TECHNICAL ARTICLE

High-Frequency Excitation for Thermal Imprint of Microstructures Into a Polymer

B. Narijauskaite[1], A. Palevicius[1], P. Narmontas[2], M. Ragulskis[3], and G. Janusas[1]

1 International Studies Centre, Kaunas University of Technology, Kaunas, Lithuania
2 Institute of Materials Science, Kaunas University of Technology, Kaunas, Lithuania
3 Department of Mathematical Research in Systems, Kaunas University of Technology, Kaunas, Lithuania

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Correspondence
G. Janusas,
International Studies Centre,
Kaunas University of Technology,
A.Mickeviciaus 37, LT-44244
Kaunas, Lithuania
Email: giedrius.janusas@ktu.lt

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Abstract

The main objective of this paper was to propose a novel method for the formation of microstructures using high-frequency excitation during the thermal imprint process. High-frequency excitation of replica during the thermal embossing process helps to fill gaps of the stamp by the polymer. This external factor can provide a possibility to increase the quality and accuracy of the replica. Furthermore, this method does not require expensive or complex developments of the experimental setup and could be applied in most equipments of thermal imprint.

Introduction

Microelectromechanical systems (MEMS) is a driving technological factor in transportation, communication, health care, and other areas of science and technology. Various fabrication technologies are used to manufacture micro or nanostructures. Microstereolithography,[1,2] electron beam lithography,[3] laser-micromachining,[4,5] and photolithography[6,7] are the methods widely used for the fabrication of prototype microstructures. But most commercial activities have been focused on the replication methods.[8,9]

The main objective of this paper was to propose a novel method for the formation of microstructures using high-frequency excitation during the thermal imprint process. High-frequency excitation of replica during the thermal embossing process helps to fill gaps of the stamp by the polymer. This external factor can provide a possibility to increase the quality and accuracy of the replica. Furthermore, this method does not require expensive or complex developments of the experimental setup and could be applied in most equipments of thermal imprint.

High-frequency vibrations are widely used in different applications and technologies. Capillary waves are used for droplet formation on a vibrating surface in Ref. 10. Surface acoustic waves are used to concentrate bioparticle suspensions,[11] to control the temperature of liquid droplets,[12] to generate solitary pulses and fracture,[13] and to produce regular, long-range, spatially ordered polymer patterns without requiring the use of physical or chemical templating.[14] Ultrasonic motors are used to drive fluids,[15] to assist cardiac compression devices,[16] and to control electrorheological fluids.[17] As mentioned previously, we will demonstrate that high-frequency vibration generated by a piezoelectric actuator can enhance the thermal imprint process of microstructures into a polymer.

Description of Experimental Techniques Used for the Thermal Imprint Process Control

A short description of experimental techniques used for the optical control of the thermal imprint process is given in this section.

PRISMA system

A number of experimental studies are needed in order to ensure high stability of the thermal imprint process. The holographic PRISMA system[18,19] was applied for the determination of working regimes of the vibroplatform. The PRISMA system (illustrated in Fig. 1) is a two-beam (the object beam and the reference beam) speckle pattern interferometer. Laser light scattered from the object is collected by the camera lens and is registered onto the CCD camera sensors. The reference beam goes directly to the camera, usually in an optical fiber, where it overlaps the image of the object. Shape changes that occur between a reference and a stressed state of the object produce fringes on top of the image of the object, which is displayed on the monitor in real time.

The PRISM system combines all the necessary equipments for the measurement of deformations and vibrations of most materials in a small lightweight system. A standard system includes holography and computer systems integrated with proprietary state-of-the-art software. The main parts of the PRISMA system setup are presented in Fig. 1. It offers a high-speed holographic technique for production measurement of vibration and deformation without surface contact, and minimal sample preparation can access complex geometries (deep recesses or curves) and can be configured for specific needs in experimental investigation of mechatronics systems.[20]

