

## ИЗПОЛЗВАНЕ НА СТОЯЩИ ВЪЛНИ В ПИЕЗОЕЛЕКТРИЧНА МАТРИЦА

### USING STANDING WAVES IN PIEZOELECTRIC ARRAY

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#### Abstract

Resonance piezoelectric arrays have high sensitivity but the data acquisition can be split in two basic approaches – detection of the frequency shift or detection of the amplitude change. Both methods have their own advantages and disadvantages but for more fast data acquisition, it is preferable to use the amplitude method. The current article reviews the problems connected with the amplitude method of data acquisition and suggests some solutions to them.

**Keywords:** piezoelectric array, resonance, standing waves.

#### INTRODUCTION

Piezoelectric resonance structures possess high sensitivity which is based upon the strong connection between their innate resonance frequency and the applied to them acoustic load. The change in the load leads to change in the frequency on which the system is oscillating (or trying to) and simultaneously to the change in the output electrical signal amplitude.

The aforementioned changes in the frequency and the amplitude can be used for determining the degree of external influence and the outline of the object that is causing the disturbance as well as the vector of the applied force. In other words the form of tactile image can be acquired with help of the piezoresonance structures.

#### EXPOSITION

##### A. Piezoelectric Resonance Sensor Array

The term “piezoelectric sensor array” in the current work means piezoelectric substrate on which multitude of sensor points are made with the help of specialized electrodes, thus the multitude of sensing points makes the sensor array field. In the case of resonance piezoelectric structure every sensing point is in fact a quasi-separate resonator as the separation can be achieved in most cases with the polarization vector of the piezoelectric substrate.

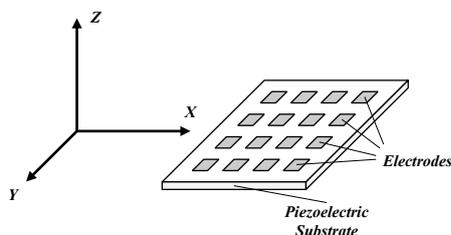


Fig. 1. Rectangular piezoelectric array

In the current case the substrate has polarization vector along the Z (Fig. 1) axis leading to the excitation of thickness waves in the piezoelectric substrate when sinusoidal signal is supplied to the electrodes.

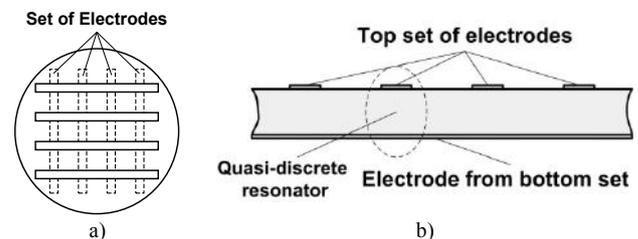


Fig. 2. Electrode configuration forming the piezoelectric array

The optimal configuration for forming an array structure considering the wiring complexity is a system of two sets of evenly spaced, parallel straight electrodes which are perpendicular to each other and are formed on the flat sides of the regular disk (Fig. 2,a) or plate from piezoelectric material and which are centered relatively to one another. The sensing points are formed in the location of electrode crisscrossing from both sets (Fig. 2,b) as these points are indeed resonators which can be excited and scanned for data retrieval.

##### B. Methods for Scanning the Array

Such type of resonance piezoelectric structure can be scanned by two methods – namely a method that detects the frequency shift and a method that utilizes the amplitude change as both of them are based on the same principle. Assuming that the mass of the piezoelectric medium is constant value, the external load for every sensing point is determined according the piezoelectric effect principles [1] using the following equation [2, 3]:

$$\frac{\Delta f}{f_0} \approx \frac{i}{\pi Z_q} \frac{-\omega^2 u_0 m}{i\omega u_0} = -\frac{2f}{Z_q} m \quad (1)$$

where:

$u_0$  – signal amplitude;

$m$  – mass;

$f_0$  – resonance frequency;

$\Delta f$  – frequency shift;

$Z_q$  – acoustic impedance of the material.

