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Frequency pressure transducer with a sensitivity of mem capacitor on the basis of transistor structure with negative resistance

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ABSTRACT

In the article the pressure transducer with frequency output based on the structure of the bipolar-field transistors with negative resistance and tenso sensitive MEMS capacitor has been considered. A mathematical model of the frequency pressure transducer in dynamic regime has been developed that allowed to determine the voltage or current in the circuit at any given moment in time when acting this pressure. Analytical expressions of the conversion function and sensitivity equation has been received. The sensitivity of the developed device is between 0,95kHz/kPa to 1,65kHz/kPa.

Keywords: frequency pressure transducer, MEMS capacitor, negative resistance

1. INTRODUCTION

Currently microelectronic pressure transducers are widely used in different applications, and their advantages over traditional due primarily to using them as sensitive elements of semiconductor materials, methods of group formation and processing them into measuring circuits' amplification and signal processing techniques of microelectronic technology.

Radiomeasuring transducers with a frequency output have a number of advantages over the current amplitude, which are to a significant increase in noise immunity, thus increasing the accuracy of measurement, as well as the ability to produce large output signals without pre-amplifying devices. Using frequency signal as an informative eliminates the analog-to-digital converters, increases efficiency measuring apparatus [1-5]. Currently intensive research on the properties of analog microelectronic pressure transducers is carrying out [3, 6, 7], although the study the frequency of pressure transducers based on the reactive properties of bipolar and field-effect transistors is in an initial stage [8-12]. Therefore, this paper is devoted to the study of the function of transformation and equation of sensitivity of the frequency pressure transducer on the basis of transistor structure with negative resistance.

2. THEORETICAL AND EXPERIMENTAL RESEARCH

Schematic diagram of the transducer is shown in Figure 1. It is a hybrid integrated circuit, which consists of bipolar and field effect transistors, R1, R2 resistances and tenso sensitive MEMS capacitor that creates an autogenerating device. Oscillating circuit device is implemented on the basis of the equivalent capacitance of the impedance at the collector electrode of the bipolar transistor VT1 and the drain of the field-effect transistor VT2, and inductance L. On tenzo sensitive MEMS capacitor acting pressure, which leads to a change in the equivalent capacitance of the oscillatory circuit, which in turn, causes a change in the resonant frequency of the oscillator [8, 10].

Energy losses in the resonant circuit offset by the negative resistance [8, 12]. For experimental research in the scheme shown in Figure 1 were used transistors UKT3101 and KP327 and tenso sensitive MEMS capacitor made in scientific laboratories Institute of Micro System Technology TUHH (Hamburg, Germany) (Figure 2).

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The frequency of generation from the pressure is determined by the reverse current loop according to the equivalent circuit based on Lyapunov stability theory. At first, the reactive component is determined by the impedance at the drain electrode-collector transistors structure, and then from the reactive impedance component is determined by the equivalent capacitance, which depends on the pressure variation. Changing the equivalent capacitance determines the frequency dependence of the pressure generation.

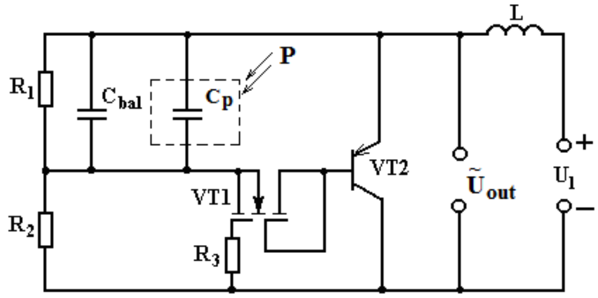

Figure 1. Schematic diagram of the frequency transducer pressure with sensitive MEMS capacitor.

Figure 2. Photo MEMS capacitor.

To determine the conversion function and sensitivity in Fig. 3 shows an equivalent circuit of the frequency of the pressure that implements dependence of generation frequency of pressure changes on the MEMS capacitor.
For ease of calculation combining parallel capacitance $C_P(P,T)$ and C_{bal} in $C_i(P,T)=C_P(P,T)+C_{bal}$ and current I_f and I_r in $I_{bt}=(I_f-I_r)/QB$ and by using state variables was compiled Kirchhoff equation system.

