Analysis of Experimentally Determined Transfer Function of Photoacoustic System Detection Part

Slobodan Todosijević, Dejan Ćirić and Branko Radičević

Abstract—**The microphone, amplifier and photoacoustic cell affect the transfer function of the gas-microphone detection of the photoacoustic measuring system. Experimental determination of the transfer function of the system detection part eliminates the influences of these components occurring due to the system design. Based on the measurements performed in an anechoic chamber where the swept sine signal was used as an excitation, the transfer function is determined. Two different acquisition cards were used for the signal detection. One of them was used to generate the excitation signal simultaneously with the microphone signal detection. The approximately flat transfer function up to 6 kHz is obtained with that card, which is not the case with the other acquisition card. In the latter case, the determined transfer function shows the oscillations in the regions where the signal to noise ratio is insufficient.**

Index Terms—**Photoacoustic measuring system, transfer function, microphone frequency response.**

I. INTRODUCTION

The photoacoustic effect (PA) represents the generation of the acoustic signal in the gas around the sample heated by the modulated light beam [1]. The sample absorbs a part of the light energy. The absorbed energy causes heating in the sample, which further causes thermal expansion. Due to the thermal expansion, thermodynamic disturbance of the sample and nearest surrounding (pressure, temperature, density) occurs, and the created effect is called the photothermal (PT) effect [1-3]. The effect related to the pressure change in the fluid surrounding the sample is called the PA effect. The PA effect is one of the PT effects. Fig. 1a shows the generation of PA process.

PA and PT methods have intensively been developed and their applications in characterization of material physical properties, such as thermal, optical, electrical, elastic and geometric properties have been found [2-4]. The research described in this paper is focused on the thermal properties of

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the sample and frequency PA method, within which acoustic signal amplitude and phase in the frequency dependence are determined [1-5]. The acoustic signal is detected by the microphone, whose frequency response limits the amplitude and phase frequency responses of the PA measuring system in the audio range to 20 Hz - 20 kHz [3, 5].
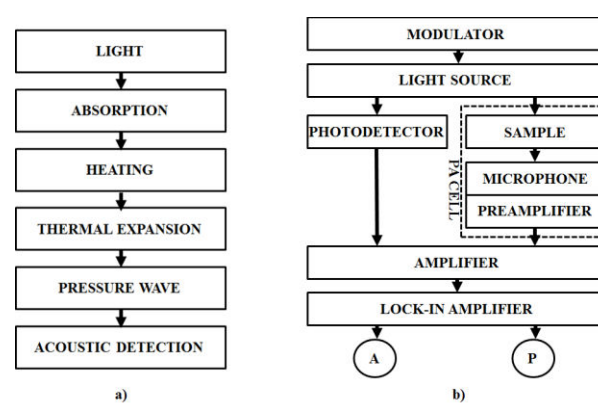

Fig. 1. a) Generation of PA effect and b) scheme of PA measuring system.

Fig. 1b shows the scheme of the PA measuring system. This system can be divided into an excitation and detection parts. The excitation part consists of the modulator and the light source with the collimator, while the detection part consists of a microphone (as a part of PA cell), an amplifier, a lock-in amplifier and a photodetector. In the PA measuring systems, an open-ended PA cell is most commonly used [3, 5-6]. It means that the sample is directly sealed on the surface of an electret condenser microphone. The microphone has a small vent, whose volume, in fact, is the PA cell.

The result of the frequency PA method is represented by the monotonously decreasing amplitude and phase with frequency. The amplitude and phase characteristics are actually ratios of amplitudes and difference in phases determined by the microphone and photodetector [3, 5].

Until recently, frequency response influence of the microphones was not taken into account in the PA measuring systems. Such use of microphones limits the use of the PA measuring system to the frequency range where the microphone response is "flat" [5]. In order to cover a wider frequency range, it is necessary to determine the microphone frequency response. Knowledge of the transfer function of the microphone, amplifier and the rest of the detection part

(acquisition card) could spread the measuring frequency range to become wider than the flat part of the microphone frequency response. If the determined transfer function shows some particular impacts, then this could be corrected by an adequate signal processing, e.g., using a proper correction function.