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The method with the frequency shift is extremely precise [1] as it implements measurements of the exact frequency at given sensing point as the difference between the innate resonance frequency and the measured one is indication for the load state. As it is not concerned with the signal amplitude there is no need for complex specialized signal preprocessing circuitry, although the difficulty lies in choosing and implementing a method for frequency recognition. These methods can vary from classical impulse-counting to properly adjusted variations of pitch detection algorithms. The parallel data processing for all of sensing array points would require undue hardware costs and in practice the serial mode of scanning is preferable [1] – the array is scanned one point at time as only one resonator is active in given time period. This also prevents the interference between multiple resonators working simultaneously and decreases the possible measurement error.

But this excludes the possibility for real time working of the sensor system and significantly reduces the ability to respond in case fast, dynamically changing external loads are present. In those cases more appropriate is the usage of amplitude change method which can be easily configured to use parallel scanning algorithms.

Thus even if the real time mode is not obtained the reaction time of the system will be improved. The amplitude method may require specialized preprocessing circuitry but after that the signal can be supplied directly to analog to digital converter (ADC) in the simplest circuit solution.

For facilitating the amplitude method the signal from electrical oscillator working on the innate system frequency should be supplied to specified electrodes in the array field as well as to insure the common electrical ground of the piezoelectric system. This can be solved with analog switching circuitry and relevant control system (Fig. 3).

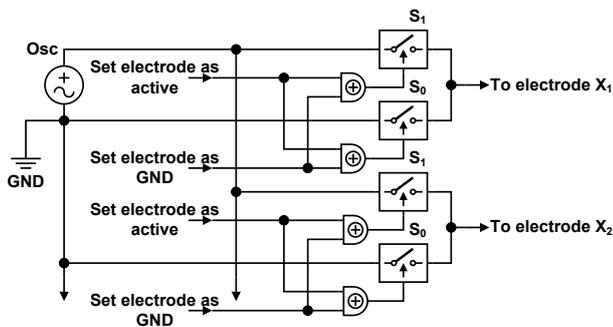


Fig. 3. Switching circuitry, servicing the piezoelectric array

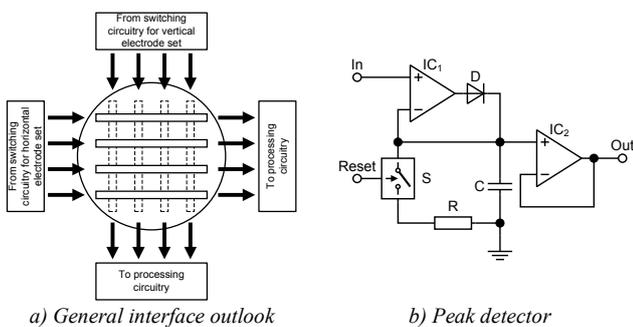


Fig. 4. Interface circuitry for piezoelectric array

Every electrode from the piezoelectric array is connected to two analog switches (designated as S<sub>0</sub> and S<sub>1</sub> on the Fig. 3) that each of them is either connected to the

electrical oscillator or to the electrical ground. This way choosing between the switches and their state multiple electrode configurations can be executed in the piezoelectric array. The XOR logical gates are included to ensure that short circuiting is not going to happen between the oscillator and the ground.

The general outlook of the interface circuit utilizing amplitude method is shown on Fig.4,a and for the preprocessing circuit are used peak detectors as the method itself demands for measuring the signal amplitude change – Fig. 4,b. The additional advantage for the peak detector circuit is that the output signal from it can be directly supplied to ADC for directly discerning the change in the amplitude if there is any. In the proposed configuration every electrode is connected with input of separate peak detection circuit.

C. Problems with Amplitude Method for Scanning

The existing problems with the amplitude method for scanning piezoelectric resonance arrays are mainly caused by the standing waves that occur when the structure is excited with the continuous sinusoidal signal. The occurrence of standing wave means that the signal amplitude in given array point will theoretically depend heavily to the overall pattern of the wave. Also the different combinations of active electrodes should cause different patterns for the standing wave and additionally it should be determined if this influences the sensitivity of the sensor system.

