Development of Microlinear Piezo-Drives for Spacecraft Actuators

A.V. Azin, S.V. Rikkonen, S.V. Ponomarev and A.M. Khramtsov

Abstract The article describes the development and experimental studies of microlinear piezo-drive for control reflective surface devices of large-sized transformable spacecraft antenna reflectors. Research target—experimental investigation of the microlinear piezo-drive to determine stable oscillatory system operating modes which would include improved energy conversion parameters. The following characteristics are briefly presented: test stand construction-design description, identification of oscillatory system resonant and actual frequencies under inertia load. A series of experiments have been conducted for both different preliminary tensions and inertia mass values.

Keywords Microlinear piezo-drive · PZT stack · Oscillatory system Frequency characteristics · Test stand · Durability · Reliability

The problem, to reduce the 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 [1, p. 196; 2, p. 103; 3, p. 160].

Control reflective surface devices of large-sized transformable spacecraft antenna reflectors involve a number of technical specifications: mass, dimensions, thrust force, vibration displacement, operation stability, durability, reliability in space environment.

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Such piezo-drives embracing the above-mentioned TS do not exist abroad or in Russia. It is mostly due to the absence of a reasonable understanding of microlinear piezo-drive operation, no calculation methods and design for MLPD as a single oscillatory system [1, p. 196; 4, p. 86; 5, p. 1].

The problem targets involve the following:

1. development of a new design conception for microlinear piezo-drives (MLPD) of spacecraft actuators, including aerospace industry;
2. development of scientific and methodological design documents of microlinear piezo-drives for SC actuators;
3. development of static and dynamic problem-solving methods in designing spacecraft MLPD actuators with world standard mass-dimensional energy indicators;
4. development of MLPD test unit and energy source with required q-band based on numerical simulation;
5. development of experimental research program and methods for MLPD of SC actuators;
6. development of experimental test stand design of MLPD to estimate the performance;
7. development and validation of technical requirements for new MLPD design.

One-Dimensional Modeling of MLPD Performance

MLPD packet mode is a mechanical oscillatory system operating in alternate mode and regenerating electrical energy into mechanical energy load. This system should be explored as a single oscillatory system including all component elements. All system elements should operate in the following integrated mode—"conversion-generation-consumption" energy. In this case, all these elements are operating synchronous, in coherent mode transferring active power from energy source to consumer. Under these conditions, high-efficient energy conversion and oscillatory system efficiency could be observed.

Electric analogy method is applied to select the MLPD design, element material and SC operation mode protype-conversion of complex oscillatory mechanical systems in electrical circuit and further transformation based on Kirchhoff laws. This conversion is illustrated in Fig. 1: mechanical MLPD system based on APM-2-7 and SC circuit scheme replacement. Solving the resulting equivalent electrical scheme, one can get a SC frequency response, resonating frequency, force on load, and vibration displacement. One-dimensional model calculation results are in Fig. 5 [1, p. 200; 4, p. 91; 5, p. 5].

Finite element modeling is applied to test one-dimensional mathematical simulation of MLPD and material selection for its design.
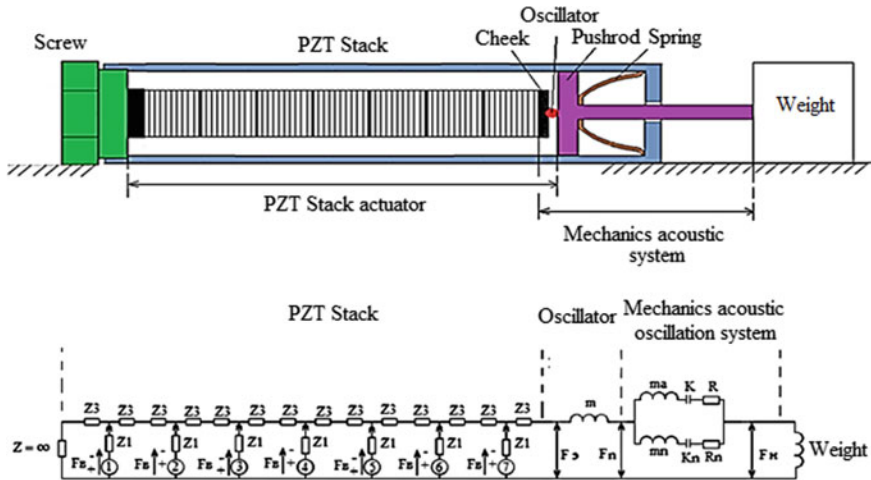
Fig. 1 Electrical circuit scheme of MLPD replacement with 7-laminar MLPD, mechanic acoustic system and load

