59th ILMENAU SCIENTIFIC COLLOQUIUM Technische Universität Ilmenau, 11 – 15 September 2017
URN: urn:nbn:de:gbv:ilm1-2017iwk-009:9

Low-Frequency Micro/Nano-vibration Generator Using a Piezoelectric Actuator

Rui-Jun Li[1], *Ying-Jun Lei*[1], *Lian-Sheng Zhang**[1], *Kuang-Chao Fan*[1,2], *Zhen-Ying Cheng*[1], *Peng-Hao Hu*[1]

[1] School of Instrument Science and Opto-electronics Engineering, Hefei University of Technology, Hefei, China
[2] Department of Mechanical Engineering, National Taiwan University, Taipei, China

ABSTRACT

Low-frequency vibration must be detected because of its harmful effects on micro/nano measuring machines. Thus, the authors developed a low-cost and high-precision detector for low-frequency micro-vibration. A high-precision vibration generator is required to calibrate the vibration detector because of the high cost and complex structure of existing vibration generators. A new vibration generator that can produce low-cost and high-precision low-frequency vibration was also developed. A piezoelectric actuator is used as a vibration exciter, which is driven by a high-precision signal generator and a high-voltage amplifier. A beryllium bronze-based leaf spring was used as an elastic component, which is optimally designed and verified by the ANSYS software. The proper size and natural frequency of the leaf spring were obtained. The leaf spring was fixed horizontally on a four-point cylinder-shaped pedestal and driven by the actuator vertically. The worktable on the top surface of the leaf spring only had an up-and-down direction. A high-precision eddy current sensor was used to test the performance of the developed vibration generator. Experimental results show that the vibration generator can produce simple harmonic vibrations with a frequency and amplitude ranges of 10–50 Hz and 0.90–19.87 μm, respectively, and the repeatability of the open-looped vibration amplitude is less than 90 nm (K=2). The developed vibration generator can be used when a micro/nano-vibration detector is calibrated.

Index Terms - Micro/nano-vibration, Low-frequency vibration, piezoelectric actuator, leaf spring

1. INTRODUCTION

The effect of environmental vibration should be considered in the measuring process at the nanometer scale. In terms of the frequency of vibration, the vibration generated by a personnel who walks on the laboratory floor ranges from 1–3 Hz, whereas the vibration of the movement of the Earth's crust ranges from 0.1–10 Hz [1]. Accordingly, our team has developed a low-frequency accelerometer for measuring environmental vibrations [1]. However, these sensors must be calibrated to achieve high accuracy in detecting vibrations. Vibration calibration refers to the process of determining the sensitivity of the sensor over the entire amplitude and frequency range.

Vibration calibration is performed on a vibrating standard device, which is composed of a vibration generator and a measuring system. The vibration generator produces a calibration excitation signal. The China National Institute of Metrology has developed an extremely low frequency vibration calibration system with a frequency range of 0.01–100 Hz [2]. The Institute for National Measurement Standards of Canada has built a cantilevered vibration calibration system with operating frequencies of less than 10 Hz [3]. The National Institute of Metrology of Japan has produced an extremely low frequency and low-frequency vibration calibration systems with operating frequency bands of 0.1–80 and 1–200 Hz, respectively [4]. Other research institutions in this area have also made great progress [5–8]. The vibration generators in these systems combined with these achieved low-frequency vibration calibration systems use electromagnetic drive mode, which exhibits a robust driving stroke and force. However, these generators are bulky, expensive, and have a complex structure.

This paper introduces a new design of a low-cost and high-precision low-frequency micro/nano-vibration generator. The piezoelectric actuator drives high-precision micro-vibrations in the low-frequency range. The second part introduces the design scheme. Then, the third part discusses the performance test results of the vibration table. The last part presents the summary and prospect of the vibration table design.

2. DESIGN OF THE VIBRATION GENERATOR

This study uses piezoelectric ceramics as drivers for vibration generators because the electromagnetic driver of the vibration generator is bulky, expensive, and has a complex structure. The piezoelectric actuator has high output accuracy, output power, and fast response. The vibration generator is designed around the piezoelectric ceramic. Figure 2-1 illustrates the overall design of the vibration generator. The design of the vibration generator is introduced from the selection of piezoelectric ceramics to the design of the leaf spring and the driving circuit.