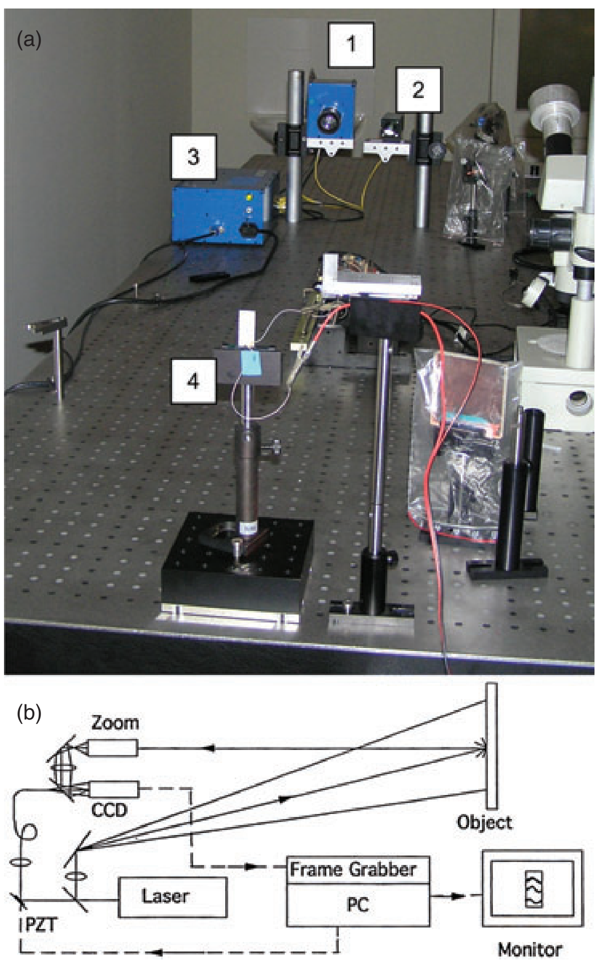

Figure 1 The PRISM system: (a) 1—CCD videohead; 2—control block; 3—illumination head of the object; 4—object and its optical setup (b).

Diffraction measurements

Analysis of periodical microstructures requires adequate tools and techniques.[21,22] A laser diffractometer system is used for the experimental measurement of optical parameters of periodical microstructures. A photodiode is used for recording the intensity and the angle in all maxima of the diffracted light (0, ±1, ±2, etc.). Diffraction maxima could be measured for TE (polarization is parallel to the grating grooves), TM (polarization is perpendicular to the grating grooves), and NP (neutral) polarization of incident light. Polarization could be chosen according to area of application of periodical microstructure and purpose of the measurement. Intensities of diffraction maxima and diffraction angles could be measured for periodical microstructures for different angles of incidence with respect to the normal. This property enables effective optical investigation of periodical microstructures as optical variable devices (OVD).[21,22]

All periodical microstructures formed in optical materials (Si, glass, polymer, Al and etc.) could be characterized by relative diffraction efficiencies. Relative diffraction efficiency $\mathrm{RDE}_{i,j}$ is defined as the ratio of intensity of diffracted light $\mathrm{DE}_{i,j}$ to the ith diffraction maxima and jth illumination angle with intensity RE_j of reflected light from surface without microrelief to jth illumination angle:

$$\mathrm{RDE}_{i,j} = \frac{\mathrm{DE}_{i,j}}{\mathrm{RE}_j}. \quad (1)$$

The comparison of modeled diffraction efficiencies with experimental results could be used for evaluation of geometrical parameters of periodical microstructure. Differences between numerical and experimental results are calculated according to the following formula:

$$D = \sum_{i,j} (\mathrm{RDE}_{i,j} - \mathrm{RDE}^{\mathrm{T}}_{i,j})^2, \quad (2)$$

where $\mathrm{RDE}^{\mathrm{T}}_{i,j}$ is the theoretical relative diffraction efficiency of the ith diffraction maxima and the

jth illumination angle. Application of such an experimental measurement method enables the evaluation of geometrical parameters with an error of less than 5%. Other methods like scanning electron microscopy (SEM), atomic force microscopy (AFM), etc. are needed to evaluate range of the expected depth in the case of deep structures (due to periodical dependence of $RDE_{i,j}$ vs the depth).[23]

The Description of the Thermal Imprint Technology

Flat embossing experiments are performed using a flat thermal pressure device. The original construction secures a controlled pressure, force, temperature, and the duration of exposure ($P = 1–5$ bar, $T = 140–200^{\circ}$C, $t = 1–15$ s) to a polymer (mr-I 8020). Thermal properties of the polymer mr-I 8020 are analyzed in detail in Ref. 24. The surface contour of the nickel stamp is transferred to the thin polymer film coated onto the glass during the process of replication.[21]

