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Low cost vibrating reed mechanical spectrometer using capacitive current detection

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Abstract

Among the various mechanical spectrometers over the whole frequency domain, the vibrating reed system is an interesting variant owing to its convenient frequency range, the possibility of exciting additional vibration modes and its ability to study thin films. In this paper a low cost set-up for such a vibrating reed spectrometer is described. The basic idea of this resonance-measuring system consists of a pulse train excitation of the specimen and a capacitive current detection of the freely decaying vibrations. Both the hardware and software concepts of the system are described. An alternative numerical algorithm, based on a Hilbert transformation, to calculate the logarithmic decrement of a collected free decay is presented.

1. The vibrating reed technique

In a vibrating reed experiment a specimen with a suitable shape is clamped at one side in a rigid support [1, 2]. In the resonance method the free end of the specimen is mechanically excited, after which the excitation source is shut off. A rectangular specimen of length l and thickness h will vibrate freely with a frequency ν given by [3]

$$\nu=\frac{h\alpha_n^2}{4\times3^{1/2}\pi l^2}\left(\frac{E}{\rho}\right)^{1/2}$$

In this equation E is the Young modulus of the material, ρ is the density and α_n is a numerical eigenvalue for the nth harmonic (for the clamped–free case $\alpha_1=1.875$, $\alpha_2=4.694$, $\alpha_3=7.855$, ...).

Owing to the anelasticity of the material, the specimen will dissipate mechanical energy during the free oscillations. In this case of a small amplitude-independent energy dissipation the decrease in the relative amplitude of the vibration after each vibration cycle will be δ, the logarithmic decrement.

Various types of apparatus are described in the literature [*e.g.* 1–4], which are in most cases electronically of a closed-feedback-loop type. In this set-up an open-loop type is described in which a sequence of mechanical excitation and detection is continuously repeated.

2. Hardware details

The hardware of the present system consists of a stabilized d.c. high voltage source (0–500 V), a fast (200 kHz) 12-bit data acquisition (DAQ) board allowing analogue multichannel input and digital output, and a control box, as sketched in Fig. 1. The control box is connected with the specimen and electrode(s) surrounding the specimen. Thus an electrical path from the specimen to the control box has to be provided. This is not a limiting factor for insulating specimens, because a thin conductive film can be deposited on the specimen. The electrode(s) can be of two types: electrode(s) for combined generating and detecting and electrode(s) for detecting only. The functions of the control box are the switching of the high voltage source

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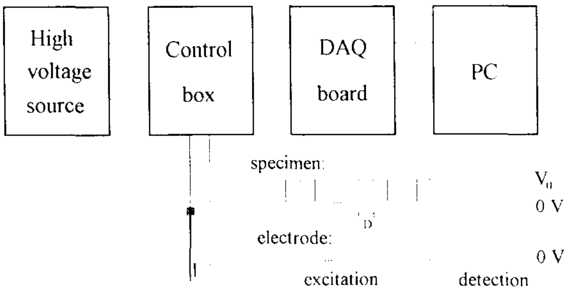

Fig. 1. Main hardware blocks (single-electrode set-up).

during excitation of the specimen and the capacitive detection of the freely decaying vibrations of the specimen.

During mechanical excitation of the specimen a voltage pulse train with amplitude V_0, duty cycle D and a frequency almost equal to the resonance frequency of the specimen is applied to both the specimen and the solely detecting electrode(s) (if present). The remaining electrode(s) are fixed at nearly zero potential. Owing to the periodic electrostatic force between the specimen and the combined generating and detecting electrode(s), the specimen will start to vibrate with a certain amplitude. In the case of a multiple-electrode set-up care should be taken in the relative positioning of the electrodes to avoid cancelling interference of the various generating electrodes. After applying a sufficiently high number of pulses, the vibration will have a steady state amplitude d_1. This amplitude can be influenced by changing the mean electrostatic power supplied to the specimen

$$P_S \approx \frac{\epsilon A V_0^2}{2d_0} D$$

in which A is the electrode–specimen surface area, ϵ is the dielectric constant and d_0 is the specimen–electrode distance. Either a decrease in the voltage V_0 or a decrease in the duty cycle D results in a lower vibration amplitude d_1.

After the mechanical excitation of the specimen the control box is switched to its measuring state, in which the specimen is now kept at high voltage and all the electrodes at nearly zero voltage. Owing to the absence of a periodic driving force, the specimen will vibrate freely. The changing specimen–electrode distances give rise to changing capacities, which in the measurement condition results in changing currents. The current from each electrode is transformed into a voltage. After amplification these signals are acquired by the DAQ board. We can derive an expression for this current. For a freely decaying vibration of the specimen we have as specimen–electrode distance

$$d(t) = d_0 + d_1 \sin(\omega t) \exp(-\delta \nu t)$$

(in which $\omega = 2\pi\nu$). The current then becomes

$$i(t) = V_0 \epsilon A \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{d(t)}\right)$$

Neglecting second- and higher order terms this becomes

$$\begin{aligned} i(t) = \frac{-V_0 \epsilon A d_1 \nu}{d_0^2} \Bigg[& 2\pi \cos(\omega t) \exp(-\delta \nu t) \\ & - \delta \sin(\omega t) \exp(-\delta \nu t) \\ & - 2\pi \frac{d_1}{d_0} \sin(2\omega t) \exp(-2\delta \nu t) \\ & + 2 \frac{d_1}{d_0} \delta \sin^2(\omega t) \exp(-2\delta \nu t) \\ & - 2\pi \left(\frac{d_1}{d_0}\right)^2 \cos(\omega t) \sin^2(\omega t) \exp(-2\delta \nu t) \Bigg] \end{aligned} \qquad (1)$$