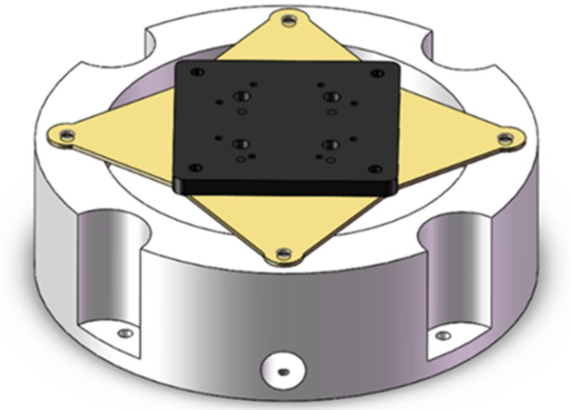

Figure 2-1 Overall design of the vibration generator

2.1 PZT actuator

The exposed piezoelectric ceramics are difficult to install because these materials cannot sustain the lack of tension and satisfy the chaos in the work environment. Encapsulated piezoelectric ceramics are selected as the vibration generator driver because the internal preload of these materials can withstand a certain tension, adapt to a variety of application environments, and be easily installed.

An encapsulated piezoelectric ceramic consists of a piezoelectric ceramic, a mechanical housing, a compression spring, and a displacement output rod. The PTO/C200/13/40 encapsulated piezoelectric ceramic (Core Technology Co., Ltd. China Harbin soluble) was selected because of its cost and driving amplitude range. The piezoelectric ceramic has a nominal maximum displacement of 40 μm, a driving voltage range of 0–150 V, maximum thrust/tension of 800/200 N, vertical stiffness of 20 N/m, an electrostatic capacity of 7.2 μF, and a resonant frequency of 36 kHz.

2.2 Design of the leaf spring

The resonant frequency of the vibration generator determines its operating frequency range. The natural frequency of the piezoelectric ceramic and the leaf spring in the vibration generator is most prominent due to the natural frequency of the exciter. However, the natural frequency of piezoelectric ceramics can be up to 36 kHz. Thus, the height of the leaf spring is directly related to the natural frequency of the vibration generator. Figure 2-2 depicts the shape of the leaf spring, in which the outer ring is fixed to the base by four screws, and the inner ring is connected to the working surface by four screws. The four-point fixation method improves the stability of the vibration generator. A large through-hole reserved in the middle of the leaf spring is used to mount the adapter plate on the lower surface of the working panel. The adapter plate is attached in a T-shaped connection with the encapsulated piezoelectric ceramic.

ANSYS 14.0 is used to build a 3D geometric model and analysis. Figures 2-3 and 2-4 demonstrate the simulation results. The first-order resonant frequency of the elastic structure, which consists of a 2-mm leaf spring, an adapter plate, and a working panel, is 400.47 Hz. Table 2-1 displays the natural frequencies of the first six orders of the elastic structure. The encapsulated piezoelectric ceramic provides a maximum tension of 200 N when the leaf spring is deformed to 40.79 µm. The operating frequency of the vibration generator should be smaller than the resonant frequency [9], and the choice of piezoelectric ceramic should have a maximum stroke of 40 µm. A 2-mm thick leaf spring should be considered to meet the requirements. The use of Wire-cut technology for processing and the actual production of the same specifications of the leaf spring are consistent with the simulation results.

Table 2-1 Modal analysis

Order	**1**	**2**	**3**	**4**	**5**	**6**
Resonant frequency Hz	400.27	665.53	667.12	2498.3	3228.4	3461.6