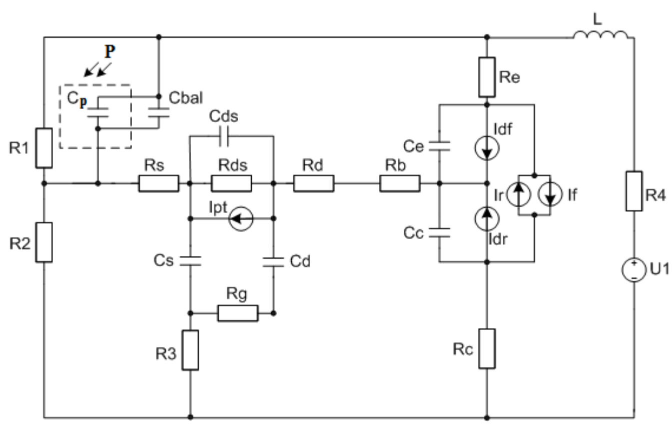

Figure 3. Equivalent circuit of the frequency transducer pressure with sensitive MEMS capacitor.

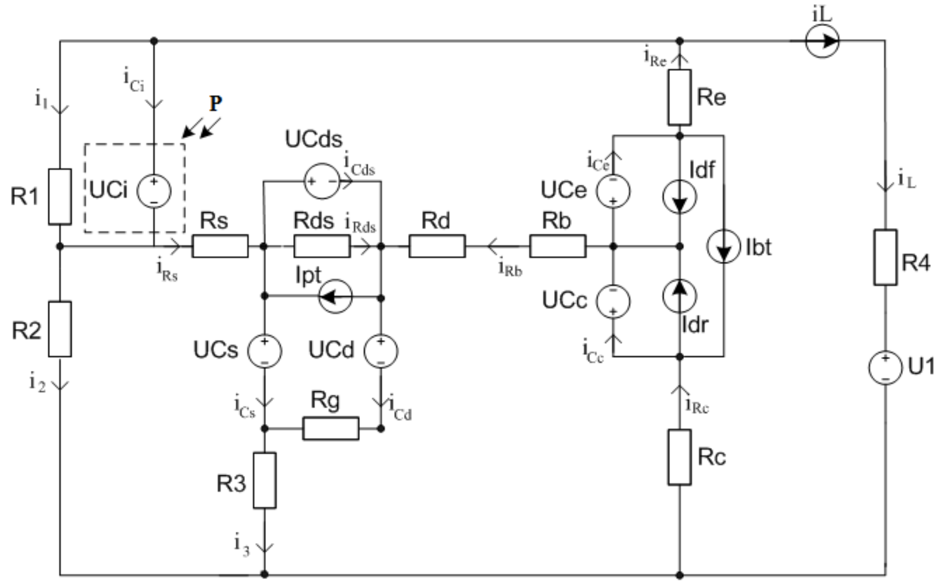

Figure 4. Converted equivalent circuit of the frequency transducer pressure.

Based on current trends favorites were drawn Kirchhoff equation system:

$$
\begin{cases}
U_L = -\left(U_{C_i}\left(P\right) + i_L R_4 + U_1 + i_{R_c} R_c + U_{C_e} + U_{C_c} + i_{R_e} R_e\right); \\
i_2 = i_1 + i_{C_i} - i_{R_s}; \\
i_3 = i_{R_c} - i_L - i_2; \\
i_{C_s} = i_{R_s} + I_{pt} - i_{C_{ds}} - i_{R_{ds}}; \\
i_{C_i} = i_{R_e} - i_1 - i_L; \\
i_{C_c} = i_{R_c} + I_{bt} - I_{dr}; \\
i_{C_e} = i_{R_e} + I_{bt} + I_{df}; \\
i_{R_{ds}} = U_{C_{ds}} / R_{ds}; \\
i_{C_d} = \left(U_{C_s} - U_{C_{ds}} - U_{C_d}\right) / R_g; \\
i_{R_b} = \left(U_{C_{ds}} + i_{R_s} R_s + U_{C_i}\left(P\right) + i_{R_e} R_e + U_{C_e}\right) / \left(R_b + R_d\right); \\
i_{C_{ds}} = i_{R_s} + I_{pt} - i_{C_s} - i_{R_{ds}}; \\
i_{R_c} = -\left(U_{C_d} + U_{C_c} + i_{R_b}\left(R_b + R_d\right) + i_{C_d} R_g + i_3 R_3\right) / R_c; \\
i_{R_s} = \left(i_2 R_2 - U_{C_s} - i_3 R_3\right) / R_s; \\
i_{R_e} = i_{R_c} - i_{R_b}; \\
i_1 = U_{C_i}\left(P\right) / R_1;
\end{cases}
\tag{1}
$$

where R_1, R_2, R_3, R_4 - load resistance; $R_b, R_e, R_c, R_g, R_d, R_s$ - volume resistivity base, emitter, collector, gate, source and drain; R_{ds} - resistance drain-source; C_e, C_c - capacity emitter and collector junctions; C_d, C_s, C_{ds} - capacity gate-drain, gate-source, drain-source; C_{bal} - ballast capacitance; $C_P\left(P,T\right)$ - capacitance tenzo sensitive MEMS capacitor; L - inductance; U_1 - DC power supply; I_{pt} - current field-effect transistor; I_{dr}, I_{df} - current internal junctions base-collector and base-emitter; I_f, I_r - forward and reverse currents of the bipolar transistor.

Considering the set values of the voltages on the containers and the current through the inductor solve a system of equations (1) with respect U_L, $i_{C_{ds}}$, i_{C_d}, i_{C_s}, i_{C_i}, i_{C_e}, i_{C_c}.

$$\begin{cases} U_L = -\left(U_1 + U_{C_e} + U_{C_c} + i_L R_4 - D_5 + D_2 R_e\right); \\ i_{C_d} = D_7 / R_g; \\ i_{C_{ds}} = -D_4 + \dfrac{D_7}{R_g} - \dfrac{U_{C_{ds}}}{R_{ds}} + I_{pt}; \\ i_{C_s} = \dfrac{C_5 R_2 - C_4 R_3 - U_{C_s}}{R_s} + \dfrac{D_1 - C_4 R_3}{R_b + R_d} - \dfrac{D_7}{R_g}; \\ i_{C_i} = -i_L - \dfrac{C_5 A_4 + C_4 A_3 + A_2}{A_1} - \dfrac{U_{C_i}(P)}{R_1}; \\ i_{C_c} = I_{bt} - (U_{C_c} + U_{C_d} + D_1 + R_g D_6)/R_c - I_{dr}; \\ i_{C_e} = I_{bt} - (C_5 A_4 + C_4 A_3 + A_2)/A_1 + I_{df}; \end{cases} \tag{2}$$

where

$$A_1 = R_{ds}\left(\left(R_c + R_e\right)\left(R_b + R_d\right) + R_e\left(R_c - R_g\right)\right);$$

$$A_2 = R_{ds} R_g \left(I_{pt}\left(R_b + R_d\right) - U_{C_e} - U_{C_i}(P) - U_{C_{ds}} + U_{C_s}\right) + \\ + \left(R_b + R_d\right)\left(R_{ds}\left(U_{C_e} + U_{C_c} + U_{C_i}(P)\right) - U_{C_{ds}} R_g\right) + \\ + R_{ds} R_c \left(U_{C_e} + U_{C_i}(P) + U_{C_{ds}} - U_{C_s}\right);$$

$$A_3 = R_{ds} R_3 \left(R_g - R_c\right);\; A_4 = R_{ds} R_2 \left(R_b + R_d + R_2 - R_g\right);$$