Three-Dimensional MLPD Modeling

Reliable MLPD operation depends on element material selection. Stress–strain state of the MLPD structure under operational loads is analyzed on the basis of calculations.

MLPD includes stack, screw, PZT Stack actuator, cheek with oscillator, pushrod and seal. Finite-element MLPD model is illustrated in Fig. 2. Maximum stress intensity zone in the MLPD reinforcement construction is the oscillator and the pushrod contact. According to the optimal mechanical and acoustic parameters the following element materials were selected: steel, aluminum, and plexiglass. MLPD reinforcement model involves the following material combinations (sequence of material element: cheek-oscillator-pushrod, seal—rubber used in all cases): steel-steel-plexiglass; aluminum-aluminum-plexiglass; aluminum-aluminum-steel; all aluminum; all steel.

Based on numerical calculations steel-steel-plexiglass materials were selected due to quality and reliability characteristics. Amplitude-frequency characteristics of pushrod vibration displacement based on calculations results are shown in Fig. 5.

Based on the mathematical approach, the designer can select suitable material for each MLPD element according to its design.

Experimental Research

According to modeling results MLPD test unit was designed. MLPD is illustrated in Fig. 3 including piezo-drive elements and assembled MLPD. To determine the force on the load in MPLD, there is a piezoelectric power indicator.

Fig. 2 Finite-element model.
1 PZT stack, *2* Cheek,
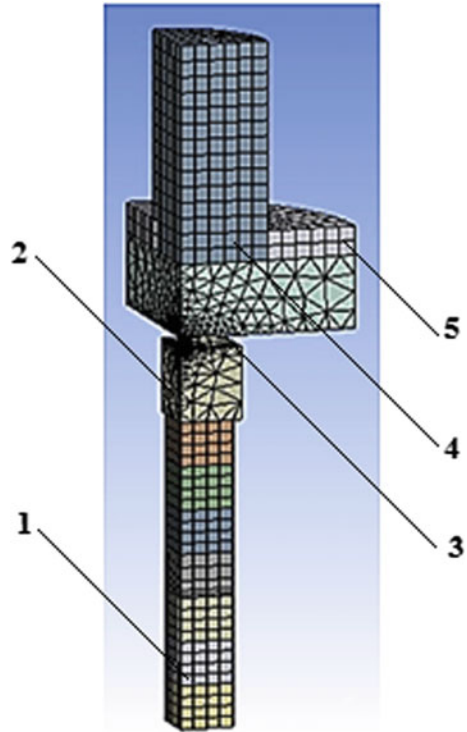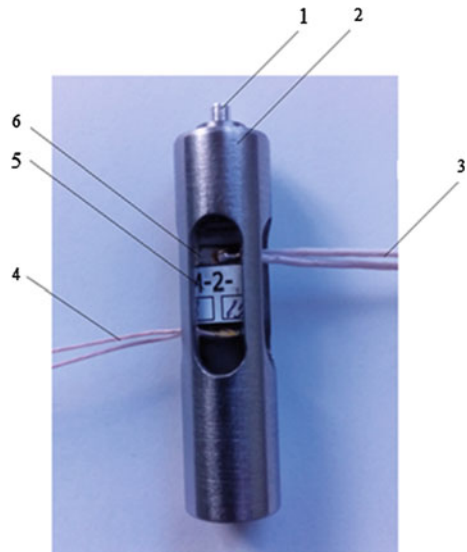*3* Oscillator, *4* Pushrod,
5 Spring

