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CHECK THE METHOD OF MEASUREMENT OF SMALL MECHANICAL VIBRATIONS

In proposed article we present the results of an experimental measurement of small mechanical vibrations using a capacitive sensor. Oscillations of a hemispherical metal resonator were measured. The calculated formulas connecting the amplitude of the mechanical oscillations of the resonator and the magnitude of the signal of a capacitive sensor are obtained. The block diagram of the equipment is described. The experimental oscillograms of the measured sensor signals, amplitudes of the measured signals, reduced to the input of the equipment amplifiers are given. Experimental wave form of measured sensor signals, the amplitudes of the electric measured signals given to the input apparatus amplifiers. The magnitudes of the electrical read out signals from a capacitive sensor were measured. The amplitude of the mechanical oscillations of the resonator is calculated. The dependence of amplitude of metal resonator mechanical oscillations of the excitation duration was obtained. An investigation was made of reading the signals in the channels during the rotation of the metal resonator. The results of the calculation of mechanical oscillations of a metal resonator during its rotation with different angular rate are obtained.

The measurements and calculation results showed that using the described technique it is possible to detect and measure mechanical oscillations of a metal resonator in the range of 33 nm. The method of measuring small mechanical oscillations of a metal resonator and the obtained numerical data can be used in the design and calculation of the parameters of various devices with capacitive sensors.

Keywords: capacitive sensor; metal resonator; small mechanical displacements; calculation of the amplitude of oscillations of the resonator.

Introduction

In many technical applications it is necessary to be able to measure small mechanical movements (vibrations) of dielectric or metal objects [1–4].

In article [5] it was proposed to use a capacitive sensor having two parallel plates lying in the same plane for measuring the amplitude of mechanical oscillations of dielectric resonator. Calculation formulas were obtained to estimate the amplitude of the signal and the corresponding amplitude of the mechanical oscillations of the resonator.

Obviously, the block diagram of the equipment depends on the algorithm for read out the signal. Next, will be analyzed the magnitude of the signal taken from the capacitive sensor in the case of a metal resonator, as well as some data characterizing the excitation process.

And the task was to check the theoretical formulas experimentally.

Main part

1. Electrostatic readout the signals from the capacitive sensor

We investigated a number of metal resonators with an intrinsic frequency of 1850...2616 Hz, whose quality factor Q was several thousands. Probably, the transfer of the obtained data to glass resonators with a Q-factor of two or three orders of magnitude more will require an appropriate correction of the expected excitation time.

The principle of reading the signal with RC-sensor is shown in fig. 1.

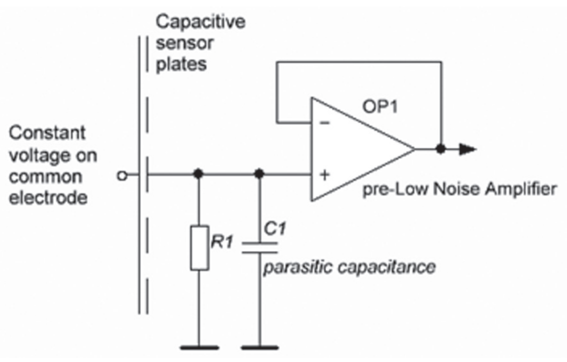

Fig. 1. Principle of reading the signal with RC-sensor

For the measurement of small mechanical vibration of resonator is proposed to use a well-known signal processing method with the capacitive sensor, as in the famous condenser microphone.

The capacitor is charged through to constant high voltage. If you change the distance between the plates of the capacitor, it caused changes and the voltage across it. Then this voltage signal is to be amplified. Thus, the mechanical vibration of resonator will modulate the voltage on the capacitor.

The process of excitation was investigated, i. e. the dependence of the mechanical oscillations magnitude from the duration of the excitation. Then was measured the signal on the input of the preamplifier (taken from the separate electrodes) without rotation and for a range of angular velocities of the resonator rotation of 20°/s. These speeds could be measured with a turntable.

Simplified block diagram of input circles is shown in fig. 2.

For reading signals, two channels are formed (U_m, U_q), each channel has four electrodes.

Each channel was formed by electrodes oriented in space at an angle of 90°. Common-mode signals were taken from diametrically located electrodes (U_{m1}, U_{q1}), and antiphase signals from those oriented at 90° (U_{m2}, U_{q2}). Further, these signals were summed up in the differential amplifiers of two channels.

