Mugla Journal of Science and Technology

COMPARATIVE STUDY OF RESONANCE FREQUENCY OF CIRCULAR PIEZO MICROPHONE BASED ON PHOTOACOUSTIC, LASER SPECKLE, AND PIEZOELECTRIC EFFECTS

Ömer Faruk DİNÇ, Department of Electrical and Electronics Engineering, Ege University, Turkey, omerfarukdinc.academic@gmail.com
(https://orcid.org/0000-0002-8014-4674)
Emre GÜRALP, Department of Electrical and Electronics Engineering, Ege University, Turkey, emreguralpacademic@gmail.com
(https://orcid.org/0000-0002-3211-3988)
Yavuz ÖZTÜRK*, Department of Electrical and Electronics Engineering, Ege University, Turkey, yavuz.ozturk@ege.edu.tr
(https://orcid.org/0000-0002-9650-6350)

Received: 17.06.2021, Accepted: 09.12.2021 Research Article
*Corresponding author
DOI: 10.22531/muglajsci.953561

Abstract

Resonance frequency of a circular piezoelectric microphone was measured by two types of methods which were named as photoacoustic and speckle method. In the photoacoustic method; acoustic waves were obtained due to the optical excitation and resulting thermally induced mechanical distortion was measured by the piezoelectric layer of microphone. Photoacoustic effect is a type of optical excitation, which creates an acoustic wave due to the absorbed light energy which causes thermal expansion of material. In contrast to the photoacoustic method, speckle method was conducted by electrical excitation of the piezoelectric layer which results in mechanical distortion and this distortion was detected by using changes in laser speckle pattern. Measurements were taken from 6 different piezo microphones in 3 different diameters of 15 mm, 35 mm, and 50 mm and the same thickness of brass plate in the frequency range of 0-11 kHz. As a conclusion, it is found that the resonance frequencies of same diameter microphones determined by the photoacoustic method are close but different with the results of the speckle method. It is believed that the differences in the results are caused by differences of excitation/detection mechanism for same microphones and shape, material parameter differences between microphones for different microphones.

Keywords: Resonance Frequency, Photoacoustic Effect, Speckle Method, Piezoelectric

FOTOAKUSTIK, LAZER BENEĞI VE PIEZOELEKTRIK ETKILERE DAYALI DAIRESEL PIEZO MIKROFONUN REZONANS FREKANSININ KARŞILAŞTIRMALI ÇALIŞMASI

Özet

Dairesel bir piezoelektrik mikrofonun rezonans frekansı, fotoakustik ve lazer benek yöntemi olarak adlandırılan iki tip yöntemle ölçülmüştür. Fotoakustik yöntemde; optik uyarılma ile akustik dalgalar elde edildi ve termal olarak oluşan mekanik bozulma, mikrofonun piezoelektrik katmanı tarafından ölçüldü. Fotoakustik etki, soğrulan ışık enerjisinden dolayı malzemenin termal genleşmesi nedeniyle akustik bir dalga oluşturan bir tür optik uyarımdır. Fotoakustik yöntemin aksine, lazer benek yönteminde, mekanik distorsiyon piezoelektrik katmanın elektriksel uyarımı ile gerçekleştirildi ve bu distorsiyon, lazer benek desenindeki değişimler kullanılarak tespit edildi. 15 mm, 35 mm ve 50 mm olmak üzere 3 farklı çapta ve aynı kalınlıkta pirinç plakaya sahip 6 farklı piezo mikrofondan, 0-11 kHz frekans aralığında ölçüm alınmıştır. Deneyler sonucunda, aynı yarıçaplı mikrofonlar için fotoakustik yöntem ile elde edilen sonuçların, lazer benek yönteminin sonuçlarıyla yakın fakat farklı olduğu tespit edilmiştir. Sonuçlardaki farklılığın, aynı mikrofonalar için uyarma/algılama yöntemlerinin değişik olmasından ve farklı mikrofonlar için ise mikrofonlar arasındaki şekil, malzeme parametre farklılıklarından kaynaklandığına inanılmaktadır.

