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New laser excitation method for modal analysis of microstructure

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ABSTRACT

A novel impulse laser excitation technique to determine the dynamic response of micro-electro-mechanical systems (MEMS) has been investigated. During the laser excitation experiments, MEMS structures are excited by the wide-band impact force created by the laser–target interaction, and Laser Doppler Vibrometer (LDV) is introduced to measure the vibration velocity of MEMS structures. A distinguishing characteristic of the methodology is that both the excitation and measurement are non-contact, which is especially suitable for the testing of MEMS microstructures that are not easily accessible. This novel excitation method and MEMS modal analysis system are verified by experiments on various cantilever beams. The results show that the laser excitation is capable of exciting the first three modes of cantilevers.

1. Introduction

Micro-electro-mechanical systems (MEMS) as a newly emerging technology have very broad application prospects. With the advance of MEMS manufacture technology such as micromachining technology, LIGA technology and chemical corrosion technology, numerous micro-sensors, micro-actuators and various mirror arrays have been created and manufactured [1]. Owning to the small size and high resonant frequency of MEMS, the traditional modal analysis methods cannot be applied to microsystems directly. Microsystems are much more complicated, and no dynamic analysis method can be applied to all kinds of microstructures. Therefore, new and accurate structural dynamics identification methods are essential to the in-depth study of microstructures' behavior.

Traditionally, experimental modal analysis is usually employed to evaluate the dynamic characteristic and predict the performance, effectiveness and reliability of micro-structures, as well as to extract, confirm and calibrate analytical and numerical models. Experimental modal analysis involves (1) exciting the tested structure with a known force, (2) measuring the impact force and the corresponding structural responses, and (3) extracting required modal parameters from measured data [2]. Excitation of microstructures is the major challenge for MEMS modal testing. The characteristics of excitation have a great impact on modal analysis results. Considering this, numerous excitation methods have been proposed and employed to evaluate the dynamic behavior of microsystem. The existing excitation method for MEMS can roughly be classified into three categories: base excitation, embedded element for excitation and outfield energy excitation [3].

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In base excitation, the excitations are usually applied to the base structure. After the excitation, the testing microstructures mounted on the base structure are being excited and come into vibration. Base excitation with piezoelectric shaker or piezo-actuator to excite the microstructures is one of the most used base excitation methods [1,4–6]. Electrical discharge excitation, which uses an electrical discharge pulse strikes the base to provide a wide band excitation, is also used [7,8]. Although base excitation is mature and easy to apply, structural coupling of base and tested structure cannot be ignored. What is more, the exciting force exerted to tested structure can hardly be measured.

In embedded element excitation, the excitation force is applied on microstructures rather than on base. A distinguish character of embedded element excitation methods is that they require additional coating materials be integrated into the tested microstructures or attached to the boundaries. Electrostatic, electromagnetic and thermal excitation are typical examples of this excitation method, they use a coating layer in the microstructures and an outside electrode to generate electrostatic excitation force [9–11]. Disadvantages of these excitation methods include that the additional coating materials will substantially alter the inherent characteristics and affect the performance of the tested structure. So these methods can only be applied in specified areas where embedded materials have little influence on the measured characteristics of microstructure.

Outfield energy excitation includes bulk acoustic wave (BAW) hammer [12,13], air hammer excitation [14] etc. BAW hammer uses a pulsed ultrasonic transducer to generate impact force, and air hammer excitation use pressurized air to generate air impulse force. Obvious features of these methods are non-contact excitation and no additional coating material, which means the excitations have little influence on inherent characteristics of microstructure. However, the excitation processes is inconvenient to operate, because the acoustic wave is hard to concentrate on one tiny area of the microstructure, and the air pulse excitation force is hard to control, and the equipment device is very complex.

In this paper, a novel laser excitation method for the modal analysis of microstructures is proposed. The laser impact force comes from the interaction of focused laser beam and target materials. A modal testing system is set up which uses the laser impact force as excitation, and uses Laser Doppler Vibrometer (LDV) to measure the vibration of microstructures. In Section 2 we will introduce the theory of this laser excitation method. The distinguish features of this excitation include the following: the excitation source can be remote layout, the excitation direction is controllable, and the excitation can be completely non-contact. The non-contact nature of this methodology is very promising for a number of experimental activities in the microsystems fields.

2. Laser excitation theory

Laser has been widely used in many fields. The mechanical effects of laser have been employed to areas such as laser shock processing [15], laser propulsion [16,17] etc. Laser–target interaction's short duration and controllable impact force inspire us to consider its application in the excitation of MEMS dynamic analysis.

The laser impact excitation used in this paper can also be called the laser impact hammer. Laser impact hammer has the capability to excite the modes of interest, because laser–target interaction duration can be very short and impact force is controllable (through controlling the value of single-pulse laser energy). When a focused high-power laser beam is acted upon a solid target, surface materials of the target will be heated up, melted, vaporized, and then plasma is formed. The high-temperature and high-pressure plasma generated at the target surface can induce mechanical impact and thermal shocks to the target. During laser–target interaction, the target material gets momentum transfer. The interaction between focused laser and target material is the excitation source of our MEMS modal analysis experiment. In laser excitation, there are inevitable material loss of target material and heating effects that will influence material properties. To minimize the influence of material loss and heating effects, we use pulse laser to excite the microstructures and use only one pulse laser to excite the target at each tested structure. In this way, these influences can be neglected.

The principle of laser excitation is similar to traditional impact hammer, but more controllable and repeatable than that of hand held hammer. The impact force can be altered through controlling the single-pulse energy of excitation laser. For specified laser energy, the value of impact force and its distribution are nearly the same. Considering that the effective frequency band of the laser impact force is inversely proportional to the impact duration, the shorter the impact duration is, the larger the bandwidth of excitation frequencies. With the increasing development of laser technology, femtosecond laser equipment has been created. So laser impact excitation has the advantage of broadband frequencies, which is especially suitable for excite microstructure with high natural frequencies.

In our experiments, the excitation laser is employed to excite the microstructure. When the high-energy focused laser acted upon the stationary target, the target was excited into vibration. Fig. 1 shows the impulse time response of the cantilever. Here the velocity increase time in Fig. 1 is defined as response time delay Δt. From the transient vibration velocity we can determine that the time delay $\Delta t \approx 30\ \mu s$. The laser impact force plays the main role in the first part of this period, and then structural inertia plays the main role later, so impact duration is much shorter than $30\ \mu s$. This impact duration is much shorter than many other excitation methods, and the frequency band of excitation is wide enough to excite many microstructures. This characteristic is quite favorable for the dynamic testing of microstructure. During the laser–target interaction, the cantilever starting from standstill to vibrate with velocity at 0.16 m/s, and mean acceleration 5000 m/s^2.