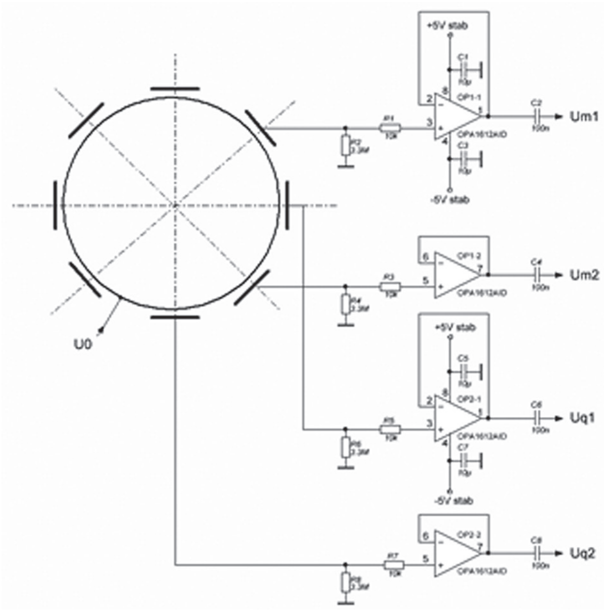

Fig. 2. Simplified block diagram of the electrostatic read out of signals

To reduce the effect of inter electrode capacitances, four buffer amplifiers were installed near electrodes.

A constant voltage U_0 = 70…250 V was applied to the metal resonator housing.

2. The value of the signal read from the capacitive sensor

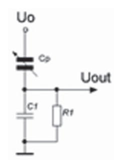

Fig. 3. Capacitive sensor and parasitic capacitance

Capacitance sensor (fig. 3) varies according to the law

$$C_p = \frac{C_0}{1 - m\cos\omega t} \approx C_0(1 - m\cos\omega t), \qquad (1)$$

where C_0 = 6pF, the constant component of the sensor capacitance,

m — modulation factor, that can be $m = 10^{-3}...10^{-6}$;

$\omega = 2\varpi f$, f — own frequency of the resonator;

C_1 = 3 pF — the parasitic capacitance;

R_1 = 3 MΩ.

Denote:

U_{1m} — unknown amplitude of the useful signal, a variable component of the voltage on the sensor;

U_0 = 70…250 V, DC voltage bias source;

U_{10} — a constant voltage on the capacitor element C1 (a priori U_0 can not be equal to U_{10}).

Then:

$$U_1 = U_{10} + U_{1m}\cos(\omega t + \varphi) \text{ — the output voltage of the sensor,} \qquad (2)$$

φ — unknown phase.

The voltage on the sensor $U_p = U_0 - U_1 = U_0 - [U_{10} + U_{1m}\cos(\omega t + \varphi)]$.

Since the sensor capacitance varies with time, the method for calculating the complex amplitudes of currents and voltages in the scheme is not applicable.

Let us find the current flowing through the capacitor — sensor C_p:

$$I_{Cp} = \frac{\partial Q_{Cp}}{\partial t} = \frac{\partial(C_p U_p)}{\partial t} = C_p\frac{\partial U_p}{\partial t} + U_p\frac{\partial C_p}{\partial t} = (C_0 - m\cos\omega t)[\omega U_{1m}\sin(\omega t + \varphi)] + m\omega C_0 \sin\omega t\,[U_0 - U_m - U_{1m}\cos(\omega t + \varphi)] =$$
$$= \omega C_0 U_{1m}\sin(\omega t + \varphi) + m\omega C_0(U_0 - U_{10})\sin\omega t - m\omega C_0 U_{1m}\sin(2\omega t + \varphi). \qquad (3)$$

Assuming further filter presence, impervious the vibrations at twice frequency, the third summand at twice frequency will be neglected.

The total current I_{RC} through the chain, consisting of parallel included capacitor C1 and resistor R1, is given by

$$I_{RC} = I_{R1} + I_{C1} = \frac{U_{1m}\cos(\omega t + \varphi) + U_{10}}{R_1} + C_1\frac{\partial U_1}{\partial t} = \frac{U_{1m}}{R_1}\cos(\omega t + \varphi) + \frac{U_{10}}{R_1} - \omega C_1 U_{1m}\sin(\omega t + \varphi). \quad (4)$$

On the other hand, current I_{RC} must be equal to the current I_{Cp}: $I_{Cp} = I_{RC}$.

