Finite Element Modelling of a Piezoelectric Accelerometer for Apparent Acceleration Measurement

Valery Gupalov
Laser Measurement and Navigation Systems department
Electrotechnical University "LETI"
Prof. Popova Str., 5
St. Petersburg, Russia
+7(812)234-08-14
vigupalov@yandex.ru

Alexander Kukaev
Laser Measurement and Navigation Systems department
Electrotechnical University "LETI"
Prof. Popova Str., 5
St. Petersburg, Russia
+7(951)645-76-19
ASKukaev@gmail.com

Vladimir Venediktov
Laser Measurement and Navigation Systems department
Electrotechnical University "LETI"
Prof. Popova Str., 5
St. Petersburg, Russia
+7(812)234-08-14
vlad.venediktov@mail.ru

ABSTRACT

In this paper, a design concept of a microscale piezo accelerometer capable of measuring nearly constant signals is proposed. Taking the advantages of both MEMS and piezo devices it provides brilliant opportunities for the development of inertial grade navigation systems. By utilizing the novel excitation method the sensors working point is pushed to the area of higher frequencies which provides a great increase in the sensors bandwidth. A finite element modelling was performed to prove the concept, find optimal design and its potential sensitivity characteristics. In case of a 2 cm length needle-like sensing element it provides the sensitivity about 36 mV/g with a perfect linearity and low cross-sensitivity.

CCS Concepts

• Hardware→Sensors and actuators **• Hardware→Sensor applications and deployments • Applied computing→Computer-aided design**

Keywords

accelerometer; apparent acceleration; navigation systems; finite element modelling

1. INTRODUCTION

Every year, the requirements for various inertial sensors and, in particular, for accelerometers, are becoming increasingly strict and complex. Previously, the key indicators were accuracy and sensitivity, but today an increasingly important role is assigned to dimensions, cost, impact resistance, and a number of other parameters. As a result, new design concepts of accelerometers were developed, such as MEMS accelerometers, for example. It should be noted that today, with a growing interest in unmanned aerial vehicles and cars, as well as smart devices and instruments, the sensor market is experiencing significant growth, which opens up new market niches. Therefore, the consumer is offered a wide range of different sensors that meet some or other requirements. However, there are applications that require the simultaneous meeting of a number of requirements. For example, for creating autonomous navigation systems an important feature is the ability to measure apparent acceleration. Popular MEMS accelerometers meet this requirement, but for them the lowest detection limit is of the order of 10^{-4} g [1, 2], which is not enough for navigational systems of tactical accuracy class. On the other hand, there are piezoelectric accelerometers that have a low detection limit (10^{-5}–10^{-6} g) and shock resistance, but are limited from below by a frequency range of the order of 0.1 Hz [3, 4]. In this paper, we propose a new design concept of the piezoelectric accelerometer to combine the advantages of the two abovementioned types of transducers.

2. PRINCIPLE OF OPERATION

The main reason limiting the bandwidth of piezoelectric accelerometers is the charge leakage effect. Therefore, if the piezoelectric effect is artificially transferred from the area of constant signals to the variable domain, it is possible to extend the lower limit of the accelerometer sensitivity band. Generally, authors do not see any limitations to measure even constant signals, but in the case of on-Earth applications, where g values change during the day due to the movement of astronomical bodies, let us take a lower detecting frequency limit of 1/86400 s or approximately 10^{-5} Hz. For such measurements, it is proposed to use the construction shown in Figure 1 [5, 6].

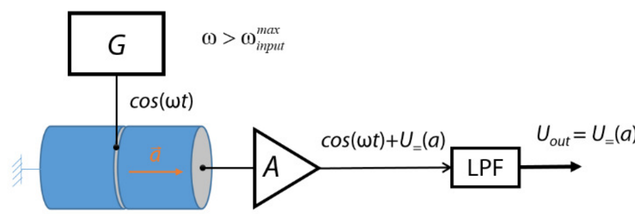

Figure 1. Design concept of a proposed microaccelerometer. G: generator; A: amplifier; LPF: low-pass filter.

