Investigation of dynamics of cantilever-type microstructure by laser Doppler vibrometry

R. Daukševičius$^{1)}$, A. Bubulis$^{1)}$, V. Jurėnas$^{1)}$, V. Ostaševičius$^{1)}$, S. Tamulevičius$^{2)}$

Kaunas University of Technology

$^{1)}$ Faculty of Mechanical Engineering

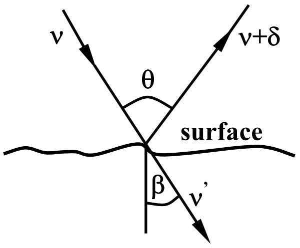
$^{2)}$ Institute of Physical Electronics

Introduction

The integration of miniature mechanical moving structures and electrical or electronic systems on a single chip leads to a new class of devices denoted as microelectromechanical systems (MEMS), which are produced employing the same photolithographic micromachining technology that is used in microelectronics. Industrial and commercial applications of MEMS are growing exponentially and some industries are calling it a breakthrough that could prove to be as revolutionary to modern technology as integrated circuits [1, 8, 9].

MEMS typically include microstructures released from the substrate which are used as mechanical supports or which can be moved or deformed. General trends of MEMS technology are decrease of pattern dimensions, integration of new thin film materials, increased use of very thin films, very thick films or multilayers and development of devices with 3D geometry. The design, performances and reliability of MEMS largely rely on the control of the whole technology and especially on the knowledge and control of the mechanical behavior of materials and micromechanical devices. It is well known that thin film mechanical properties are very dependent on processing conditions. Even when the film properties are known, a complete and accurate modeling of MEMS is not always possible because it is difficult or too time-consuming to take into account all geometrical imperfections inherent to the technology, stress gradient effects, real boundary conditions and damping mechanisms. Consequently, experimental characterization of the real mechanical and particularly dynamical properties of MEMS is crucial at various stages of their development [2 – 4]. Traditionally, experimental modal analysis is used to characterize dynamic behavior of both macro- and microstructures. It is very useful for validation and correction of mathematical models of MEMS (especially for adequate modeling of coupled-physics phenomena such as the effects of electrostatic actuation and gas damping), determination of energy dissipation extent, detection and characterization of structural faults and defects, determination of operational characteristics and fatigue behavior of microstructures. Since miniature size of MEMS hinder direct measurement of some inherent characteristics, experimental modal analysis can be used as tools to infer such mechanical and geometrical properties as the Young's modulus, residual stresses, average density and thickness. These can be deduced by dynamically testing well-characterized microstructures (e.g. beams or plates) and comparing the results with analytical formulas for natural frequencies and mode shapes [4].

Many experimental methods have been developed for the mechanical assessment of thin films and micromechanical devices. Most of them need measurement of static or load-induced displacements, internal strains or vibrations of the whole substrate or of micromechanical devices fabricated on it. Because they are non-contact and sensitive, optical techniques are well suited for this task [2]. In this paper we will consider extensively- applied optical method for experimental research of MEMS dynamics – laser Doppler vibrometry (LDV) and its applicability to experimental modal analysis of a microcantilever element of electrostatically actuated microswitches that have been fabricated at the Institute of Physical Electronics at Kaunas University of Technology.



$$\Delta\phi = \frac{4\pi\delta}{\lambda}\cos\theta/2$$

$$\frac{\Delta\nu}{\nu} = \frac{2\nu'}{c}\cos\beta\cos\theta/2$$

Fig. 1. **Doppler effect: phase and frequency change of a laser beam (wavelength λ, optical frequency ν) reflected on a surface vibrating with a velocity υ'. δ is the displacement normal to the surface**

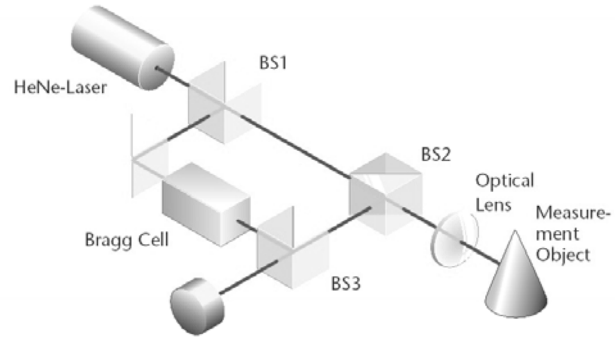


Fig. 2. **Schematic representation of implementation of laser Doppler vibrometry technique in practice**

Laser Doppler vibrometry

The most common optical methods for out-of-plane vibration measurements of MEMS are laser deflection, homodyne two-beam interferometry and laser Doppler vibrometry. Historically, the LDV has been a valuable technique for non-contact vibration measurements on large, macroscopic structures. The earliest systems dating over 20 years ago were used for measuring resonance and mode shapes on large objects like automotive components. The use of the LDV technology for MEMS research started since the early 1990's [2, 4].