Equating the formulas (3) and (4), we obtain

$$\omega C_0 U_{1m}\sin(\omega t + \varphi) + m\omega C_0(U_0 - U_{10})\sin\omega t = \frac{U_{1m}}{R_1}\cos(\omega t + \varphi) + \frac{U_{10}}{R_1} - \omega C_1 U_{1m}\sin(\omega t + \varphi).$$

Solve this equation for U_{1m}, and recording solution in the form (2), we obtain

$$U_{1m}\cos\left[\omega t + \varphi + \arccos\frac{1}{R_1\sqrt{\frac{1}{R_1^2} + \omega^2(C_0 + C_1)^2}}\right] = \frac{m\omega C_0(U_0 - U_{10})\sin\omega t - \frac{U_{10}}{R_1}}{\sqrt{\frac{1}{R_1^2} + \omega^2(C_0 + C_1)^2}}. \quad (5)$$

Hence, we obtain the formula for the amplitude and phase of the output signal

$$U_{1m} = \frac{m\omega C_0(U_0 - U_{10})}{\sqrt{\frac{1}{R_1^2} + \omega^2(C_0 + C_1)^2}}, \quad (6)$$

$$\varphi = -\frac{\pi}{2} - \arccos\frac{1}{R_1\sqrt{\frac{1}{R_1^2} + \omega^2(C_0 + C_1)^2}}. \quad (7)$$

Also, it can be concluded vanishing DC voltage on the capacitor C1, as equation (5) is satisfied for any value of time t only if $U_{10} = 0$.

These formulas can be used to calculate the ratio of the amplitude signal to rms noise at the output of the amplifier:

$$\frac{signal}{noise} = \frac{U_{1m}}{\sigma_{nin}} = \frac{U_{1m}}{\sqrt{\sigma_{nR}^2 + \sigma_{namp}^2}} = \frac{m\omega C_0 U_0}{\sqrt{\frac{1}{R_1^2} + \omega^2(C_0 + C_1)^2}} \cdot \frac{1}{\sqrt{4kTR_{eq}\Delta f + (I_n R_{eq})^2 + N_{namp}^2\Delta f}},$$

where $R_{eq} = R_{in} + R_1 \approx R_1$ — input circuit resistance;

I_n — current noise density of op amp;

$N_{n\,amp}$ — voltage noise density of op amp;

Δf — subsequent bandpass filter bandwidth.

In this equations takes into account the noise components caused by the Johnson–Nyquist thermal noise of the resistor and op amp noise.

3. Results of measuring of the resonator excitation

Series of measurements were made, the results and oscillograms of which are given in fig. 4–9.

The oscillations were excited along the axes of the main channel. Oscillations in the main and quadrature channels were measured.

The results of measurements for a resonator with natural frequency f = 2581,7 Hz are shown below. A bipolar impulse voltage of ± 100 V was used for the excitation. The constant voltage on the common electrode is + 100 V. The amplification factors in the narrowband amplifier channels are the same G = 1123.

The excitation impulses were fed in turn for the excitation of the main channel (the electrodes are arranged conditionally along the axis 0°).

The voltage swing was measured in two channels, in main channel (No. 1, green) or in quadrature (No. 2, yellow, the electrodes are located 45° to the electrodes of main channel. The naming of channels is main or quadrature are relative.

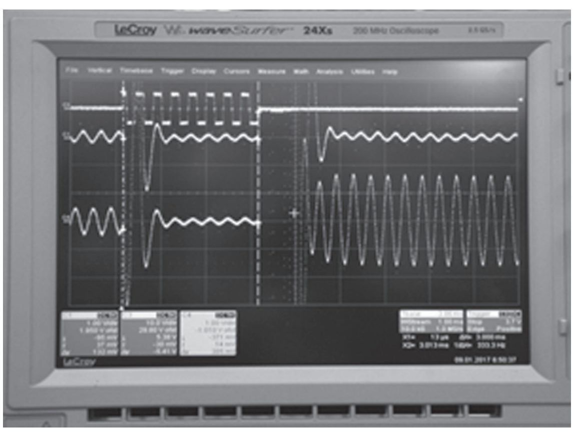

Fig. 4. A typical oscillogram. Blue color — impulses of swing. Green — the output of the main channel Yellow — the output of the quadrature channel

The duration of the burst of pulses varied from 0 to 10 ms. The time interval between neighboring excitation processes was 0,1899s.

