ARCHIVES OF ACOUSTICS
28, 2, 93—100 (2003)

THE INFLUENCE OF THE SURFACE LOAD EXERTED BY A PIEZOELECTRIC CONTACT SENSOR ON TESTING RESULTS: II. THE ELECTRICAL TRANSIENTS GENERATED BY PIEZOELECTRIC SENSOR

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The influence of a strong discontinuity wave on its measurement with a piezoelectric sensor was analysed analytically. The one-dimensional model of the mechanical contact between the ultrasonic sensor and the solid medium was developed. Part I of the paper contained the discussion of the displacement field in the solid, the analysis of electrical transients generated by piezoelectric transducer are given in this paper. The evaluation was made locally at the front of the distortion. It was found that the relative error of PZT transducer's indication ranges from 26% up to 70%. After a long period of time (depending on the mass M) the influence of surface loading becomes much smaller.

1. Model of electrical transients generated by a piezoelectric transducer

The propagation of the wave distortion in a piezoelectric transducer causes an electric flux [1] $D=\frac{\varepsilon}{h}U-\frac{e}{h}[u(L+h)-u(L)]$, where U – voltage between front and back faces of the transducer, $u(L+h)$ – displacement of back surface with coordinate $x = L + h$, $u(L)$ – displacement of front surface with the coordinate $x = L$, ε – electrical permeability by strain equal to zero, e – piezoelectric coefficient. The abbreviations L, h, x are concerned with Fig. 2 from [2]. The current in the transducer with a cross-section surface F_2 is equal to the derivative of electric flux in time $J=\frac{d}{dt}D\cdot F_2=\frac{\varepsilon F_2}{h}\frac{dU}{dt}-\frac{eF_2}{h}[v(L+h)-v(L)]$, where $\frac{\varepsilon F_2}{h}=C_0$ is the static capacitance of the transducer. Putting the static capacitance aside, the value of the output current of the transducer is

$$J=-\frac{eF_2}{h}[v(L+h)-v(L)]. \tag{1}$$

The electrical voltage which appear on the front and back face of the transducer under influence of mechanical distortion, causes in the same time on both boundary surfaces velocity waves which propagate in the transducer and the surrounding media. These phenomena will be left out of account in the next analysis. The indications of the piezoelectric transducer (visible on oscilloscope) are according to our model proportional to the relative change of the velocity of the end surfaces of the rod 2 and to the relation of transducer's cross-section surface F_2 to its thickness h. Let us assume that the relation F_2/h is constant.

2. The measurements of a strong discontinuity wave with a piezoelectric transducer

We want make an investigation of the relative change of the velocity of the rod 2 ends with coordinates $x = L + h$ and $x = L$ in the time interval $t \in \left(\frac{L}{a_1}, \frac{L}{a_1} + \frac{5h}{a_2}\right)$. It is worthy to analyze how the transducer behave when a strong discontinuity wave incidents on it.

For the time interval $t \in \left(\frac{L}{a_1}, \frac{L}{a_1} + \frac{h}{a_2}\right)$, the face of the disturbance has yet not arrived at the back face of the rod 2 with the coordinate $x = L + h$ but the electrical flux is present in the transducer because the steady state of the continuum was disturbed and the difference between the velocity of the front and back surfaces is $v_3(t) = \frac{2a_2 P_0 a_1}{(a_2 + \alpha a_1)\; E_1 F_1}$. For the time $t = \frac{L}{a_1} + \frac{h}{a_2}$, the velocity difference on both ends of the rod 2 is still equal to $v_3(t) = \frac{2a_2 P_0 a_1}{(a_2 + \alpha a_1)\; E_1 F_1}$, which results from the boundary condition for the velocity of back surface with a coordinate $x = L + h$ at this moment (see Part I, Appendix). The conclusion is that in this time interval the transducer indicates correctly the velocity of the loaded end of the rod 1. In the time interval $t \in \left(\frac{L}{a_1} + \frac{h}{a_2}, \frac{L}{a_1} + \frac{2h}{a_2}\right)$ after a little simple manipulation we achieve

$$\Delta v(t) = v_3(L, t) - v_5(L + h, t) = -\frac{2P_0 a_1 a_2}{(a_2 + \alpha a_1)\; E_1 F_1}\left[1 - 2e^{-k_1\left(t - L/a_1 - h/a_2\right)}\right]. \tag{2}$$

Figure 1 explores the range of validity of the formula (2) $\Delta v(t)$ for different values of the loading mass M. From the formula (2), it is possible to calculate that if the loading mass approaches zero $M \to 0$, then $\Delta v(t) \to -\frac{2a_2 P_0 a_1}{(a_2 + \alpha a_1)\; E_1 F_1} = -v_3(L, t)$. This value of the velocity approaches each curve in Fig. 1. But if the loading mass M increases, the time of stabilization increases too. Both the extreme values of the amplitude velocity are equal but they have an opposite sign. The conclusion is that the transducer measures first the velocity of the face of incident wave and after that the velocity of the face of the reflected wave.