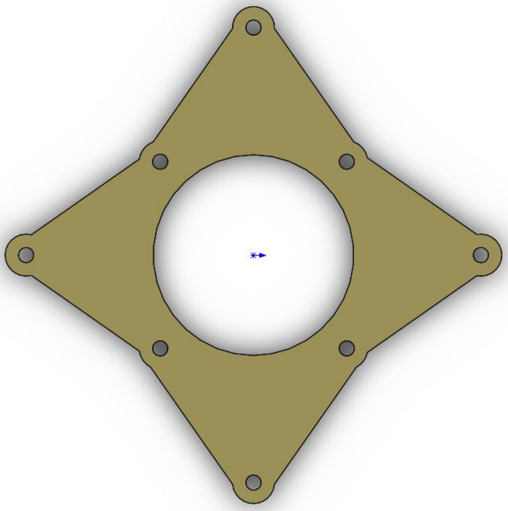

Fig. 2-2 Leaf spring

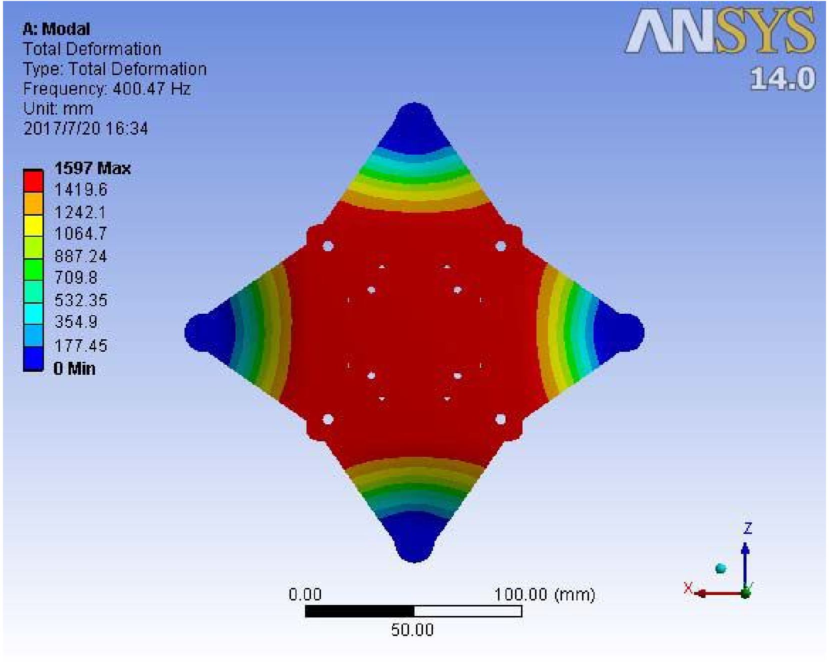

Fig. 2-3 Modal analysis

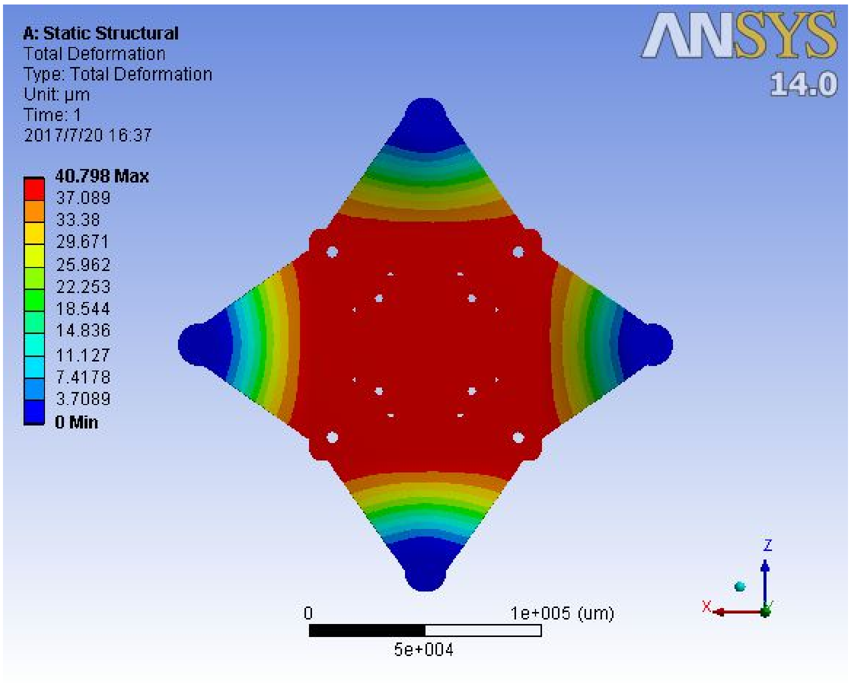

Fig. 2-4 Static analysis

2.3 Wave generator and power amplifier

Figure 2-5 illustrates the vibration generator, which is driven by high-precision waveform generators and power amplifier. The Keysight33519B waveform generator is used for output excitation signal, and the excitation signal is intensified by a power amplifier to drive the vibration generator. The Keysight33519B waveform generator has a 250 MSa/s sampling rate, 16-bit resolution, and 1 mVpp–10 Vpp amplitude range. The power amplifier is based on Apex PA94 high-voltage/high-speed power amplifier. Apex PA94 is a new type of high-voltage/high-speed power operational amplifier with the high output voltage and current capability. Its output voltage has an approximate range of ±200 V and has an output current peak of 100 mA. The Apex PA94 also has an extremely high slew rate of SR>500 V/µs and a very low quiescent current (<1 mA).