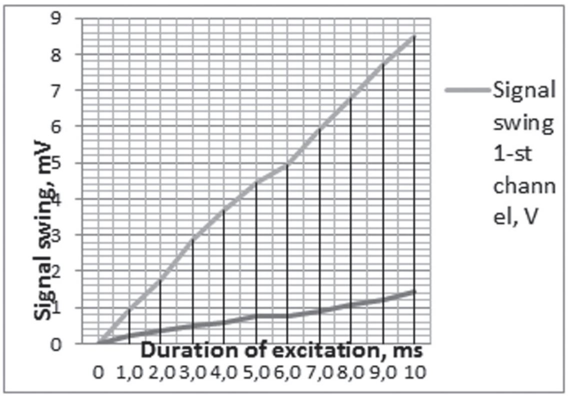

Fig. 5. Dependence the signal swing of the excitation duration. Excitation process in channel No. 1.

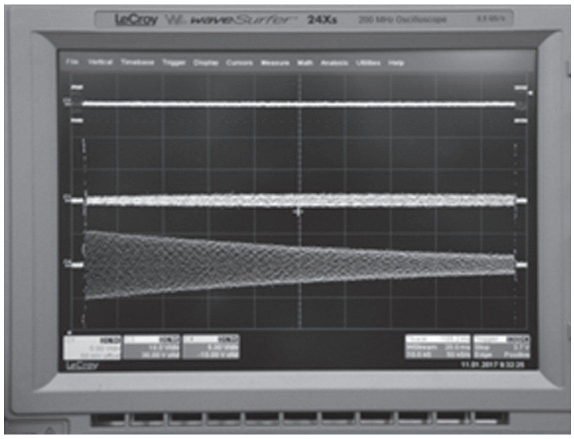

Fig. 6. Investigation of the excitation process in channel No. 1

As clearly seen in the oscillograms, when oscillations are excited in the first channel, oscillations also appear in the second channel.

The modulation coefficient and the amplitude of the mechanical oscillations of the resonator are calculated from the measurement results:

$$d_m = d_0 \cdot m = \frac{d_0 U_{1m} \sqrt{\dfrac{1}{R_1^2} + \omega^2 \left(C_0 + C_1\right)^2}}{\omega C_0 U_0},$$

where $d_0 = 0{,}1$ mm — average distance between plates of capacitive sensor.

The results of the calculations are given in the table 1.

Table 1

Mechanical oscillations amplitude. Excitation in channel No.1

Duration of excitation, ms	1	2	3	4	5	6	7	8	9	10
Signal swing 1st channel $U_{1m\ p-p}$, mV	0,92	1,76	2,88	3,70	4,46	4,96	5,92	6,78	7,72	8,50
Amplitude in 1st channel, d_m, μm	1,72	3,29	5,38	6,92	8,34	9,27	11,1	12,7	14,4	15,9
Amplitude in 2nd channel, d_m, μm	0,430	0,692	0,935	1,05	1,38	1,44	1,70	2,00	2,30	2,65

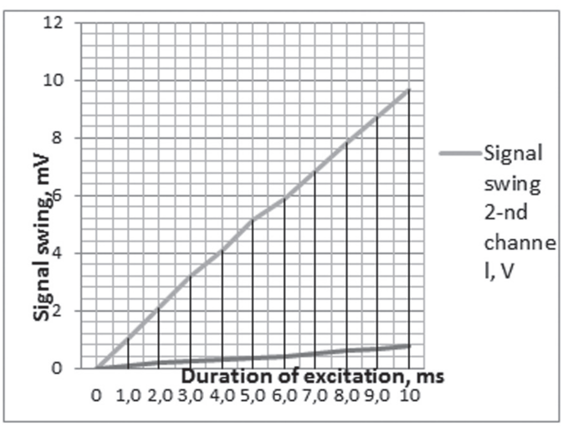

Fig. 7. Dependence the signal swing of the excitation duration. Excitation process in channel No. 2