$$B_1 = A_4 R_s + A_1\left(R_s + R_2\right);\; B_2 = A_1 R_3 - R_s A_3;\quad B_3 = A_1 U_{C_s} - R_s A_2;$$

$$C_1 = B_1\left(R_2 - R_3 - 2R_s\right);$$

$$C_2 = R_s\left(A_1\left(R_2 - R_s\right) + B_1\right);\quad C_3 = B_3\left(R_s - R_2\right) + B_1 U_{C_s};$$

$$C_4 = \frac{i_L C_2 + C_3}{C_1};$$

$$C_5 = \frac{C_4 B_1 - i_L A_1 R_s + B_3}{B_1};$$

$$D_1 = U_{C_e} + U_{C_i}(P) + U_{C_{ds}} - U_{C_s} + \\ + C_5 R_2 - \frac{R_e\left(C_5 A_4 + C_4 A_3 + A_2\right)}{A_1};$$

$$D_2 = -\frac{C_5 A_4 + C_4 A_3 + A_2}{A_1};\quad D_3 = \frac{C_5 R_2 - C_4 R_3 - U_{C_s}}{R_s};$$

$$D_4 = \frac{U_{C_e} + U_{C_i}(P) + U_{C_{ds}} + D_2 R_e + D_3 R_s}{R_b + R_d};$$

$$D_5 = R_g\left(\frac{U_{C_s} - U_{C_{ds}} - U_{C_d}}{R_g} - D_4 - \frac{U_{C_{ds}}}{R_{ds}} + I_{pt}\right) + \\ + C_4 R_3 + U_{C_d} + U_{C_c} + D_4\left(R_b + R_d\right);$$

$$D_6 = -\frac{D_1 - C_4 R_3}{R_b + R_d} + \frac{U_{C_s} - U_{C_{ds}} - U_{C_d}}{R_g} - \frac{U_{C_{ds}}}{R_{ds}} + I_{pt}; \quad D_7 = U_{C_s} - U_{C_{ds}} - U_{C_d}.$$

Draw replace the left side of the equations of equations (2) according to the expressions that describe currents in capacitance $i_C(t) = C\frac{dU_C(t)}{dt}$ and voltage in inductance $U_L(t) = L\frac{di_L(t)}{dt}$ and consider that all voltages and currents in the system change over time

$$\begin{cases} L\frac{di_L(t)}{dt} = -\left(U_1 + U_{C_e}(t) + U_{C_c}(t) + i_L(t)R_4 - D_5 + D_2 R_e\right); \\ C_d\frac{dU_{C_d}(t)}{dt} = \frac{D_7}{R_g}; \\ C_{ds}\frac{dU_{C_{ds}}(t)}{dt} = -D_4 + \frac{D_7}{R_g} - \frac{U_{C_{ds}}(t)}{R_{ds}} + I_{pt}; \\ C_s\frac{dU_{C_s}(t)}{dt} = \frac{C_5 R_2 - C_4 R_3 - U_{C_s}(t)}{R_s} + \frac{D_1 - C_4 R_3}{R_b + R_d} - \frac{D_7}{R_g}; \\ C_i\frac{dU_{C_i}(P,t)}{dt} = -i_L - \frac{C_5 A_4 + C_4 A_3 + A_2}{A_1} - \frac{U_{C_i}(W,t)}{R_1}; \\ C_c\frac{dU_{C_c}(t)}{dt} = I_{bt} - \frac{U_{C_c}(t) + U_{C_d}(t) + D_1 + R_g D_6}{R_c} - I_{dr}; \\ C_e\frac{dU_{C_e}(t)}{dt} = I_{bt} - \frac{C_5 A_4 + C_4 A_3 + A_2}{A_1} + I_{df}. \end{cases} \tag{3}$$

The system of equations (3) is nonlinear because contains nonlinear elements such as current sources I_{pt}, I_{dr}, I_{df}, $I_{bt} = \left(I_f - I_r\right)/QB$ and capacity C_c, C_e.

The system of equations (3) is a dynamic mathematical model of frequency pressure transducer which allows to determine the voltage and current at any point of the circuit at a given time.

