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Alignment of distributed oscillation systems in piezo motors

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Abstract. The pressing problem in the space domain is the development of large-sized reflectors for spacecrafts. The specified criteria for reflector structure are precise reflector surface shape and structure mass. Precise reflector surface shape during long-term performance is provided by the alignment of piezoelectric motors used in the reflector structure. These motors exhibit both limited mass-dimensional coefficient and can produce high force. Piezo-motor is distributed mechanical – acoustic oscillation system. In the piezo-motor mechanical – acoustic oscillation is generated by PZT-stack being transferred to the oscillator then to the load action element.
The objective of the work is the study the alignment of distributed oscillation systems in piezo-motors. The novelty of the work is using the alignment of oscillator impedance and load impedance to determine the performance resonance frequency of distributed oscillation system in piezo-motor. This method simplifies the possibility of analyzing distributed in piezo-motor oscillation system characteristics. The method was tested under different in piezo-motor load modes.

1. Introduction

The problem- reducing spacecraft (SC) system mass-dimension parameters – is especially acute in the space field. One current solution is to replace electro-mechanical drives in different SC units for piezo-drives which, in its turn, would decrease the mass-dimension parameters n-fold times. In this case, the most reliable and high-performance could be piezo motor (PM) executed on lead zirconate titanate (PZT) stack – based [1–4].

Linear PM stack includes oscillation system (OS) with characteristic parameters of these systems. To effectively convert electrical energy into mechanical, the performance mode of actuating elements should be optimal, i.e. operation mode of the OS itself. OS operation mode depends on such factors as system parameters, system linearity and intensity and frequency of the loads [5]. Existing two conversion energy OS impede the possible selection of the operation mode in designing stacked PM. The system operates on the basis of two principles- either "kinetic" (vibration) under conditions of low frequencies or predominately "acoustic" under high frequencies. There are simultaneously two conversion principles within the PM frequency band [6–8].

Based on electric circuit conversion rules, PM electric circuit (Figure 1) is converted into equivalent circuit [5–10]. The final equivalent circuit of mechanical-acoustic PM system is illustrated in Figure 2. Moreover, this circuit makes provision for PZT-stack APM-2-7 [11]: number and thickness of piezo elements, their mass and the mechanical friction loss between piezo elements.
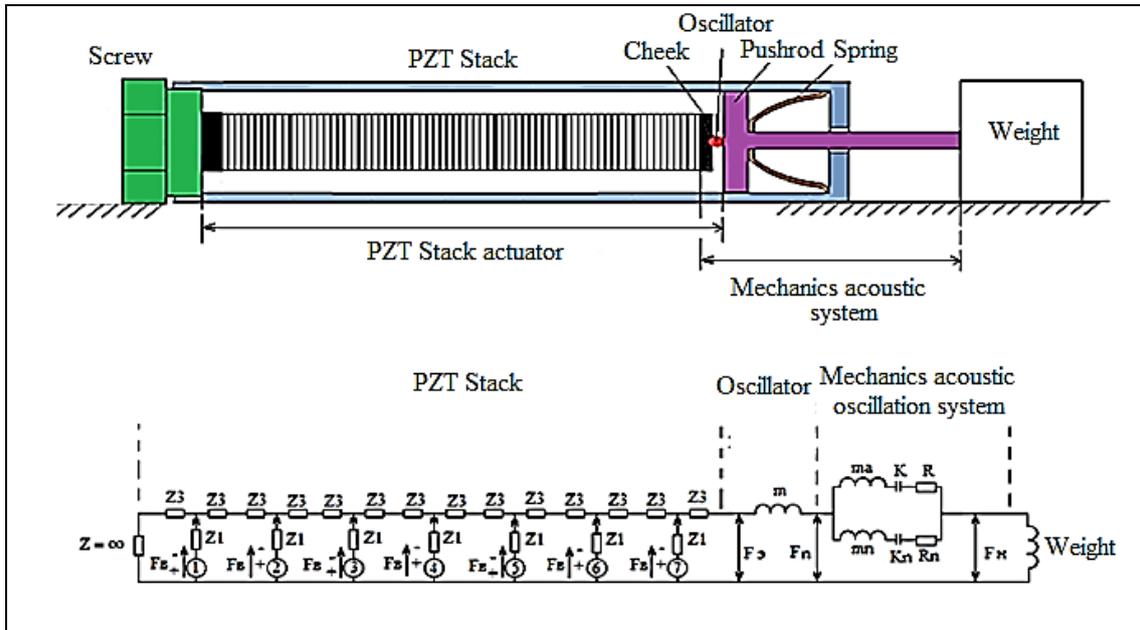
Figure 1. PM includes 7 piezo elements and equivalent electric circuit with allowance for inertia mass of piezo elements and mechanico-acoustic OS loads.
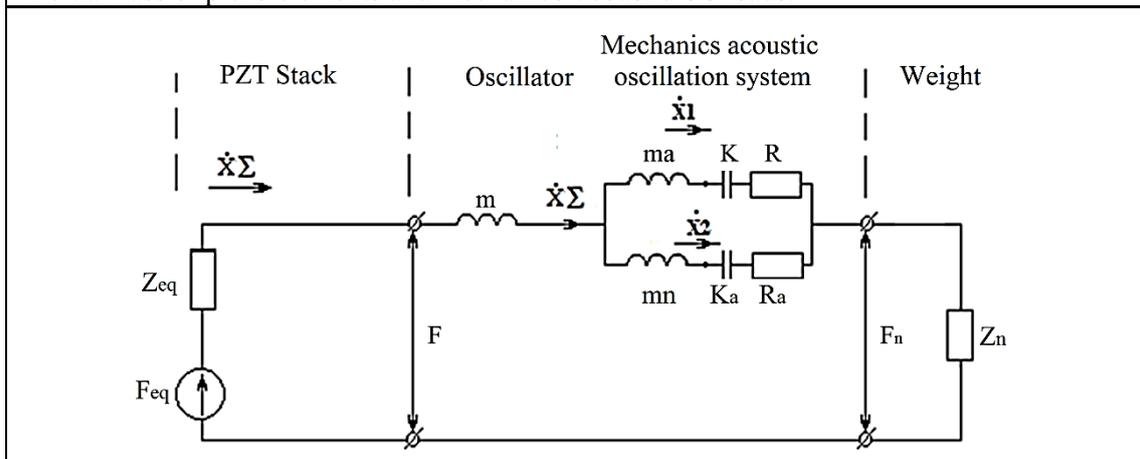