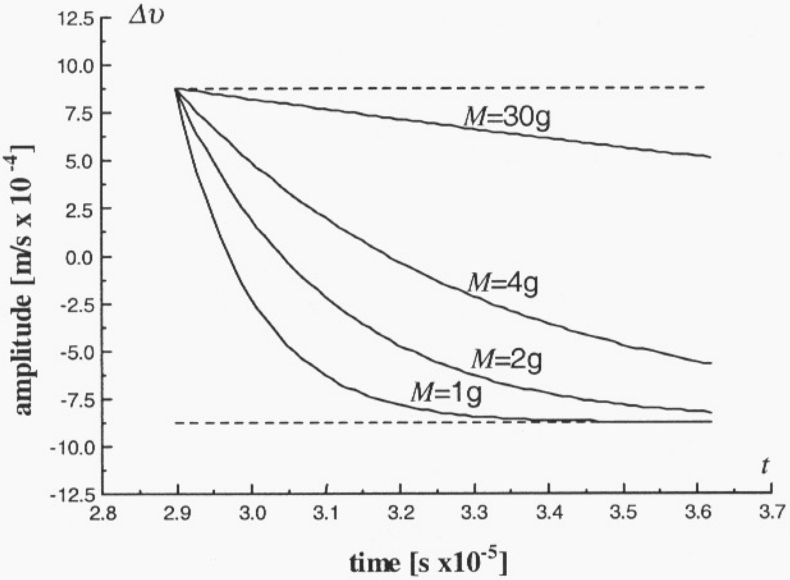

Fig. 1. The indication of the piezoelectric transducer as function of time for different values of the loading mass M (rod 1 from PVC).

The amplitude of the wave's velocity, which incident on the back face of the PVC rod, depends on the kind of transducer's material which is coupled to its back face. The velocity of the wave reflected from this interface has an absolute value equal to that of the incident wave after some time. The time after that both velocities are equal also depends on the kind of transducer's material and the mass M. Enlarging the mass M causes a lengthening of this time.

For the time interval $t \in \left(\frac{L}{a_1} + \frac{2h}{a_2}, \frac{L}{a_1} + \frac{3h}{a_2}\right)$, the difference in velocity of both ends of the rod 2 is

$$\Delta\upsilon(t) = \upsilon_7(L,t) - \upsilon_5(L+h,t) = -\frac{4P_0 a_1 a_2^2}{E_1 F_1 (a_2 + \alpha a_1)^2}$$
$$+ \frac{4P_0 a_1 a_2}{E_1 F_1 (a_2 + \alpha a_1)} e^{-k_1\left(t - \frac{L}{a_1} - \frac{h}{a_2}\right)} - \frac{8P_0 a_1 a_2 \alpha a_1}{E_1 F_1 (a_2 + \alpha a_1)^2} e^{-k_1\left(t - \frac{L}{a_1} - \frac{2h}{a_2}\right)}. \tag{3}$$

In this way we would determine the difference in the velocity of both ends of the rod 2 for the time interval $t \in \left(\frac{L}{a_1}+\frac{3h}{a_2}, \frac{L}{a_1}+\frac{5h}{a_2}\right)$:

for the time interval $t \in \left(\frac{L}{a_1}+\frac{3h}{a_2}, \frac{L}{a_1}+\frac{4h}{a_2}\right)$

$$\Delta \upsilon(t) = \upsilon_7(L, t) - \upsilon_8(L+h, t) = \frac{4P_0 a_1 a_2 \alpha a_1}{E_1 F_1 (a_2 + \alpha a_1)^2}$$
$$- \frac{4P_0 a_1 a_2}{E_1 F_1 (a_2 + \alpha a_1)} (1 - e^{-k_1 \tau})\, e^{-k_1\left(t - \frac{L}{a_1} - \frac{3h}{a_2}\right)} - \frac{8P_0 a_1 a_2 \alpha a_1}{E_1 F_1 (a_2 + \alpha a_1)^2}\, e^{-k_1\left(t - \frac{L}{a_1} - \frac{2h}{a_2}\right)}; \tag{4}$$