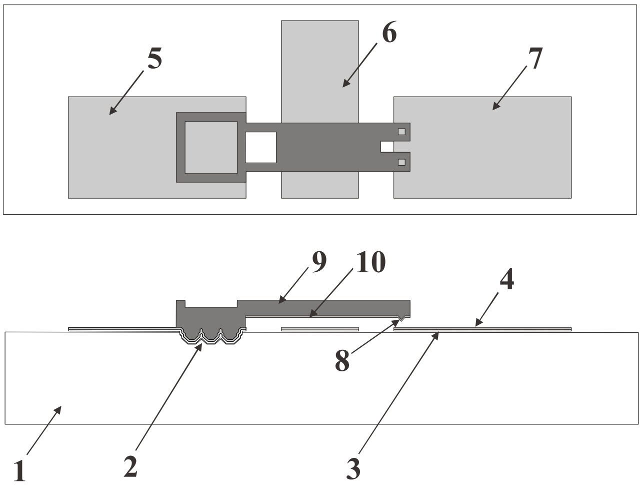


Fig. 3**. Configuration of fabricated microswitch**

The LDV technique is based on the principle of measuring phase shift $\Delta\varphi$ or/and optical frequency shift $\Delta\nu$ induced by the Doppler effect of a laser beam reflected by the surface (Fig. 1). These shifts are detected from the interferences between the reflected beam and the reference beam. In practice the LDV technique is realized as shown in Fig. 2. The beam of a HeNe laser is split by a beam splitter (BS 1) into a reference beam and a measurement beam. After passing through the second beam splitter (BS 2), the measurement beam is focused onto the object under investigation, which reflects it. This reflected beam is now deflected downwards by BS 2, is then merged with the reference beam by the third beam splitter (BS 3) and is then directed onto the detector. As the path length of the reference beam is constant over time, movement of the object under investigation generates a dark and bright fringe pattern typical of interferometry on the detector. One complete dark-bright cycle on the detector corresponds to an object displacement of half of the wavelength of the light used. In the case of HeNe laser, used almost exclusively for vibrometers, this corresponds to a displacement of 316 nm. Changing the optical path length per unit of time manifests itself as the Doppler frequency shift of the measurement beam. This means that the modulation frequency of the interferometer pattern determined is directly proportional to the velocity of the object. An optical frequency shift between the beams is introduced by using acousto-optic modulator (the Bragg cell). In principle, the LDV can directly measure displacement as well as velocity. Displacement demodulation is better suited for low frequency measurements and velocity demodulation is better for higher frequencies. It is generally required that the laser light is perpendicular to the surface whose motion is being measured. Adequate reflectivity of the surface is also necessary. For high frequency measurements (>100 MHz) and rough surfaces, a better way is to produce interferences between the reflected laser beam with itself shifted in time by using an interferometer with a large optical path difference. Heterodyne laser vibrometers have typically a detection limit below 10 pm in a frequency bandwidth of a few MHz. When they are coupled to a microscope or an optical fiber, a spatial resolution in the (sub)micron range can be obtained. In addition, they can provide a whole vibration spectrum in a few (tens) seconds, they are not sensitive to drift and low frequency vibrations and can be used both on smooth and rough surfaces. That is why they are extensively used for MEMS vibration spectra measurements. Moreover vibration mode mapping can be performed by scanning the sample or the laser beam but this can be time-consuming. The scanning LDV system is established by incorporating controlled scanning elements such as positioning stages, scanning mirrors or acousto-optic deflectors [2 – 7].