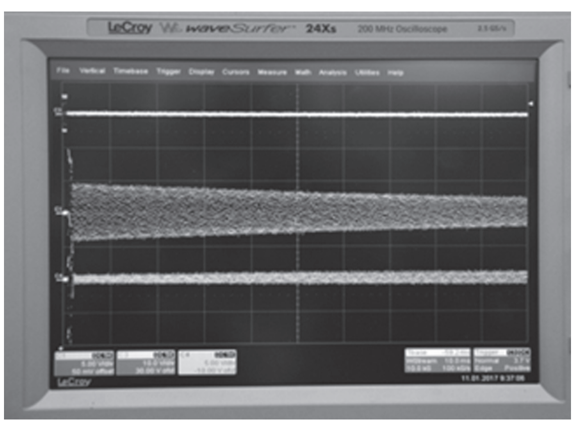

Fig. 8. Investigation of the excitation process in channel No. 2

Then the excitation impulses were fed in turn for the excitation of the quadrature channel.

The results of the calculations are given in the table 2.

The results of the measurements show that with a excitation time of 10 ms, the signal amplitude at the input of the buffer amplifier in the channel that is swinging can be 8…10 mV. The result was then used to select the channel gains during design of the equipment.

Table 2

Mechanical oscillations amplitude. Excitation in channel No.2

Duration of excitation, ms	1	2	3	4	5	6	7	8	9	10
Signal swing 1st channel $U_{1m\ p-p}$, mV	1,01	2,08	3,18	4,10	5,14	5,89	6,81	7,82	8,74	9,66
Amplitude in 1st channel, d_m, μm	0,206	0,318	0,449	0,542	0,654	0,748	0,935	1,12	1,27	1,42
Amplitude in 2nd channel, d_m, μm	1,72	3,29	5,38	6,92	8,34	9,27	11,1	12,7	14,4	15,9

4. Investigation of signal read out in channels during rotation of the metal resonator

Conditions for the measurement of signals remained the same: the excitation voltage was ± 100 V, the duration of the excitation time was 10 ms, the duration of the suppression pulses was varied from 0 to 10 ms, the gain in the channels was G = 1123.

The process of compensating the signal of the quadrature channel at a given time (fig. 9) by means of pulses of the same amplitude was investigated. Compensating pulses could be formed simultaneously with the excitation of the main channel, or later.

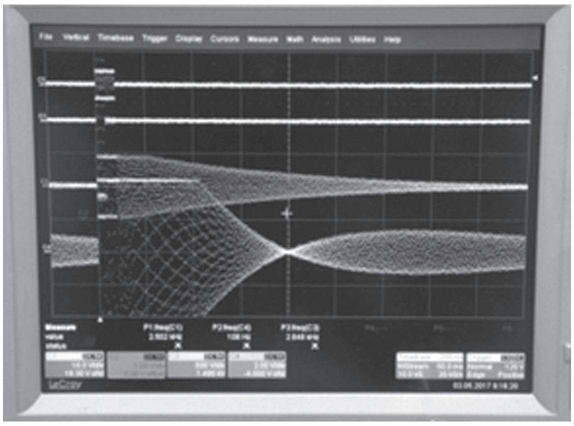

Fig. 9. Compensation of the quadrature channel signal at a predetermined time

Fig. 10. Signals in the region of the minimum in the quadrature channel. Without rotation