The transfer function of the detection part of the PA measuring system is obtained from its impulse response measured in the anechoic chamber using the swept sine signal as an excitation. Seven microphones were tested. The two different acquisition cards were applied for the measurements, and it is interesting to note that they do not give the same characteristics when determining the transfer function.

II. EXPERIMENT

The experimental setup comprised a sound source with its own amplifier on the excitation side and a microphone, an amplifier and an acquisition card on the detection (receiving) side. The excitation signal was generated by the PC, and the same PC was used for detection and storing the receiving signal. Fig. 2 shows the experimental setup.
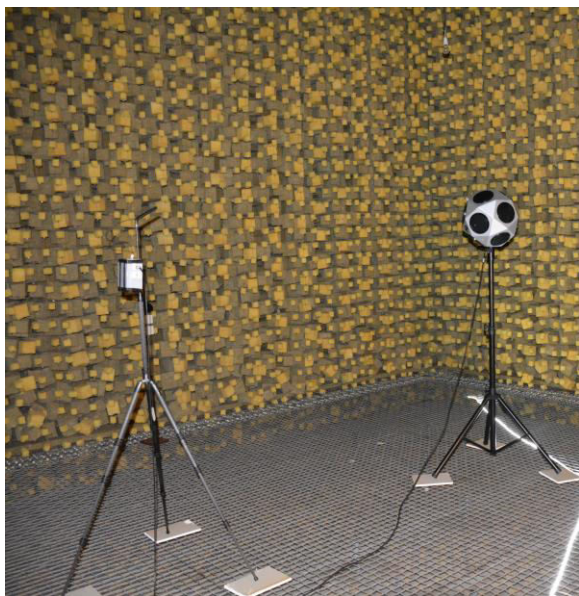

Fig. 2. Experimental setup in the anechoic chamber (the picture shows B&K sound source which was not used for the measurement, but the used sound source had the same position as B&K sound source in the picture).

The measurements were performed in the anechoic chamber of the Faculty of Electronic Engineering, University of Niš, located in the town of Svrljig. The inner dimensions of the chamber are approximately 7 m × 7 m × 7 m. The low cutoff frequency of the chamber is near 50 Hz. The microphone and sound source were positioned at least 1.5 m from the chamber walls, and the distance between them was larger than 3 m. Acoustic centers of the microphone and the sound source were on the same axis (at the same height). The positions of the source and receiver were the same for all measurements including reference and test measurements.

The dodecahedral omnidirectional sound source from the Laboratory of Acoustics of the Faculty of Electronic Engineering, University of Niš was used for both the test and reference measurements. The signal was amplified by the commercial Sony TA-FE510R amplifier and led to the sound source.

Commercial electret microphones are used in the PA measuring systems. These microphones are inexpensive with a small diameter and therefore convenient for the use in the PA measuring systems. The microphone dimensions determine the PA cell volume, the small volume being necessary because of the larger signal amplitude. The reason for that is the small signal amplitude generated in the PA cell.