Description of specimen

Dynamic measurements by our LDV measurement setup were performed on a cervit substrate with the array of microswitches on it. The substrate has the dimensions of 2,7×2,3×1,0 mm. The microswitches (Fig. 4, Fig. 5) were fabricated using novel nickel surface micromachining technology developed at KTU, which is based on such processes as thermoresistive and electron-beam vacuum deposition, wet and reactive ion etching, electrochemical metal deposition, etc. Such electrostatic microswitches are

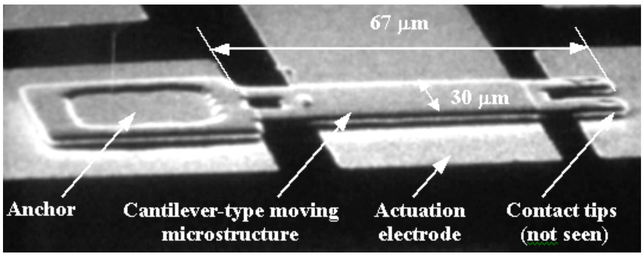


Fig. 4**. Photo of fabricated surface-micromachined electrostatically actuated microswitch**

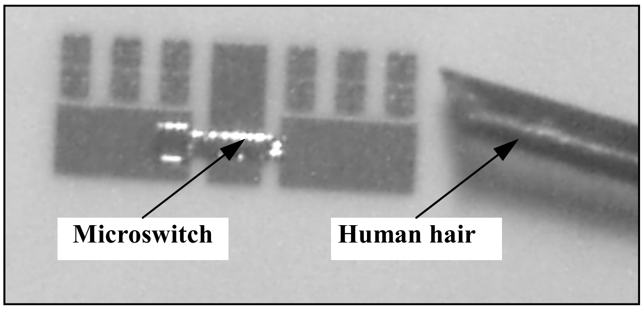


Fig. 5**. Comparison of 150 µm long microswitch with size of human hair**

currently extensively studied worldwide since their performance combines best attributes that are characteristic to current switching technologies. Firstly, due to small size they can maintain high integration levels of solid-state switches (i.e. field-effect transistors and p-i-n diodes). Secondly, they exhibit electrical performance similar to traditional electromechanical relays, namely, low contact resistance and the complete isolation between actuation and contact circuits. Moreover, due to electrostatic actuation microswitches are characterized by low power consumption, which results in higher efficiency. As compared to semiconductor devices, they exhibit higher linearity and consequently lower signal distortion. Other advantages include higher radiation resistance as well as superior tolerance for high temperature environments. However, what is most attractive is that due to technological compatibility they can be integrated with other electronic devices into conventional integrated circuits. Due to these unique properties, microswitches have the potential to replace electromechanical relays and solid-state devices in significant market areas, particularly in automated test equipment, telecommunication systems, wireless applications, battery-operated equipment, industrial and medical instrumentation [1].

Configuration of the fabricated MEMS switch is shown in Fig. 3. Its main structural element is a microcantilever element 9, which is bimetallic and made of layers of nickel and gold with thickness of 3.0 μm and 0.2 μm respectively. The width of the beam is 30 μm and the length ranges from 67 to 150 μm. When the voltage is applied to the actuation electrode (gate) 6, the beam is pulled down by the electrostatic force until the switch closes. When the gate voltage is removed, the restoring force of the beam returns it to its original position. The beam has contact tips 8 at the free end, which are small by design and serve both to increase the pressure of electrical contact and to reduce the pull-in voltage, which is needed to close the microswitch. The spacing between tips and the contact electrode (drain) 7 is about 1 μm. As can be seen the free end of the beam is fork-shaped. This is meant to reduce the capacitance between the source and the drain and therefore increase the breakdown voltage, i.e. the potential between the source and drain that can actuate the switch and cause excessive currents to flow thereby destroying the switch.

Experimental procedure and results

Schematic representation of the LDV measurement setup used for experiment is shown in Fig. 6. Its main component is Ometron laser Doppler vibrometer VH300+ type 8329, which is based on Michelson interferometer and uses a HeNe (λ=632.8 nm) continuous wave laser as a coherent light source. The LDV is mounted on the tripod and is perpendicularly directed upon the substrate that is rigidly put into a fixture attached to electromagnetic shaker. The shaker is connected to harmonic signal generator via an amplifier. The measured vibrations are recorded by PicoScope® PC oscilloscope and analyzed with the computer using spectrum analyzer software.

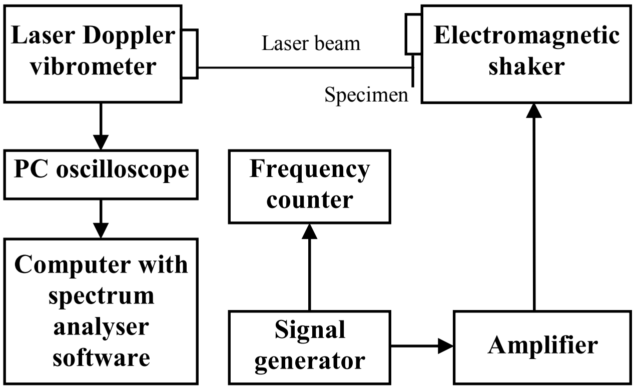


Fig. 6. **Block representation of experimental setup for dynamic measurements with laser Doppler vibrometer**

