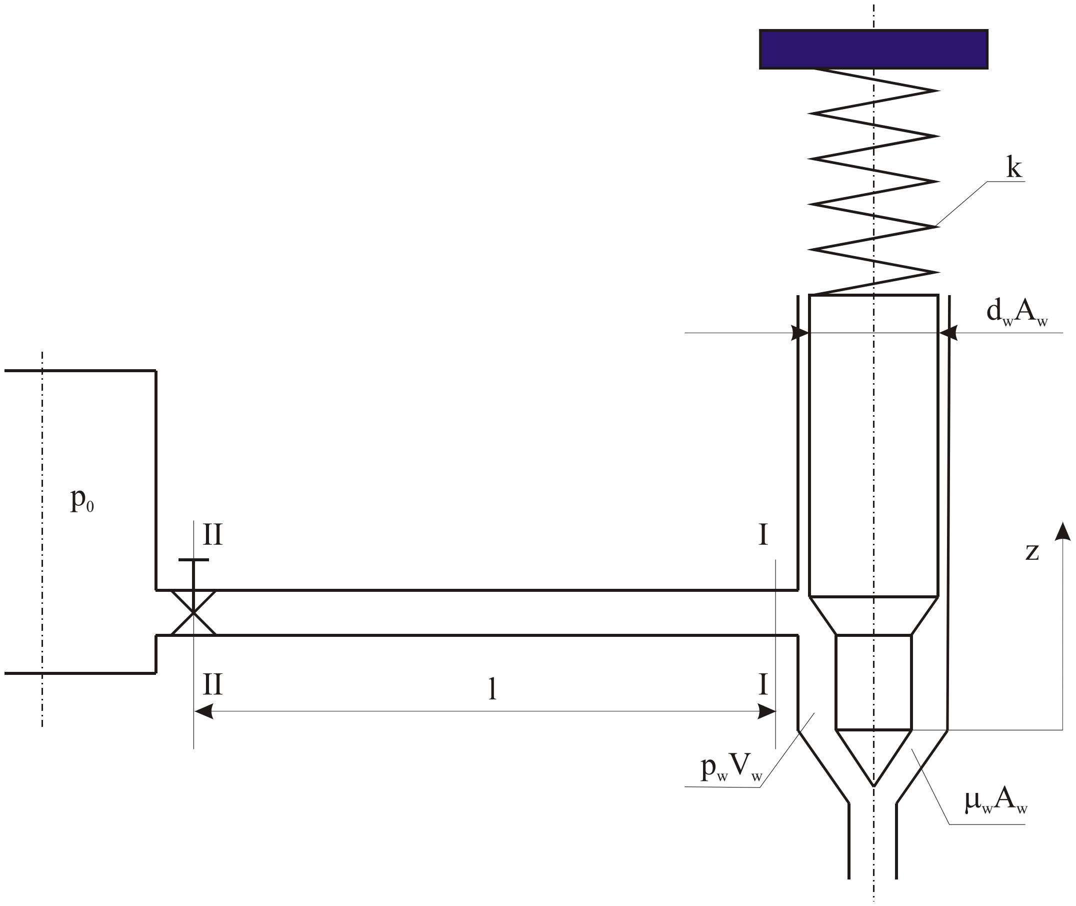

Fig. 1. Scheme of accumulator system of fuel dosing

fuel pressure affecting on the needle and as a consequence evoking different vibrations of needle, for its appropriate locations.

If the needle vibrated around some medium location in the time of fuel flow through the injector, this location could be described as a location of static balance ($h_1 > z > 0$).

Following equations for the needle movement are correct in this state of static balance:

- equation of balance of power:

$$P_{st} - A_w \cdot p_{st} \cdot \chi = 0 \tag{1}$$

where:

P_{st} – static load power of spring;

A_w – surface of cross-section of needle;

p_{st} – static pressure under the needle;

χ – coefficient, which considers the influence of flow damping on pressure value under the needle.

- equation of fuel delivery through the atomizer:

$$Q_0 - A_p \cdot v_{st} = 0 \tag{2}$$

where:

Q_0 – static delivery;

A_p – surface of cross-section of high pressure pipe;

v_{st} – static speed of fuel flow in the high pressure pipe.