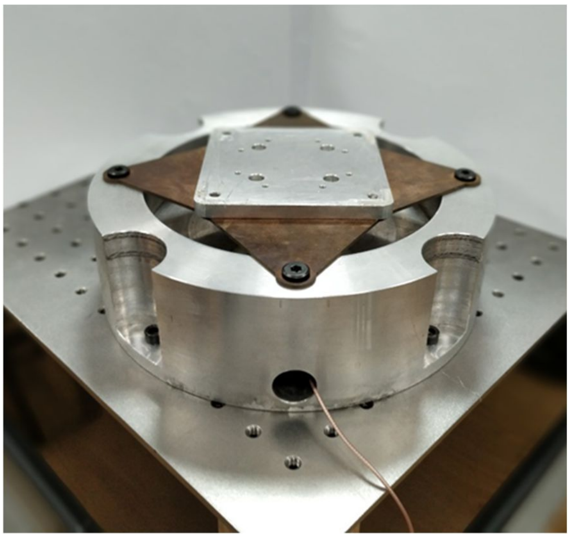

Fig. 2-5 Vibration generator

3. EXPERIMENTS

Figure 3-1 illustrates the experimental program, the vibration generator fixed on the optical platform, the use of Keysight33519B waveform generator output with the excitation signal, and the excitation signal intensified by the power amplifier to drive the vibration generator. A high-precision eddy current sensor is used as a standard sensor, and the NI USB-6002 DAQ is used to acquire the signal of the eddy current sensor. The high-precision eddy current sensor has an output sensitivity of 0.2312 V/μm, a detection range of 50 μm, and bandwidth of 0.1 Hz–10 kHz [10].

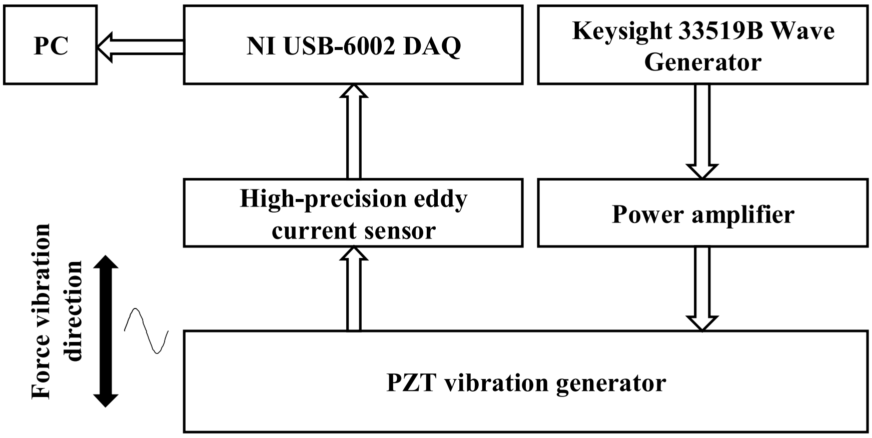

Fig. 3-1 Schematic of the experimental setup

The specific test items include the resonant frequency and the dynamic performance tests. A comprehensive test is conducted based on the three aspects of the performance of the vibration generator.

