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PULSE AMPLIFIER USED IN ULTRASONIC NONDESTRUCTIVE TESTING

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The metal ultrasonic nondestructive testing by the echo-pulse procedure uses short ultrasonic pulses generated by a piezoelectric transducer in contact with the metal, both immersed in water. Short, high amplitude controlled energy electric pulses are furnished to the transducer and converted into short ultrasonic pulses which penetrate the examined material. After propagation through the material, they are reflected by the opposite surface or by the material internal discontinuities and are received by the same transducer which converts them, again, into electric echo-signals. Measuring the ultrasonic pulse round trip duration and supposing the same wave speed through the material is precisely known, the material dimensions and the discontinuities positions will be accurately determined. An algorithm correcting the errors due to the signal phase change on the transducer-material interface ensures an accuracy of 10^{-5} in dimension measurement in applications where high precision and sensitivity are asked, without using delay circuits or other procedures specific to such measurements.

The nondestructive ultrasonic testing equipment consists in a pulse generator exciting a piezoelectric transducer, an echo-pulse amplifier and a time interval measuring system.

In this paper, an echo pulse amplifier is presented, which is characterized by a variable 2–80 dB gain, a distortion factor $\delta < 0.8$ %, a signal-to-noise ratio < 1 % adapted to the impedance of a 17 MHz, spherically focalized ultrasonic transducer used for metallic tubes wall thickness measurement.

1. INTRODUCTION

A nondestructive ultrasonic equipment consists in a pulse generator exciting a piezoelectric transducer in direct contact with the tested metal, an electrical echo pulse amplifier and a time interval measuring system (TIMS). The generator furnishes short, high amplitude electric pulses to the transducer which converts them into short ultrasonic pulses which penetrate the inspected material. After propagation through the inspected material, these pulses are reflected by the material opposite surface or by its discontinuities. The resulting ultrasonic echo pulses excite the same transducer which converts them back into electric pulses; the echo electric pulses are amplified by a low noise amplifier. By measuring the ultrasonic pulse round trip duration and supposing the wave speed through the material is constant and precisely known, the material dimensions and the discontinuities positions will be accurately determined.

The ultrasonic wave propagation through a material is strongly influenced by the material microstructure mechanic and elastic properties; if these properties are modified, simple or multiple reflections, diffractions and spreading of the incident ultrasonic wave occur which alter the wave parameters. Inspection of these parameter modifications yields information on the investigated material structure discontinuities nature and dimensions.

The noteworthy parameters in the material ultrasonic nondestructive testing are: incident ultrasonic wave attenuation, amplitude of the echo-signals received from the internal discontinuities or from the walls, ultrasonic wave speed in the material, incidence critical angles (Rayleigh angle). At low frequencies, the attenuation is smaller, the penetration distance increases, but the capacity of close faults detection or small wall thickness measurement decreases.

In order to increase measurement resolution, a high frequency ultrasonic transducer must be used. In this case, the resulting echo pulses are short, with short rising edge and fall times (Fig.1), imposing certain requirements to the pulse amplifier.

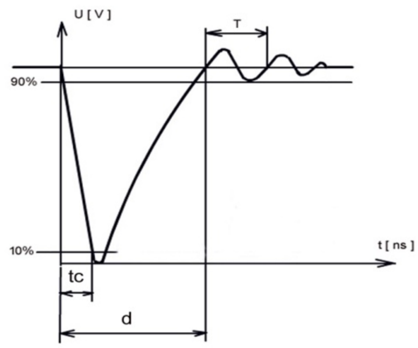

Fig. 1 – Pulse diagram: t_f = fall time; d = pulse duration; T = decaying oscillation period [1].

The piezoelectric disk oscillation amplitude is maximum if the pulse frequency spectrum is centered on the natural disk frequency f_c [1]. Ideally, the excitation pulse fall time must be equal to 70 % – 90 % of λ /4, where λ is the wavelength corresponding to the disk natural frequency.

An original pulse generator using bipolar transistors for exciting the piezoelectric transducer was designed by us [1].