By using the setup above experimental modal analysis was performed on the substrate with the purpose of detecting vibrations of the microcantilever element of the microswitch and determining its fundamental frequency, which is very useful for validation and correction of the currently developed mathematical model of the microswitch. Firstly, the free end of the substrate was excited mechanically by impact. Using the obtained curve of damped free vibrations (Fig. 7) the fundamental frequency was determined to be approximately 918 Hz. In order to verify this value the fundamental frequency was also determined by applying harmonic excitation to the substrate and measuring vibration amplitudes. The obtained time and frequency responses, shown in Fig. 8 and Fig. 9, confirm that the value of 918 Hz is correct. However, the finite element analysis of the microcantilever element indicates the fundamental frequency to be between 100 kHz and 150 kHz depending on the length. Therefore it is obvious that the LDV measurement system detected vibrations of the substrate but not the microcantilever. Efforts were made to capture vibrations of the microcantilever by repeating the experimental procedure with laser beam directed to different locations on the substrate. Unfortunately, this did not give positive outcome.

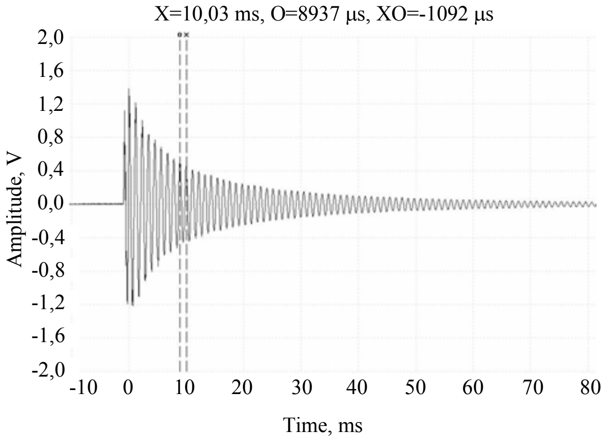


Fig. 7. **Experimental curve of damped free vibrations of the substrate with the microswitches fabricated on it**

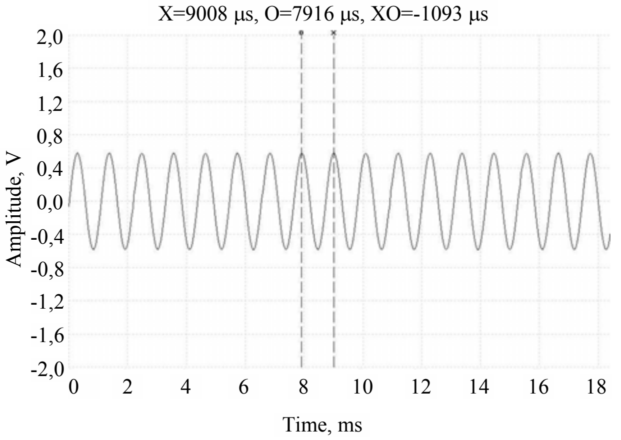


Fig. 8. **Measured time response of the substrate when excited by harmonic signal**

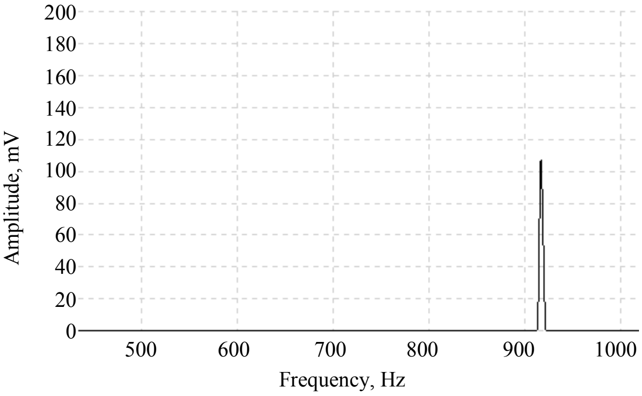


Fig. 9. **Frequency response characteristic of the substrate with the resonance peak at approximately 918 Hz**