In the location different from location of static balance the above equations are following:

- equation of balance of power:

$$m\ddot{z} + \vartheta\dot{z} + P_s - p_w \cdot A_w \cdot \chi = 0 \tag{3}$$

where:

m –needle mass and mass of part of spring;

ϑ – damping constant proportional to speed $\dot{z}$;

P_s – power of spring;

p_w – pressure in the chamber above the atomizer seating;

z – location of needle.

- equation of flow continuity in the atomizer:

$$A_p \cdot v - \frac{V_w}{E_v} \cdot \dot{p}_w - A_w \cdot \dot{z} - Q = 0 \tag{4}$$

where:

V_w – chamber volume over the atomizer seating;

E_v –fuel compressibility module.

Treating phenomenon of impulse passing in fuel and in the needle spring as a wave phenomenon, it is possible to write the individual variables in equations (3) and (4) in the form of following relation:

- location of needle to the top from its seating:

$$z = z_{st} + z_s(t) - \sigma_s \cdot z_s(t - T_s) \tag{5}$$

In the formula this deformation of free end of spring is treated as a wave z_s which goes up along the spring wire to the end which is permanently fastened. The third section of equation (5) describes the reflected wave which is a result of deformation of free end of the spring arisen in the moment $(t - T_s)$.

Coefficient σ_s describes loss at the deformation wave reflection from the constant end of spring.

- pressure in the chamber above atomizer seating:

$$p_w = p_{st} + p_p + p_L = p_{st} + p_L(t) + \left(\sigma_p + e^{-\xi_{sr} \cdot \alpha \cdot T_p}\right) \cdot p_L(t - T_p) \tag{6}$$

As it is presented in this equation pressure p_w is the total of static pressure value p_{st}, pressure wave into right p_p and pressure wave into left p_L.

Pressure wave into left arise as a result of wave reflection process into right from the tank. Coefficient σ_p is a coefficient of wave reflection from the tank outlet. Section $e^{-\xi_{sr}\cdot\alpha\cdot T_p}$ considers the loss of amplitude of pressure wave flowing through the fuel pipe.

- fuel speed in section I-I (Fig. 1):

$$\vartheta = \vartheta_{st} + \vartheta_p + \vartheta_L = \vartheta_{st} + \frac{1}{a\rho} - p_L(t) + \left(\sigma_p + e^{-\alpha\xi_{sr}T_p}\right)\cdot p_L(t - T_p) \tag{7}$$

As it is clear from formula (7) fuel speed is also the resultant of constant (static) speed and wave speed into right and left.

- power of spring:

$$P_s = P_{st} + P_1 + P_2 \tag{8}$$

Power P_s is resultant power from the power of spring in the state of static balance, power of the deformation wave of spring material along the wire and power of the reflected deformation wave from the permanent end of spring.

Instead of wave running along the spring wire it is possible to define the following wave along the axis of spring (along z axis). From the theory of strength of materials were introduced following relations, for instance:

$$EA_{\text{równoważnego pręta}} = \frac{4\cdot c\cdot h}{\pi\cdot D^3};\ (\rho A)_z = \frac{\pi\cdot d^2}{4}\cdot\frac{l_s}{l_z}\cdot\rho_s;\ k = \frac{4\cdot c}{\pi\cdot d^3\cdot i_z};\ tg\Theta = \frac{h}{\pi\cdot D}; \tag{9}$$

$$l_s = i_z\cdot\pi\cdot D \qquad c = \frac{\pi\cdot d^4}{32}\cdot G$$

where:
c – stiffness to the torsions of spring wire
h – coil lifting;
D, d – average diameter of spring and wire;
G – elasticity module, second type;
l_s – length of spring wire;
i_z – amount of working coils;
l_z – length of substitute bar;
k – permanent springs;
Θ –slope angle of spring coils.

From relation (9)we obtain:

$$(EA)_z = k\cdot l_s\cdot tg\Theta;\quad l_z = i_z\cdot h;\quad \frac{l_z}{l_s} = tg\Theta \tag{10}$$