Simple experiments show that the quality of a replica after the thermal imprint cannot be good enough. The question is if high-frequency excitation of the polymer during the process of thermal imprint could help to fill gaps of the microstructure. The piezoelectric element PZT-19[25] was chosen as a source of high-frequency vibrations—it is a 50-mm external-diameter ring (20 mm internal diameter, 3 mm thickness). The piezoelectric exciter was mounted under the platform holding the polymer in order to eliminate possible shortcuts or cracks caused by the pressure. The schematic diagram of the thermal imprint experimental setup with the piezoelectric element mounted under the plate holding the glass coated by the polymer is shown in Fig. 2.

An aluminum cylinder with the top surface and a mounting hole in the side wall was chosen as a vibrating platform (Fig. 3(a)). The drawing of the vibrating platform with the mounted piezoelectric element is shown in Fig. 3(b); the scheme of the electric circuit is presented in Fig. 4.

The material and geometrical parameters of the vibration platform were chosen according to the conditions of application (Fig. 3)—the platform should sustain the pressure of 5 bar and at the same time it should be flexible enough to transmit vibrations to the specimen.

The applicability of the vibration platform in the process of hot embossing was analyzed numerically. The deformation of the platform (Fig. 5(a)) under the pressure of 5 bar was calculated using program COMSOL Multiphysics 3.2. The deformation in

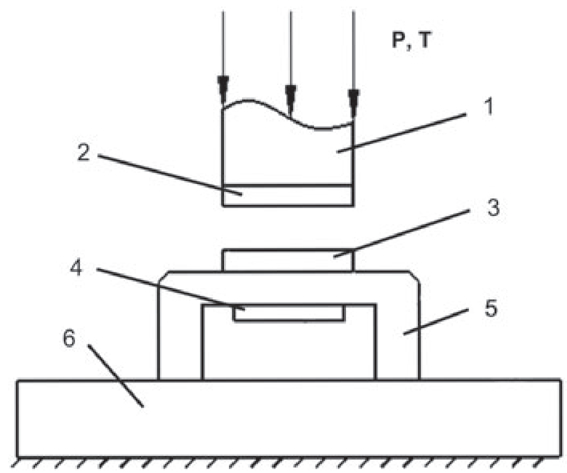

Figure 2 The schematic diagram of the thermal imprint experimental setup with high-frequency excitation: 1—the coin; 2—the master structure; 3—glass coated by the polymer; 4—the piezoelectric element; 5—the vibrating platform; 6—the base.

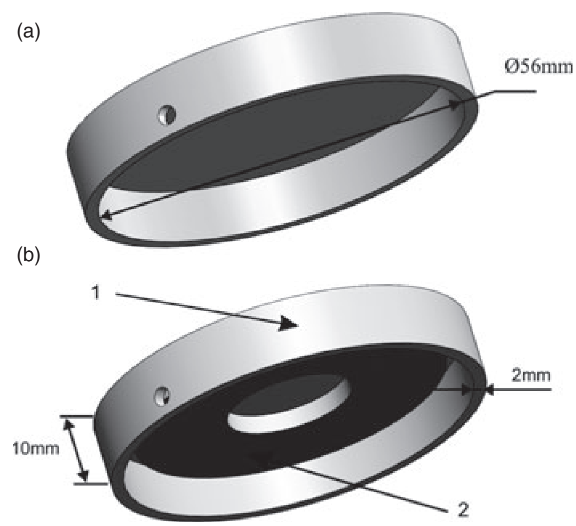

Figure 3 The 3D view of the vibration platform (a) and the vibration platform (1) with the piezoelectric element (2) attached (b).

the contact place is constant in all areas; thus, the specimen is not deformed in the process of hot embossing.

Dynamic properties of the vibration platform were analyzed theoretically using finite-element method too. From the set of results, eigenshape shown in Fig. 5(b) has been chosen for the first experiments. The operating regimes were determined experimentally using the PHASE III PRISM system.[18,20] The PRISM working principle is based on a time-average real-time laser holographic interferometry.