Here, the exciting generator *G* creates a harmonic signal with frequency ω and directs it to the piezoelectric transducer, divided into two parts: exciting and sensitive. Each of them is a cylinder made of piezo ceramics, with longitudinal polarization. One of the sides of the converter exciting part is rigidly fixed, and the second is rigidly connected to the sensitive part through the electrode to which the generator is connected. The second part also acts as a test mass (if necessary, to increase the sensitivity of the sensor, the free end of this converter can be additionally loaded). Under the action of the exciting signal the converter performs harmonic oscillations and a corresponding signal appears at the output of its sensitive part. The latter goes to the amplifier *A* and then to a low-pass filter (LPF), which forms a constant voltage U_{out} equal to the midline of the harmonic signal. It should be noted that for an excitation signal any alternating signal, including cantered random noise, might be used. The excitation signal frequency ω should be higher than the maximum frequency of the acceleration to be measured.

Under the action of acceleration, a rod, formed by piezoelectric transducers, deforms and an additional charge proportional to the actual acceleration is excited on the electrodes of the sensitive part. As a result, the midline of the harmonic output signal will change its position and, after that, the value of the voltage U_{out} taken from the filter output will change. In this case, the acceleration measurement range will be primarily determined by the parameters of the amplifier and can be easily adapted to the requirements of a particular consumer or even changed during the sensor operation. The output signal is presented by a constant voltage, convenient for further processing. It is necessary to emphasize that the piezoelectric part is always in a dynamic mode. Literally, it means that the effect of a charge leakage is almost neglected, because its time constant is much higher than the one of the excitation signal. By the time that the charge leaks by a significant value, the total output voltage already changes its sign.

If necessary, this scheme can be modified to organize a differential operation mode. Such an option is shown in Figure 2 [7].

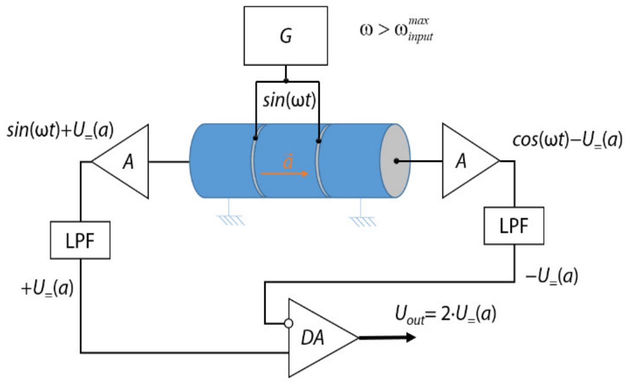

Figure 2. Differential piezoelectric accelerometer design concept. DA: differential amplifier.

In this case, the piezoelectric transducer consists of three parts: one exciter (in the centre) and two rigidly fixed receivers (at the edges). Each of their outputs is also connected to a charge amplifier and a low-pass filter connected in series. The outputs of the latter are connected to the inputs of the differential amplifier (*DA*), which forms the differential output signal. Such a design provides high temperature stability of the sensor.

Let us now consider the influence of the piezoelectric transducer dimensions on the sensor characteristics. An informative signal is the voltage U_{out}, which arises from the deformation of the converter under the action of acceleration. We can write the following chain of expressions [8]:

$$U_{\text{out}} = \frac{Q}{C} = \frac{d_{33}F}{\left(\varepsilon\varepsilon_0 S \big/ h\right)} = \frac{d_{33}}{\varepsilon\varepsilon_0}\frac{F}{S}h = \frac{d_{33}}{\varepsilon\varepsilon_0}\frac{ma}{S}h = \frac{d_{33}}{\varepsilon\varepsilon_0}\frac{\rho hSa}{S}h = K_{\text{p}}h^2 a$$

where Q is the charge generated by the acceleration, C is the capacitance of the piezoelectric transducer, d_{33} is the piezoelectric module, F is the force acting on the piezoelectric transducer, ε, ρ are the permittivity and density of the piezoelectric transducer material, respectively, S, h, m is its cross section, thickness, and mass, respectively, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m is the dielectric constant of vacuum, $Kp = d_{33}\rho/\varepsilon\varepsilon_0$ is the coefficient of proportionality, depending only on the parameters of the selected material. Thus, the value of the scale factor, which is equal to $\Delta U_{out}/\Delta a$, quadratically increases with increasing length of the piezoelectric transducer and does not depend on its cross section. Therefore, the needle shape of the sensing element is optimal from the point of sensitivity. In this case, there are opportunities for microminiaturization of sensors.