Figure 2. Equivalent PM circuit.

The mechanical system, i.e. PM load, is the distributed OS, and consequently, internal and external resistance alignment should be the load to transfer energy from oscillator, which, in its turn, includes the alignment of energy source and load parameters. In this case, the system would operate with maximal coefficients of converted electric energy into mechanical energy loads.

Referring to literature, OS – load alignment is frequently applied in the electric circuit in the case of high-frequency signal transmission. In [12], energy relation during energy transfer from active impedor to passive impedor is considered.

Active impedor- any electric energy source, while passive impedor- its load. If the active impedor is considered to be the voltage source with established output impedance (Figure 3a), what would be the maximal load resistance capacity imparted on the load itself. The calculation results are illustrated in Figure 3b. Thus, the maximal capacity is imparted on the load under conditions of output active impedor resistance and load resistance equivalence. In this case, it could be stated that the load resistance is aligned to the output resistance of electric energy source and / or output resistance of signal source [12].
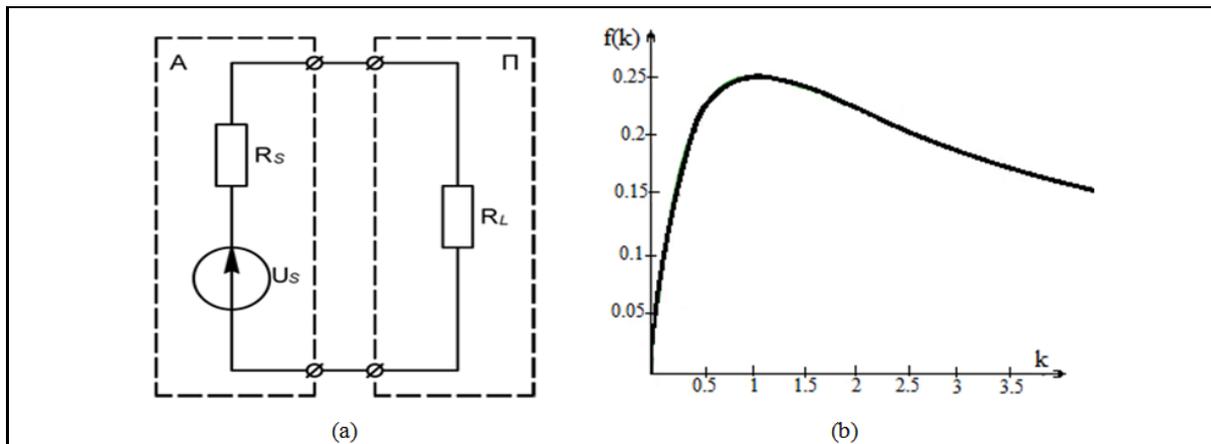
Figure 3. OS – load alignment: a) connection diagram of load to voltage source; b) load capacity dependence of load resistance to output active impedor resistance.

