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Improving the Efficiency of the Ultrasonic Flaw Detector

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Abstract
In this paper, the physical principle underlying modern ultrasonic flaw detectors is considered. It is proposed a more effective algorithm for acoustic oscillation excitation. The phenomenon of electric damping was studied, a mathematical model of its realization was suggested and an experiment was conducted to confirm the above theory. The proposed way of modernizing the flaw detectors will increase the informative testing and reduce the dimensions of the device. This solution creates an opportunity to automate the system of data extraction and processing.

Keywords: non-destructive testing, ultrasonic flaw detector, electric damping.

1. Introduction

Today there is an urgent need for improvement, automation [1] and an increase in the performance of instruments and non-destructive testing systems [2]. More than 90% of the objects to be tested by acoustic methods use the reflection method (echo method). The quantity and quality of information received about the test object depends on the acoustic characteristics of adjacent materials, as well as the nature of the excited ultrasonic wave [3].
The resolution of the acoustic device depends on the frequency of the excited wave. An increase in the excitation ultrasonic wave frequency entails an increase in resolution. The geometrical resolution depends on the size of a quarter of the wavelength. If the size of the obstacle is less than a given wavelength, then the wave bypasses the obstacle without reflection. This factor determines the use of high-frequency oscillations as a method for defects searching. On the other hand, with a significant increase in the frequency of oscillations, the depth of testing decreases, since at high frequency we have a significant weakening of the signal level, this fact limits of the testing depth. The minimum testing depth is determined by the depth of the dead zone, which includes the duration of the probe sounding and the reverberation noise of the transducer. The echo-pulse method is used to measure the wall thickness of pieces and the presence of defects in them with one-sided access. When monitoring an object with a small thickness, the reflected signal returns earlier than the dead zone ends, which makes it impossible to detect a defect. To control objects with a small thickness, you should minimize the duration of the dead zone.

2. Background of problem solving

The main method of eliminating the dead zone is the use of a delay line [4]. The delay line is a prism with an acoustically transparent material that is glued directly into the piezoelectric element. The height of the prism is usually selected depending on the duration of the dead zone or the depth of the near zone. Delay lines are used to detect subsurface defects, which is impossible to find using a conventional ultrasonic sensor [5]. The main disadvantage of sensors with a delay line is pulse amplitude decreasing in several times after passing through the delay line, which limits the scope of application. Another way to reduce the dead zone is to damp the transducer. The most effective way of damping is the electric method, which greatly affects the quality factor of the sounding pulse [6, 7].

Let's consider the principle of operation of electrical damping and construct a mathematical model of the processes occurring in piezo transducers. In order for mathematical modeling to correspond to reality as much as possible, we take the real values of the quantities that will be used in the experiment. Namely, the amplitude value of the voltage *A = 5 V* and the resonant frequency of the ultrasonic sensor *f= 1.25 MHz.*

In general, the dependence of the amplitude of damped harmonic oscillations on time can be determined by the formula:

$$y(x) = A \cdot e^{-k \cdot x} \cdot \sin(2 \cdot \pi \cdot f \cdot x - \pi)(V), \quad (1)$$

where *f* – signal frequency, *x* – time, *k* – coefficient of attenuation.

In real closed systems, after the body receives some energy, it cannot remain unchanged. Energy is constantly transformed from one type to another to establish a balance. So, the energy of electrical and mechanical vibrations is transformed into heat and is expended on the performance of an effective action. Attenuation of harmonic oscillations occurs according to the exponential law (Fig. 1).