3. FINITE ELEMENT MODELLING

To test the efficiency of the proposed design, as well as to evaluate some of its potential characteristics, a finite-element model of the piezoelectric transducer was created. Its calculation was carried out in OOFELIE::Multiphysics [9].

The model consisted of two cylindrical piezoelectric transducers 2 mm in diameter, 10 mm in length, and longitudinal polarization. It represents the parameters of existing sensing elements (Figure 3) which are planned to be tested in future.

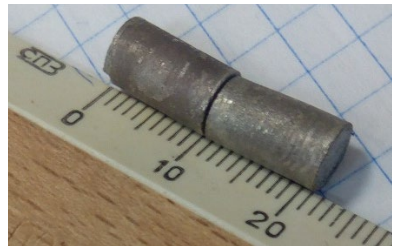

Figure 3. Sensing elements made of CTS-19 that were simulated.

The end of one of them was rigidly fixed and a harmonic voltage of 1 V and a frequency of 20 kHz was applied to it. The second end, which is common for the two transducers, was connected to null potential and the remaining end of the second converter was the surface of equal potentials and served as the source of the output signal. In addition to the electric signal, a constant linear acceleration *a* directed as it is shown in Figure 1, was applied to the model. As a material for piezoelectric transducers, we used CTS-19 with the characteristics presented in Table 1 [10]:

Table 1. CTS-19 characteristics

Parameter	Value
Density, kg/m^3	7500
Piezoelectric modules	
d_{31}, C/N	-155×10^{-12}
d_{33}, C/N	360×10^{-12}
Coefficients of electromechanical coupling	
Kp	0.56
K_{31}	0.64

To take the charge leakage effect into account, a serial RC dipole between the output electrodes and the ground was introduced with the following parameters: capacitance $C = 3.3$ pF, resistance $R = 10^8$ Ohm. It gives a value of leakage RC constant equal to 3.3×10^{-4} s, which is 330 times larger than the period of excitation signal.

The time variation of the electric potential on the surface of the free end of the piezoelectric transducer was evaluated. As expected, the midline of the harmonic signal generated by the exciter has shifted (Figure 4).

At the same time, during the entire time of acceleration acting, it does not change, despite the possible leakage of charge. A line depicting a change of output signal without excitation but with other parameters the same is also plotted for comparison. Thus, the operational performance of the proposed concept is confirmed.

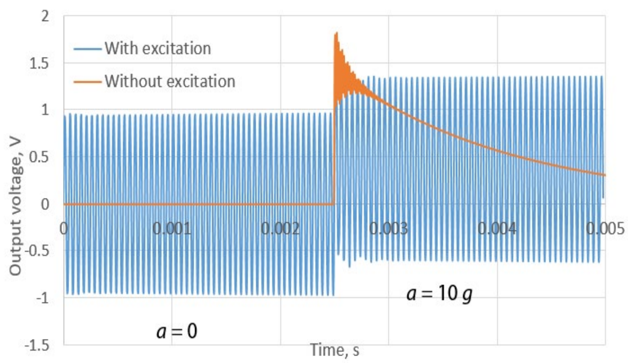

Figure 4. Output signal at different values of acceleration (simulation results).

Further, various values of acceleration acting along the main and orthogonal axes were specified. On the basis of the obtained results, the output characteristic shown in Figure 4 was plotted. The output signal is the shift of the midline of the harmonic signal from its value at $a = 0$.