Thus the detected signal consists of five terms. For low damping levels and low vibration amplitudes the second, fourth and fifth terms in eqn. (1) can be neglected. In these cases a basic term and a harmonic term remain. Digital bandpass filtering (Chebychev) of the collected data around the drive frequency yields the first term of eqn. (1), from which the logarithmic decrement and the resonance frequency can be calculated. Digital bandpass filtering of the collected data around twice the drive frequency results in the third term of eqn. (1), from which the relative vibration amplitude d_1/d_0 can be derived.

3. Software details

Various approaches to obtain the logarithmic decrement and the resonance frequency from the collected signals can be applied. In a very convenient classical way the logarithmic decrement can be obtained from the maxima and minima of the free decay and the resonance frequency from the zero transitions of the free decay. Other convenient methods are the nonlinear fitting of the collected data to the main term in eqn. (1) [5] and the discrete Fourier transform (DFT) analysis of the data as described by Yoshida *et al.* [6].

An alternative numerical treatment consists of applying a Hilbert transformation to the collected free decay. The Hilbert transform $h(t)$ of a real function $v(t)$ is given as

$$h(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{v(\rho)}{\rho - t} \, \mathrm{d}\rho$$

(in which the integral is a Cauchy principal value) [7]. A sine is transformed into a cosine and a damped sine into a damped cosine (for tables of transforms see *e.g.*

ref. 8). The Hilbert transform can be calculated using DFT algorithms [9].

Let $v(t)$ be the collected free decay and $h(t)$ the Hilbert transform of this free decay. Then the envelope and the phase of the free decay as a function of time can be easily obtained as

$$[v(t)^2+h(t)^2] \approx \exp(-\delta\nu t)$$

$$\tan^{-1}\left(\frac{v(t)}{h(t)}\right)=2\pi\nu t$$

This results in the logarithmic decrement and the resonance frequency of the specimen.

A simulation to compare this Hilbert transform method with the classical maximum method shows that the former is more noise insensitive, in such a way that even with a high noise level of the collected decay the internal friction can be derived within an acceptable error level. On the other hand, the proposed Hilbert transform method is sensitive to an offset of the collected free decay, which can easily be taken into account before applying the transform. Since most of the electronic parts of this set-up are software controlled, automatic measurements are possible. Such measurements *e.g.* as a function of temperature need feedback from the measured resonance frequency to the drive frequency of the pulse train. To obtain a constant vibration amplitude during the measurement, the duty cycle of the pulse train has to be changed with the changing damping level of the specimen.

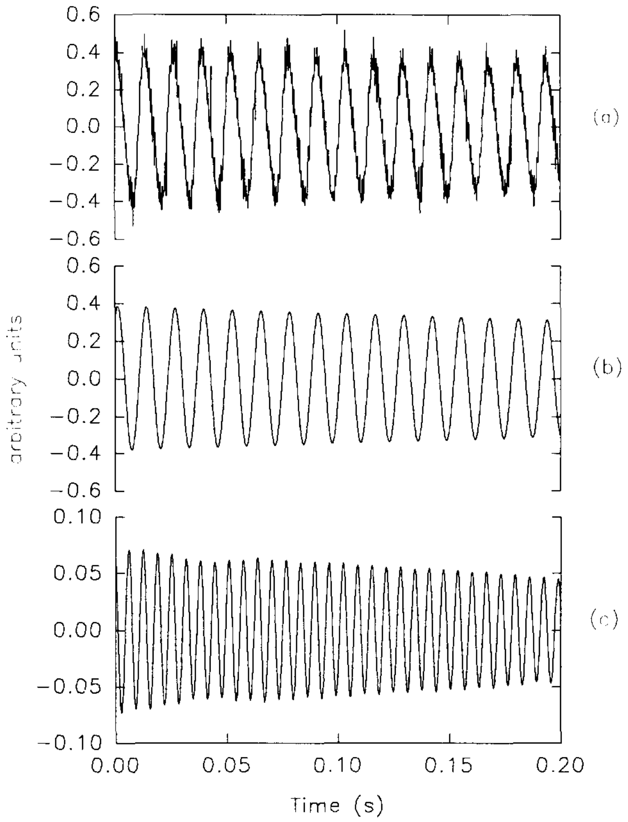

Fig. 2. First part of the collected free decay of a steel sample: (a) as collected; (b) after bandpass Chebychev filtering around ω (yielding the logarithmic decrement); (c) after bandpass Chebychev filtering around 2ω (yielding the relative vibration amplitude).

4. Results

As an illustrative result the collected free decay of a low damping material (commercial steel) sample is shown in Fig. 2 (room temperature). The specimen with dimensions $45\times7\times0.2$ mm^3 vibrated at 78 Hz, its fundamental mode. From the various signals the logarithmic decrement (0.01 in this case) and the relative vibration amplitude (18% in this case) can be derived. The specimen was excited by a pulse strain of 2000 pulses, a duty cycle of 0.5 and a V_0 of 50 V.

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