Speed of deformation disperse along the spring wire

$$a_s = \frac{1}{\sqrt{2}} \cdot \frac{d}{D} \cdot \sqrt{\frac{G}{\rho_d}} = \sqrt{\frac{k \cdot l_s^2}{M_s}} \tag{11}$$

$$a_z = \frac{(EA)_z}{(\rho A)_z} = \frac{h \cdot d}{\sqrt{2} \cdot \pi \cdot d^2} \cdot \sqrt{\frac{G}{\rho_s}} = \sqrt{\frac{k \cdot l_z^2}{M_s}} \tag{12}$$

$$\frac{a_z}{a_s} = \frac{l_z}{l_s} = tg\Theta \tag{13}$$

From the Hooke's equation we obtain:

$$P_1 = \sigma_1 \cdot A_z = \Delta\xi_1 \cdot E_z \cdot A_z = \xi_1 (EA)_z = \Delta\xi_1 \cdot k \cdot l_s \cdot tg\Theta$$

similarly $P_2 = \Delta\xi_2 \cdot k \cdot l_s \cdot tg\Theta$

So the power of spring

$$P_s = P_{st} + k \cdot l_s \cdot tg\Theta \cdot (\Delta\xi_1 + \Delta\xi_2) \tag{14}$$

Relative deformations $\Delta\xi_1$ and $\Delta\xi_2$ are the results of speed differences $\dot{z}_1$ i $\dot{z}_2$ equivalent bar and speed of sound of equivalent bar, so their total can be presented in the form:

$$\Delta\xi_1 + \Delta\xi_2 = \frac{\dot{z}_1}{a_z} + \frac{\dot{z}_2}{a_z} \tag{15}$$

After substituting values from equation (15) to equation (14) considering relations $tg\Theta = \frac{a_z}{a_s}$ we obtain:

$$P_s = P_{st} + k \cdot \frac{l_s}{a_s} \cdot (\dot{z}_1 - \dot{z}_2) = P_{st} + k \cdot \frac{l_s}{a_s} \cdot [\dot{z}_s(t) + \sigma_s \dot{z}_s(t - T_s)] \tag{16}$$

Substituting relations (16), (6), (5) to equation (3) considering equation (1) we obtain:

$$\begin{aligned} &m[\ddot{z}_s(t) - \sigma_s \ddot{z}_s(t - T_s)] + \vartheta[\dot{z}_s(t) - \sigma_s \dot{z}_s(t - T_s)] + k \cdot \frac{l_s}{a_s}[\dot{z}_s(t) + \sigma_s z_s(t - T_s)] - \\ &- [p_L(t) + (\sigma_p + e^{-\alpha\xi_{sr} \cdot T_p}) \cdot p_L(t - T_p)] \cdot A_w \cdot \aleph = 0 \end{aligned} \tag{3a}$$

Similarly after substituting relations (7), (6), (5) to equation (4) considering relation (2) we obtain:

$$\frac{A_p}{\rho_a}\left[p_L(t)-\left(\sigma_p+e^{-\alpha\xi_{sr}T_p}\right)p_L(t-T_p)\right]+\frac{V_w}{E_v}\left[\dot{p}_L(t)+\left(\sigma_p+e^{-\alpha\xi_{sr}T_p}\right)\dot{p}_L(t-T_p)\right]+ \\ +_{A_W}\left[\dot{z}_s(t)-\sigma_s\dot{z}_s(t-T_s)\right]+Q-Q_0=0 \tag{4a}$$

System of equations (3a) and (4a) have two unknown elements p_p and z_s. Assuming low disturbances $p_p(t)$ and $z_s(t)$, it is possible to treat the above system of equations as a linear system.

It is possible for the linear system to calculate the increase value of expense function using the Taylor's amplification.. Presented fragment of wave phenomenon analysis is only an introduction to description of these processes.

The results of measurements in case, where single dose was triple-divided in following proportions 10% – 80% – 10% are presented in the further part of studies.

REAL FUEL FLOW IN THE SECTION TANK – INDICATED CHAMBER

Below is presented the example of phenomenon which occurs in the hydraulic tank and in the fuel indicated chamber in the case when initial injection pressure in the tank is equal to 150 MPa and fuel dose is divided in proportion: 10% – pilot dose; 80% – main dose; 10% – supplementary dose.