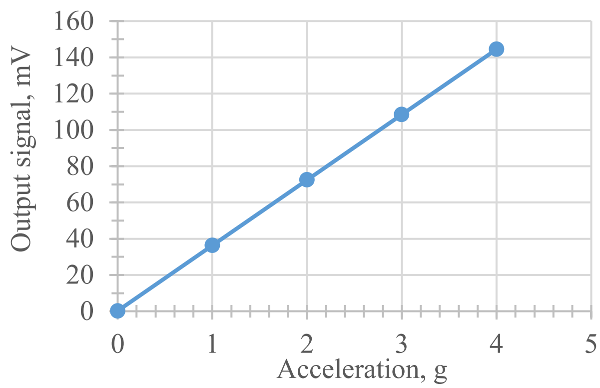

Figure 5. Proposed sensor sensitivity (modelling results).

As can be seen from Figure 4, the output characteristic is linear. The value of the scale factor along the x-axis (measurement one) was 36 mV/g. The sensitivity along the y and z axes was 0.29 and 0.12 mV/g, respectively.

Next the length of a sensing element was varied from 5 to 20 mm. Obtained result are shown at Figure 6.

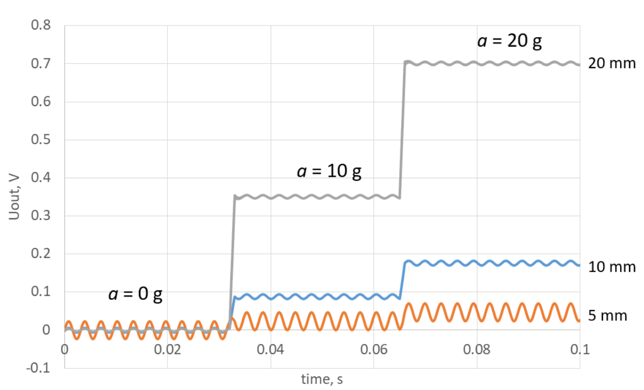

Figure 6. Output signals from sensing elements of different length (modelling results).

As can be seen from the Figure 6 the longer the element is the larger would be the induced voltage difference and, consequently, the sensitivity. From the other hand, for longer elements the amplitude of the harmonic signal is lower. To overcome this problem it is possible to take longer sensing part and shorter exciting one. To test this proposal one more step of simulation was made. This time the whole length of a transducer remained constant, while the ratio between the sensing part (l_1) and exciting part (l_2) varied from 1:2 to 2:1. Corresponding results are shown in Figure 7.

The figure clearly depicts that the longer the sensing part, the higher the sensitivity. The reason should be in increasing of the proof mass, which consequently increases the internal stress in the sensing part. In addition, due to the excitation part becomes thinner the output signal gets more amplitude. From the other hand, it is seen that the effect is not quadratic as it should be from the expression for U_{out} mentioned above.

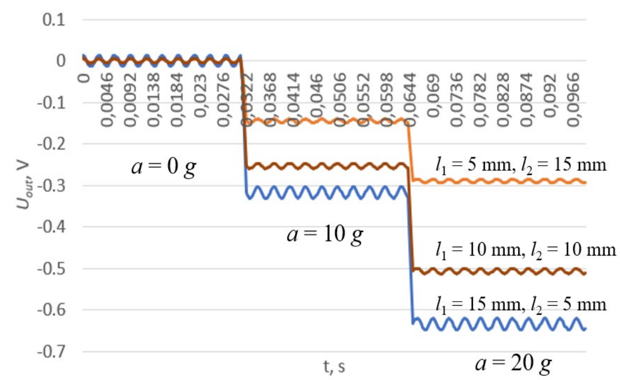

Figure 7. Output signals from sensing elements with different ratio of sensing part (l_1) and exciting part (l_2) (modelling results).

We suppose that it shows the imperfection of formula that considers the sensing part as a parallel-plate capacitor, which is in fact a cylinder. Therefore, to make a proper theoretical analysis the expression requires minor revision. However, if we consider h equal to the length of the whole sensing element (sensing and exciting parts together), than the formula shows a good match with results shown in Figure 6.

Next, the effect of sensing element radius change was also investigated (Figure 8).

