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A digital measurement system based on laser displacement sensor for piezoelectric ceramic discs vibration characterization

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ABSTRACT

This study describes the innovative design of a digital measurement system based on a laser displacement sensor (LDS) as a vibrometer which is capable to measure a dynamic displacement response dependence on a stimulated vibration. The frequency response of a piezoelectric ceramic disc is obtained by processing the input/output signals obtained from the function generator and digital oscilloscope (digitizer) cards driven by a personal computer. Resonant frequencies of vibration are achieved utilizing the swept-sine signal excitation following the peak values in the signal response measured by LDS. The analogue signal from LDS controller represents directly a mechanical vibration of a piezoceramic disc. The test measurement results indicate that the system can distinguish resonance frequencies of piezoelectric ceramic discs up to 40 kHz with the resolution 1 Hz. Piezoelectric coefficient d_{33} and its linearity along the excited voltage amplitudes have been calculated by the applied methods as a demonstration of a successful system concept. The results achieved are in compliance with the reference value declared by the manufacturer of the piezoceramic disc.

1. Introduction

Vibration measurement and its analysis play a key role in an industrial and laboratory research, i.e. for the machinery diagnosis [1] or piezoelectric sensors/actuators characterization [2]. Mechanical displacement of the vibrating surface (object) is defined as a distance from the reference zero position (in equilibrium state). Generally, the measurement of the vibration can be realized by contact or noncontact measurement methods [3,4]. The vibration can be described in terms of measurement of displacement (m), velocity (m/s) and acceleration (m/s^2) separately or simultaneously, in a given frequency range. Acceleration of the vibration is measured mostly with piezoelectric sensors.

Piezoelectric ceramic (piezoceramic) sensors can be used as accelerometers with an integration of the measured acceleration signal to get the velocity signal on the output. Piezoceramic actuators serve mainly to produce mechanical or acoustical dynamic power based on its excitation. The mechanical displacement characterization is crucial in the processes of piezoceramic actuators development and application. The analysis of the measured signals can be performed in time or frequency domains. In the first method, time monitoring of actual and effective values of the measured signals is performed. The second method, frequency domain analysis, is commonly used in signal analysis of an amplitude and a phase. These frequency spectra can be calculated from one record of the time signal as a random noise excitation (one pattern in the given frequency region) or by a swept-sine generation of the excitation voltage signal with the sensor/actuator dynamical response measured simultaneously.

The dynamic testing of piezo-structures includes an excitation (random noise and swept-sine) methods with vibration measurement techniques which can be divided into two types: noncontact optical methods and methods with an embedded sensing element [4]. In a piezoceramic actuator field of investigation, the vibration measurement should be contactless; otherwise, the contact sensing will influence the vibration of the vibrating mass/surface

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itself. Moreover, in a noncontact vibrometry, a sensor is not influenced by the temperature of the studied surface. These vibrometry systems have been developed as a multiparametric for multichannel analysis when dynamic parameters are studied. The vibration sensing performing is done by interferometric optical methods with application of lasers. The optical systems are based mostly on the principle of Michelson interferometer and the Doppler Effect. Laser interferometer vibration measurement technique is widely employed due to its higher sensitivity and precision [5].

The convenient way is to utilize a laser Doppler vibrometer (LDV) system [3,5] which is used to perform noncontact vibration (displacement, velocity, acceleration) measurement of the material surface. The laser beam from LDV is directed to the studied surface. The amplitude and frequency of LDV output signal depend on the vibration and are deducted from the Doppler shift of the reflected laser beam due to the surface's motion.

Nowadays, piezoelectric ceramic discs (PCDs) are used in many areas such as health monitoring of steel structures [6] using thickness modes study of piezoelectric patches, in electricity storage systems for power harvesting [2,7] by converting a mechanical energy into an electrical one, in monitoring a body structure of aircrafts [8], in the moving parts of the mechatronics systems [9] where a piezoelectric strain sensor for damping and accurate tracking control of a high speed nanopositioning stage in an atomic force microscope is utilized. PCDs are used in such voice stimulators as a buzzer, microphones, head phones [10], for pressure measurement [11], in the underwater wireless ultrasonic communication [12], and in the medical equipment as a source of power for implantable sensors [13]. Focusing on the characterization of PCD, many investigators have used LDV systems to understand dynamic behavior of piezoceramic structures under operation conditions.

