Fuzzy Logic Positioning System of Ship's Diesel Generators Actuating Mechanisms

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***Abstract*—Hydraulic and electromagnetic drive are used as actuating mechanisms for fuel oil and gas injection on ships equipped with electronically controlled diesel generators. It leads to weight and size increasing, high power consumption for servo oil pump driving, reducing life time and reliability of control valves. Piezoelectric drive (stack actuators, linear and rotary motors) can be used as alternative to hydraulic and electromagnetic. It lacks the drawbacks of hydraulic and electromagnetic drives, but requires to use amplifiers to create high displacements and dynamic properties correcting devices due to high internal damping of piezo drive.**

Developed fuzzy logic positioning system models allow to correct the dynamic properties of the piezo drive and apply it to control the actuating mechanisms of marine diesel generators, reduce the energy consumption and expand the range of possible fuel injection curve.

Keywords—fuzzy logic control system, piezoelectric drive, common rail fuel system, dual-fuel marine diesel generator.

I. Introduction

Tighter requirements for emissions into the atmosphere by marine diesel engines motivate shipowners and shipbuilders to search for alternative fuels and develop automated control systems for its injection. Since the 2000s, large shipping companies have converted old vessels or ordered new vessels capable for operating on liquefied gas or mixtures of different types of fuel [1, 2]. Simultaneously, electronic fuel control systems replaced conventional [3], which exhausted their capabil-ities.

Hydraulic drive is used as an actuating mechanism to supply fuel oil on vessels equipped with electronically controlled diesel generators and electromagnetic on ships with dual-fuel diesel generators to supply gas fuels, especially SOGAV-250. Using of hydraulic systems has led to increase mass, dimension, power consumption for the drive of servo oil pumps [4] and led to emergency situations in case of malfunctions in servo oil system [5]. And use of electromagnets led to reduce life time and reliability of the control valves [6].

An analysis of the existing types of actuating mechanisms has shown that the improvement of the electromagnetic and hydraulic drive of actuating mechanisms is already almost exhausted. Therefore, research and development of control systems with actuating mechanisms based on new physical principles are relevant. The purpose of this study is to create new types of drives and their control laws. One of the most promising areas is the piezoelectric drive (stack actuators, linear and rotary motors).

II. Model Development

The main requirements [7, 8] to marine diesel generators fuel systems are the force, speed and displacement (Table 1).

Since the arrival of the piezo drive, its applicated only to create micro-displacements with a small force [9 - 12]. The use of piezoelectric drives in transport is limited for the following reasons:

- nonlinear frequency response curve of piezo elements, which determines its operation at the resonance frequency or in a narrow linear frequency range up to 20 kHz;

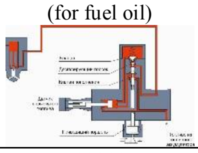
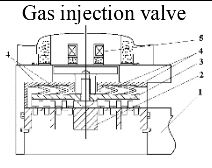
- hysteresis and the high dependence of the displacement on the load;

- high dependence of the displacement on the ambient temperature. However, at the present time, a high-temperature type of piezoceramics is producing, which not losing its properties up to 350 °C [18];

- creepage of ceramic, which can be reduced by preloading;

- the properties of piezo-manipulators are combined with high internal damping, which lead to strong oscillation in the transient processes due to changing of control field and the mechanical load.

TABLE I. MAIN PARAMETERS OF THE ACTUATING MECHANISMS DRIVE

	Injection control unit (for fuel oil) 	Gas injection valve 
Force, N	12300	100
Speed, ms	≥ 6.5	≥ 20
Displacement, mm	4	0.4

The advantages of the piezo drive is:

- absence of copper windings and simplicity of manufacturing technology;

- high starting torque and specific power;

- high efficiency, reaching 54%;

- no risk of short circuit on the mechanical side (no coupling is needed);

- linear mechanical characteristic;

- simultaneous flow of direct and reverse piezoelectric effects provides high sensitivity to changing the moment of loading, which allows to estimate the load of the piezo drive.

Another advantage of using a piezoelectric drive is the absence of any kinematic transducers intended for changing speeds. The range of actively processed frequencies can be extended to several kHz for piezoceramic manipulators and motors. It's significantly expands the range of speed changes.

However, having such properties, the piezoelectric drive for a long time did not find wide application in ship diesel engine construction, where the displacement ranges are 2-5 mm. Construction of injection control unit with piezoelectric drive were developed in the studies [13-17].

