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Impulse response measurement of ultrasonic transducers

F. KADLEC

Czech Technical University, Faculty of Electrical Engineering, Department of Radioelectronics, Technická 2, 16627 Prague 6, Czech Republic

ABSTRACT: Digital processing of acoustic signals introduces pulses to measurement of impedances and transfer functions of ultrasonic systems. Digital impulse measurements of electroacoustic transducers described in the paper are based on comparison between the Fourier transforms of the input signals and the responses of the ultrasonic systems. Measuring signals consisting of two separate parts have been used where the power piezoelectric transducer is the input part of the system. Similarly, the output response also has two parts.

1. INTRODUCTION

Classical analog methods of measurements allow to measure desired parameters and characteristics of an ultrasonic system as a whole. The impulse method, which is based on recording and spectral analysis of the system's response to a defined measuring signal, can be used for obtaining transfer functions of common electroacoustic systems and their impedances. Also physical phenomena occurring in the ultrasonic transducers can be observed and diagnosed in detail when the impulse method in association with digital processing of the signal is employed.

2. DETERMINING THE AREA OF LINEARITY FOR ULTRASONIC SYSTEMS

As the impulse method is theoretically valid for linear systems only, special attention was paid to verification of linearity of measured transducers in conditions given by the impulse method. An electroacoustic system is linear if the response characteristics are additive, homogeneous and stable. In equation form, where $v(t)$ represents the output to an input $u(t)$, the system is linear if for two inputs $u_1(t)$, $u_2(t)$, and constant c

$$v\{c[u_1(t) + u_2(t)]\} = c v[u_1(t)] + c v[u_2(t)]. \quad (1)$$

Measuring signals $u(t)$ have been used as inputs

$$u(t) = c l(t-t_0), \quad (2)$$

where $l(t)$ is a unit step function, t_0 is the time delay

and $c = 20, 40, 60, \dots, 200$ volts.

The measurement setup is represented by the block scheme in Fig. 1 [$u_R(t) = 0$]. The results are documented by Fig. 2a, from which the linearity of the ultrasonic transducer is obvious. Its linearity was fully verified for the conditions of the experiment.

Fig. 1. Block diagram of the frequency response measurement of power ultrasonic system by means of the impulse method. The ultrasonic system consists of a piezoelectric transducer (PZT) and waveguides (WG); AC - accelerometer.

3. IMPULSE MEASUREMENT OF TRANSFER FUNCTIONS

The measurement setup is shown in Fig. 1 [$u_R(t) = 0$]. Theoretically, the voltage pulse to the ultrasonic transducer should have the form of a delta function [1]. In our case the input impulse signal $u(t)$ consists of two parts

$$u(t) = u_1(t) + u_2(t), \quad (3)$$

where

$$u_1(t) = c \left[1 - e^{-a \left(t - t_0 + \frac{\tau}{2} \right)} \right], \quad t - t_0 + \frac{\tau}{2} \geq 0, \quad (4)$$

$$u_2(t) = c \left[e^{-a \left(t - t_0 - \frac{\tau}{2} \right)} - 1 \right], \quad t - t_0 - \frac{\tau}{2} \geq 0, \quad (5)$$

$$u_1(t) = 0, \quad t - t_0 + \frac{\tau}{2} < 0, \quad u_2(t) = 0, \quad t - t_0 - \frac{\tau}{2} < 0, \quad (6)$$

and τ is the temporal length of the impulse, a and c are constants.