Anahtar Kelimeler: Rezonans Frekans, Fotoakustik Efekt, Benek Metodu, Piezoelektrik,

Cite

Dinç, Ö. F., Güralp, E., Öztürk, Y., (2021). "Comparative Study of Resonance Frequency of Circular Piezo Microphone Based on Photoacoustic, Laser Speckle, and Piezoelectric Effects", Mugla Journal of Science and Technology, 7(2), 52-58.

1. Introduction

Optical methods such as laser speckle or photoacoustic effect can be used for the determination of mechanical changes on the materials or excite such structures. One of these methods, the Photoacoustic effect, was the first discovered by Graham Bell finding out the sound waves due to the light absorbed in a material in 1880. After that, this effect has been studied extensively from biomedical to material analysis, especially in recent decades [1]. For example, in recent studies based on modulated laser exposures to material and as a result analyzing stress waves [2]. Photoacoustic effect, besides optical absorption, thermal expansion and material due to its mechanical properties, has been the subject of many studies on the determination of material properties or defects [3]. Some of well-known applications are the detection of gas-type and small-scale materials or materials solved in liquids [4]. One of the important advantages of photoacoustic effect for all in these studies is that photoacoustic allows measurement on contactless and curved surfaces in the range of kHz to GHz. It also provides detection or investigating many structures from microstructure to macrostructure.

On the other hand, piezoelectric effect is the subject of many studies based on conversion of mechanical energy to electrical energy and has many applications such as pressure, stress measurement, air flow sensors, alarms, depth sensors, ultrasonic imaging, and detection of acoustic waves [5]. Different methods are also used to detect acoustic waves. Sensitive microphones, and optical vibration measurement methods can be given as some examples [6]. Simply a piezoelectric transducer can be used to detect acoustic waves by attaching directly to the material to detect photoacoustic waves [7,8]. Piezoelectric or any wide band detection transducers usually have an important factor which is resonance frequency (also referred to as the natural frequency). This factor can increase the transducer output due to the increase of vibration amplitude [9]. Resonance frequencies are determined by the energy, force and stiffness characteristic connections peculiarities and the total stiffness of the nonlinear dynamical system [10]. Determining the resonance frequency of a microphone is quite important, especially in photoacoustic signal detection. It is clear that the photoacoustic signal will fall at high frequencies, especially because of the decrease of energy transfer to the system per period. For this reason, working at resonance frequency in applications requiring high frequency will be important in increasing the signal-to-noise ratio (SNR) level. In addition, it is very important to determine the resonance frequency in frequency dependent studies where piezo sensors are used as sensors or transmitters. Therefore resonance frequency has been determined, simulated or modeled by different methods in many studies [11-13]. To contribute to these studies, it was aimed to examine and compare the difference between optical excitation, and piezo detection or piezo excitation, optical detection.

In this paper, photoacoustic effect, laser speckle and piezoelectric effect were used to investigate the resonance frequencies of several piezo microphones (contact microphones). Investigation of resonance frequency of circular piezoelectric microphones was first carried out by optical photoacoustic excitation piezoelectrical detection. After that the obtained results were compared via the results of electrical excitation and optical laser speckle based detection. In the first method, the vibration of the piezo material was measured by creating photoacoustic waves with a modulated laser at different frequencies [14]. In the second method, vibration measurements were taken by using continuous laser reflection which forms a speckle pattern and vibrations were excited by applying voltage to the piezoelectric layer at different frequencies [15]. The results of these two methods are presented. Besides practical applications such as determining the resonance frequencies of piezo microphones, we believe that the results of this study will contribute to studies on the determination of natural or resonance frequencies of materials.

2. Method

The generation of acoustic waves in matter by absorbed non-ionizing optical radiation is commonly referred to as "photoacoustic" (PA) or "optoacoustic." The major mechanism of the photoacoustic effect is the conversion of absorbed light energy to heat and thus thermal deformation, which results in acoustic waves [16]. Thermal deformation is commonly defined as a change in the volume of the absorbing region caused by changing thermal energy as a result of light absorption, as shown in figure 1. The heat diffusion that occurs as a result of this event is also a part of the process.