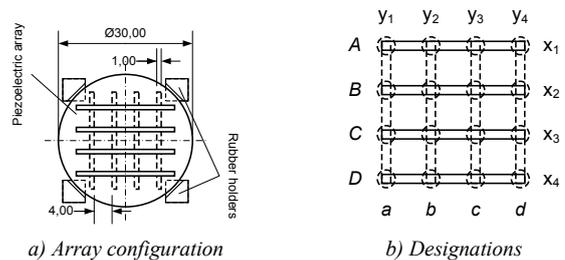


Fig. 5. Experimental sample

To investigate the influence of the standing wave experimental research is carried out on sample of 4x4 piezoelectric resonance array formed on the disk shaped substrate as shown on Fig. 5,a. The horizontal set of electrodes is designated with upper case letters (Fig. 5,b) and the vertical electrode set is designated with small case letters (Fig. 5,b) as the two letter designator defines how the excitation signal is applied – the first letter defines where the active phase of the oscillator is applied and the second where the electrical ground is connected. Table 1 shows some of the results from the unloaded resonance structure which confirms the occurrence of the strong standing waves in the sensor array.

TABLE 1. RESULTS FROM CONFIGURATION AA

Measurements Points for Aa	Signal pk-pk, V	RMS, V
A	10	3,536
B	5,884	2,08
C	4,859	1,718
D	2,665	0,942
a	0	0
b	3,223	1,139
c	3,95	1,396
d	8,626	3,05

The used oscillator supplies the sinusoidal wave with frequency of 220 kHz (which is equivalent to the natural one for the current structure) and 10 V peak-to-peak signal (*pk-pk*) as the measured data is given in peak-to-peak and in root mean square (RMS) values.

The obtained results show that indeed there is a standing wave that affects the signal amplitude which in turn will lead to difficulties in applying the amplitude scanning method. From practical point of view more interesting is the question if the array sensitivity is dependent on the standing waves and is this fact to be of any practical use? Experiments were carried out as in the center of the piezoelectric array was placed dielectric load of 2,764 g and 18 g were additionally inserted for comparing the sensitivity of the different standing waves. Some of the obtained results are shown in Table 2.

TABLE 2. SENSITIVITY FOR SOME OF THE CONFIGURATIONS

Configuration	Initial Load		Load with Added 18g		Reaction	
	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V
<b>Bc</b>						
A	5,826	2,060	5,803	2,051	-0,023	-0,009
B	10	3,535	10	3,535	0	0
C	3,082	1,090	3,106	1,098	0,024	0,008
D	5,258	1,859	5,191	1,835	-0,067	-0,024
a	3,872	1,369	3,905	1,381	0,033	0,011
b	6,094	2,154	6,070	2,146	-0,024	-0,008
c	0	0	0	0	0	0
d	3,421	1,209	3,447	1,219	0,026	0,010
<b>Ca</b>						
A	3,188	1,127	3,228	1,141	0,040	0,014
B	4,456	1,575	4,490	1,587	0,034	0,012
C	10	3,535	10	3,535	0	0
D	3,694	1,306	3,717	1,314	0,023	0,008
a	0	0	0	0	0	0
b	4,605	1,628	4,782	1,691	0,177	0,063
c	4,978	1,760	5,175	1,829	0,197	0,069
d	4,829	1,707	4,999	1,767	0,170	0,060
<b>Dc</b>						
A	3,435	1,214	3,439	1,216	0,004	0,002
B	4,183	1,479	4,181	1,478	-0,002	-0,001
C	4,606	1,628	4,614	1,631	0,008	0,003
D	10	3,535	10	3,535	0	0
a	6,418	2,269	6,408	2,650	-0,010	-0,004
b	4,253	1,504	4,256	1,505	0,003	0,001
c	0	0	0	0	0	0
d	6,149	2,174	6,141	2,171	-0,008	-0,003

From the collected data can be assumed that the pattern of the standing waves changes when shifting between different electrode combinations and there is also different sensitivity depending on the currently excited standing wave as the sensitivity for given array point changes with accordance with the wave configurations.

The discrepancies between the sensitivities for the distinct standing waves configurations are enough to consider the applicability of amplifiers. In this case the distinction between the influences of different loads can be detected using differential amplifier which will compare the signal values. The most efficient hardware wise approach is to use 8-to-1 analog multiplexer and 1-to-2 analog demultiplexer connected consequentially as shown on Fig. 6. The signals from piezoelectric array electrodes are fed to the 8-to-1 multiplexer which is used to pick the desirable signal and transfer it to the analog 1-to-2 demultiplexer controlling two peak detectors which in turn

are connected to the inputs of a differential amplifier. Generally, peak detectors can be considered as kind of memory elements which memorize the peak value of the alternating signal as a charge stored in the capacitor. Thus the peak detector firstly connected to the demultiplexer can store the initial signal value and the secondly connected peak detector can supply the referent value for the differential amplifier. The amplifier output is connected then to ADC.