The echo pulse amplitude is strongly dependent on the reflecting surface properties (form, surface, roughness, acoustic impedance, etc.). In most cases, it is recommended to measure the signal amplitude by comparison, using one of the following procedures:

– a single reflector technique: only one reference reflector is used for evaluating the echos occurring in the same distance range;

– amplitude in terms of distance correction technique (DAC): the echo pulses amplitudes reflected by a series of identical reflectors placed on the sound way at different distances in standardized blocks are used;

– distance-gain-dimension (DGS) technique; a series of theoretically determined curves are used, in correlation with the ultrasonic beam covered way, the amplifier gain and the dimension of a reflecting disk normal on the beam axis.

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The aim of this paper is the design of an echo-pulse amplifier.

The echo pulse amplifier necessary features have been examined by several researchers and different electric diagrams have been proposed, every one of them presenting good performance in a limited field.

High sensitivity and accurate gain control have been obtained by connecting in parallel a noise cancelling amplifier (NCA) and a transimpedance amplifier (TIA) [2] whose common inputs are connected through a 50 ohms coaxial cable to the piezoceramic disc (Fig. 2).

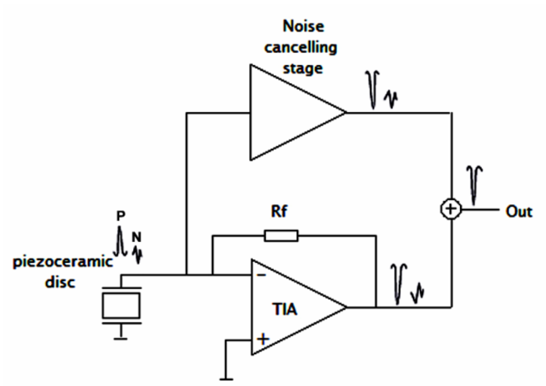

Fig. 2 – Low noise amplifier (LNA) employing noise canceling[2]; *P* = echo-pulse; *N* = noise.

The noise cancelling amplifier (NCA) contains a cascade of two stages: a MOS transistor voltage controlled stage and a common mode feedback reversing stage implemented with an operational amplifier. TIA is an integrated amplifier. For the circuit in Fig. 2 a noise reducing algorithm has been implemented ensuring a considerable radiofrequency noise reduction when the amplifier input impedance and the ultrasound echo-signal transducer impedance are perfectly matched. The frequency band is limited by the operational amplifier (3–10 MHz).

Another solution in pulse amplifier noise cancelling [3] consists in small level echo pulse conditioning and using an accurate comparator for their analog-to-digital conversion (Fig. 3).

The signal amplifier A_1, matched to the ultrasonic transducer impedance, is implemented by two operational amplifiers LTC 6248. A bandpass filter able to suppress all signals outside the used band is introduced between the transducer and the first amplifier stage. The A_2 output pulses are applied to an envelope detector (a Schottky diode precision rectifier) and, then, introduced in a low pass filter (LPF).

In this paper, a low noise bipolar transistor, time gain compensation (TGC) amplifier is proposed.

The gain of this echo-pulse amplifier may vary between 2 and 80 dB, its harmonic distortion factor is $\delta < 0.8$ %; its equivalent noise reported to the input is 7.5 nV/Hz; the amplifier is adapted to a 17 MHz spherically focalized ultrasonic transducer.

The amplifier gain is constant in the frequency bandwidth which is desirable in ultrasound NDT applications.

The pulse amplifier global transfer function compensates the steel or zirconium ultrasonic wave attenuation characteristic.

The circuit diagram ensures successfully a small power consumption necessary to portable equipments.

The paper is organized as follows: in Section 2, the pulse amplifier is described and some considerations on its design are given. The way the preamplifier matched to the transducer impedance and the low noise final amplifier are running is explained. Section 3 is dedicated to the accomplished experiments. In Section 4, the experimental measurement results are presented. The opportunity of using the proposed amplifier in a complex ultrasound metal tube dimensions measuring system is analyzed in Section 5.

2. PULSE AMPLIFIER DESIGN

The pulse amplifier electric diagram has been proposed after designing and analyzing several pulse amplifier circuits realized with commercial electronic devices (high frequency switching MOS and bipolar transistors) and after performing dimensional measurements on metallic tubes with a spherically focalized ultrasonic transducer (working frequency equal to 17 MHz and focal distance $f = 12$ mm.).

The circuit design takes into account the received echo-pulse characteristics and the ultrasonic transducer impedance and resonance frequency. It consists in two parts: a preamplifier and a final amplifier. The preamplifier is presented in Fig. 4.