Stack actuators (Fig. 1), fixed one end on a base. It consists of a piezoelectric washer set with cross-sectional area S_0 and the initial thickness l_0. The length of the column changes under the action of the electric field E in the direction of the field action by the value Δ, moving the actuator with mass m_0, connected with its free end. In addition to the actuating mechanisms, the active part volume elements of the piezoelectric stack also move. Their mass m_k is usually less than the mass of the actuating mechanisms. In this case, the piezoelectric element moving volumes inertia can be neglected. Agree that the stack is fixed at one end and this part doesn't participate in the movement. The total reduced mass m_Σ will be equal, kg,

$$m_\Sigma = m_0 + 0.382\, m_k$$

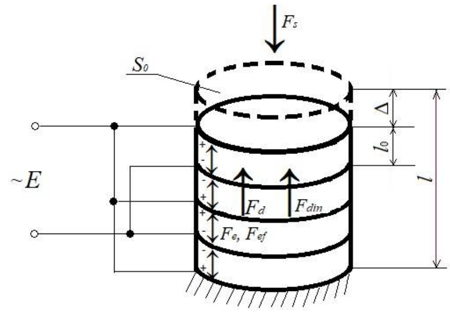


Fig. 1. Construction of piezoelectric stack actuator

According to Newton's third law, for the forces acting on the column, the following equilibrium condition is valid [1]:

$$\bar{F}_e = \bar{F}_{ef} + \bar{F}_s + \bar{F}_d + \bar{F}_{din},$$

where $F_e = K_e\Delta$ – elastic deformation force, N;
$F_{ef} = d_p Y S_0 E$ – force in the piezoelectric element caused by an applied electric field, N;
F_s – static force from the actuating mechanisms, N;
$F_d = -K_d((d\Delta)/(dt))$ – damping force in the piezoelectric element, N;
$F_{din} = -m_\Sigma\ ((d^2\Delta)/(dt^2))$ – dynamic force in the piezoelectric element, N;
$K_e = YS_0/l_0$ – elastic coefficient of the piezoelectric element, N/m;
K_d –internal damping coefficientof the piezoelectric element, kg/s;
m_Σ – total reduced mass, kg;
Δ – deformation of the piezoelectric element, mm;
l_0 – washer initial thickness, mm;
Y – Young modulus, N/m^2;
d_p – piezoelectric constant, C/N;
E – field strength, V/m.

Mechanical stress σ determined by static force F_s applied to the actuator and acting on the piezoelectric element from the side of the actuator, by the dynamic force F_{din} proportional to the acceleration of the actuating mechanisms and the damping force F_d proportional to the displacement speed of the actuating mechanisms.The dynamic force F_{din} in this case act on the piezoelectric element in the direction of the applied field.

We obtain a block diagram of piezoelectric washers stack (Fig. 2).

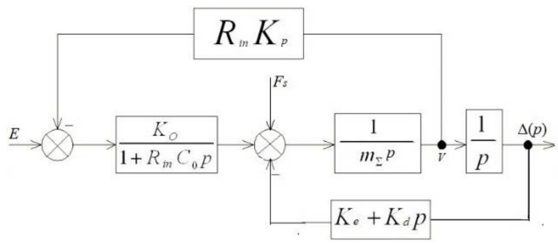


Fig. 2. Structural diagram of a piezoelectric washer stack

The transformation of the obtained structural scheme leads to a transfer function of the following form

$$W_{\Delta}(p)=\frac{K_0}{R_{in}C_0 m_{\Sigma} p^3+(m_{\Sigma}+R_{in}C_0K_d)p^2+(R_{in}C_0K_d+} \rightarrow .$$
$$\rightarrow \frac{}{K_d+R_{in}C_0+R_{in}C_0K_p)p+K_e}$$

where $V= d\Delta/dt$ – speed of actuating mechanisms, m/s;
$C_0= \varepsilon_0\chi S_0(1\text{-}K^2_{em})/l_0$– capacity of piezoelectric element, F;
$K_p = K_e d_p$ – direct piezoelectric effect coefficient, C/m.
$K_0 = l_0/YS_0d_p =d_p/K_e$– inversepiezoelectriceffectcoefficient, m/C.