The frequency spectrum $U(\omega)$ of the signal $u(t)$ is

$$U_1(\omega) = \Pi c \delta(\omega) - \frac{a c}{\omega(a^2 + \omega^2)} (\omega + ja) e^{-j\omega \left(t_0 - \frac{\tau}{2} \right)}, \quad (7)$$

$$U_2(\omega) = -\Pi c \delta(\omega) + \frac{a c}{\omega(a^2 + \omega^2)} (\omega + ja) e^{-j\omega \left(t_0 + \frac{\tau}{2}\right)}, \quad (8)$$

$$U(\omega) = U_1(\omega) + U_2(\omega) = a c \tau \frac{(a - j\omega)}{(a^2 + \omega^2)} \frac{\sin\left(\frac{\omega\tau}{2}\right)}{\frac{\omega\tau}{2}} e^{-j\omega t_0} \quad (9)$$

The ultrasonic transducer's transmissibility displacement/input voltage, velocity /input voltage, acceleration/input voltage as a function of frequency can be determined as the ratio of the frequency spectrum $V(\omega)$ of the output signal $v(t)$ and the frequency spectrum $U(\omega)$ of the input signal $u(t)$ [2].

The transmissibility function $G(\omega)$ is thus computed according to the formula

$$G(\omega) = \frac{\mathcal{F}\{v_1(t) + v_2(t)\}}{\mathcal{F}\{u_1(t)\} + u_2\{(t)\}}, \quad (10)$$

where $\mathcal{F}\{u(t)\}$, $\mathcal{F}\{v(t)\}$ are Fourier transforms of signals $u(t)$ and $v(t)$, respectively.

4. IMPULSE MEASUREMENT OF ELECTRICAL INPUT IMPEDANCE

The electrical impedance $Z(\omega)$ could be defined as a ratio of Fourier transforms of the voltage function $u(t)$ and the current function $i(t)$. The measurement setup is shown in Fig. 1. The input impedance $Z_i(\omega)$ of the ultrasonic transducer can be expressed in the following form

$$Z_i(\omega) = R \left[\frac{\mathcal{F}\{u(t)\}}{\mathcal{F}\{u(t)\}} - 1 \right]. \quad (11)$$

where $\mathcal{F}\{u(t)\}$ is the Fourier transform of the input impulse voltage function, $\mathcal{F}\{i(t)\}$ is the Fourier transform of the current impulse flowing through the impedance $Z(\omega)$ and $\mathcal{F}\{u_R(t)\}$ is the Fourier transform of the voltage measured on the resistor R .

When a unit step impulse (2) is used as the measuring signal, then its frequency spectrum $U(\omega)$ can be expressed as

$$U(\omega) = \mathcal{F}\{c \, 1(t-t_0)\} = c \left[\Pi \delta(\omega) - j \frac{1}{\omega} \right] e^{-j\omega t_0}. \quad (12)$$

If the time delay t_0 is compensated during the digital processing of the signals and the frequency $\omega = 0$ is removed from the calculation of spectrum $U(\omega)$, we may express the result for the input impedance $Z_i(\omega)$. From Eqs. (11) and (12) we obtain

$$Z_i(\omega) = -\frac{c R}{\omega} \frac{U_{Ri}(\omega)}{U_{Ri}^2(\omega) + U_{Ri}^2(\omega)} - R - j \frac{c R}{\omega} \frac{U_{Ri}(\omega)}{U_{Ri}^2(\omega) + U_{Ri}^2(\omega)}, \quad (13)$$

$$\omega \neq 0,$$

where $U_{Rr}(\omega)$ and $U_{Ri}(\omega)$ are the real part and the imaginary part of the Fourier transform of the impulse $u_R(t)$, respectively.

5. CONCLUSIONS

The method described in the paper is documented by an example of an impulse response measurement of a ultrasonic transducer consisting of a piezoelectric disc, cylindrical and conical waveguides. Figs. 2b, 2c show the results of the transmissibility modulus $|\text{acceleration} / \text{input voltage}|$ as a function of frequency and the calculation of the modulus of the input impedance $|Z_i(\omega)|$. The impulse response measurement of piezoelectric systems compared favorably with results obtained using the analog measurement and the network analysis program [3].

Analyses of ultrasonic systems were carried out on many power piezoelectric transducers. Results were published in [4].

Fig. 2 Impulse measurement of an ultrasonic transducer; a) Linearity of the ultrasonic transducer; b) Modulus of the transmissibility $|\text{acceleration} / \text{input voltage}|$ as a function of frequency; c) Modulus of the input electrical impedance $|Z_i|$ as a function of frequency.

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