for the time interval $t \in \left(\frac{L}{a_1}+\frac{4h}{a_2}, \frac{L}{a_1}+\frac{5h}{a_2}\right)$:

$$\Delta \upsilon(t) = \upsilon_9(L, t) - \upsilon_8(L+h, t) = -\frac{4P_0 a_1 a_2}{E_1 F_1 (a_2 + \alpha a_1)} (1 - e^{-k_1 \tau})\, e^{-k_1\left(t - \frac{L}{a_1} - \frac{3h}{a_2}\right)}$$
$$+ \frac{8P_0 a_1 a_2 \alpha a_1 (1 - e^{-k_1 \tau})}{E_1 F_1 (a_2 + \alpha a_1)^2}\, e^{-k_1\left(t - \frac{L}{a_1} - \frac{4h}{a_2}\right)}. \tag{5}$$

Figures 2 and 3 illustrate these relations (3, 4, 5), the rod 1 is made of PVC or aluminum. The above results confirmed that for the time $t \le \frac{L}{a_1}+\frac{h}{a_2}$, the indication of the piezoelectric transducer is correct. The transducer measures the velocity in region IV of the right loaded end of the rod 1 (the incident wave). Since the velocity of the free end of rod 1 in the same time is $\upsilon(t) = \frac{2P_0 a_1}{E_1 F_1}$, the measuring error can be calculated of as $\frac{\Delta \upsilon(t)}{\upsilon(t)} = 1 - \varphi = \frac{\alpha a_1}{a_2 + \alpha a_1}$. For the rod 1 made of PVC and the PZT transducer its value is 70%. For the rod 1 made of aluminum and the PZT transducer this error is 26%.

We can conclude that in time interval $t \in \left(\frac{L}{a_1}+\frac{h}{a_2}, \frac{L}{a_1}+\frac{2h}{a_2}\right)$ the indication of the transducer changes its value at the beginning and depends on the mass M, but with increasing time it approaches the value of the velocity of the face of the reflected wave $-\upsilon_3(L, t)$ (from the interface $x = L$).

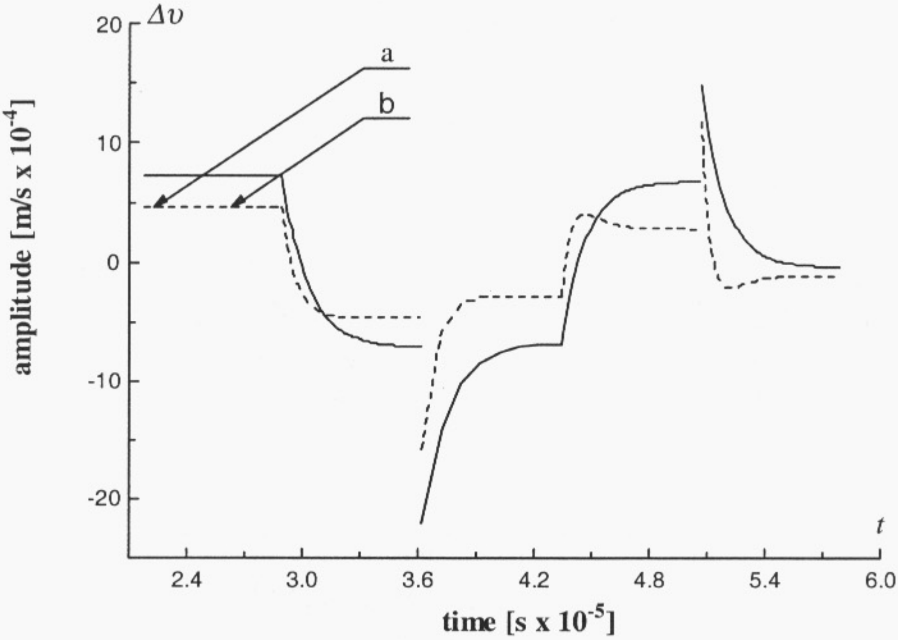

Fig. 2. Velocity $\Delta \upsilon$ as function of time for the PVC rod 1 loaded by: a) a PZT transducer, b) a quartz transducer (loading mass $M = 2 \times 10^{-3}$ kg).