3.1 Resonant frequency

Figure 3-1 depicts the experimental setup. The amplitude of the fixed sinusoidal signal is 7.5 Vpp, and the output amplitude is recorded every 1 Hz in the 200–450 Hz band. The experimental results are shown in Figure 3-2. The encapsulated piezoelectric ceramic limits the amplitude of the spring vibration at the resonant frequency because the elastic portion of the vibration generator spring is indirectly fixed given the displacement of the piezoelectric ceramic. Therefore, the output amplitude does not change greatly when the leaf spring arrives. Fig. 3-3 demonstrate that the first resonant frequency of the vibration generator, which is 420 Hz, can be obtained. The experimental results are consistent with the simulation results using ANSYS14.0. The difference in the results is mainly due to the machining error of the leaf spring and the overall assembly error of the vibration generator.

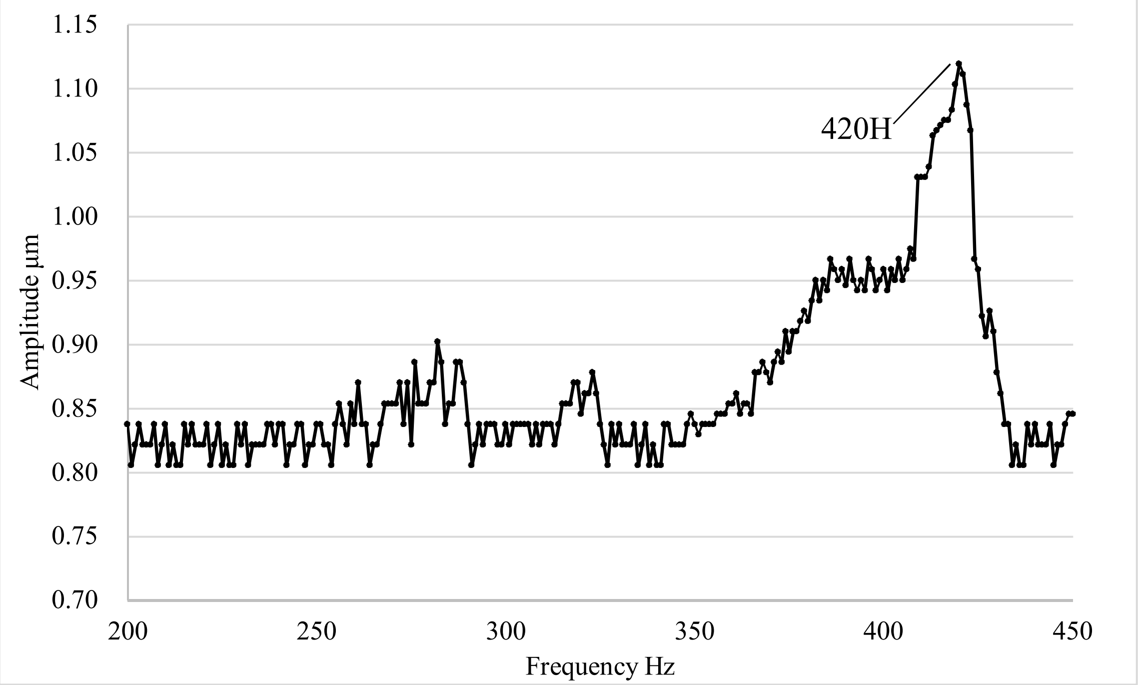

Fig. 3-2 Resonant frequency

3.2 Dynamic performance

Amplitude–frequency response is the most critical feature of the vibration generator. The amplitude–frequency response is used to detect the output range and the accuracy of the amplitude and frequency of the vibration generator. In the experiment, the input signal level ranges from 9 Vpp to 135 Vpp, and the frequency range is 10–50 Hz. The test is repeated five times every 10 Hz, the data is collected every 9 V, and the mean and standard deviation are obtained according to the results of the repeated tests. Figures 3-3 and 3-4 illustrate the experimental results. The relative standard deviation of the amplitude output is calculated by Formula (3-1), and the results are presented in Table 3-1. Figure 3-4 and Table 3-1 indicate that the standard deviation of the amplitude output is 11.35–45.79 nm, the relative standard deviation is 0.09%–1.79%, the amplitude is in the range of 9–135 Vpp, and the output range is 0.90–19.87 μm.