For the transfer function determination, the following microphones were used: 1) two KECG2742TBL-A microphones from Kingstate Electronics Corp. [7], 2) two KEEG1538WB-100LB microphones from Kingstate Electronics Corp. [8], 3) one POM-5238L-R microphone from PROJECTS UNLIMITED [9], 4) one microphone from an unknown producer with a diameter of 9.7 mm sealed in a solid aluminum housing with a diameter of 25 mm and 5) one microphone from an unknown producer with a diameter of 9.7 mm. Fig. 3 shows the microphones.
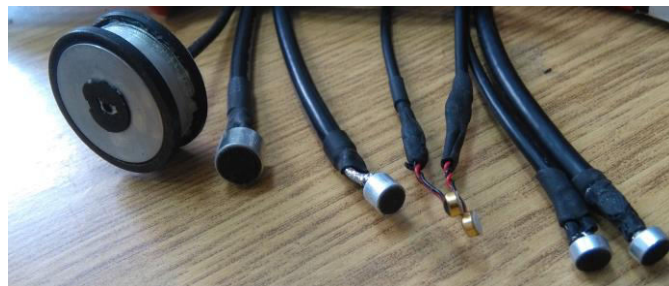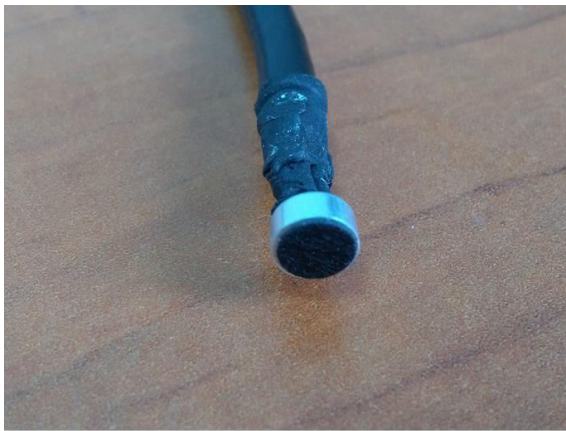

Fig. 3. Microphones from the left to the right: 1) microphone from an unknown producer with a solid aluminum housing of 25 mm diameter, 2) microphone from an unknown producer with 9.7 mm diameter, 3) POM-5238L-R microphone from PROJECTS UNLIMITED and the other microphones from Kingstate Electronics Corp. 4) two KEEG1538WB-100LB and 5) two KECG2742TBL-A microphones.

Table I summarizes the microphones' characteristics. Fig. 4a shows the KECG2742TBL-A microphone with soldered RG58C/U cable. Fig. 4b shows the producer microphone frequency response. For all the mentioned microphones from Kingstate Electronics Corp., the producer gives the same microphone frequency response.
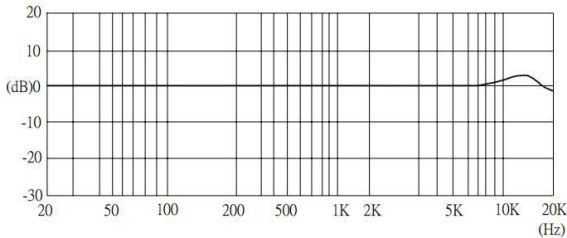
Fig. 5a shows the schematic of the microphone power supply with the LM78l voltage regulator. Fig. 5b shows the schematic of the operational amplifier power supply of ±5 V. The used operational amplifier is OP07 CP and it is important to emphasize its characteristic of the typical bandwidth of 0.5 MHz. Fig. 5c shows the amplifier with amplifications of 2, 4.9, 7.8, 11, 19, 48, 69 and 101. At the non-inverting input of the operational amplifier, the series connection of C9 and C10 capacitances with R2 resistor forms a high-pass filter with a cutoff frequency of 5.3 Hz.

| Microphone	KECG274 2TBL-A	KEEG1538 WB-100LB	POM-5238L-R
Operating voltage	2 V	2 V	2 V
Maximum supply current	0.5 mA	0.5 mA	0.5 mA
Output impedance	2.2 kΩ	2.2 kΩ	2.2 kΩ
Diameter	6 mm	4 mm	6 mm
Signal/noise	60 dB	58 dB	60 dB
Sensitivity 1kHz, 1Pa 0dB=1V/Pa	-42±3 dB	-38±3 dB	-38±3 dB

Fig. 4. a) Commercial electret microphone (KECG2742TBL-A) with the diameter of 6 mm, and b) producer microphone frequency response.

At the operational amplifier output, the parallel connection of C11 and C12 electrolytic capacitors with R12 resistor forms a high-pass filter with a cutoff frequency of 1.42 Hz. Both of cutoff frequencies do not influence the transfer function characteristic in the audio range of the microphone.