Alignment of distributed OS of PM is consistently relevant to the active source impedance Z_{eq} and oscillation system impedance Z_{os} equivalence, which includes inertial resistance oscillator element, mechanical-acoustic system impedance and load impedance (Figure 2).

2. Simulating distributed OS of PM for different load types

2.1. Alignment of oscillation system of PM in short circuit mode

Short circuit mode of distributed oscillation system of PM are characterized by no load impedance (Z_n=0). This is the most heavy-duty operating mode associated with piezo motor breakdown risk. This mode exists where vibration velocity is maximal, force on load equals zero, mechanical energy on load equals zero and all energy used for the loss within mechanical-acoustic system. The alignment analysis of distributed oscillation system of PM in short circuit mode and this prevailing mode could be only under high impedance Z_{os} values being comparable to Z_{eq}.

2.2. Alignment of oscillation system of PM in inertia load mode

Let's consider mechanical-acoustic OS having the following parameters: oscillator element, radius R_{oe}=0.2·10^{-3} m, longitudinal velocity V_p= 2500 m/s, medium density ρ = 1.2·10^3 kg/m^3, oscillator element mass m = 8·10^{-3} kg, pushrod mass ma = 1.791·10^{-3} kg, spring pretension stiffness K=1·10^4 N/m, vibration dissipation factor R = 0.764 kg/s, apparent additional mass m_n = 8.736·10^{-8} kg, acoustic impedance K_a = 1.789·10^7 N/m, acoustic dissipation factor R_a = 0.764 kg/s.

Symbolical method in Mathcad is applied to obtain frequency response characteristics of distributed oscillation system of PM.

Let's consider oscillation system of PM performance in inertia load mode (Figure 4). Frequency response characteristics of this system (Figure 5) indicate the fact that the alignment mode "frequency oscillator" (equivalent impedance Z_{eq} and Z_{os} equality) is carried out in three points. However, not all equivalent impedance points could be involved in a stable energy efficient mode. In this case, there are three equivalent impedance points and two OS performance resonance points (Figure 5).

The point of stable distributed OS alignment could be the impedance intersection point being based on the following requirements:

$$\begin{cases} \dfrac{dZ_{os}}{df} > 0, \\[2mm] \dfrac{dZ_{eq}}{df} < 0. \end{cases} \qquad \text{or} \qquad \begin{cases} \dfrac{dZ_{os}}{df} < 0, \\[2mm] \dfrac{dZ_{eq}}{df} > 0. \end{cases}$$
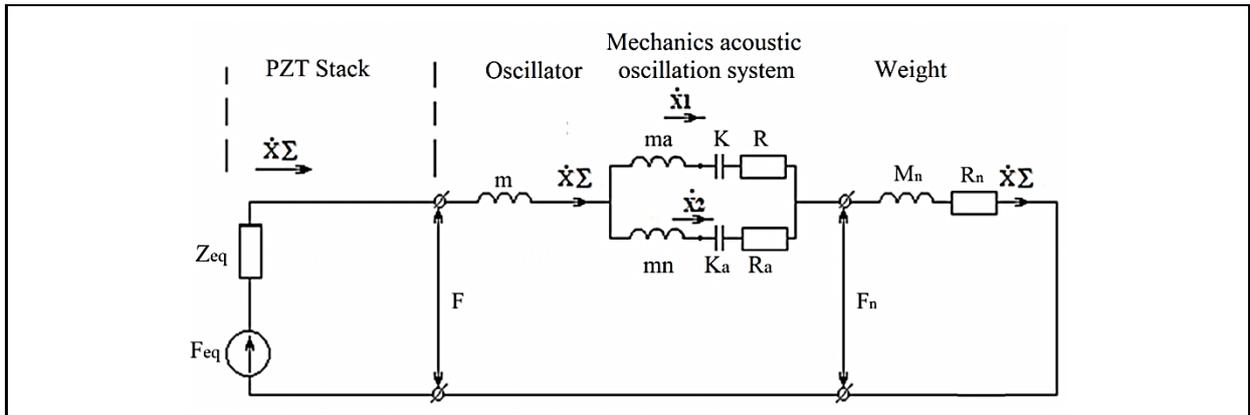
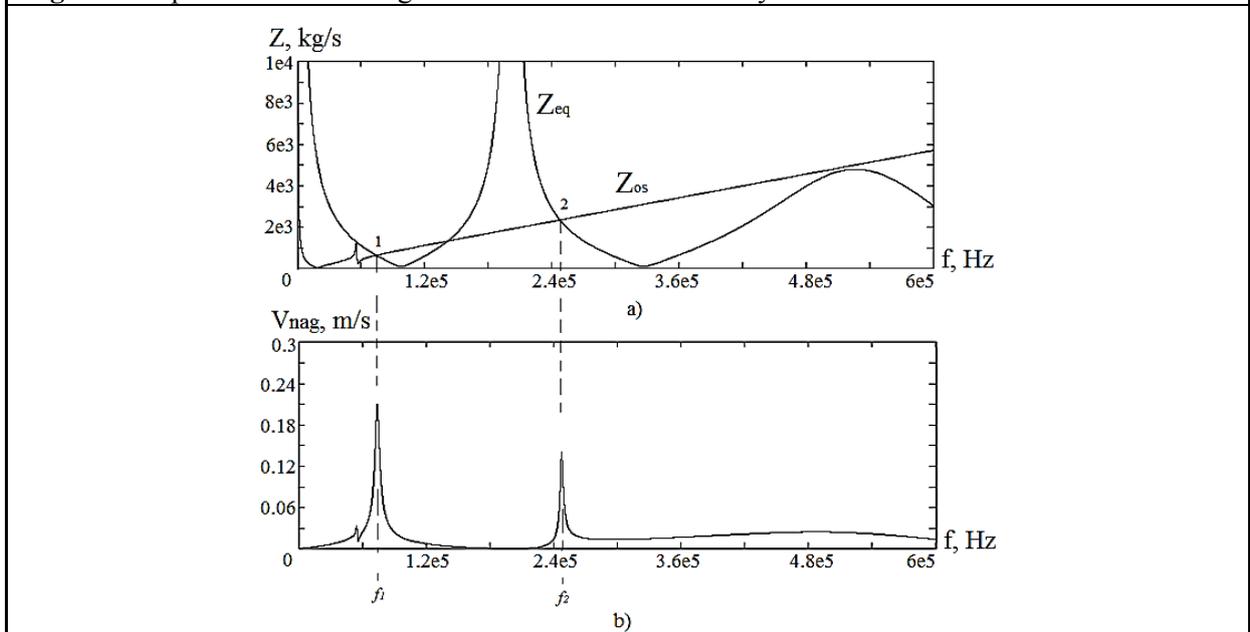**Figure 4.** Equivalent circuit diagram of mechanical-acoustic system in inertia load mode.

Figure 5. Frequency response characteristics of PM distributed oscillation system in inertia load mode, where, inertia load $M_{nag} = 0.0015$ kg: a) impedance Z_{os} and Z_{eq}; b) vibration velocity load.