$$\text{RSD (relative standard deviation)} = \frac{SD\text{ (standard deviation)}}{X\text{ (Arithmetic mean)}} \times 100\% \qquad (3\text{-}1)$$

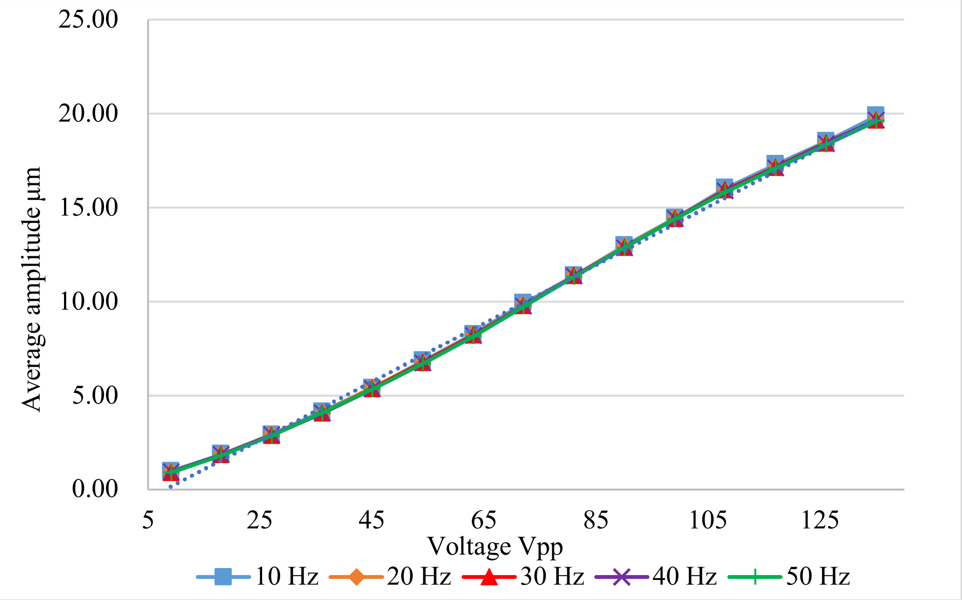

Fig. 3-3 Average amplitude

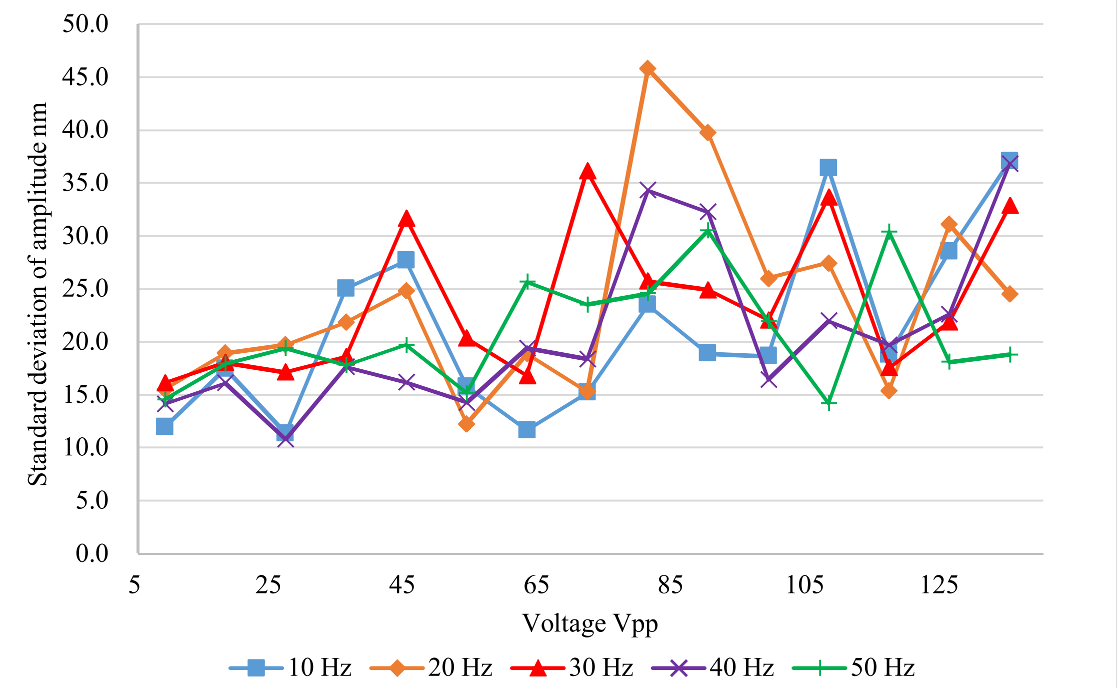

Fig. 3-4 Standard deviation of amplitude

Table 3-1 Relative standard deviation of amplitude

	Relative standard deviation of amplitude %				
Voltage Vpp	10 Hz	20 Hz	30 Hz	40 Hz	50 Hz
9	1.26	1.70	1.79	1.55	1.61
18	0.93	1.03	0.98	0.88	0.99
27	0.39	0.68	0.59	0.37	0.68
36	0.61	0.54	0.46	0.44	0.44
45	0.51	0.46	0.59	0.30	0.37
54	0.23	0.18	0.30	0.21	0.23
63	0.14	0.23	0.20	0.24	0.32
72	0.15	0.16	0.37	0.19	0.24
81	0.21	0.40	0.23	0.30	0.22
90	0.15	0.31	0.19	0.25	0.24
99	0.13	0.18	0.15	0.11	0.15
108	0.23	0.17	0.21	0.14	0.09
117	0.11	0.09	0.10	0.12	0.18
126	0.15	0.17	0.12	0.12	0.10
135	0.19	0.12	0.17	0.19	0.10

4. CONCLUSION

This paper proposes a low-cost and high-precision low-frequency micro/nano vibration system that consists of piezoelectric ceramic actuators and leaf springs. The first-order resonant frequency of the vibration generator is 420 Hz, and the maximum amplitude is 19.87 μm (input voltage = 135 V). The relative standard deviation of the output amplitude of the vibration generator in the frequency range of 10–50 Hz is 0.09%–1.79%. The current vibration generator is not only easy to implement but also exhibits satisfactory performance, especially the high accuracy of the amplitude output.

REFERENCES

[1] Liu Y C, Fan K C, Chu C L, et al. Development of an optical accelerometer for low-frequency vibration using the voice coil on a DVD pickup head[J]. Measurement Science & Technology, 2008, 19(8):817-822.