For acquisition of recorded data, National Instruments (NI) USB-6351 [10] and NI PCI-6014 [11] acquisition cards were used. Both cards have the resolution of 16 bits.

The reference measuring system for recording and acquisition of data consisted of the B&K 4188-A-021 microphone and the data acquisition system B&K 3560-B dr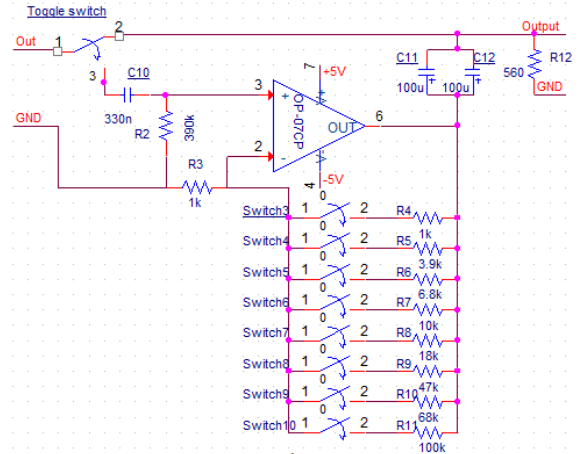iven by the Time data recorder application of the Pulse software package. Fig. 6 shows the B&K microphone frequency response. It is "flat" in the range from 10 Hz to 10 kHz. The acquisition system has a built-in high-pass filter with a cutoff frequency of 22.4 Hz.
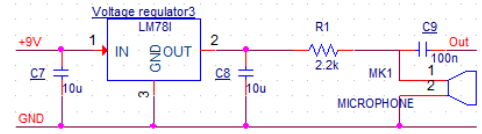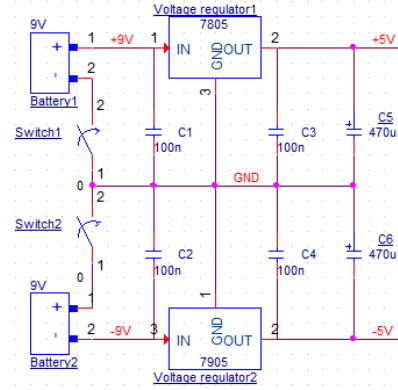
Fig. 5. a) Microphone power supply, b) power supply of operational amplifier OP07 CP and c) amplifier with an operational amplifier.
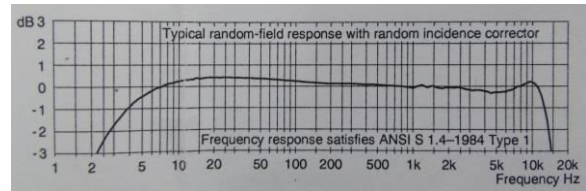

Fig. 6. The frequency characteristic of microphone used in the reference measuring system.

A. Experimental Procedure

The exponential swept sine signal was used for the excitation [12]. That signal has a spectrum as pink noise, and its frequency increases with time. The swept sine signal used

in this paper has a smooth gradual set up of the amplitude in its start realized by the appropriate fade in function. Similar gradual decrease exists at the end of this signal realized by the appropriate fade out function. The sweep signal covers the frequency range from 20 Hz to 22050 Hz. Its duration is set to be 16 s for the sampling rate of 65536 Hz. A pause of 3 s follows the swept signal excitation. The signal was stored in the WAV format and used as a file on the PC. The signal of 19 s length was led from the PC to the acquisition card D/A converter and from the analog output of the acquisition card to the sound source amplifier. After amplification, the signal was emitted by the sound source.

The emitted signal was detected by the microphone and then led to the microphone amplifier, where it was amplified by 69 times and finally to the analog input of the acquisition card. In the card, the signal was converted to the digital form by the A/D acquisition card converter.

