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Acoustic Spectrum Analysis of Genuine and Counterfeit Euro Coins

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***Abstract*—In this paper acoustic signal spectrum analysis using FFT and modal analysis based coin validation methods for authentic and counterfeit coins has been presented and investigated. For acoustical coin validation spectrum analysis has found to work well. Optimal parameters and methods for time-spectrum co-analysis has been estimated and discussed.**

In addition, the modal analysis for acoustic signals of coins has been implemented, the results of which has been presented and provide the authentication of the coin even with close ~~acoustical~~ signal spectrum. Proposed solutions has been implemented in Matlab and tested on real euro coins with denomination 50 cent, 1- and 2-euro, providing by first evaluations cost efficiency with high reasonable accuracy of described solutions.

The counterfeited coins with domination of 2 euro have been tested with acoustical spectrum analysis and modal analysis evaluated in Matlab. The presented results provide the authentication of euro coins with high accuracy.

***Index Terms*—Acoustic signal, spectrum analysis, modal analysis, real and counterfeit coins.**

I. INTRODUCTION

In ancient times, before discovering of the validation machine, the genuine coin authentication process was performed by simple means. For example, the coin under test has been examined by striking the hard surface and the authentication of the coin has been identified by ear, according to the quality of the sound. Even the part of signal spectrum of the coin that could be picked up by the human ear was enough for coin validation.

Nowadays a number of techniques and methods has been used for coin validation process. The main idea of recognition process of coin validator is the detection of the most important feature or group of features (or physical characteristics) of the coin under test and comparison to the genuine coin. The various of methods based on different techniques and sensors such as electromagnetic and imaging approaches have been proposed for coin validation [1]–[3]. The simplest of them are typically based on mechanical and electromagnetic methods, where the magnet and aperture with different size holes, according to size of various coin denomination. Imaging based solutions provide unfit and counterfeit coin detection visually, what is usually not enough for authentic coin validation. Thus the very special attention is focused on the complicated alloy of euro coin, which is difficult to counterfeit.

For security reason euro coins have a sophisticated composition of metal so called *bi-metal* and sandwich technologies for the 1 and 2 euro coins, and unique alloys for other coins. These distinguished features ensure the reliable coin validation based on the strong specified physical and electromagnetic features of coins that can vary very slightly.

Eddy current sensors have been used for electrical conductivity measurements in most promising solutions for coin validation process, because of high-speed, accuracy, cost–efficiency and simplicity [4].

Another way for examination of the metal of the coin is the acoustical sensor implementation. The different alloys of metal and the hardness of different coin produce a special vibration spectrum on impact, which could be used for discrimination of coins with various denomination, which are otherwise quite similar. Using the acoustical sensor in the coin validation application make it possible to determine the authentication of the coins. Theoretically, it means that the acoustic signal of each euro coin is unique, what makes it possible to match and validate coin with different denomination from its acoustic signal by spectrum analyses techniques.

The acoustic validation techniques of coins have been widely employed, because this increases the accuracy of the coin validation system and allows the counterfeit coin detection [5]–[8].

II. PREVIOUS WORKS

The invention [9] is related to the coin validation using acoustic measurement of coin upon an impact member. The vibrations of the impact element have been stored and analysed. The various alloys of metal material produce a different vibration spectrum on the impact, which could be used for coin classification process.

The patent [10] with the description of coin validation apparatus based on acoustic sensor was published in 1991. The main idea was to detect and store the acoustic vibrations of coin after kick specified surface by microphone. Then,

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after signal spectrum analysis, by comparison of the results of the coin under test and etalon ones, the coin is accepted or rejected. In 2006 was published the patent, where the spectrum analyses using FFT for coin validation was presented. The main idea was to calculate the standard deviation of each signal spectrum by six peaks and then to classify according frequencies. Described method allows to determine the authentication of the coin and to specify the denomination. According to this method it could be defined that the coin under test is genuine, if one of the measured values of maximas of the frequency spectrum and corresponding magnitude match the values for the stored frequency.

In conjunction with other visual processing and multimodal sensors, the acoustic sensors are applied in the professional vending service machines [5]. The combination of different technical solutions, based on acoustic sensor, multimodal sensor and visual processing, makes this vending machines fast, accurate, robust and sensitive to counterfeit coins.

III. Proposed Solution

The proposed setup for coin validation consists of acoustical signal capturing setup. In Fig. 1, it has been presented the block diagram of the device used for examination of the coins, where metal plate and microphone are used.

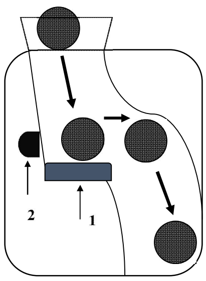

Fig. 1. Device used for coin acoustic signal capturing, where 1 is metal plate and 2 is microphone.