Figure 6 illustrates the selection principle of a stable alignment system. In this case, the load is the inertia mass of any structure action element. To determine the alignment performance of distributed piezo motor OS, it is necessary to compare the in-system electric energy value and on-load mechanical energy value.
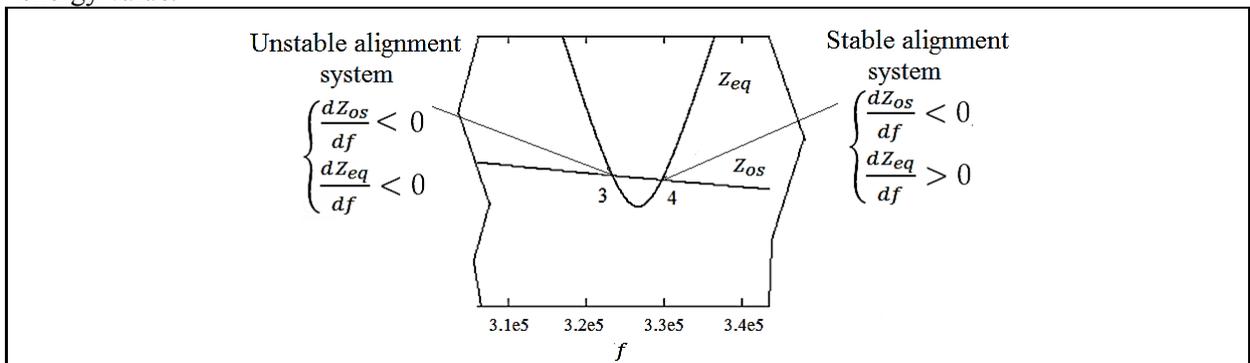

Figure 6. Selection principle of a stable alignment system.

Progressive inertia mass results in the fact that OS of PM has one equivalent impedance point. Consequently, OS of PM has only one pronounced resonance, where mechanical energy on load increases and coefficient of performance tends to 1. In [13] ultrasonic motor model is considered, showing identical coefficient of performance.

Based on calculation results, it was determined that where inertia mass of 0.480 kg. The PM system has one resonance at frequency $f = 5.8 \cdot 10^3$ Hz (Figure 7).
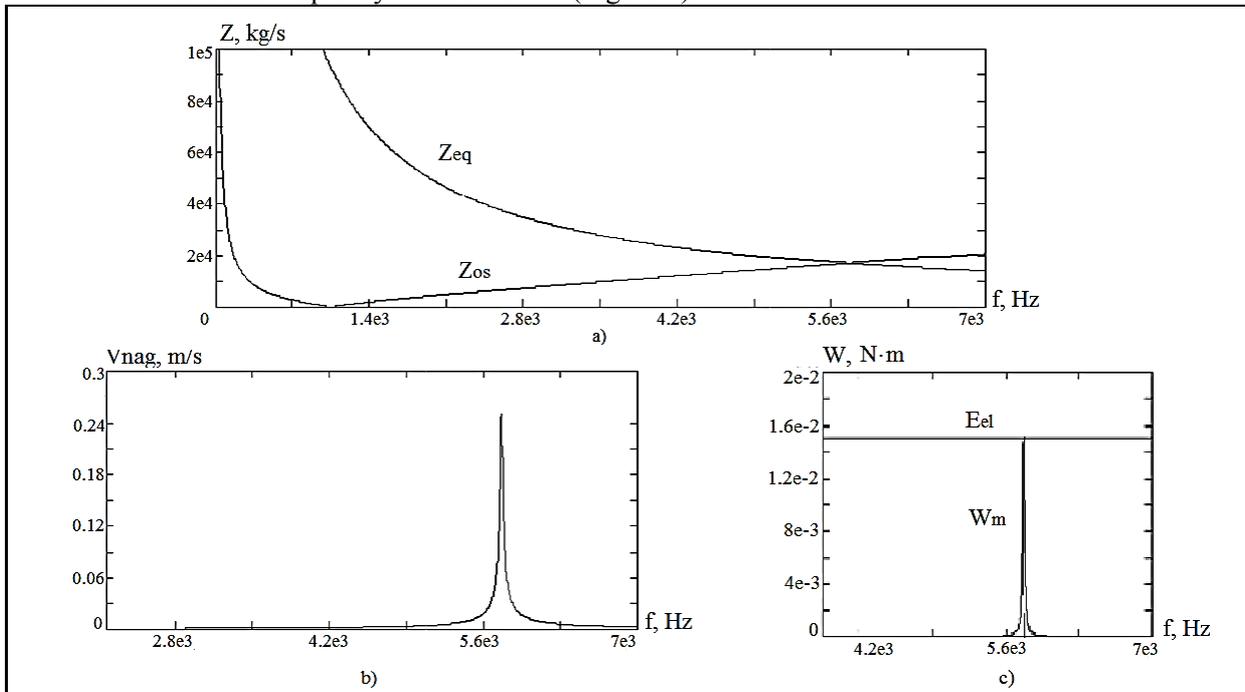

Figure 7. Frequency response characteristics of distributed PM OS where, inertia load $M_{nag} =$ 0.480 kg: a) impedance Z_{os} and Z_{eq}; b) vibration velocity load; c) characteristics of electrical E_{el} and mechanical W_m energy of OS.