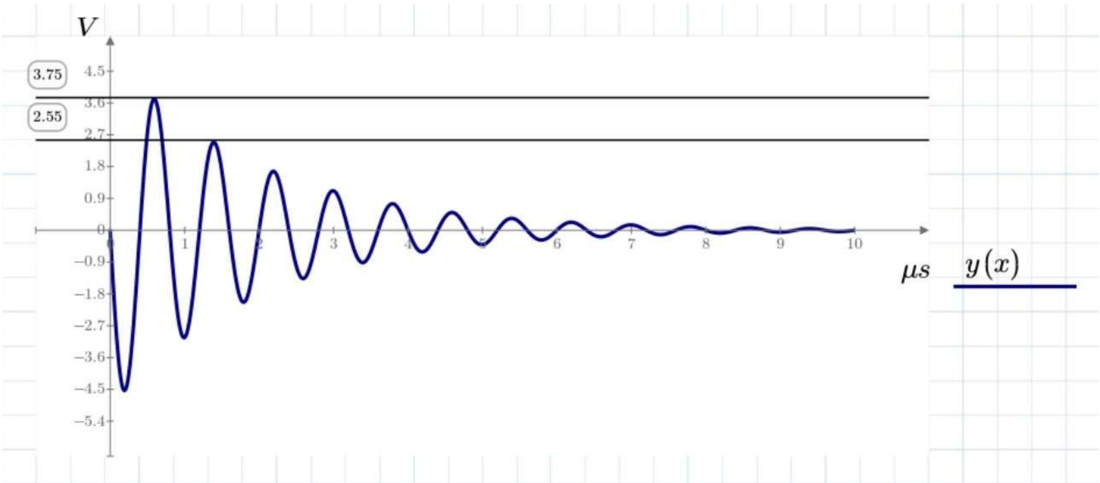

Figure 1. Attenuating harmonic oscillations (*k* = 0.5)

The total attenuation time of the oscillation depends on the level of the applied voltage and the frequency of the signal. During the experiment was determined duration of the dead zone, it was 8 – 10 μs.

The process of electrical damping involves grounding the piezoelectric element immediately after the completion of the sounding pulse formation. Since the piezoelectric capacity is several *pF* (pico farad), the discharge process occurs extremely quickly, namely at $T = 5\tau = 5RC$ (99.9% of the capacitor charge), where *R* is the sum of the resistances of the open MOS transistor and the resistance of the conductors (in our case, $R \approx 6 \div 10$ R ≈ 6 ÷ 10ohm), which in approximation gives us $T \approx 50 \div 200 ps$ T ≈ 50 ÷ 200ps. However, to increase the quality of the probing signal, it is necessary to increase the electrical damping time (t_{ed} t_{ed}) to at least half the oscillation period $t_{ed} = T_0 / 2$ $t_{ed} = T_0/2$. Since besides the capacitor charge energy, mechanical oscillations of the test object surface also affect the attenuation.

In order to describe such a damping process mathematically, function (1) must be divided into intermediate equations:

$$y(x) = \begin{cases} A \cdot \sin(2 \cdot \pi \cdot f \cdot x - \pi), t > x \geq 0 \\ A \cdot e^{-k \cdot x} \cdot \sin(2 \cdot \pi \cdot f \cdot x - \pi), 10 \geq x \geq t \end{cases} (V), \quad (2)$$

The first equation describes a zero-loss sensing pulse (*k = 0*). This is because the piezoelectric transducer is directly connected to the power supply. The duration of the first gap is equal to one oscillation period (the period is *t = 0.8 μs* for a sensor with a frequency of *f = 1.25 MHz*) after which the piezoelectric element is grounded. For the second equation, k was chosen by fitting. The main criterion for selection was the value of the p – n junction of the protective diode (≈0.65 V), since only after reaching this value, the capacitor will begin to discharge. In fig. 2 shows the attenuation of the harmonic oscillations at *k = 1.5*.

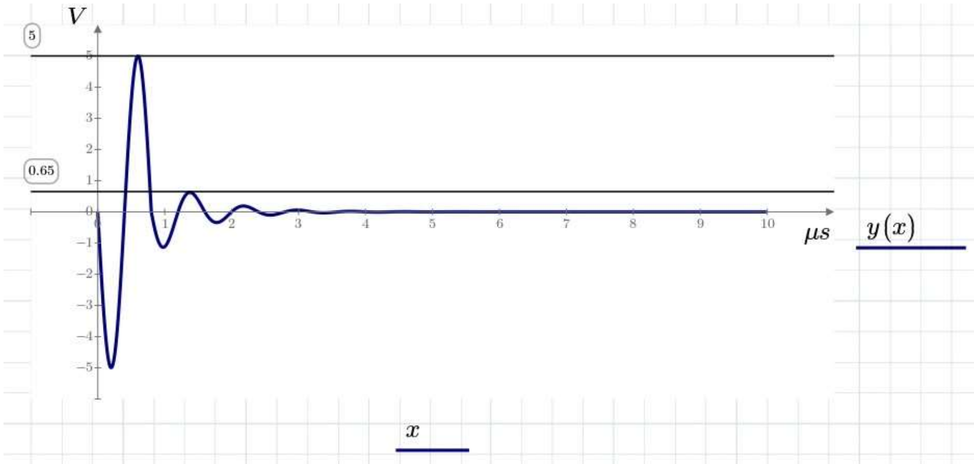

Figure 2. Application of electric damping to harmonic oscillations

As you can see, the attenuation time in the case of electric damping significantly decreases, namely to 3 – 4 μs.