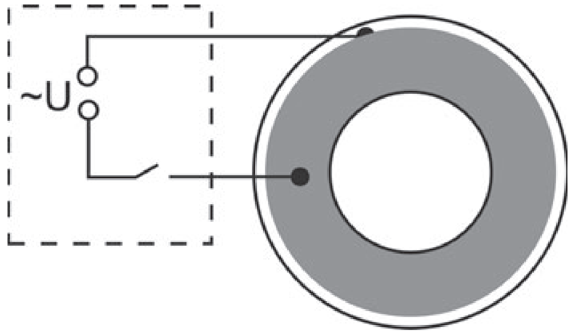

Figure 4 The schematic diagram of electric circuit of the piezoelectric element.

The resonance frequency of excitation of the vibration platform is 8.5 kHz; the time-averaged hologram of the platform at a driving amplitude of 145.6 V is shown in Fig. 6. This resonance eigenshape was chosen as the starting point for hot embossing experiments. We speculate that it produces a mechanical balance type motion which helps to distribute the polymer and to fill gaps of the microrelief. The influence of eigenshapes and amplitudes on the quality of the replica is a definite objective of the future research.

Results and Discussion

Thermal embossing experiments were performed with nickel periodical microstructure of 4 μm period. Three-dimensional (3D) AFM view of the original

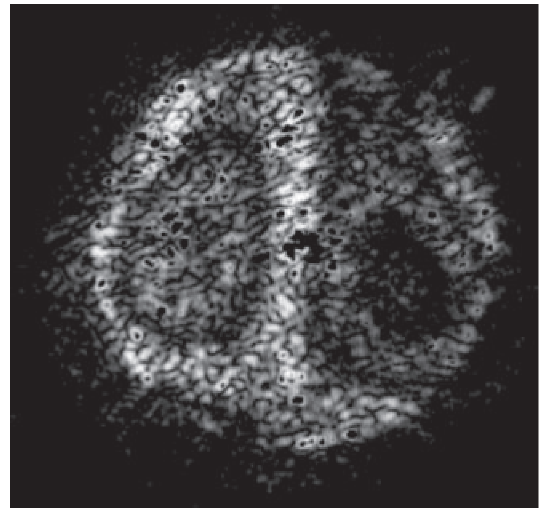

Figure 6 The time-averaged hologram of the vibration platform; the frequency of excitation is 8.5 kHz.

periodical microstructure is presented in Fig. 8(a). Experiments were done at two different conditions, that is, without excitation and with vibration excitation (frequency 8.5 kHz, amplitude 145.6 V) at a temperature of 160°C and pressure of 5 bar. Optical microscope photos with different enlargement of replicas are presented in Fig. 7. It is clear that all areas of the stamp are replicated better when the vibration excitation is turned on.

Atomic force microscopy measurements (Figs. 8 and 9) of the original periodical microstructure and