2.3. OS of PM alignment in elastic load
Let's consider the oscillation system, having analogue system parameters, but involving elastic load (Figure 8). Elastic load value is stiffness factor: $K_{nag} = 8.5 \cdot 10^8$ N/m.
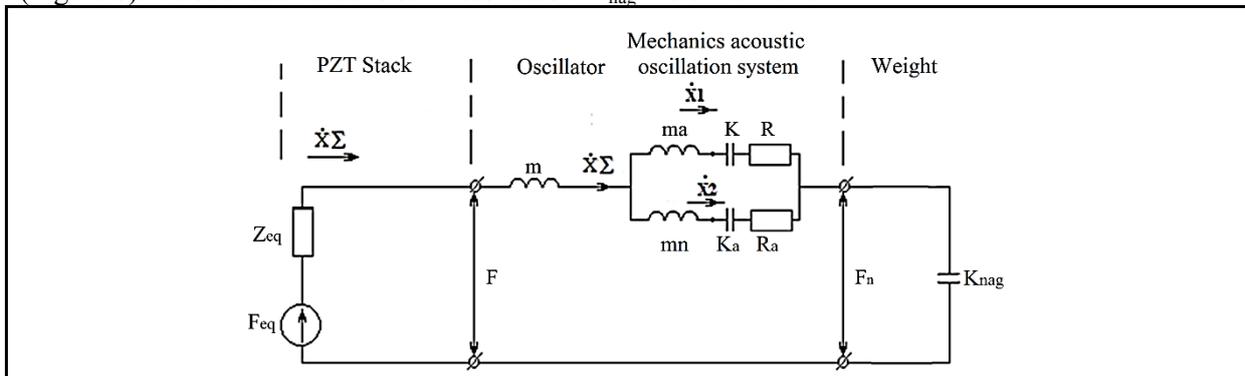

Figure 8. Equivalent circuit diagram of distributed PM OS in net elastic load.

Alignment principle of distributed PM OS is performed under conditions of net elastic load. Resonance shifts to high frequency zone $f_1 = 1.4 \cdot 10^5$ Hz и $f_2 = 3.5 \cdot 10^5$ Hz (Figure 9). Although there is resonance, under conditions of high frequency PM performance mode is similar to short circuit mode, where mechanical velocity tends to zero.
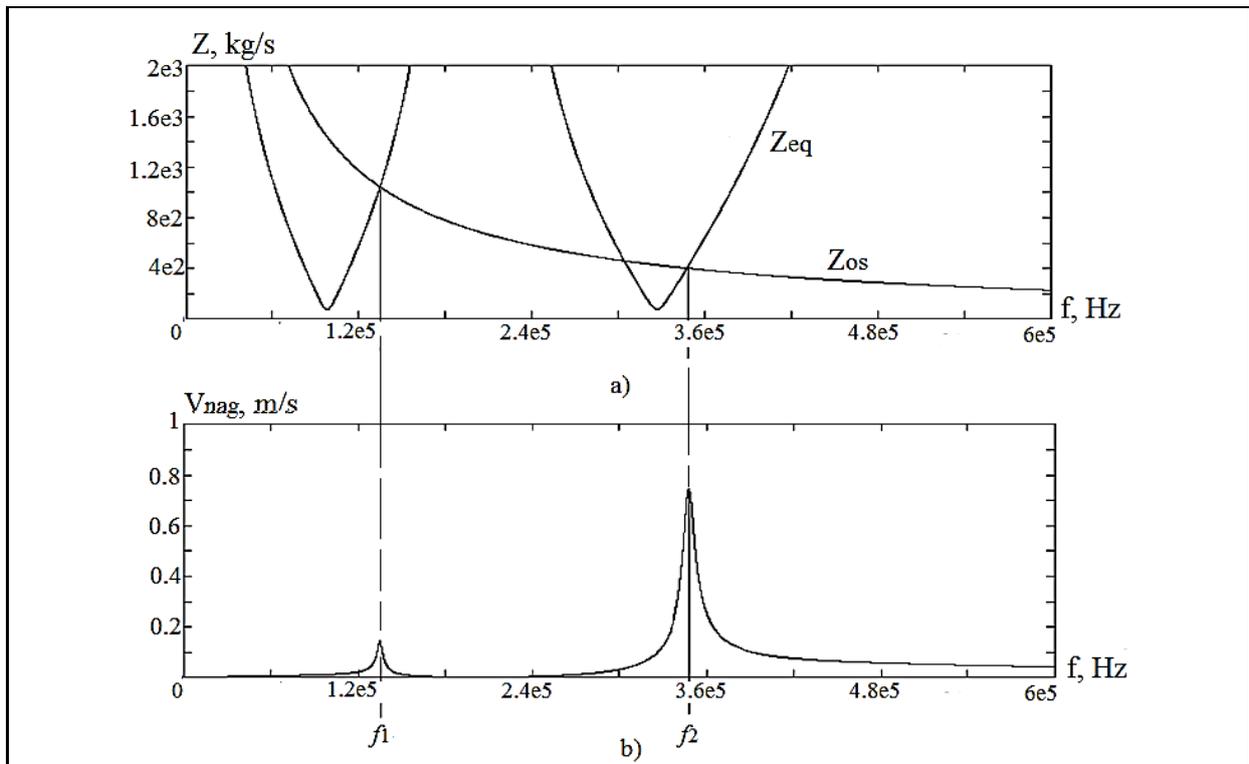
Figure 9. Frequency response characteristics of distributed PM OS in net elastic load: a) impedance Z_{os} and Z_{eq}; b) vibration velocity load.