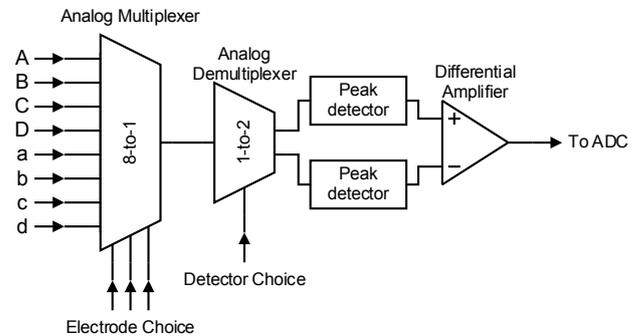


Fig. 6. Simple output interface circuitry

For better response time the analog multiplexer can be entirely omitted and every electrode can be connected to its own preprocessing circuit containing the analog multiplexer, the two peak detectors and the differential amplifier. It can be costly from hardware standpoint but the fast response of the piezoelectric sensor array is assured.

#### D. Increasing the array sensitivity

The proposed solution with the amplification does not consider the differences in the sensitivity and only deals with the small differential values in some of the cases. The more efficient solution is to use only these combinations of working electrodes that give more palpable differences in the monitored signals.

Research was carried out to find more suitable standing wave configurations as the complexity of the wave was increased through adding one more active phase electrode to the active ones. The designation "Aa+B" can be interpreted as A and B electrodes are active ones and a is the electrical ground. The obtained data indicates that the complex standing waves are more suited for sensor application because some of the examined combinations do not even need the amplifier to discern between different stages (Table 3).

The results show that depending on the used electrode combination the sensitivity of the piezoelectric resonance array can be improved but some combinations do not worth their usage because the response is of the same magnitude as in the case of the simple electrode combinations. Generally, the complex electrode combinations are increasing the sensitivity of the array but only small number of them is suitable for unaided measurement application. This reduction of usable combinations can be perceived as both advantage and disadvantage. The smaller number of useful combinations means more rigid, limited search algorithms but this will indeed increase the reaction time of the resonance array as there will be fewer operations that consume time and hardware resources.

As the standing waves are indeed influenced by the additional load the limited number of useful combinations raises a question regarding the influence of the load

location over the wave spread pattern. If there is a noticeable impact then only these useful electrode combinations can be used for the easing of the search methods.

TABLE 3. SENSITIVITY FOR SOME OF THE COMPLEX COMBINATIONS

Configuration	Initial Load		Load with Added 18g		Reaction	
	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V
A	8,803	3,112	8,490	3,001	-0,313	-0,111
B	4,348	1,537	4,438	1,569	0,090	0,032
C	10	3,535	10	3,535	0	0
D	9,522	3,367	9,171	3,242	-0,351	-0,125
a	4,454	1,575	4,553	1,610	0,099	0,035
b	0	0	0	0	0	0
c	8,007	2,831	7,774	2,749	-0,233	-0,082
d	10	3,535	10	3,535	0	0

Configuration	Initial Load		Load with Added 18g		Reaction	
	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V
A	8,893	3,144	8,719	3,083	-0,174	-0,061
B	10	3,535	10	3,535	0	0
C	10	3,535	10	3,535	0	0
D	9,063	3,204	8,854	3,130	-0,209	-0,074
a	5,186	1,833	5,243	1,853	0,057	0,020
b	0	0	0	0	0	0
c	9,021	3,189	8,886	3,142	-0,134	-0,047
d	5,852	2,069	5,908	2,089	0,056	0,020

Configuration	Initial Load		Load with Added 18g		Reaction	
	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V	Signal pk-pk, V	RMS, V
A	10	3,535	10	3,535	0	0
B	11,043	3,904	10,746	3,799	-0,297	-0,105
C	11,160	3,946	10,844	3,834	-0,316	-0,112
D	10	3,535	10	3,535	0	0
a	17,045	6,026	16,510	5,837	-0,535	-0,189
b	7,666	2,710	7,675	2,713	0,009	0,003
c	7,210	2,549	7,233	2,557	0,023	0,008
d	0	0	0	0	0	0

For the purpose of determining the influence of the load location some experiments were carried out with the complex standing waves and the locations were selected as shown on Fig. 7. The peripheral locations were chosen to be near the rubber holders which are supposed to act as dampers for the excited standing waves and therefore to be less sensitive to external loads. The designation "0" is for the unloaded resonance piezoelectric sensor array.