[2] Ma S, Shu Y, Yang Q. The Digital Upgraded Reconstruction of Ultra-low Frequency Vibration Calibration Standard Apparatus[C]// 14th world conference on earthquake engineering. 2008.

[3] Ohm W S, Wu L, Hanes P, et al. Generation of low-frequency vibration using a cantilever beam for calibration of accelerometers[J]. Journal of sound and vibration, 2006, 289(1): 192-209.

[4] Usuda T, Ohta A, Ishigami T, et al. The current progress of measurement standards for vibration in NMIJ/AIST[C]//Sixth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications. International Society for Optics and Photonics, 2004: 30-38.

[5] Koyanagi R S. Development of a low-frequency-vibration calibration system [J]. Experimental Mechanics, 1975, 15(11): 443-448.

[6] Ferreira C D, Ripper G P, Dias R S, et al. Primary calibration system for vibration transducers from 0.4 Hz to 160 Hz[C]//Journal of Physics: Conference Series. IOP Publishing, 2015, 575(1): 012003.

[7] He W, Zhang X, Wang C, et al. A long-stroke horizontal electromagnetic vibrator for ultralow-frequency vibration calibration [J]. Measurement Science and Technology, 2014, 25(8): 085901.

[8] Ferreira C D, Ripper G P, Dias R S, et al. Primary calibration system for vibration transducers from 0.4 Hz to 160 Hz[C]//Journal of Physics: Conference Series. IOP Publishing, 2015, 575(1): 012003.
[9] Fleming A J, Leang K K. Design, Modeling and Control of Nanopositioning Systems[M]. Springer International Publishing, 2014.
[10] Wang H, Liu Y, Li W, et al. Design of ultra-stable and high resolution eddy-current displacement sensor system[J]. 2014:2333-2339.

CONTACTS

Rui-jun Li	rj-li@hfut.edu.cn
Lian-sheng Zhang	lszhang@hfut.edu.cn