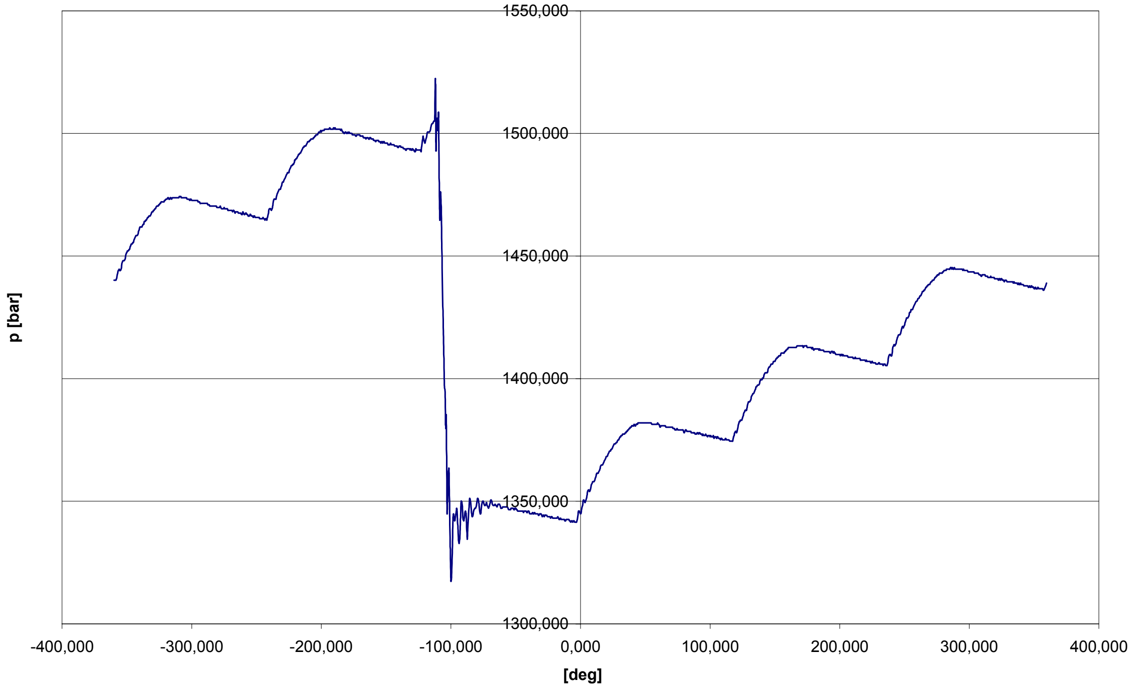

Fig. 2. Course of fuel pressure changes in the hydraulic tank

Figure 3 presents the quality course of fuel dose. Values defining the axis of ordinates do not reflect values of fuel dose – in this case this value is equal to 147,2 mg.

Presented diagrams show how important is wave phenomenon during fuel flow through the elements of feed system, among all these Common Rail type.

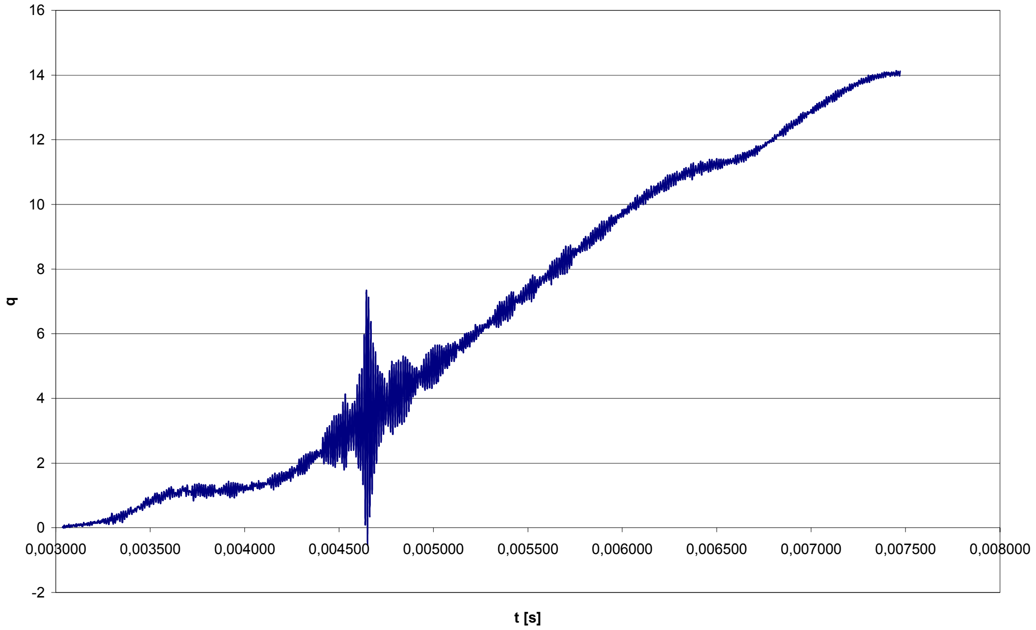

Fig. 3. Quality course of fuel dose in case of triple fuel injection with visible interferences which are results of wave phenomenon occurring during the engine feeding