The vibrational displacement of a circular aluminum plate with a piezoelectric ring is employed for a noncontact ultrasonic transportation of small objects in [14]. Study [15] investigates the transverse and planar vibration characteristics of two-layered piezoceramic discs for traction-free boundary conditions by theoretical analysis, finite element numerical calculation, and experimental measurements using LDV. It was used to determine the resonant frequency of transverse vibration for two-layered PCDs [15]. The nonlinear vibration behavior of piezoceramics was observed [10] in the form of a resonance frequency dependence on the vibration amplitude and nonlinear relationship between the excitation voltage and the vibration amplitude using LDV. The nonlinear effect of a piezo-beam system with experimental setup was verified by finite element model [10]. LDV-based precision characterization system [16] has been explored to measure the three-dimensional dynamic motions of piezo-stack actuators within a wide frequency range. The application of the approach has been demonstrated by testing the two actuators. The measurement frequency range was selected as 0.5–100 kHz, a commercial LDV system [17] was used for the displacement measurements. An interferometric vibration measurement of PCDs is described in [5] as well. A system for the dynamic characteristic testing of MEMS micro-devices has been built based on a piezo-transducer as shock excitation source [4], the resonance frequency of the tested microstructure has been determined. The response characteristics of a spherically symmetric piezoelectric shell under random boundary micro-vibration excitations were analyzed and calculated in [8]. The applicability and limitation of the base excitation method combined with embedded sensing element for the dynamic testing of microstructures were discussed in [4]. Sensing and actuating transducer based on a lead titanium zirconium oxide (PZT) bimorph cantilevers for measuring point impedance to the moment is presented in [18]. The development of a resonant sensor to measure mass which has been built using cantilever structure with a piezoelectric excitation is described in [19].

A contactless vibration measurement represents the main aspect in the design of the above mentioned measurement systems in a digital form, as a computer-based. The precision of the vibration measurement is then related to the quality of the sensor (LDS), the measurement hardware as data acquisition (DAQ), the digital signal processing (DSP), and a control system as a computer. In such LDS-based vibrometry systems such parameters as resolution and sampling rate of analog inputs, AI, and analog outputs, AO, should be considered. Analog outputs are used to produce excitation signals, while on analog inputs a signal from LDV is acquired. Most of the recently published designs have utilized National Instruments (NI) measurement hardware and software, the LabVIEW™ graphical environment [3,5,16,17] or from other measurement hardware manufacturers [4,10,15].

1.1. Mechanical displacement and piezoelectric coefficient evaluation of PCDs

Piezoelectric materials generate a charge on the surface after applying a mechanical stress on it. The charge is roughly proportional to the force. This is called the direct piezoelectric effect. The potentials and the associated currents in piezoelectric materials are functions of the continuously changing mechanical deformations practically used in situations involving dynamic strains of an oscillatory nature [20]. In reverse the shape of a thin piezoelectric film of thickness t_p which has electrodes on its top and bottom surfaces is deformed if an input voltage V is applied across the film. If the piezoelectric film is used as an actuator, the film works under ac as well as dc voltage, since charges are supplied from a voltage source [21] and the film is deformed. The most used response of the piezoelectric films to the applied voltage is studied in the parallel direction (3-direction) of the electric field which causes the changes (elongation) of thickness, t_p, expressed as Δt_p. If the film is on a frictionless surface, a strain in 3-direction is developed and can be expressed as

$$\varepsilon_3 = d_{33}E_3, \tag{1}$$

where ε_3, d_{33} and E_3 denote the normal strain (in the elastic range) in the 3-direction, defined as $\Delta t_p/t_p$, the piezoelectric coefficient depending on materials and the electric field strength in the 3-direction [21]. If the direction of E_3 is reversed, the sign of the strain is also reversed. Eq. (1) can be rewritten for the film as

$$\Delta t_\mathrm{p} = d_{33}V. \tag{2}$$

The change in thickness is proportional to the applied voltage V but is independent of thickness t_p [21].

An excitation alternating voltage $V(t)$ can be defined as a periodic function of time by the following equation:

$$V(t) = V_\mathrm{peak}\sin\omega t, \tag{3}$$

where $V(t)$ is an alternating voltage (V), V_peak is the maximum amplitude of the excitation voltage (V), $w = 2\pi f$ is an angular frequency (rad/s), f is a frequency of the alternation (Hz), t is time (s). A piezoelectric material under an alternating voltage exhibits mechanical vibration as changes in Δt_p (elongation) according to the excitation voltage signal parameters (f, V_peak). An electromechanical resonance of the vibration occurs when the frequency of the applied electric field is equal to the frequency of the natural vibration mode system [21–23].

The electromechanical properties of the piezoelectric materials are characterized by coupling factor k, piezoelectric coefficient d, permittivity ε, Young modulus Y, elastic compliance s, etc. The coupling factor k is a measure of the efficiency of a piezoelectric