The diodes D_1, D_2, D_5 and D_6 protect the preamplifier input from high amplitude pulses occurring when the excitation pulses are transmitted. In this way, the received negative pulses amplitudes on transistor T_1 basis are limited at the value $U_{Z2} + U_{D1}$. The transistor T_1 (2N2369) emitter is grounded in ac by the series dipole $C_{22} – R_3$; it amplifies the pulses applied on its input and adapts the piezoelectric transducer high impedance (according to the Butherford - Van Dike mode) to the preamplifier input impedance. The amplifier sensitivity increases as its own noise decreases. The smaller is the amplifier noise, the greater is its capability to amplify weak signals.

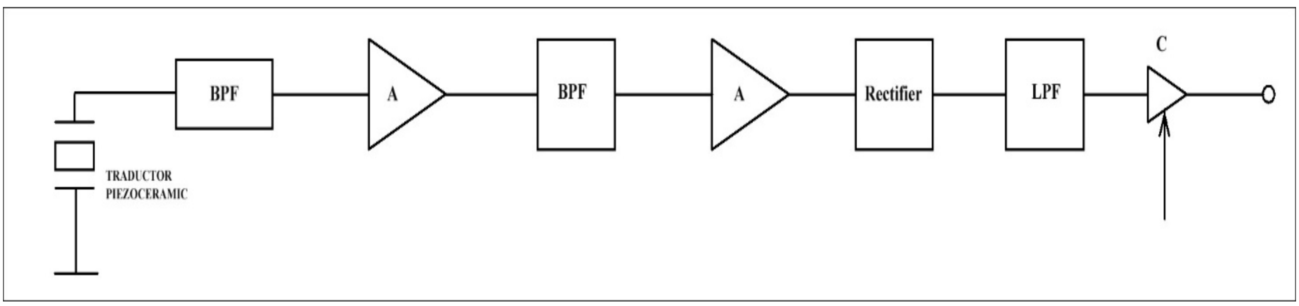

Fig. 3 – General architecture of the NDT amplifier: BPF – band pass filter; A – amplifier; LPF – low pass filter; C – comparator.

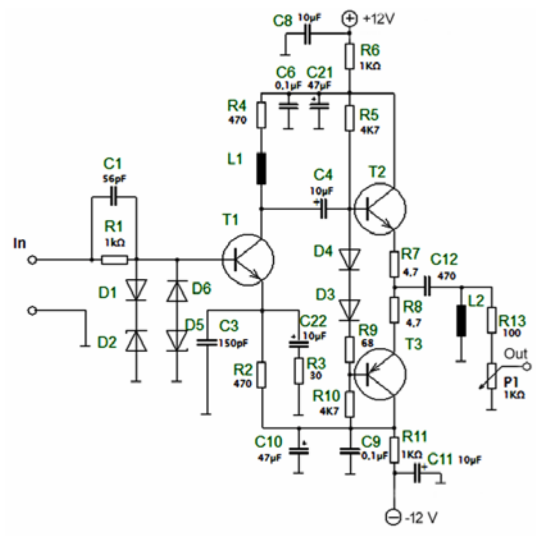

Fig. 4 – Schematic of the pulse preamplifier.

If the signal is absent, the noise power P introduced in the receiver may be expressed in terms of the frequency band, the receiver resistance R and the absolute temperature T in equation (1)

$$P = \frac{U^2}{4R} = kT(f_2 - f_1), \tag{1}$$

where U^2 is due to the signal source thermal noise and k is the Boltzmann constant [4].

The maximum preamplifier output noise power – considering its own noise equal to zero – for a frequency band equal to 1 Hz ($f_2 - f_1$ = 1 Hz) – is equal to kT. If the noise factor F is defined as

$$F = \frac{P}{kT}. \tag{2}$$

One says that the preamplifier sensitivity is big when the noise factor F is small, that is when its own noise power P is small. If A is the input receiver gain, the total output noise P_T is

$$P_T = kTFA(f_2 - f_1), \tag{3}$$

and the noise factor is

$$F = \frac{P_T}{kTFA(f_2 - f_1)}. \tag{4}$$

The final preamplifier stage is realized with the two complementary transistors T_2 and T_3. The low frequency components of the signal spectrum are not transmitted further to the final amplifier as they are filtered by the group C_{12}, L_2 (10 µH).