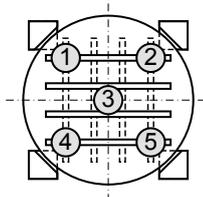


Fig. 7. Load locations in array field

TABLE 4. INFLUENCE OF LOAD LOCATION FOR Ad+D

Location	0	1	2	3	4	5
Signal pk-pk from A, V	10	10	10	10	10	10
Signal pk-pk from B, V	11,140	11,069	11,062	10,468	10,982	10,965
Signal pk-pk from C, V	11,261	11,222	11,190	10,610	11,054	11,085
Signal pk-pk from D, V	10	10	10	10	10	10
Signal pk-pk from a, V	17,032	17,150	17,078	16,008	16,876	16,930
Signal pk-pk from b, V	7,590	7,682	7,654	7,683	7,682	7,660
Signal pk-pk from c, V	7,201	7,255	7,238	7,273	7,235	7,223
Signal pk-pk from d, V	0	0	0	0	0	0

The experimental results (part of them in the form of signal pk-pk is shown in Table 4 and 5) show that load location indeed influence the standing wave pattern which fact can be used for precisely indicating the application point of an external load.

TABLE 5. INFLUENCE OF LOAD LOCATION FOR Ad+B

Location	0	1	2	3	4	5
Signal pk-pk from A, V	10	10	10	10	10	10
Signal pk-pk from B, V	10	10	10	10	10	10
Signal pk-pk from C, V	6,507	6,511	6,495	6,458	6,539	6,367
Signal pk-pk from D, V	3,734	3,626	3,656	3,464	3,572	3,605
Signal pk-pk from a, V	9,370	9,363	9,349	9,184	9,427	9,249
Signal pk-pk from b, V	6,215	6,203	6,200	6,217	6,144	6,208
Signal pk-pk from c, V	5,755	5,738	2,923	5,769	5,706	5,752
Signal pk-pk from d, V	0	0	0	0	0	0

Despite the obvious influence of the load location upon the standing wave pattern (Fig. 8) in some cases it is so miniscule that the signal difference should be amplified. In this case the aforementioned differential amplifier circuit is suitable for discerning the occurring change in the pattern.

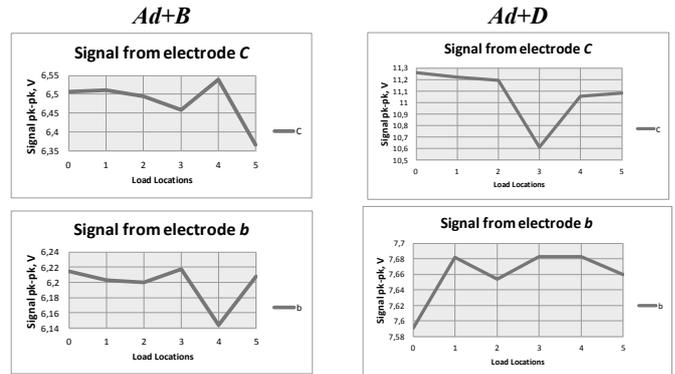


Fig. 8. Load location influence on the standing waves

For obtaining better results it is more appropriate to execute measurement across several electrode combinations and then repeat it again as in the end to make comparison between the gathered data from both measurements searching for occurring changes in the piezoelectric sensor array.

CONCLUSION

The amplitude scanning method for piezoelectric resonance sensor array offers possibilities for faster scanning process but also is more difficult for application because the influence of the standing waves that are excited in the resonant structure.

But experimental data shows that these same standing waves are readily influenced by an external load and the site of its application as they change their patterns accordingly. This fact can be used for even more speedy scanning procedures with the utilization of only the standing waves with the most prominent sensitivity and reaction.

For further development of this research a reliable mathematical model for the resonance array structure should be created as to increase the array dimensions and applicability.

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