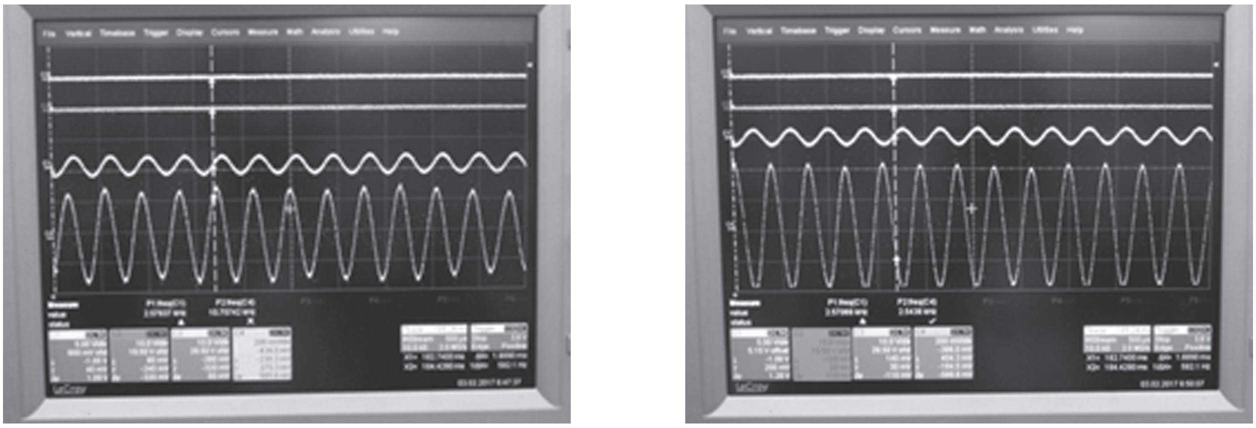

Fig. 11. Rotate counter clockwise

The range of the useful signal in the quadrature channel was measured, and the signal level at the input of the buffer amplifier was recalculated. The final results of the calculations are given in the table 3.

In the approximation, the averaged value of the proportionality coefficient between the magnitude of the signal and the angular velocity 21μV: (°/s).

Signals in the quadrature channel without rotation offers fig. 10. Rotate counter clockwise presents fig. 11.

The results of the calculation of mechanical oscillations of a metal resonator during its rotation

The measurements and calculation results showed that using the described technique it is possible to detect and measure mechanical oscillations of a metal resonator in the range of 1 μm … 33 nm.

Table 3

Angular velocity, °/s	Measurement results					Approximation	
	20°/s	10°/s	5°/s	3°/s	1°/s	1°/min	1°/hour
The measured swing V_{p-p} of the quadrature channel signal at the input of the buffer amplifier, μV	330	250	125	65	18	0,35	0,0058
Amplitude in quadrature channel, d_m, μm	0,617	0,467	0,234	0,122	0,0337	$0{,}654 \cdot 10^{-3}$	$10{,}8 \cdot 10^{-6}$

The method of measuring small mechanical oscillations of a metal resonator and the obtained numerical data can be used in the design and calculation of the parameters of various devices with capacitive sensors.

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ПЕРЕВІРКА МЕТОДИКИ ВИМІРЮВАННЯ МАЛИХ МЕХАНІЧНИХ КОЛИВАНЬ

У пропонованій статті наводяться результати експериментального вимірювання малих механічних коливань за допомогою ємнісного датчика. Вимірювалися коливання напівсферичного металевого резонатора. Отримано розрахункові формули, що пов'язують амплітуду механічних коливань резонатора і значення сигналу ємнісного датчика. Описано структурну схему апаратури. Подано експериментальні осцилограми виміряних сигналів датчика, а також амплітуди вимірюваних сигналів, приведені до входу підсилювачів апаратури. Здійснено розрахунок амплітуди механічних коливань резонатора. Здобуті результати підтверджують можливість застосування описаної методики для побудови ємнісних датчиків малих механічних переміщень.

Ключові слова: ємнісний датчик; металевий резонатор; малі механічні переміщення; розрахунок амплітуди коливань резонатора.

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ПРОВЕРКА МЕТОДИКИ ИЗМЕРЕНИЯ МАЛЫХ МЕХАНИЧЕСКИХ КОЛЕБАНИЙ

В предлагаемой статье приводятся результаты экспериментального измерения малых механических колебаний при помощи емкостного датчика. Измерялись колебания полусферического металлического резонатора. Получены расчетные формулы, связывающие амплитуду механических колебаний резонатора и значение сигнала емкостного датчика. Описана структурная схема аппаратуры. Представлены экспериментальные осциллограммы измеренных сигналов датчика, амплитуды измеряемых сигналов, приведенные ко входу усилителей аппаратуры. Проведен расчет амплитуды механических колебаний резонатора. Полученные результаты подтверждают возможность применения описанной методики для построения емкостных датчиков малых механических перемещений.

Ключевые слова: емкостной датчик; металлический резонатор; малые механические перемещения; расчет амплитуды колебаний резонатора.