To test the adequacy of the model written program for calculating the parameters of the scheme among the «Maple». The calculation shows that the output frequency pressure transducer really will be periodic oscillations, whose frequency will vary with the changing capacitance tenzo sensitive MEMS capacitor (Figure 5, Figure 6).

So when $C_P(P,T) = 25$ pF frequency f = 601kHz, when $C_P(P,T) = 45$ pF frequency f = 585kHz, when $C_P(P,T) = 60$ pF frequency f = 575kHz, when $C_P(P,T) = 90$ pF frequency f = 560kHz, and when $C_P(P,T) = 115$ pF frequency f = 552kHz, when the supply voltage U_1 = 1,7V.

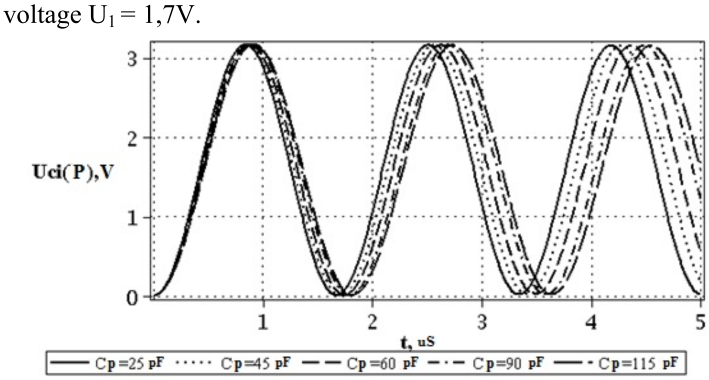

Figure 5. Changing the voltage output from the time at different values of capacitance MEMS capacitor.

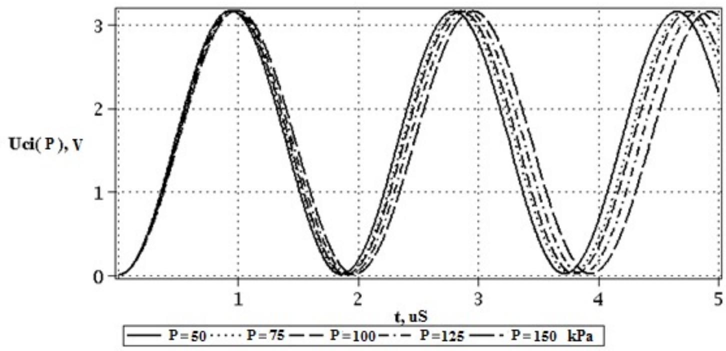

Figure 6. Changing the voltage output from the time when different pressure values.

Conversion function frequency pressure transducer based on the structure of the bipolar and field-effect transistors with tenzo sensitive MEMS capacitor is described by expression

$$F=\frac{\sqrt{2}\sqrt{LC_cC_i\left(P,T\right)\cdot\left(A_3C_cC_i\left(P,T\right)+R_{ds}{}^2A_1+\sqrt{A_2}\right)}}{4\pi LC_i\left(P,T\right)C_cR_{ds}C_{ds}},\tag{4}$$

where:

$A_1=C_{ds}{}^2\left(C_c+C_i\left(P,T\right)\right);$

$A_2=R_{ds}{}^4C_{ds}{}^2C_c{}^2C_i^2\left(P,T\right)+2R_{ds}{}^4C_{ds}{}^3C_cC_i\left(P,T\right)\times$

$\times\left(C_c+C_i\left(P,T\right)\right)-2LR_{ds}{}^2C_{ds}C_c{}^2C_i^2\left(P,T\right)+R_{ds}{}^4C_{ds}{}^4\times$

$\times\left(C_c{}^2+2C_c+C_i^2\left(P,T\right)\right)+2LR_{ds}{}^2C_{ds}{}^2C_cC_i\left(P,T\right)\times$

$\times\left(C_c+C_i\left(P,T\right)\right)+L^2C_c{}^2C_i^2\left(P,T\right);$

$A_3=R_{ds}{}^2C_{ds}-L;$

L - inductance; C_{DS} - drain-source capacitance of the transistor VT1; R_{DS} - resistance drain-source transistor VT1; $C_P(P)$ - capacity of tenso sensitive MEMS capacitor; P - pressure.