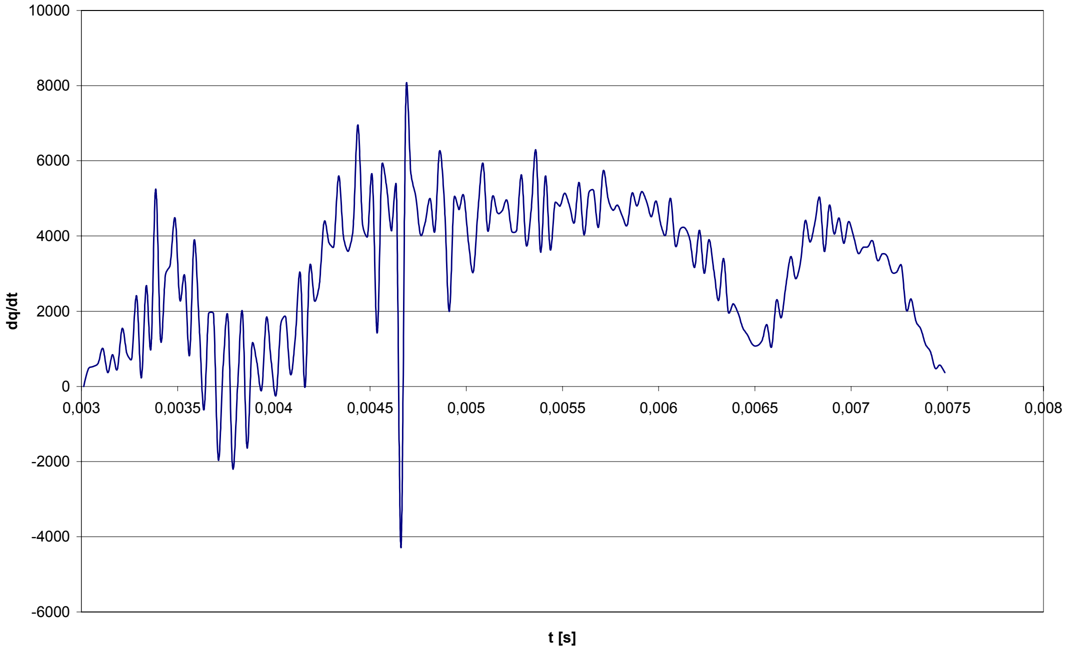

Fig. 4. Quality course of changes of single fuel dose considering the wave phenomenon

RÉSUME

Analysis of theoretical research and results of measurements in the indicated chamber shows that changes in construction of atomizer needle in the C – R system consider significance of wave phenomenon which occurs during the fuel injection.

Irregular course of characteristics presenting fuel pressure changes in the hydraulic tank and consequently disturbances in the run of fuel dose measured in the indicated chamber proves the turbulent and wave character of phenomenon, which occurs in the fuel system of self-ignition engines.

Rapid decrease of fuel pressure in the hydraulic tank is a result of fast test of controlling valve in the injector and source of the wave phenomenon at the same time

To full test of fuel dose by the controlling valve some minimum time is essential to overcome the hydraulic resistance and to consider the inertial power from atomizer needle mass and atomizer spring mass.

Electronic control of injection process enables precise fuel dosing in the predicted range of crankshaft motion angle.

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MODEL DYNAMIKI ZJAWISK FALOWYCH PODCZAS WTRYSKU PALIWA W UKŁADZIE COMMON RAIL

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Streszczenia: W pracy wyprowadzono ogólne równanie do obliczania częstotliwości drgań iglicy. Uwzględniono przy tym wpływ zjawiska falowego w przewodzie i w sprężynie oraz wpływ straty amplitudy fali ciśnienia w przewodzie wtryskowym na częstotliwość drgań iglicy rozpylacza. Ponadto na podstawie przykładowego pomiaru ciśnienia w komorze indykatorowej przedstawiono przebiegi zjawisk falowych we wtryskiwaczu i ich źródła w zasobniku hydraulicznym.

Słowa kluczowe: drgania iglicy rozpylacza, zjawiska falowe, common rail