Before the test measurements using the electret commercial microphone, the reference measurements using the mentioned B&K receiving equipment were carried out. This reference measuring system was used in order to take into account the contribution of the sound source, that is, its frequency response. In the reference measurements, the used microphone was in the same position as the test microphone in the test measurements. The sampling rate of 65536 Hz was set in the Time Data Recorder. The signal was recorded by the PC in the PTI format. This format was later exported by the Time Data Recorded into the MAT format, in which the signal was saved on the PC. Further processing of the signal was done in the Matlab using the developed script and Data Acquisition Toolbox.

The processing of the results of both reference and test measurements was done in an automated way where the results of five consecutive measurements were processed in a row. This means that the measurement was repeated five times under the same conditions. NI USB-6351 acquisition card was used for both the generating and recording of the signal and NI PCI-6014 was used only for the recording of the signal. The analog output and input on NI USB-6351 card were synchronized, while the synchronization for the analog NI USB-6351 output and NI PCI-6014 input was not performed.

Digital signal processing included the use of an inverse filter of the excitation swept sine. The inverse filter was generated as a WAV file on the PC with the sampling rate of 65536 Hz and it also lasted 16 s as the excitation signal. If the inverse filter is denoted by $X_s(f)$, and the response of the measured system to the excitation signal is denoted by $Y(f)$, then the impulse response of the measured system $h(t)$ can be extracted as [13]:

$$H(f) = X_s(f) \cdot Y(f)$$
$$h(t) = real\{iFFT[H(f)]\}$$

(1)

This implies that the transfer function of the PA measuring

system can be obtained as the Laplace transform of the extracted impulse response $G(s)=L[h(t)]$.

In order to apply the described procedure, the recorded signals are first calibrated to have correct values in dB and then transformed to the frequency domain. The determined frequency spectra from five measurements are averaged. This is done for both the reference measurements (the signals recorded by the reference microphone) and test measurements (the signals recorded by the tested microphones). Finally, the averaged frequency spectra of the reference measurements are subtracted from the averaged frequency spectra of the test measurements. In this way, the transfer functions of the detection part of the PA measuring system only are determined excluding the contribution of the sound source and its amplifier.

III. RESULTS

Fig. 7a shows the two determined transfer functions of the detection part of the PA measuring system, that is, of the KECG2742TBL-A microphone. The first one was measured using the NI USB-6351 card, while the second one was measured using the NI PCI-6014 acquisition card.
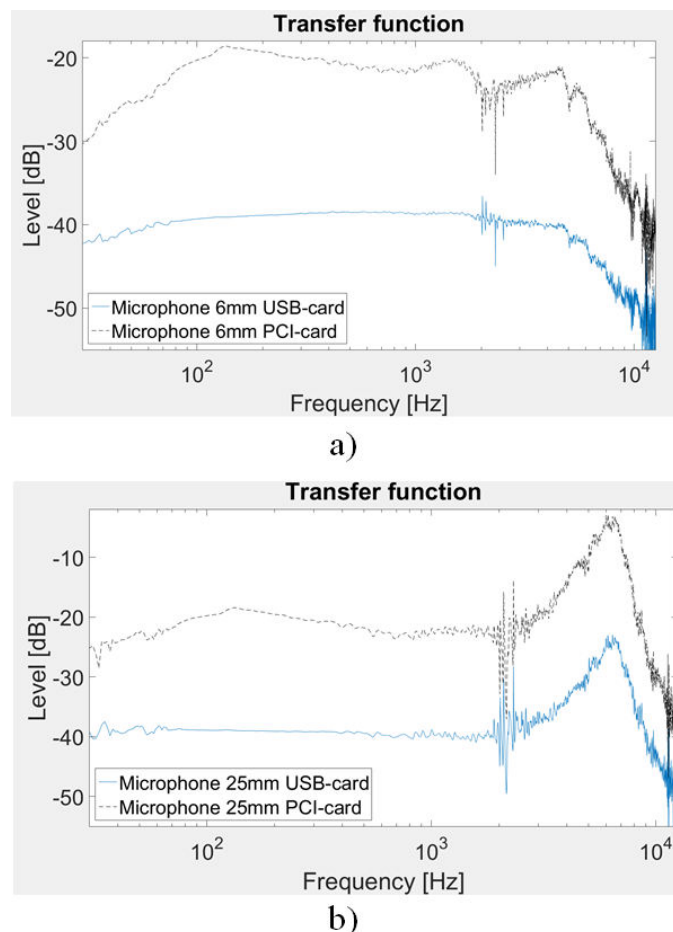

a)

b)