Numerical calculations on the PC allow obtaining a frequency conversion function for pressure transducer in the form of a graph (Figure 7). On the basis of the expression (4) is defined the sensitivity of the frequency pressure transducer conversion based on the structure of the bipolar and field-effect transistors

$$S_P^F=\frac{\sqrt{2}\left(\frac{B_6\partial C_i\left(P,T\right)}{\partial P}+B_7\left(\frac{B_3\partial C_i\left(P,T\right)}{\partial P}+\frac{\frac{B_4\partial C_i\left(P,T\right)}{\partial P}}{B_2}\right)\right)}{8\cdot\left(B_5\sqrt{B_7\left(B_2+B_1\right)}-\frac{\sqrt{2B_6C_i\left(P,T\right)}\frac{\partial C_i\left(P,T\right)}{\partial P}}{4B_5C_i\left(P,T\right)}\right)},\tag{5}$$

where:

$B_1=R_{ds}{}^2C_{ds}{}^2\left(C_c+C_i\left(P,T\right)\right)+\left(C_cC_i\left(P,T\right)\right)\left(R_{ds}{}^2C_{ds}-L\right);$

$B_2=sqrt(R_{ds}{}^4C_{ds}{}^2C_c{}^2C_i^2\left(P,T\right)+2R_{ds}{}^4C_{ds}{}^3C_cC_i\left(P,T\right)\times$

$\times\left(C_c+C_i\left(P,T\right)\right)-2LR_{ds}{}^2C_{ds}C_c{}^2C_i^2\left(W,T\right)+R_{ds}{}^4C_{ds}{}^4\times$

$\times\left(C_c{}^2+2C_c+C_i^2\left(W,T\right)\right)+2LR_{ds}{}^2C_{ds}{}^2C_cC_i\left(W,T\right)\times$

$\times\left(C_c+C_i\left(W,T\right)\right)+L^2C_c{}^2C_i^2\left(W,T\right));$

$$B_3 = R_{ds}{}^2 C_{ds} C_c + R_{ds}{}^2 C_{ds}{}^2 - LC_c;$$

$$B_4 = R_{ds}{}^4 C_{ds}{}^2 C_c^2 \left(C_i(P,T) + C_{ds}\right) - 2LR_{ds}{}^2 C_{ds} C_c^2 C_i(P,T) +$$

$$+L^2 C_c^2 C_i(P,T) + R_{ds}{}^4 C_{ds}{}^4 \left(C_i(P,T) + C_c\right) +$$

$$+R_{ds}{}^2 C_{ds}{}^2 C_c \left(2C_i(P,T)\left(R_{ds}{}^2 C_{ds} + L\right) + LC_c\right);$$

$$B_5 = \pi LR_{ds} C_{ds} C_c C_i(P,T);$$

$$B_6 = LC_c\left(B_2 + B_1\right); \quad B_7 = LC_c C_i(P,T).$$

For example, Figure 8 shows frequency pressure transducer, in which the conversion function is depended on the capacity of the tenzo sensitive element MEMS capacitor, for different values of the control voltage U_1.