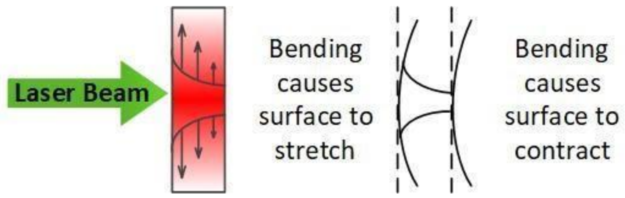


Figure 1. Mechanism of surface stress formation [2].

As a result, the mechanical, thermal, and optical properties of the material all play a role in the photoacoustic effect. In summary, the optical absorption constant, thermal expansion constant, specific heat, and sound speed in the material are all significant parameters. These relationships are clearly revealed by the general photoacoustic wave equation, depending on the defined material parameters:

$$(\nabla^2 - \frac{1}{v_s}\frac{\partial^2}{\partial t^2})\, p(r,t) = -\frac{\beta}{\kappa v_s^2}\frac{\partial^2 T(r,t)}{\partial t^2} \quad (1)$$

where p (r,t) shows acoustic pressure at position r and time t, temperature T, thermal coefficient of volume expansion "β", isothermal compressibility "κ", speed of sound "v" the wave equation is shown in the left hand side of the equation, whereas the right hand side represents the source equation of the wave [17].

The structure of a commercial piezo microphone (contact microphone) is shown in figure 2. The microphone consists of a piezoelectric material structure sandwiched between the metal brass plate and the silver electrode. In the experiments, the laser beam is exposed on the metal layer, which is thicker than the other two layers. Detailed information about piezo microphones can be found in references [11-13].

Due to the absorbed laser light, thermal deformation is expected due to thermal expansion of the brass plate shown in figure 1. By transferring this deformation to the piezo material, a potential difference is formed between the two metal layers due to the piezoelectric effect [18]. It is mandatory to use modulated light with frequency f to obtain both piezoelectric response and periodic photoacoustic signal. Dependence of measured potential difference to optical absorbed power and modulation frequency can be simplified as follows [2]:

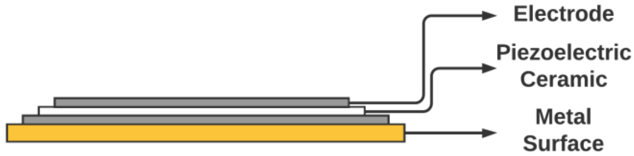
$$V = \frac{kP}{2f} \quad (2)$$

In Equation (2), P is the optical power, f is the modulation frequency of light, and k is a coefficient which depends on the properties of the piezo material and the conductive surface on the piezo. This coefficient depends especially on the optical and thermal properties of the metal surface, the coefficient of linear expansion. On the other hand, piezo material properties depend on piezoelectric material constants and dielectric constants. In this equation, the expression P/2f indicates the energy absorbed during each period of modulated light. Therefore, the voltage induced in the piezo microphone will be directly proportional to the energy absorbed over a period. As the modulation frequency increases, the energy absorbed over a period will decrease so the induced voltage [7].

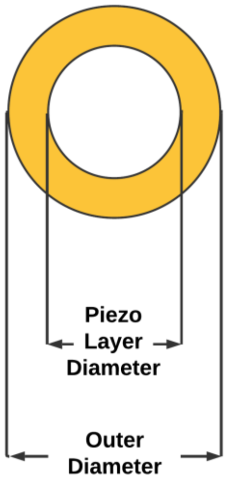
The resonance frequency of a circular plate (membrane) can be express as:

$$f = \frac{k\prime}{r}\sqrt{\frac{T}{\sigma}} \quad (3)$$

where r is the radius of a plate, T is the tension, σ is the mass per unit area of the plate and k' is a constant [11].



(a)



(b)

Figure 2. (a) Layers of piezo microphone, (b) Diameters of piezo microphone.

Table 1. Sizes of Piezo Microphones Layers.