2.4. OS of PM alignment in combined load

Let's consider OS, having analogue system parameters, but involving combined load: stiffness factor $K_{nag} = 8.5 \cdot 10^8$ N/m, load mass $M_{nag} = 0.480$ kg. Equivalent circuit diagram of distributed PM OS in combined load is illustrated in Figure 10.

Calculated frequency response characteristic results of above-mentioned oscillation system are presented in Figure 11. OS has one impedance intersection point and one pronounced resonance. Alignment principle of distributed PM OS distinctly determines one performance resonance frequency $f = 0.7 \cdot 10^4$ Hz, where performance coefficient equals 0.913.
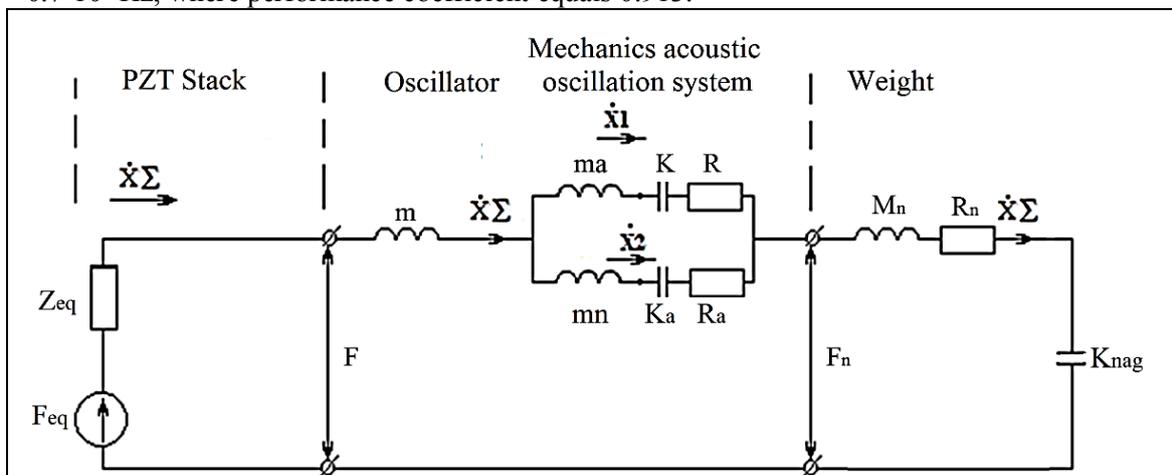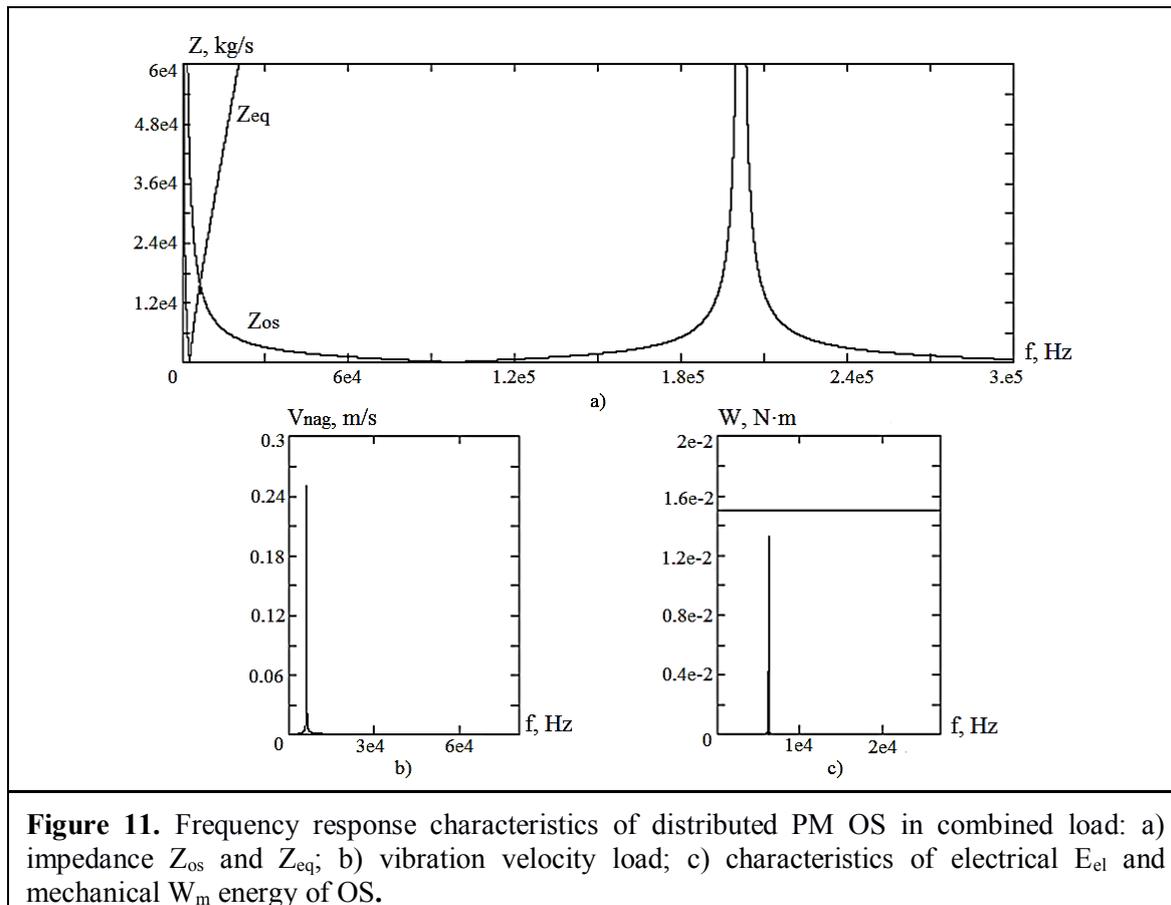

Figure 10. Equivalent circuit diagram of distributed oscillation system of PZT-stack in combined load.

Figure 11. Frequency response characteristics of distributed PM OS in combined load: a) impedance Z_{os} and Z_{eq}; b) vibration velocity load; c) characteristics of electrical E_{el} and mechanical W_m energy of OS.

3. Conclusion

It is viable that mathematical simulation should be applied in the preliminary calculations of distributed PM OS, which, in its turn, is based on analogue equivalent circuit diagrams of PZT-stack, including piezo element mass and mechanical piezo element motion loss.

In determining performance frequency response characteristics of distributed PM OS, it is relevant to apply the alignment of oscillator and load impedance This method simplifies the possibility of analyzing distributed PM OS characteristics under different load conditions.

Acknowledgments

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