Fig. 3 MLPD based on APM
2-7: *1* Pushrod, *2* MLPD
jacket, *3* Force pickup lead,
4 PZT stack pickup lead,
5 PZT stack APM-2-7,
6 Force sensing unit

A test stand was designed to obtain research data on the MLPD modes. The test stand is used to investigate MLPD operation modes (Fig. 4a). MLPD modes depend on the following characteristics: SC type and PZT Stack power; vibration acceleration (mass load/mass weight); PZT Stack pretension force; PZT Stack tension; PZT Stack current; frequency response. During MLPD tests, operation modes were recorded as electrical signals: PZT Stack tension, PZT Stack current, PZT Stack force indicator signal, vibration acceleration (mass load/mass weight). During pretesting one more characteristic—pretension force was determined.

The test results showed the following: frequency characteristics of load acceleration, recalculation of defined vibration displacement load characteristics, and frequency parameters of force on load. According to SC frequency characteristics, operating oscillating frequencies were defined.

Varying SC characteristics and frequency responses on the test stand it is possible to investigate the numerous operation modes of this system. Based on the results it was concluded that there is an optimal frequency response for this load, where maximum force on load, maximum vibration displacement load, and maximum power on load. Figure 4 presents the test stand. Description of the following scheme: on the base (5) via adjusting screw (4) the PZT Stack (6) is installed through force sensor (7) which bottoms on the pushrod (2), the pushrod (2) via elasticity (8) acts on the inertia load/weight load (1). Acceleration inertia load (1) is measured by acceleration sensor (9). Adjustment screw (4) provides the actuator preload force.

MLPD power is produced from the multichannel power supply with adjustable frequency and voltage. Figure 4b shows the overall view of the designed workplace for MLPD operation modes.

When applying AC voltage of different frequencies, the actuator generates disturbance force through the oscillator-pusher acting on the inertia load, causing its
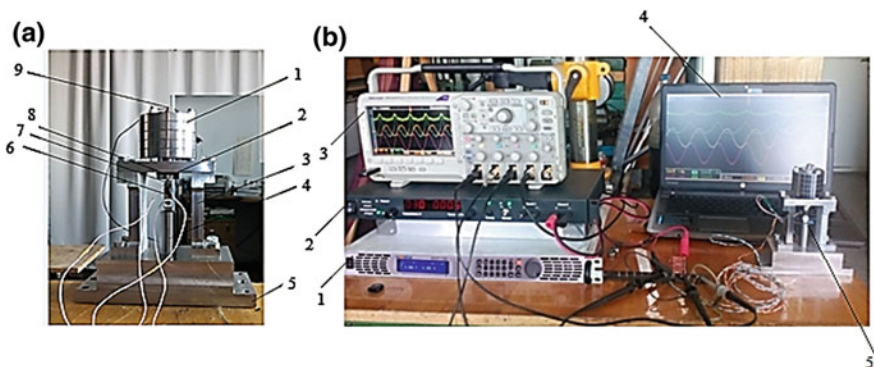

Fig. 4 MLPD operation modes studying workplace: **a** test stand: *1* Inertia mass load (weight load), *2* Pushrod, *3* Supports, *4* Adjusting screw, *5* Base, *6* PZT stack APM-2-7, *7* Force sensor, *8* Elasticity, *9* AR 1019 accelerometer; **b** overall view: *1* DC power supply, *2* AC multi-channel, variable frequency, AC voltage, *3* Electronic oscilloscope, *4* PC information archive, *5* Test stand

vibration at predetermined frequency. Based on the vibration displacement magnitude, magnitude of inertia load is determined, frequency characteristics are based on the experimental results. Actuator current is maintained at 0.5 A, whereas power supply voltage was decreased proportionally to the actuator capacitance. The experiment was conducted at weight mass $M_w = 3$ kg and preload strength $F_0 = 240$ H.

Frequency response analysis obtained by mathematical modeling of one-dimensional and three-dimensional models showed good agreement with the frequency responses (curves 1 and 2, Fig. 5a). Experimental frequency response also showed an oscillating frequency close to the theoretically calculated characteristics X, µm.