The second stage input signal level is adjusted by the potentiometer P_1 (1 kΩ/5 turns) mounted on the outside of the experimental equipment box.

The final amplifier is represented in Fig. 5. The transistors T_4, T_5, T_6 and T_7 constitute a 20 dB pulse amplifier and T_8 is a high amplitude final amplifier distributing the echo-pulses to the circuits video monitor (VM) evaluation gate generator (EGG) of the TIMS circuits. The amplifier input is protected against high voltage pulses by the diodes D_9 and D_{10} antiparallely connected. The amplifier sensitivity is not critical as the preamplifier output signal level is high enough (hundreds of mV).

In order to reduce the noise, RC and inductive filters have been utilized for suppressing the radiofrequency signals propagating from the source to the amplifier (group C_{15}, R_{21}, C_{13} or inductors L_3, L_4, L_5 and L_6).

The amplifier output echo signals amplitude is high enough (about some volts) for the TIMS logic circuits signal level.

The noise effect and the signal-to-noise ratio have been estimated using a simplified schema for the echo pulse amplifier chain (Fig. 6) from the piezoelectric transducer to the EGG output block [5–7]. If the signal received from the ultrasonic transducer is represented by $s_{in}(n)$ and the EGG output useful signal is represented by $s_{out}(n)$, the following equation results:

$$s_{out}(n) = A_{AF}\left[A_{PA}\left(s_{in}(n) + n_{PA}\right) + n_{AF}\right] + n_{EGG}, \tag{5}$$

where A_{PA} is the pulse amplifier voltage gain, A_{AF} is the final amplifier voltage gain, n_{PA}, n_{AF} and n_{EGG} are the input referred noise of the pulse amplifier, final amplifier and evaluation gate generator respectively.

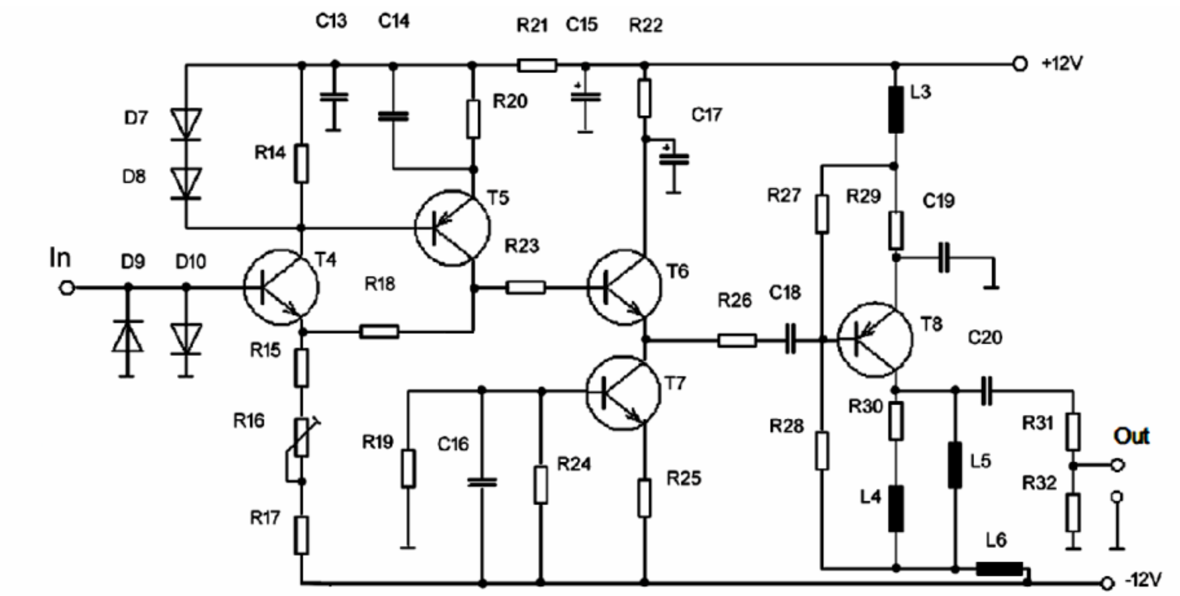

Fig. 5 – Schematic of the pulse amplifier.