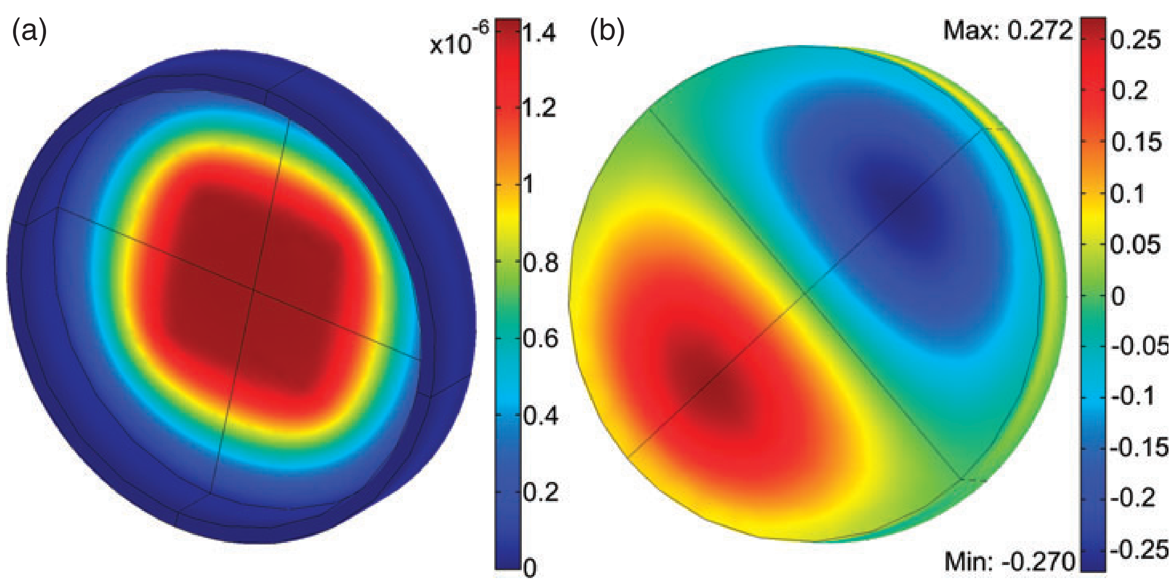

Figure 5 The deformation of the platform (a) under the pressure of 5 bar (maximum deformation 1.1 μm) and its eigenshape (b) (eigenfrequency 5701 Hz).

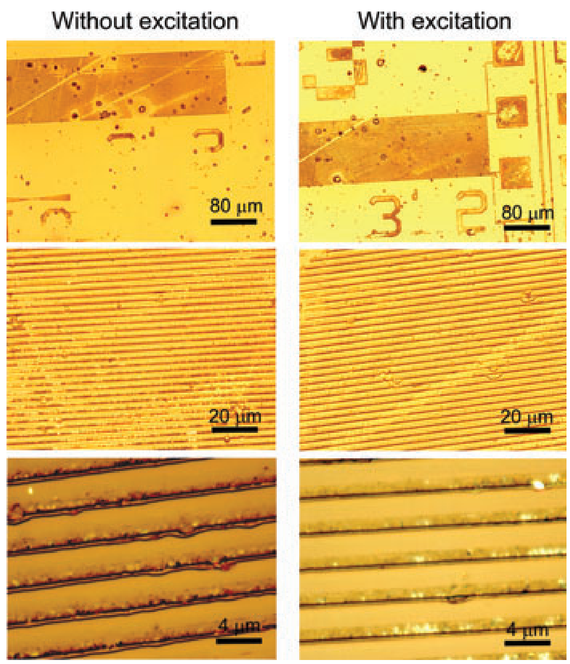

Figure 7 Photos of replicas ($T = 160°C$, $P = 5$ bar) without excitation and with vibration excitation (frequency 8.5 kHz, amplitude 145.6 V).

replicas confirm results of the optical microscope. Replicas done with vibration excitation look like the original structure (Fig. 8). The average depth of the original stamp is 567.65 nm, the average depth of the replica done without excitation is 545.36 nm, and the average depth of the replica produced with vibration excitation is 556.69 nm. High-frequency excitation helps to fill gaps of the original structure by the polymer. The filling of gaps increases from 62.5 to 75%. The surface roughness is another important parameter, which has a great influence on optical, electrical, and mechanical properties of the replicated structure. Vibration excitation definitely helps to improve the quality of the surface of replicas. Roughness measurements of the surface of the original stamp and replicas are shown in Fig. 9. The roughness of nickel stamp is in average 8 µm, but replicas' are much higher: 55 µm is the roughness of the replica produced without excitation and 23 µm is the roughness of the replica produced with vibration excitation. The roughness of replicas is still much greater compared to the original stamp, but the vibration excitation helps to decrease it by about 50%.

The quality of replicas was tested using an indirect optical method—it is based on the measurement of the diffraction efficiency. Replicated periodical structures are manufactured from optical materials, so optical methods could be used for the evaluation of the quality of replicas. Diffraction efficiency of ith maximum was measured using a photodiode and calculated as the ratio of the energy of its maximum and total energy reflected from the analyzed microstructure. This calculation method of the diffraction efficiency allows the elimination of properties of the material of the microstructure and helps to analyze and compare its geometrical properties.[21]

Measurements show that the high-frequency vibration excitation increases the diffraction efficiency of the first-order maximum 1.5 times (from 11.25% measured for the microstructure replicated without excitation up to 17.89% for the microstructure replicated with vibration excitation). It can be noted that this is still 40% worse than the theoretical result (32%), but it shows a promising direction for future research.