The duration of the acoustical signal is about 0.4 sec and the bandwidth from 0 kHz to 35 kHz. After signal acquisition, it has been decimated by a factor 10 using an FIR filter that reduce the sample rate and the computational effort 10 times, and minimise the influence of the noise and distortion of acoustic signal. Than the mean value of decimated signal and the difference of original signal have been calculated. Next, the Hamming window, the size of which is the same as dimensions of the input signal, has been used for convolution calculation. Windowing of acoustical signal allows to extract frequencies from spectrum more clearly.

Next, the signal is transformed by using Fast Fourier Transform (FFT) from time into frequency domain. As could be seen from Fig. 2 (left), where the acoustical signal and spectrogram (right) of real 2 euro coin are presented, the maximum vibration of signal is located in 0.2 sec by time domain in space representation. In frequency representation, this maximum is located at same place by time domain and have maximum frequencies near 12 kHz, 18 kHz and 24 kHz.

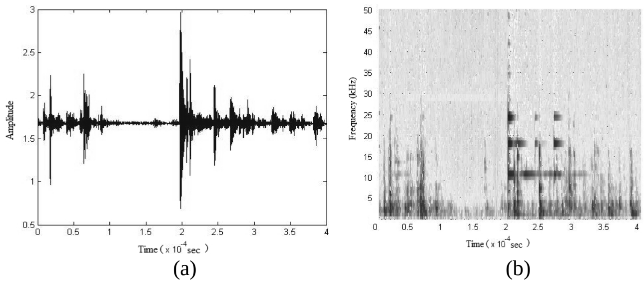

Fig. 2. Oscillogram of 2 euro coin (a), spectrogram of 2 euro coin (b).

The vibrations in the beginning of the signal from 0 sec until about 0.08 sec in time domain is the noise from falling coin. Thus, this part of signal would be discarded from calculations. Couples of frequencies with most intensive magnitudes would be fixed for each euro coin under test. The extracted set of acoustical signal properties could be used for validation and classification of euro coins.

A. *Experiments with Authentic Euro Coins*

The absolute values of the FFT output has been used for visualization of the frequencies (Fig. 3), the sampling rate is 50000. The implemented method of signal spectrum analysis demonstrate that the maximum frequency and magnitude of each coin with different denomination is unique.

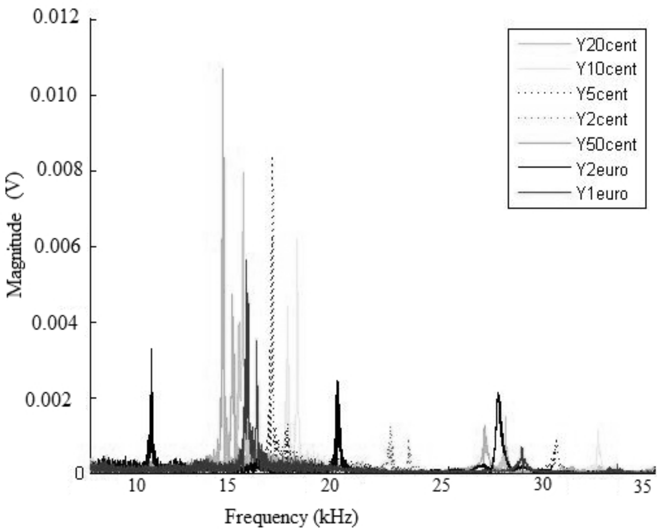

Fig. 3. FFT of euro coins with domination 2 euro, 1 euro, 50 cent, 20 cent, 10 cent, 5 cent and 2 cent.

The numerical results of proposed solution based on the FFT are presented in Table I.

TABLE I. FREQUENCIES AND MAGNITUDES OF EURO COINS.

Denomination of coin	Frequency, kHz	Magnitude (max)
2 euro	11.12	164
1 euro	15.51	281
50 cent	15.99	98
20 cent	16.27	397
10 cent	18.73	309
5 cent	17.58	420
2 cent	22.96	63

The results of acoustical signal analysis shows that every coin has his own frequency and magnitude value, but some of them are located quite close to each other. Several experiments with the same coin shows that the frequency of signal spectrum can vary slightly, what is some cases cause the difficulty in authentication of the coin. Thus the additional methods of sound signal analyses should be implemented.

Another method for evaluation of the acoustic signal vibrations is applying the modal analyses what makes it possible to measure and analyse the dynamic response of structures during vibration [11]. The computation of modal analyses is more complicated, to determine the natural frequency of the signal the stabilization chart is implemented [12]. The greater is the number of computed modes, the more accurate is the result. The stabilization chart of 2 euro coin is presented in Fig. 4. Experimentally it has been found that the minimum number of calculated modes should be 20.

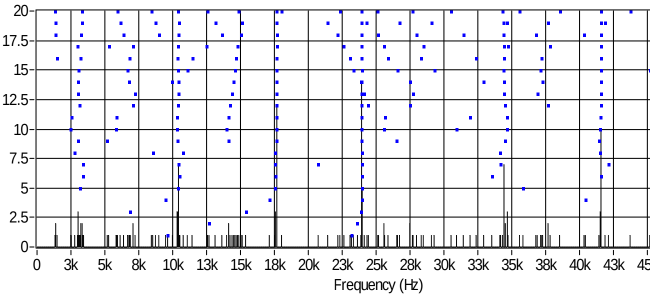

Fig. 4. The stabilization with 20 calculated modes chart of 2 euro coin.