Samples	Outer Diameter (mm)	Piezo Layer Diameter (mm)	Thickness of Brass Plate (mm)
P15-1 P15-2	15.0	10.0	0.1
P35-1 P35-2	35.0	20.0	0.1
P50-1 P50-2	50.0	22.6	0.1

In the experiments, a set of piezo microphones with diameters of 15, 35, and 50 mm was used, whose layers and dimensions summarized in Table 2 and visualized in figure 2. Photoacoustic and piezoelectric stimulated vibrations generated in the piezo microphone were measured with the systems shown in figure 3 and figure 4. The laser diode was modulated with a signal generator and Laser Diode Driver, in the first stage of measured photoacoustic (figure 3). The frequency was changed during modulation, but the laser diode was driven with a square wave current with a 50 mA peak even as keeping the power amplitude constant. The Beam Splitter was used to control the laser power by directing some of the light to the photodetector, which is connected to the oscilloscope. The laser beam with an area of about 1.7 mm^2 was passed through the iris and exposed on the center of the brass metal of the piezo microphone. Piezo microphone is attached to the clamp (Thorlabs SCL04). which applies pressure from three points at intervals of 120 degrees.

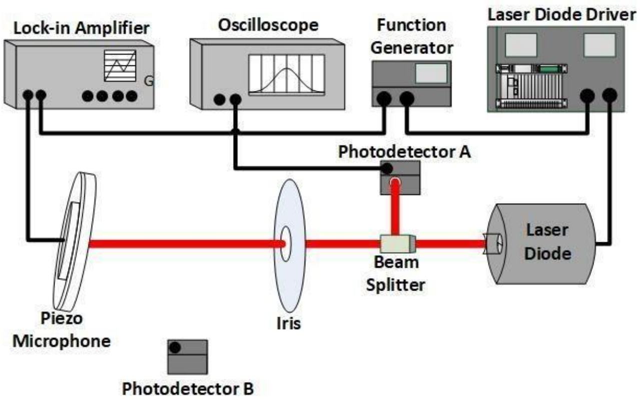


Figure 3. Photoacoustic setup.

The piezoelectric material was vibrated in the second stage (figure 4). Frequency scanning is done by applying a square wave voltage to the piezo microphone with a constant peak value of 500 mV. The laser diode driver was set to a constant value of approximately 6.20 mW at 73mA. The speckle pattern created by light reflected from the surface of the piezo disc was directed to a photodiode with an iris. The voltage change due to the vibration of the microphone plate was measured using Lock in Amplifier (LIA) [19]. Since LIA mainly measures the voltage of reference and also excitation frequency, the measured voltage will be proportional to the vibration amplitude at the reference frequency.

The laser power is measured using an ILX Lightwave 0MM-6810B model optical multimeter. All measurements were taken at intervals of 10 Hz in the frequency range of 0-11 kHz. In addition, LIA was used with a 100 ms integration time and a sensitivity of 1mV. The room temperature was about 19*C during the measurements, and the piezo microphone location and angle were fixed. Agilent 33210A model function generator, Melles Griot 06-DLT-302 model laser diode driver, Thorlabs PDA100A-EC (Photodetector A), New Focus Model 2051(Photodetector B) Photodetector, Thorlabs TCLDM9 Laser Diode, GW INSTEK GDS-2062 oscilloscope ve SR830 Lock in Amplifier (LIA) were used in the systems. The entire system was controlled by computer via GPIB and measured data was transferred to the computer.

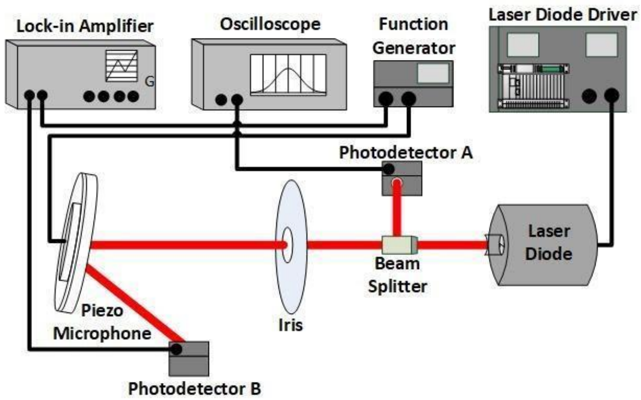


Figure 4. Photodetector setup.