Fig. 7. The transfer function of the detection part of the PA measuring system measured by using NI USB-6351 and NI PCI-6014 acquisition cards for a) KECG2742TBL-A microphone with a diameter of 6 mm and b) the microphone from an unknown producer with a diameter of 25 mm.

If the regions lower than 80 Hz and around 2 kHz (where some oscillations are present) are neglected, the characteristic determined by the NI USB-6351 card can be considered to be "flat" up to about 6 kHz. Here, the characteristic has approximately 3 dB lower level than in the "flat" region, where the level is close to -39 dB. Deviations from the "flat" response are larger in the transfer characteristic measured by the NI PCI-6014 card than in the corresponding one measured by the NI USB-6351 card. The regions with oscillations are present in the transfer characteristics measured by both cards. The noticed decrease of the transfer characteristic above 6 kHz exists in the characteristic measured by the NI PCI-6014 card, too, and decrease with frequency is even larger than in the characteristic measured by the NI USB-6351 card.

Fig. 7b shows the transfer functions of the microphone with a solid aluminum housing of a diameter of 25 mm from an unknown producer. The most obvious difference in reference to the transfer functions given in Fig. 7a is the resonance appearing at the frequencies between 6 kHz and 7 kHz.

The response to the excitation swept sine signal recorded by the microphone KECG2742TBL-A using the NI USB-6351 card is presented in Fig. 8. It is interesting to note that there are some regions in the time domain where the signal amplitude is small. The assumption is that these low levels of the response signal cause appearance of the regions with oscillations of the transfer function in the frequency domain. In Fig. 8a, the larger arrow points to the region in the time domain where the frequencies between 2 kHz and 2.6 kHz are located. Fig. 8b shows the sinusoidal signal from that region (left figure), where the signal amplitude is the smallest, compared with the noise (right figure).
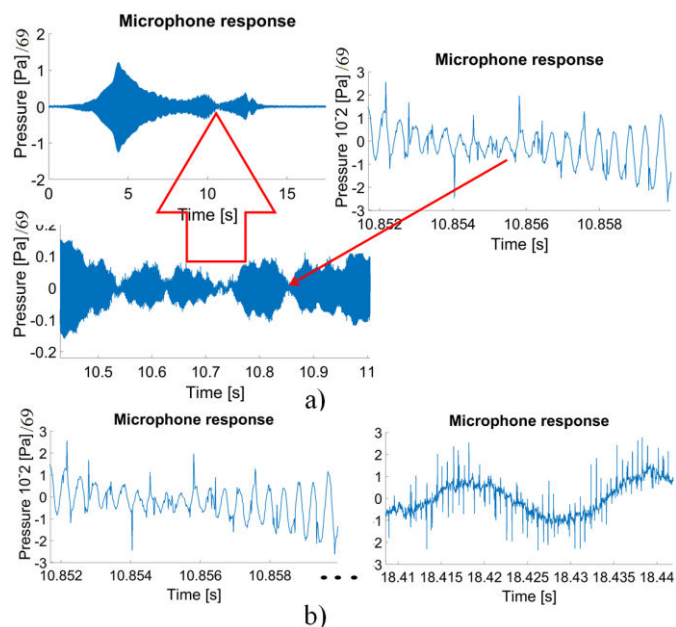

Fig. 8. Response to the excitation swept sine signal recorded by the microphone KECG2742TBL-A: a) the whole signal is shown in the left-up figure, while the region where the signal amplitude is the smallest – from 10.5 to 10.9 s is shown in the figure left bottom (there are four nodes in this region) and one of the nodes is further zoomed in the figure right; b) the signal from the fourth node compared with the noise on the same y-axis.