3. Conduct an experiment

The experimental data were obtained using a piezoelectric transducer with frequency *f = 1.25 MHz*. The total pulse amplitude is $V_{(p\text{-}p)} = 10V$. For a better signal display, readings were taken from an oscilloscope with a sampling frequency of *300 MHz*.
In fig. 3 shows the process of damped harmonic oscillations that occur when a piezoelectric sensor is connected without using electrical damping. The formation of the excitation pulse occurs in two stages. At the first stage, a negative half-wave with duration of 200 ns is formed. Then a positive half-wave is formed with duration of 400 ns.

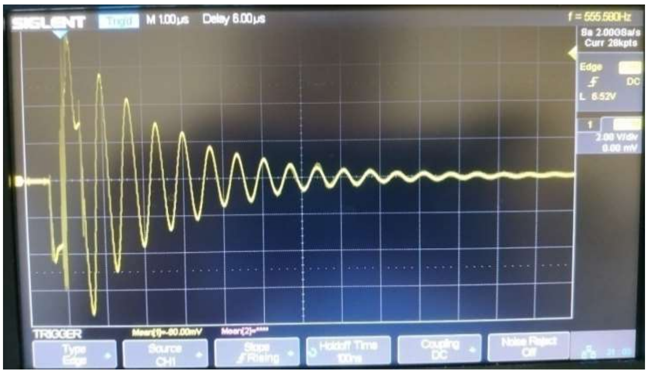

Figure 3. Harmonic oscillations of an ultrasonic transducer without damping

The picture clearly shows that the total amplitude of the signal ($V_{(A\ (pp))} = 15V$) exceeds the amplitude of the effective voltage, this can be explained by the quality contact of the sensor with the test object and the fact that the total energy consists of electrical and mechanical components. The sensing impulse itself undergoes significant distortions; this is due to mechanical noise. It does not affect its quality in any way. Let's take for comparison the eighth period, the positive half-wave of which the amplitude value is *1 V*.
In the image of Fig. 4 shows the effect of applying electrical damping on signal attenuation.

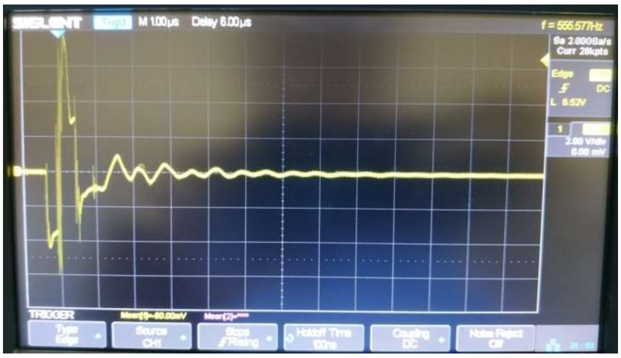

Figure 4. Harmonic oscillations of an ultrasonic transducer with electric damping

It can be noted that the sensing impulse has not undergone significant changes. The electric damping effect on the harmonic oscillation is obviously, the second oscillation period has completely disappeared, however, the third positive half-wave is clearly visible, the amplitude of which is *1 V*. Comparing this result with the previous image, we conclude that the effect of the proposed electrical damping qualitatively affects the signal quality.
The effectiveness of electrical damping has been tested experimentally on a number of some materials. Table 1 show the penetration depth of the ultrasonic signal, which corresponds to the reduction of the dead zone by 5 periods.

Table 1. Depth of the dead zone with electrical damping

Material	Penetration depth (mm)	Material	Penetration depth (mm)
Copper	7.1	Steel	11.8
Glass	9.6	Aluminum	12.5

4. Conclusions

Based on the ultrasonic flaw detector, the limitations arising during the inspection of materials were investigated. In order to improve the characteristics of the device, the excitation system of ultrasonic oscillations was revised, which led to the emergence of new ways of modernization.
According to the results of the study, a mathematical model was created that describes the processes that occur during the formation of an acoustic wave in a piezo plate. The influence of electric damping on the processes of oscillations damping is described.
The experimental results showed the adequacy of the proposed model. The use of electrical damping makes it possible to reduce the duration of the dead zone without losing the amplitude of the probe pulse, which qualitatively affects the result of the subsurface defects monitoring.

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