3. Results and Discussion

The determination of these resonance frequencies is important in many applications such as direct or indirect photoacoustic effect measurements by using piezo microphones [11]. It is clear that since the SNR ratio will be much greater in measurements at the resonant frequency of the microphone it will increase measurement quality and accuracy. Experiments were carried out by two methods to compare and determine resonance frequency of circular piezo microphones (contact microphone). The first, for the photoacoustic method, excitation was made by laser and the deformation of the microphone as a result of thermal expansions caused by the absorbed energy was detected by the piezoelectric material on the microphone. In this method, if the resonance phenomenon is neglected, it is expected to have decreased piezo signal intensity and deformation amplitude as a result of the increasing modulation frequency and decreased absorbed energy in each period as given in Equation 1 [20, 21]. In the figure 5, measured piezo-electric signal of piezo microphone of 35 mm diameter and calculated photoacoustic signal by equation 1 is given with respect to the modulation frequency of laser light. In the calculations the k value is kept constant and its value was determined by fitting equation 1 to the experimental results. In inset of figure 5 the log-log plot of the data given in logarithmic scale to present the relationship between photoacoustic signal and frequency at high frequencies.

The deviations from theoretical calculation were observed in certain frequency bands which attributed to the resonance of mechanically developed waves as a result of photoacoustic effect.

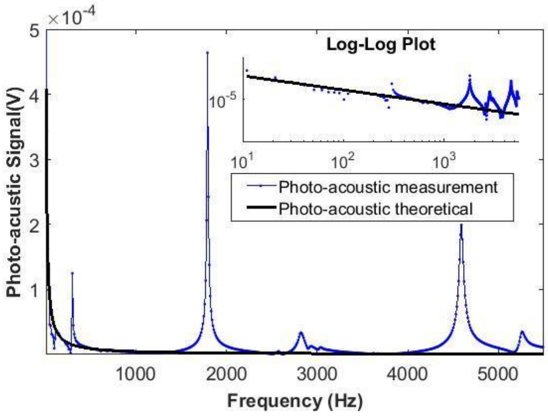


Figure 5. Photoacoustic signal of experimental (blue dot line) and calculated voltage by using equation 2 (black line) with respect to frequency (P35-1: the piezo microphone of diameter 35 mm).

Since both the measured voltage and the thermal deformation amplitude will decrease with increasing frequency at constant optical power as given in Equation 2, it is chosen to present the V*f versus f to determine resonance frequency of piezo microphone. Since the optical power is constant V*f=k*P will be proportional to the k constant which depends on material properties and resonance of acoustic waves. The maximum amplitude of V*f is observed around 4556±5 and determined as a resonance frequency for the microphone with diameter of 35 mm (P35-1). The same procedure is applied to determine the resonance frequency of all microphones in the frequency range of 0-11 kHz.

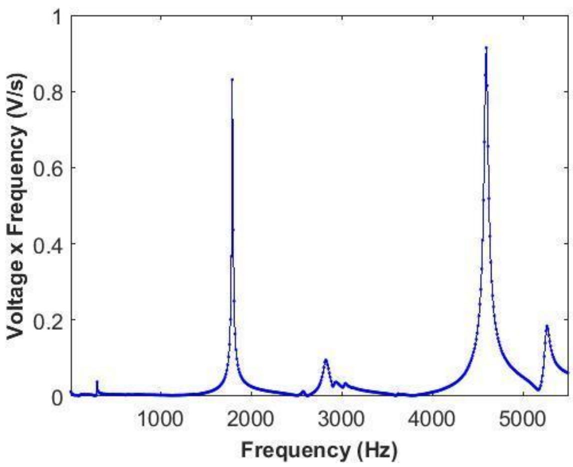


Figure 6. The product of experimental piezo voltage (photoacoustic signal) and frequency (V*f) with respect to frequency. (P35-1: piezo microphone with diameter of 35 mm).

As a second method, the mechanical excitation was applied by a piezo-electric layer and vibrations were measured optically by using laser speckle pattern. In this speckle method, the low-power laser sent to the piezo microphone and the changes in the part of the laser speckle pattern were measured by using a photodiode [22]. The measurement results of the speckle method are presented in figure 7 along with the photoacoustic measurement results of the same microphone (P35-1). Although several peaks (local maximum) were observed, the frequency at the tallest peak (global maximum) was taken as a resonance frequency for all the piezo microphone samples. The difference in both amplitude and resonance frequencies of the methods can be attributed to the difference of both the excitation type and the measurement type. For the laser speckle method, the excitation was applied by a large area piezo layer and for the photoacoustic method excitation is applied by the optical absorption at the point-like region. As for the measurement of vibrations, for the laser speckle method, measurements were taken from a point-like region where the laser light shined and for the photoacoustic method piezo layer voltage was used to measure.