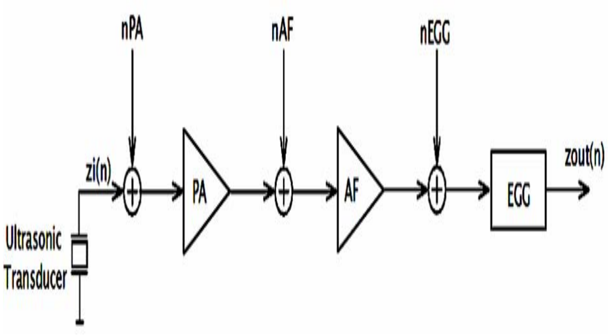

Fig. 6 – Ultrasound receiver noise model.

The system signal-to-noise ratio is:

$$\mathrm{SNR} = \frac{s_{in}(n)}{n_{PA} + (n_{AF}/A_{PA}) + (n_{EGG}/(A_{PA} + A_{AF}))} . \qquad (6)$$

3. **EXPERIMENTS**

Before the measurements, a calibration is always necessary.

In the experiments, a 17 MHz, spherically focalized ultrasonic transducer with a focal distance equal to 32 mm and a calibration block A_3, both immersed have been used.

The transducer was fixed within an immersed holder on the superior side of a water tank and the A3 calibration block according ASTME797 whose width ranges from 1 to 10 mm was immersed under the transducer (Fig. 7). In order to permit the ultrasonic beam to penetrate normally the transducer surface, the holder allows a 3D adjustment. In order to place the focal point within the calibration block, the distance between the transducer and the calibration block is adjusted. At the amplifier output the successive echo-signals received from the opposite side of the calibration block have been visualized on the oscilloscope.

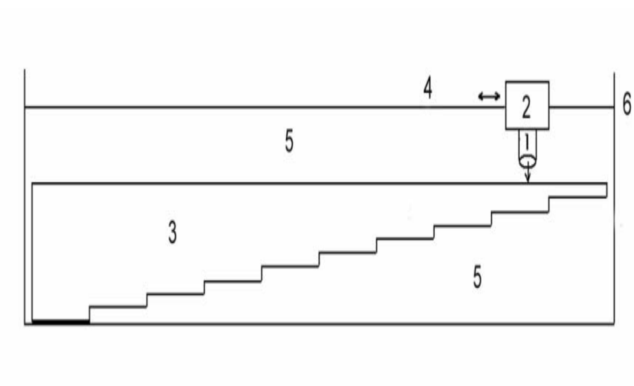

Fig. 7 – Experimental measurement stand: 1 – ultrasonic transducer; 2 – holder; 3 – the A3 calibration block; 4 – gear screw; 5 – water (ultrasonic couplant); 6 –water tank.

4. **RESULTS AND DISCUSSIONS**

The ultrasound speed has been determined at a temperature 20ºC, measuring the time interval *t* between two successive echo-pulses received from the opposite surface of the A3 block. As *t* was found equal to 0.677 μs:

$$v = \frac{2D}{t} = \frac{2 \times 2 \cdot 10^{-3}}{0.677 \cdot 10^{-6}} = 5900 \ \text{m/s}. \qquad (7)$$

The amplifier output echo signal amplitude is higher than 5 V, great enough for the logic circuits which control the wall thickness measurements.

The echo pulse duration, smaller than 10 ns doesn't influence the measurements accuracy of the metallic tubes wall thickness in the range 0,5 – 10 mm, as the time interval necessary to the ultrasonic wave for covering the minimum distance 0.5 mm is t = 677/4 ns = 169.25 ns, much bigger than the echo-pulse duration.

5. **CONCLUSIONS**

In this paper, an echo-pulse amplifier is presented; manufactured with commercial discrete components, it satisfies the small price and high performance desiderata.

The designed electronic circuits have been successfully used for amplifying the echo-pulses received by a 17 MHz, spherically focalized piezoelectric transducer, specific to the measurement of the metallic tubes wall thickness in the range of 0.5 – 10 mm. The high sensitivity, the distortion factor δ < 0.8 %, the reduced signal-to-noise ratio (SNR < 1 %) and the input impedance optimally adapted to the ultrasonic transducer impedance ensure the amplifier high performance.

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