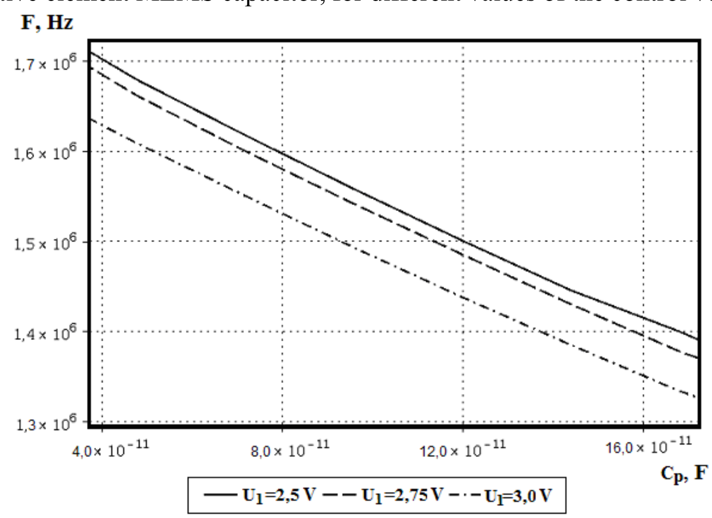

Figure 7. The theoretical transfer function for different values of strain-sensing MEMS capacity.

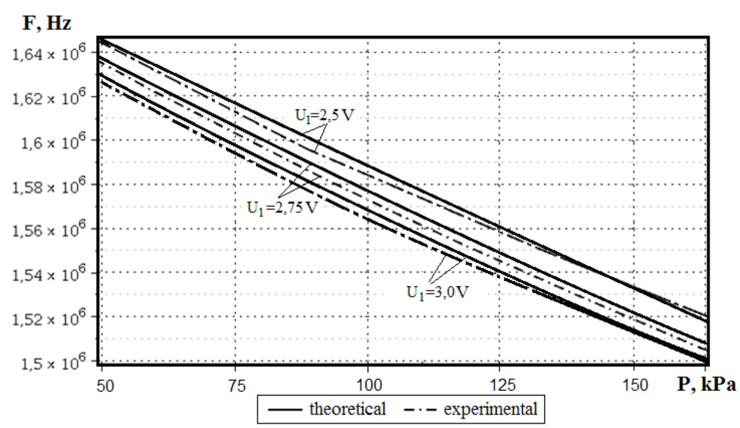

Figure 8. Theoretical and experimental radio conversion function of the frequency pressure transducer.

As can be seen from Fig. 9, the function of converting the frequency pressure transducer is almost linear. Graph of the sensitivity of the pressure change is shown in Figure 5. The sensitivity of the frequency pressure transducer with a tenso sensitive MEMS capacitor to pressure changes range from 50kPa to 150kPa is from 950 to 1650Hz/kPa.

Adequacy of the developed model in comparing with the experiment is defined as the relative error not exceeding ± 1,5%.

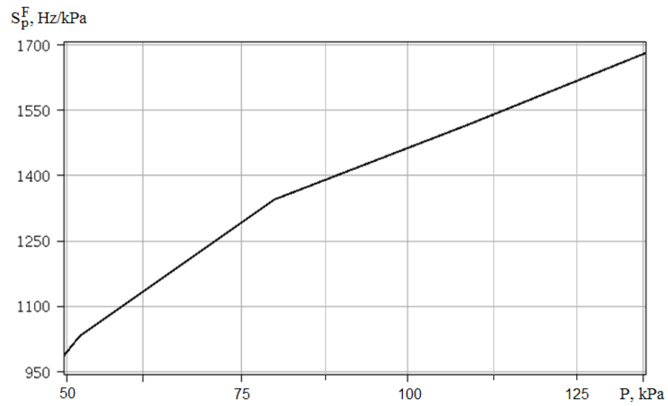

Figure 9. Dependence of the sensitivity of the frequency pressure transducer from the pressure change.

3. CONCLUSIONS

Frequency pressure transducer on the basis of the bipolar and field-effect transistors structure with negative resistance and strain sensitivity MEMS capacitor has been proposed and investigated. The mathematical model of the frequency pressure transducer has been developed which allows to determine the oscillation frequency when the pressure.

Adequacy of the developed model in comparing with the experiment is defined as the relative error not exceeding ±1,5%. Analytical expressions of conversion function and sensitivity equation are obtained. Therefore, this paper is devoted to the study of characteristics of the developed frequency pressure transducer on the base of transistors structure with tenso sensitive MEMS capacitor. The sensitivity of the developed device is between 0,95 kHz/kPa to 1,65 kHz/kPa..

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