The blocks taking into account preload spring stiffness and the spool spring stiffness coefficient are introduced into the block diagram for modelling injection control unit with piezoelectric washers stack. Thus, the block diagram of the injection control unit driven by the piezoelectric washer stack shown in Fig. 3.Thus, the transfer function takes the form,

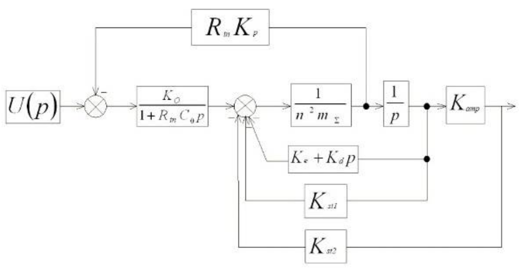


Fig. 3. Model of the injection control unit with piezoelectric washer stack drive: $U(p)$ - control voltage; K_{amp} – amplification coefficient of stack displacement; K_{st1} - preloading spring stiffness coefficient; K_{st2} - spool spring stiffness coefficient

$$W_{\Delta}(p)=\frac{K_0K_{amp}}{R_{in}C_0m_{\Sigma}p^3+(m_{\Sigma}+R_{in}C_0K_d)p^2+(R_{in}C_0K_d+}\rightarrow$$
$$\rightarrow\frac{}{+K_d+R_{in}C_0K_{st1}+R_{in}C_0K_p+R_{in}C_0K_{st2}K_{amp})p+}\rightarrow .$$
$$\rightarrow\frac{}{+K_e+K_{st1}+K_{amp}K_{st2}}$$

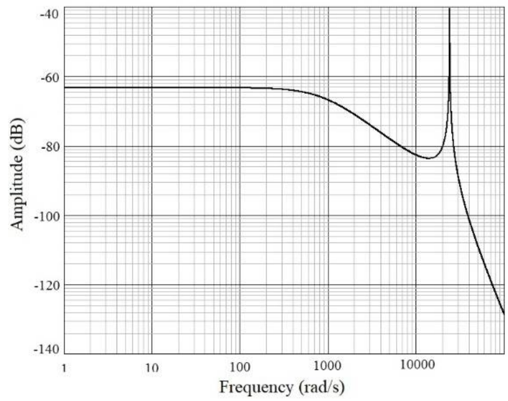
According to Physik Instrumente (PI) [18], currently, one of the most common materials used for the production of piezo-manipulators is PIC 255, which has the following parameters: density ρ – 7800 kg/m^3, relative permittivity ε – 1750, piezoelectric charge coefficient d_{33} – 400·10^{-12} C/N, piezoelectric coupling factor k_{33} – 0,69, Young modulus Y_{33} – 10·10^{10} N/m^2, resistance R_{in} – 50 Ω, damping coefficient k_d – 8,9·10^{-3} kg/cm^2, elastic coefficient K_y – 1,599·10^9 N/m, inverse K_0 and direct K_p piezoelectric effect – 49,2 N/V and 49,2 V/N.

Model P-056.90 manufactured with PIC 255 material with the following parameters was chosen for the study: displacement Δ – 180·10^{-6} m, diameter - 0,056 m, length - 0,154 m, blocking force - 78000 N, electric capacity, C_0 – 2,7 · 10^{-5}F, resonant frequency - 7000 Hz, weight of the column is 2,96 kg.

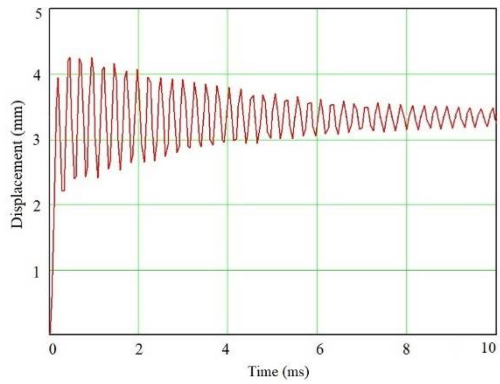
After substituting the values in (11), obtain the following transfer function,

$$W_{\Delta}(p)=\frac{1094}{3{,}105\cdot10^{-3}p^3+2{,}95p^2+1{,}8\cdot10^6p+1{,}599\cdot10^9}.$$

The analysis of the frequency response curve and the step response (Fig. 4) allows us to conclude that it is possible to obtain the required displacement with the required force, without exceeding the time limit requirements for the the transient process, which is less than 1 ms with the required 6.5 ms. In addition, the linearity of the frequency response curve in the frequency range from 0 to 100 Hz indicates the possibility of using this construction in marine diesel generators with a rotational speed of up to 6,000 rpm. However, due to strong internal damping of the piezoceramics, the oscillations of the actuator appear, which leads to irregularity of the fuel supply and increase wear of injection control unit spool.



a)



b)

Fig. 4. Frequency response curve (a) and the step response (b)

The use of the piezo drive positioning system with a PID controller [8] make it possible to reduce the amplitude of the oscillations (Fig.5) with increasing transient time, but did not completely eliminate it.