For the time $t = \frac{L}{a_1} + \frac{2h}{a_2}$, $t = \frac{L}{a_1} + \frac{4h}{a_2}$ on the interface $x = L$, there is a rapid change of the value of the velocity wave's amplitude. A part of the incident wave energy is reflected and a part is transmitted back to the rod 1. The indication of the transducer in the remaining analysed regions changes in value and sign but with increasing time it approaches the value zero as the limit (the increase of the loading mass M causes a lengthening of this time). According to the proposed model of electrical phenomena in transducer, such situation exists when the velocities of the front and back faces of the rod 2 are almost equal. At this time we have in the transducer almost a steady-state of equilibrium. The conclusion from the above analysis is that by measurements of transient signals with a piezoelectric contact transducer we should measure the beginning of the signal. If it is not possible we should measure the difference of velocity amplitudes pick-pick in time $t = \frac{L}{a_1} + \frac{h}{a_2}$ and $t = \frac{L}{a_1} + \frac{2h}{a_2}$ or in the time $t = \frac{L}{a_1} + \frac{2h}{a_2}$ and $t = \frac{L}{a_1} + \frac{4h}{a_2}$. Such measurements are not as accurate as the measurement for the time $t \in \left(\frac{L}{a_1}, \frac{L}{a_1} + \frac{h}{a_2} \right)$ and have a systematic error, but it could be easier to realize.

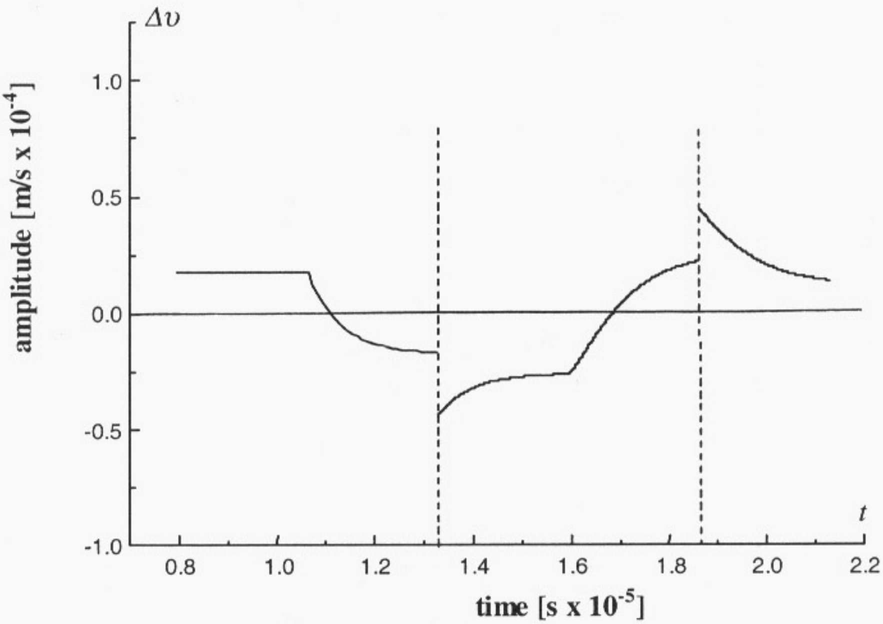

Fig. 3. Velocity $\Delta \upsilon$ as function of time for the aluminum rod 1 loaded with a PZT transducer (loading mass $M = 2 \times 10^{-3}$ kg).

3. The experimental results

During the experimental investigations, the PZT transducer was mounted on a thick plate made of PVC or epoxy constrained with glass fiber [3]. The impact excitation was generated with a pulsed Nd:YAG laser Q-switched. The puls width was 10 ns. In Fig. 4, a picture from oscilloscope of experimentally measured signal with time duration 0.5 μs is presented. According to our model, the amplitudes of the received signal are caused by the face wave reflections from the piezoelectric transducer's front and back faces. The experimentally indicated period of time between the extreme values of the amplitude of the following picks is $\Delta t_{exp} = 1.6 \times 10^{-7}$ s, while that one calculated analytically is $\Delta t_{calc} = 7.25 \times 10^{-6}$ s (Fig. 3). If we take into account the complicated structure of the PZT transducer and that the measurements were made in a plate (not in a rod), the agreement of both the results is satisfactory. The structure of the piezoelectric element can be very complicated and therefore the rise of the time of pulses and their amplitude are irregularly changeable. It is proposed to take as the signal's amplitude the extreme values of the differences of following picks just at the beginning of signal. Choosing these two picks is not so easy because the change of transducer's position on investigated material causes a change of the relations between the amplitudes of the following picks. Because of this fact it was decided to take in experimental investigations the amplitude of pick after the first reflection from the back face of the transducer. This value was taken as an indication of the PZT transducer.