The transfer functions of the other tested microphones determined using the NI USB-6351 card are shown in Fig. 9. It can be noticed that the microphone with a diameter of 10 mm has the lowest sensitivity of around -53 dB in the "flat" region. Other microphones have similar sensitivity. The "flat" region for most of the microphones is up to about 5 kHz or 6 kHz, where "flatness" is not completely the same for these microphones. This "flat" region is followed by the region of the characteristic decrease with frequency.
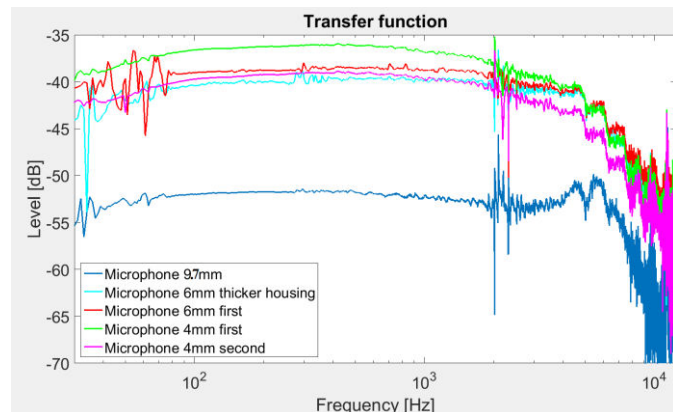

Fig. 9. The transfer functions of the other tested microphones determined using the NI USB-6351 card.

IV. DISCUSSION AND CONCLUSION

This paper presents a continuation of the work from [14]. The determined transfer functions show that the PA measurement system can be used for material testing up to 6 kHz without any correction if it is assumed that oscillations in narrow frequency regions appear due to the imperfection of the experimental setup and used excitation level. The amplification of 69 is included in the final formula, and the calculations show that the microphone sensitivity obtained from the transfer function characteristic using the NI USB-6351 acquisition card is approximately the same as sensitivity given by the producer. Either the microphone or amplifier can cause a limitation of the useful frequency range up to 6 kHz (deviation from the "flat" response). However, due to the operational amplifier bandwidth limitation that matches the transfer function limitation, it is deduced that the amplifier limits the transfer function characteristic. It could also be a solution to realize the microphone amplifier in two stages, each of which would have smaller amplification than the overall amplification achieved in the present amplifier. In this way, the required bandwidth could be obtained. An alternative could be to use another operational amplifier, such as TL071/072 or NE5532.

The sound source characteristic is not "flat" in the frequency range of analysis, with the smallest signal amplitude in the region between 2 kHz and 2.6 kHz. With the used excitation level, it seems that sufficient signal to noise ratio is not reached in that region, which causes the appearance of the noticed oscillations of the transfer function. The appearance of the oscillations is noticed in the frequency region below 80 Hz, due to insufficient signal to noise ratio,

too.

One more conclusion from the presented results is that the simultaneous use of synchronized A/D and D/A converter on the same acquisition card gives the transfer function characteristic with fewer deviations in relation to the characteristic given by the producer than the use of the unsynchronized A/D and D/A converter on different acquisition cards. The difference in synchronization between two (A/D and D/A) converters implies the difference in the determined transfer function. Therefore, it is preferable for this type of measurement to excite the tested system and record the response using the acquisition card with synchronized analog input and output.

It is necessary to perform some additional measurements where the operational amplifier with wider frequency bandwidth is used. In that way, it will be confirmed that the limitation of the transfer characteristics comes from the amplifier. The useful frequency range of testing, but also of the microphones will be expanded. In addition, it will be desirable to use the sound source with "flat" characteristic in a wider frequency range and to avoid insufficient signal to noise ratio.

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