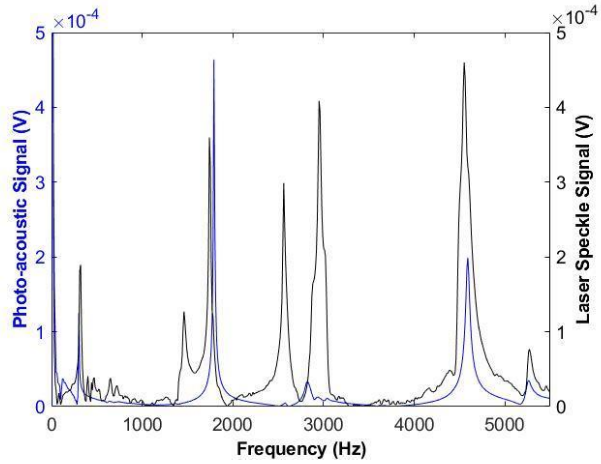


Figure 7. The results of photoacoustic-piezoelectric and laser speckle based measurements. signal of a piezo microphone with diameter of D=35mm.

Measurements with two methods were repeated 4 times for the total of 6 piezo microphones with 3 different diameters. Results of all measurements are summarized in table 2. The increase of resonance frequency with diameter decrease can be explained by the inverse dependence of resonance frequency to the plate radius as given by equation (3) [11]. We observed close but different resonance frequencies for the microphones of the same diameter. There are 250 Hz differences for P15-1 and P15-2 35 Hz differences for P35-1 and P35-2, and 0 Hz differences for P50-1 and P50-2 mm samples in the photoacoustic method. Also, in the speckle method there are 216 Hz differences for P15-1 and P15-2, 55 Hz differences for P35-1 and P35-2, and 35 Hz differences for P50-1 and P50-2 mm samples. Each difference may be caused by the very small change in the material properties as well as material geometries such as the off center placement of the piezo layer which are generally observed. The resonance frequencies are found to be different for even the microphones with the same radius in previous studies [13]. This kind of resonance frequency differences for same microphones can be attributed to the material properties such as stiffness and other nonlinear working conditions as mentioned in [13]. It is also worth to mention that, two layer structure of microphones and differences of material properties such as tension and mass per unit area between materials all contributed to the resonance frequency discrepancy of microphones [11]. For the same samples between measurements, maximum 35 Hz deviation (P35-4) for the speckle method and maximum 10 Hz (P35-3) deviation for the photoacoustic method is observed. These results showed that more successful results were obtained in terms of measurement repeatability with the photoacoustic method. Since the only difference for the same microphone is measurement and excitation method it is concluded that the both excitation and measurement method are important parameters to consider. The modes corresponding to the resonance frequencies have not been considered. The results of this study can be used in such future studies and sensing the point-like vibration sources with plates.

Table 2. Resonance frequency differences with two methods. (PA: Photoacoustic Method, SP: Speckle Method).

Samples	Resonance Frequency (Hz)		Difference
	PA	SP	
P15-1	9875±5	9645±15	230.0
P15-2	10125±5	9861±11	264.0
P35-1	4591±10	4681±10	-90.0
P35-2	4556±5	4626±35	-70.0
P50-1	2776±5	2696±5	80.0
P50-2	2776±5	2731±0	45.0

4. Conclusion

The resonance frequencies of several piezoelectric microphones were measured by two different methods. One of the methods is applied by optical excitation, piezoelectric detection which is called photoacoustic method. The other method is applied by piezo electric excitation and optical detection, called the speckle method. Even for the same measurement method, it was obtained different resonance frequencies in most cases for the same diameter microphones. That shows the end users should consider when they chose and use this type of microphones when the resonance frequency is important such as sensing applications. Although both excitation and measurement mechanisms are different, close results were obtained which supports the results obtained by the proposed photoacoustic method. This nondestructive approach in the measurements of resonance frequency of the piezo microphones has been presented.

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