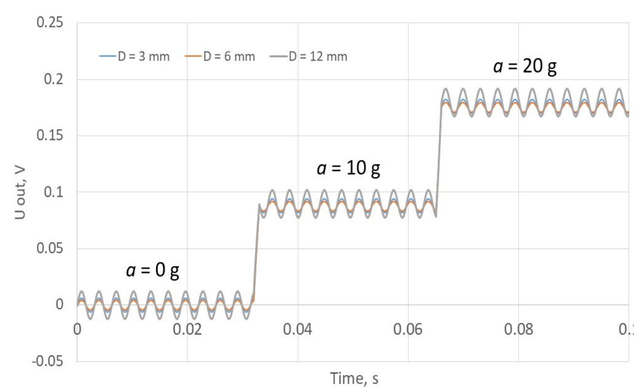

Figure 8. Output signals from sensing elements of different diameter D (modelling results).

As it is seen from Figure 8, the radius change does not affect the sensitivity, but for larger diameters, the amplitude of harmonic signal is higher, which makes it easier to detect.

4. SIMULATION OF CHARGE LEAKAGE

Separate simulation was performed to find the effect of sensing element electrical parameters (capacitance and surface resistance) on the leakage process. The element was organized as described earlier with the following dimensions: $l_1 = l_2 = 10$ mm; radius equal 1 mm. Additionally a serial RC dipole was introduced with $R = 10^8$ Ohm and variable C. Acceleration was kept at constant level of 10 g. Obtained results are shown in Figure 9.

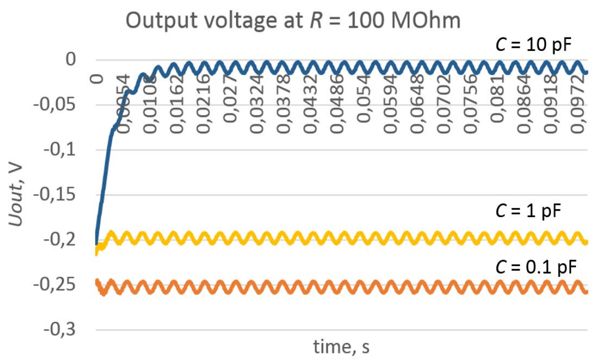

Figure 9. Output signals from sensing elements of different diameter *D* (modelling results).

The results show that dependence of the output voltage change from the sensing element capacitance is not linear as it was proposed by the abovementioned formula. It, once again, gives the hint that capacitance should be taken into account more accurately. In addition, Figure 8 shows that leakage speed relies heavily on the capacitance and at the values of C = 10 pF grows dramatically. At the level of 1 pF and lower the leakage is negligible.

The effect of surface resistance change was also studied. At $C = 0.1$ pF the leakage was not observed for any sensible value of R. therefore, from the leakage point of view, which is crucial for sensor operation) it is recommended to take keep the capacitance of the sensing element below 0.1 pF In this case not only the leakage becomes negligible, but also the sensitivity increases.

5. CONCLUSION

The proposed design of the piezoelectric accelerometer has a number of significant advantages:

- wide frequency range (from 10^{-5} Hz);
- high detection limit (up to 10^{-5} g);
- absence of moving parts;
- simplicity in manufacturing;
- low cross-sensitivity;
- possibility of miniaturization.

Due to the abovementioned benefits the sensor should find its niche in the existing accelerometer market and, therefore, its development is economically sensible.

Using the finite-element analysis, the operability of the proposed accelerometer design was confirmed and the scaling factors for all three axes (36, 0.29, and 0.12 mV/g) were evaluated. Also, the effect of length, radius, and sensing to exciting part ratio change was investigated. For the increase of sensitivity it is better to use long and thin needle-like sensing elements with a long sensing part and thin exciting part. In this case the sensitivity and the amplitude of the output harmonic signal becomes higher. In addition, thin disk-like exciting part makes theoretical analyses easier as it might be considered as a parallel-plate resonator.

Leakage effect and its dependence on resistance and capacitance of sensing element was also investigated. The results show that to keep the leakage negligible it is necessary to keep the capacitance lower. Additionally low capacitance of the sensing element increases the device sensitivity.

In future, it is planned to manufacture a laboratory model of a proposed piezoelectric accelerometer utilising the simulated sensing elements and find out its operational characteristics.

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