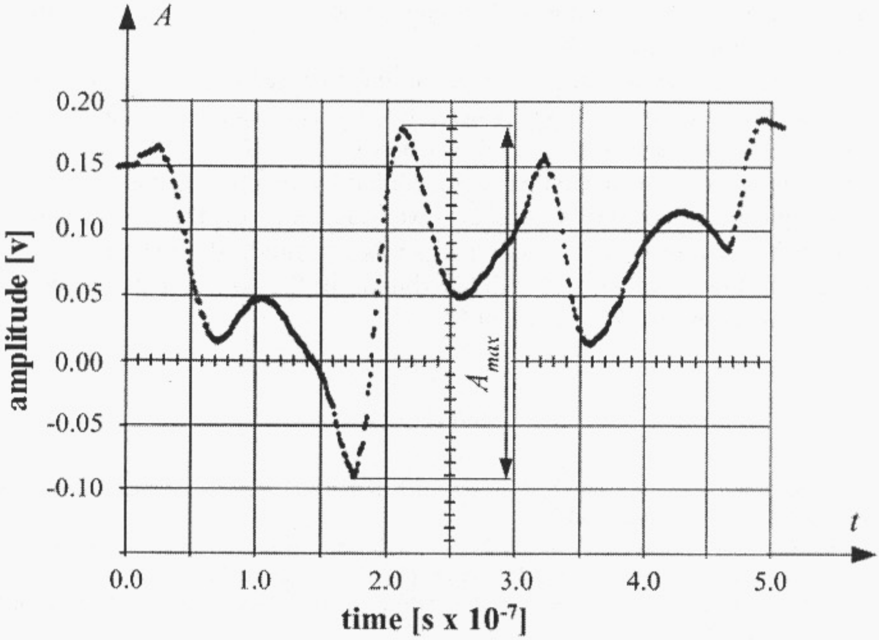

Fig. 4. Laser generated experimental pulse measured with a PZT transducer. Time duration of the measurement is 0.5 μs.

4. Final remarks and conclusions

Let us summarize the simplifying assumptions, which restrict the validity of the results presented here. The assumptions are:

1. The static capacitance of the transducer was left out of account;
2. The relation of the transducer's cross-section surface to his thickness is constant;
3. The analysis concerns local changes at the distortion front.

On the basis of above calculation results one can conclude that the intrusive influence of the contact PZT transducer in the tested specimens is extremely important in the initial period of time after the distortion occurs.

The PZT transducer measures the velocity correctly in the region IV of the right loaded end of the rod 1. As we are interested in the velocity of free end of the rod 1 at the same time, we have evaluated the error. The error depends on the type of the sample and the transducer applied. We could calculate it as 70% for the rod 1 made of PVC and a PZT transducer and 26% for the rod 1 made of aluminum and a PZT transducer. The mass M has no influence on the indication of the PZT transducer in the first analysed time interval because the evaluation is made locally at the front of the distortion wave. We can conclude that in time interval $t \in \left(\frac{L}{a_1}+\frac{h}{a_2}, \frac{L}{a_1}+\frac{2h}{a_2}\right)$ the indication of the transducer changes its value at the beginning and depends on the mass M, but with increasing time it approaches the value of the velocity of the reflected wave's face.

The indication of the transducer in the remaining analysed regions changes in value and sign but with increasing time it approaches the value zero as a limit (the increase of the loading mass M causes a lengthening of this time).

From the above analysis it can be concluded that by the measurements of the transient signals with a piezoelectric contact transducer we should measure the beginning of signal. If it is not possible, we propose to take as signal's amplitude the extreme values of the differences of following picks just at the beginning of the signal. This values should be taken as the indication of PZT transducer.

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[3] L. Radziszewski, *Propagation parameters of ultrasonic waves in polymer composites,* Archives of Acoustics **25**, 4, 465–478 (2000).