Conclusions

An aluminum vibration platform was designed in order to increase the quality of thermal replica;

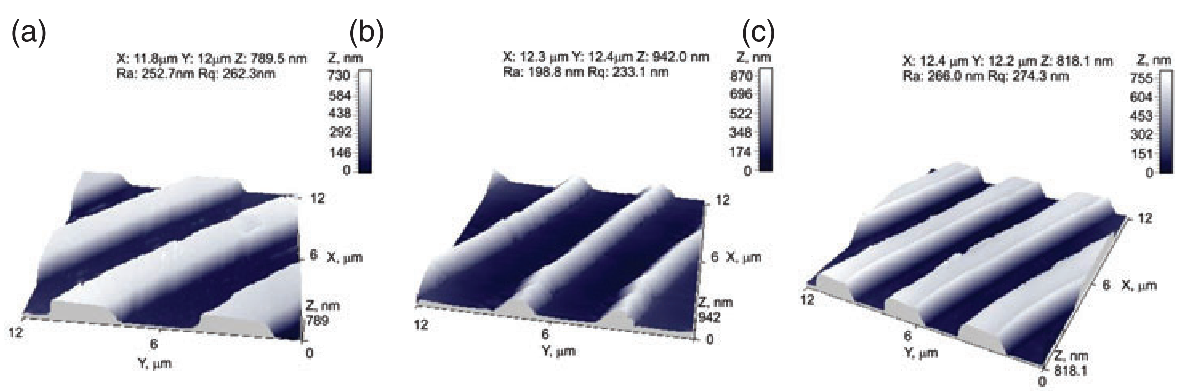

Figure 8 The 3D view of the original periodical microstructure (a) and its replicas done without excitation (b) and with vibration excitation (c).

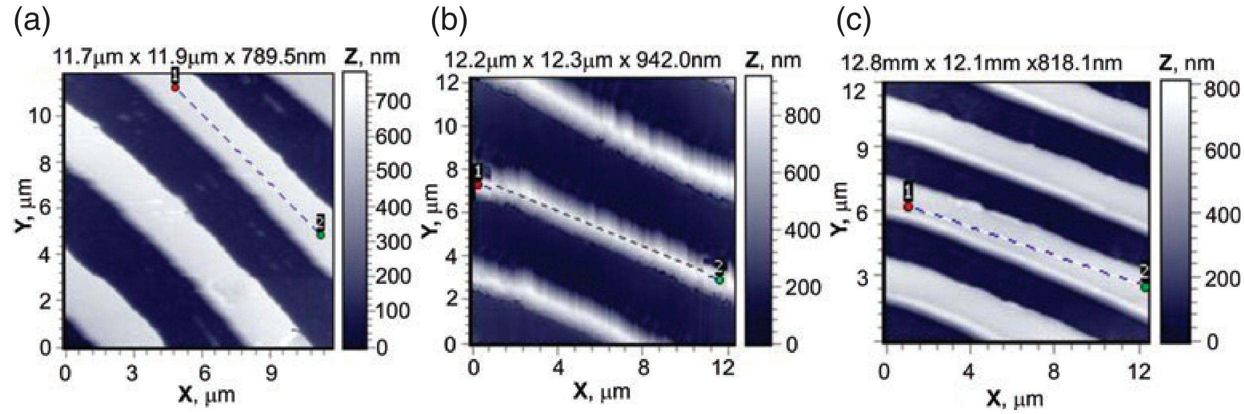

Figure 9 2D view and roughness measurement of the original periodical microstructure (a) and its replicas produced without excitation (b) and with vibration excitation (c).

the piezoelectric element (PZT-19) was chosen as the source of high-frequency vibrations. It was determined optically that high-frequency excitation (frequency 8.5 kHz; amplitude 145.6 V) during the thermal embossing process (temperature 160°C; pressure of 5 bar) of the nickel periodical microstructure (the period 4 μm) increases the quality of replicas.

Atomic force microscopy measurements of the original periodical microstructure and replicas confirm preliminary results of the optical microscope. High-frequency excitation helps to fill gaps of the original structure by the polymer. The filling of gaps increases from 62.5 to 75% and the roughness of replicas decreases about 50%.

Moreover, these results were confirmed with an indirect method also. Measurements of the diffraction efficiency shows that the high-frequency excitation increases the diffraction efficiency of the first-order maximum 1.5 times from 11.25% measured for the microstructure replicated without excitation up to 17.89% for the microstructure replicated with vibration excitation.

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