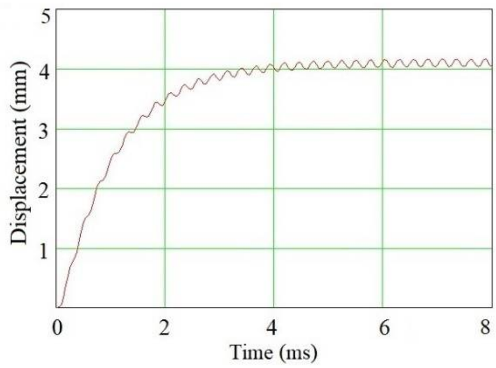


Fig. 5. Injection control unit spool movement with piezo drive by step change PID controller set point

Retrieval for possible options for an additional decrease in the amplitude of the oscillations has shown that the use of a fuzzy regulator leads to an almost complete elimination of oscillations in the electromechanical system [19]. It was a prerequisite for creation of a new automated piezo drive positioning system, based on the principles of fuzzy logic (Fig. 6).

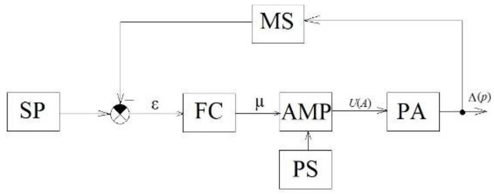


Fig. 6. Functional diagram of actuating mechanisms fuzzy logic positioning system: SP – set point, FC – fuzzy controller, AMP – amplifier, PS – power supply unit, PA –piezo actuator (control object), MS– displacement sensor, A is the amplitude, $U(A)$ is the voltage

Approbation of the proposed fuzzy positioning system on the mathematical model (Fig.7) demonstrated its effectiveness. Thus, the oscillations of the spool of the fuel delivery control unit are almost eliminated.

So, the use of a piezoelectric actuator with a fuzzy positioning system will reduce the energy intensity of the engine and expand the range of possible fuel injection curve, increasing the energy and environmental efficiency of the diesel generator. And also the number and capacity of rails will be reduced.

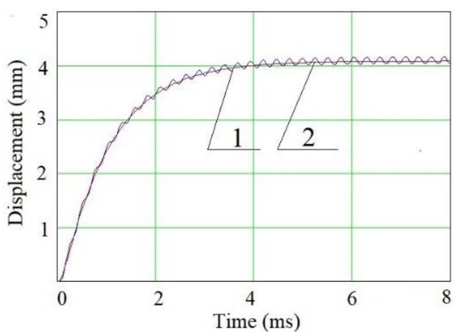


Fig. 7. Displacement of the injection control unit spool with piezo drive due to step change of set point for the systems: 1 – with PID controller; 2 – with fuzzy controller

Replacement of the electromagnetic drive of the SOGAV gas valve of dual-fuel diesel generators can be realized by using linear piezoelectric motors and piezoelectric washers stack. Construction of a valve with a linear piezoelectric motor drive (Fig. 8) and a construction with a stuck (Fig. 9), has been developed and patented.

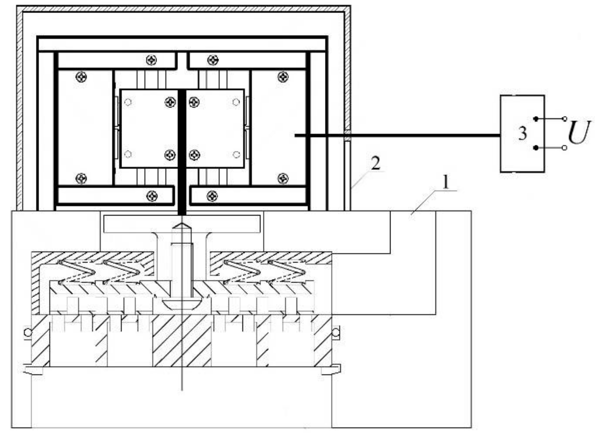


Fig. 8. Gas supply valvewith a linear piezoelectric motor: 1 – gas supply valve; 2 – linear piezoelectric motor; 3 – control unit

The requirements for the gas valve drive displacement are lower than to the injection control unit drive, as shown in Table 1. This makes it possible to use a piezoelectric washers stack without an additional amplifier.