Discussion

The employed LDV experimental setup, though successfully measured vibrations of the substrate (i.e. macrostructure), was unable to capture dynamic response of microcantilever elements. Their small size, sub-micron scale amplitudes and very high natural frequencies were major challenges for our conventional LDV measurement setup. For successful dynamic measurements on the microcantilevers and other microstructures undergoing out-of-plane vibrations some significant improvements are therefore necessary for the current experimental setup. First of all, an advanced high-frequency laser Doppler vibrometer is required with the resolution in the picometer range and ability to detect vibration frequencies at least up to 150 kHz. Secondly, an optical microscope is needed to be coupled to the LDV for focusing the laser beam on a spot size of a few (tens) micrometers. This is important since the velocity is averaged over a spot area and the motion of the tiny features of the microstructure can only be measured by a small spot [4]. Thirdly, a new excitation method must be applied since the current electromagnetic shaker has a limited frequency range. The most viable solution for excitation of microstructures to their high values of natural frequencies would be the use of piezoelectric shaker. Furthermore, vibration isolation table is necessary for protection of the delicate microstructures from unwanted vibrations. Lastly, for determination of mode shapes scanning capability must be introduced into the LDV measurement system by using set-up with mirrors to move the laser beam manually by two micrometer screws in x-and y-direction on the specimen. Automatic scanning of the sample by means of piezoactuators would be more effective and accurate way of obtaining mode shapes of the microstructure.

Conclusions

Applicability of the laser Doppler vibrometry for dynamic characterization of microcantilever element of fabricated electrostatic microswitches was considered in the paper. It was demonstrated that the employed conventional LDV measurement system is not able to detect out-of-plane vibrations of the microstructures. Their submillimeter-scale dimensions and submicrometer-scale vibration amplitudes as well as associated high natural frequencies were major challenges for our LDV setup. Therefore its insufficient resolution, large laser beam spot area, limited range of detectable vibration frequencies as well as low excitation frequencies, non-isolated vibration environment are considered to be key factors that should be taken into account when upgrading the current LDV measurement system.

References

1. **Daukševičius R., Ostaševičius V., Bubulis A., Gaidys R**. Modeling of surface-micromachined electrostatically actuated microswitch. Proceedings of the international conference. Mechanika-2004. Kaunas: Technologija. 2004. P. 448-453.
2. **Bosseboeuf A., Petitgrand S.** Characterization of the static and dynamic behavior of M(O)EMS by optical techniques: status and trends. Journal of Micromechanics and Microengineering. 2003. No. 13. P. 23–33.
3. **Rembe C., Kant R., Muller R. S.** Optical measurement methods to study dynamic behavior in MEMS. Proceedings of SPIE. 2001. Vol. 4400. P. 127-137.
4. **Ozdoganlar O. B., Hansche B. D., Carne T. G.** Experimental modal analysis for microsystems. Proceedings of 21st International Modal Analysis Conference (IMAC). 2003. P. 26-38.
5. **Castellini P., Marchetti B., Tomasini E. P.** Scanning laser Doppler vibrometer for dynamic measurements on small- and micro-systems. Proceedings of SPIE. 2002. Vol. 4827. P. 486-493.
6. **Lawrence E. M., Speller K. E., Yu D.** Laser Doppler vibrometry for optical MEMS. Proceedings of SPIE. 2002. Vol. 4827. P. 80-87.
7. **Schnitzer R., Rummler N., Michel B.** Laser-based modal analysis of smart electronic structures. Proceedings of SPIE. 2002. Vol. 4827. P. 88-93.
8. **Lyshevski S. E.** MEMS and NEMS: systems, devices, and structures, Boca Raton [etc.]. 2002. P. 461. ISBN 0-8493-1262-0.
9. **Gad-el-Hak M.** The MEMS Handbook. CRC Press. 2002.

R. Daukševičius, A. Bubulis, V. Jurėnas, V. Ostaševičius,
S. Tamulevičius

Gembinės mikrokonstrukcijos dinamikos tyrimas lazerinės Doplerio vibrometrijos metodu

Reziumė

Pateikti KTU sukurtos elektrostatinės mikrorelės gembinės mikrokonstrukcijos virpesių tyrimo lazerinės Doplerio vibrometrijos metodu pradiniai rezultatai. Nustatyta, kad esamas lazerinių matavimų stendas gali registruoti tik plokštelės, ant kurios yra mikrorelės, virpesius ir dėl itin mažų mikrokonstrukcijų matmenų, virpesių amplitudžių bei itin aukštų savųjų dažnių yra netinkamas juos tirti. Pasiūlyta, kaip matavimų stendą patobulinti, kad ateityje būtų sėkmingai tiriamos mikrokonstrukcijų dinaminės charakteristikos.

Pateikta spaudai 2004 08 16