When inertia load changes, SC oscillating frequency decreases to the increase of inertia mass (Fig. 6a).

MLPD temperature stability tests show that frequency response values do not change with the temperature increase. When the temperature approaches the limit values of the oscillating frequency of the passport, MLPD moves towards higher frequencies (curves 1, 2, 3 Fig. 5b), which is in agreement with [6, p. 41; 7, p. 272; 8, p. 3; 9, p. 1].

An important point is the actuator preload force in operating MLPD. It is noted that pre-tensioning is the reason of actuator pre-deformation "smoothing" the malfunction of its production and assembly and providing a "single mechanism" packet for SC operation mode. When the preload force increases, the power to the load increases (Fig. 6b).
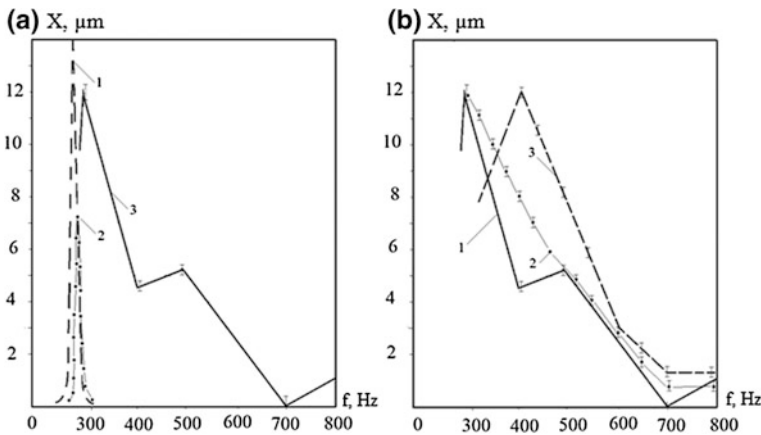

Fig. 5 Vibration displacement frequency responses of operating MLPD: **a** Frequency characteristics comparison: *1* One-dimension modeling results, *2* 3D-dimension modeling results, *3* Test results; **b** Vibration displacement frequency test responses during temperature stability test: *1* temperature 21 ºC, *2* temperature 50 ºC, *3* temperature 80 ºC
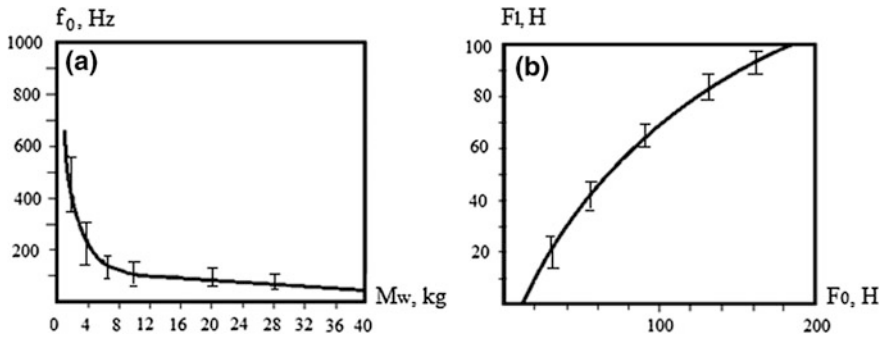
Fig. 6 Test dependences: **a** MLPD operating oscillation f_0 and weight mass M_w; **b** F_1 force on the load at oscillating frequency of system to F_0 pre-load force

Conclusions

1. Newly developed approach for identifying oscillatory frequency system for MLPD;
2. Updated mathematical model to calculate different designed MLPD modes;
3. Experimental data are in good agreement with the results of numerical experiments for three-dimensional and one-dimensional mathematical models, as SC with inertia load is an oscillatory system, then based on the calculation results corresponding MLPD configuration with desired range of oscillating frequency can be selected;
4. Experimentally, pretension is the reason of the actuator pre-deformation, smoothing the malfunction of its production and assembly and providing a "single mechanism" packet for SC operation mode. When the preload force increases, the power to the load increases;
5. Designed multi-channel power supply provides synch and coherent operation modes of several actuators.

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