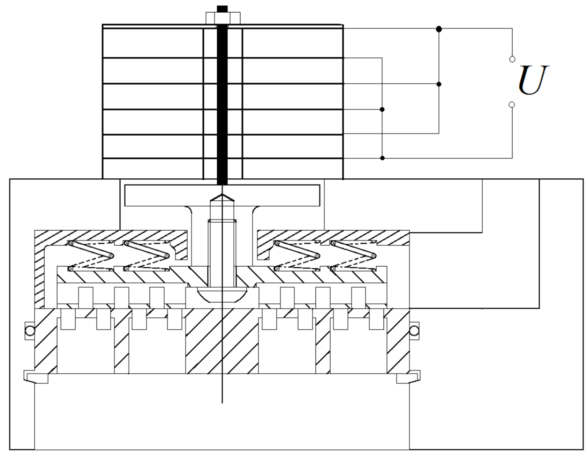


Fig. 9. The gas supply valvewith piezoelectric washer stuck

The market review showed that the company Physik Instrumente (PI) [18], offers manipulators that provide movement up to 0.3 mm. Therefore, by combining them in parallel, it is possible to obtain a displacement of up to 0.6 mm. PIC 151 material is used for their production, which has the following parameters: density ρ – 7800 kg/m^3, relative permittivity ε – 2400, piezoelectric charge coefficient d_{33} – $500 \cdot 10^{-12}$ C/N, piezoelectric coupling factor k_{33} – 0,69, Young modulus Y_{33} – $10 \cdot 10^{10}$ N/m^2, resistance R_{in} – 50 Ω, damping coefficient k_d – $8{,}9 \cdot 10^{-3}$ kg/cm^2, elastic coefficient K_y – $2.011 \cdot 10^8$ N/m, inverse K_0 and directK_p piezoelectric effect – 12.3 N/V and 12.3 V/N.

Model P-025.200 manufactured with PIC 151 material with the following parameters was chosen for the study: displacement Δ – $300{\cdot}10^{-6}$ m, diameter - 0,025 m, length - 0,244 m, blocking force - 16000 N, electric capacity, C_0 – $0.8{\cdot}10^{-5}$F, resonant frequency - 5000 Hz, weight of the column is 0.93 kg.

Parallel connection allows to obtain the required movement without the use of additional gears, but increases the electrical capacity of the system by 2 times. So, the block diagram of the gas valve drive will have the form shown in Fig. 5 Therefore, the transfer function after substitution of the values will have the form,

$$W_{\Delta}(p)=\frac{12{,}3}{7{,}47\cdot 10^{-4}\,p^{3}+0{,}93p^{2}+1{,}7\cdot 10^{5}\,p+2{,}011\cdot 10^{8}}\ .$$

The study of the developed positioning system with two parallel-connected stacks, with a PID and fuzzy regulator, confirmed the possibility of its application in marine diesel generators (Fig. 10).

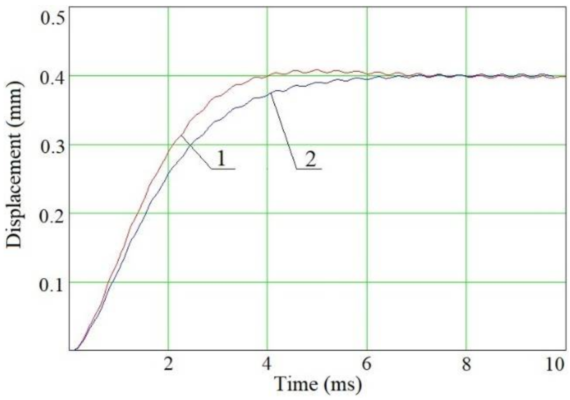


Fig. 10. Displacement of the gas valve plate with a step change of positioning system set point: 1 - with a PID controller; 2 - with fuzzy controller

CONCLUSIONS

The use of a piezo drive also will increase the life time of the gas valves from 5000 hours to 50,000, save its operating characteristics and reduce the operating costs for servicing the diesel generator.

Thus, the goal of the research was achieved.

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