In Table II the experimental results of modal analysis with real euro coins with denomination 2 euro, 1 euro and 50 cent are presented.

TABLE II. THE RESULTS OF MODAL ANALYSES BASED ON THE AUTHENTIC COINS.

Coin type	Natural frequencies (1; 2 and 3), kHz	Damping ratio (according to frequencies 1; 2 and 3)
2 euro	10.4; 17.7; 23.9	-0.591; -0.161; -0.189;
1 euro	14.2; 24.8; 31.2	-0.226; -0.537; -0.106;
50 euro	13.3; 23.4; 30.1	-0.319; -9.648; -0.072

The experimental result of modal analysis of real coins shows that every coin has unique frequency and damping ratio what could be used for euro coin validation.

B. *Experiments with Counterfeit Euro Coins*

To verify the proposed methods the experiments with counterfeit coins have been performed using Matlab. Three counterfeit coins with denomination of 2 euro with various classification of the quality, have been tested with different techniques, the results of which have been compared and analysed.

Firstly, coins have been stroked to the hard metal surface and the acoustical sound have been tested by human ear. All thee coins have various acoustical tones which differs from the tone of the genuine coin.

Secondly, fraud coins have been tested by eddy current, the results of the experiments was compared to the real coins:

– The results of 2 euro coin number 1 differs from the original one a lot;

– The results of 2 euro coin number 2 differs from the original one a lot, but less than the previous fraud coin;

– The results of 2 euro coin number 3 was is acceptable area comparing to the real 2 euro coin. The quality of this coin is the best from the fraud coins under test.

The results of eddy current method implementation for counterfeit coin detection show that counterfeit coins with high quality could not be matched by eddy current method.

Next, the spectrum analysis has been applied to the acoustical signals of counterfeit coins. In Fig. 5(a) and Fig. 5(b) the acoustic signals of the counterfeit 2 euro coin number 1 and 2 are presented, where x-axis is frequency in Hz and y-axis is an amplitude.

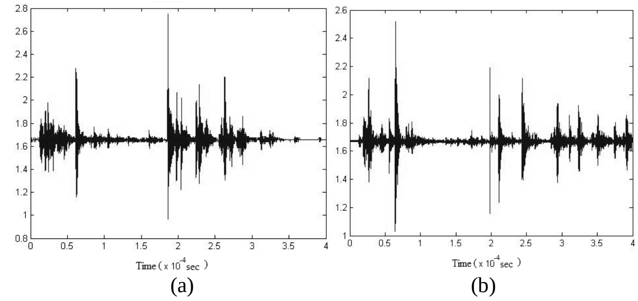

Fig. 5. The acoustic signal of counterfeit 2 euro coin: a) number 1; b) number 2.

The FFT analysis has been applied to the counterfeit 2 euro coin signals, the results of which are presented in Fig. 6 and compared with the frequency spectrum of the genuine 2 euro coin.

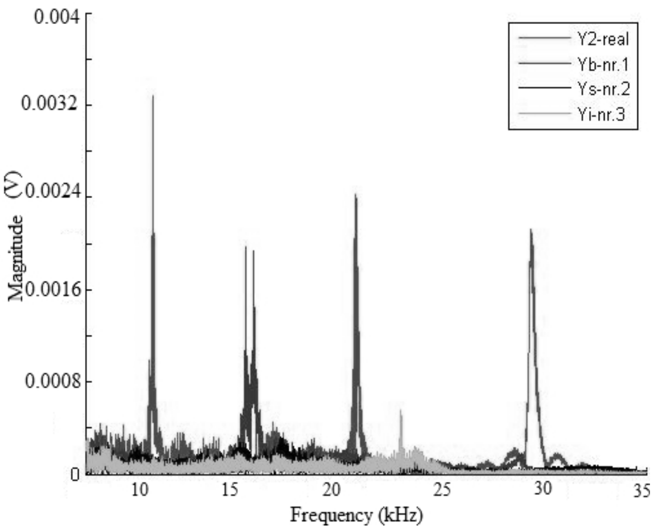

Fig. 6. Output of FFT applied to counterfeit and real euro coins.

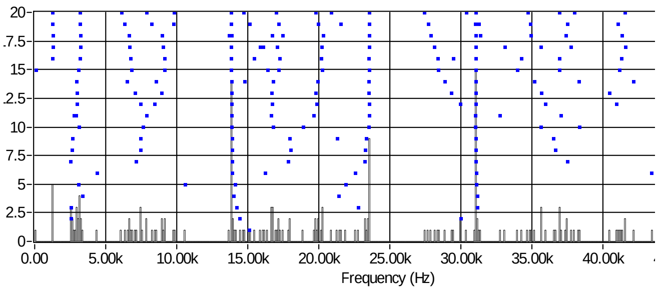

Fig. 7. Output of modal analyses statistical chart with counterfeit 2 euro coin number 1.

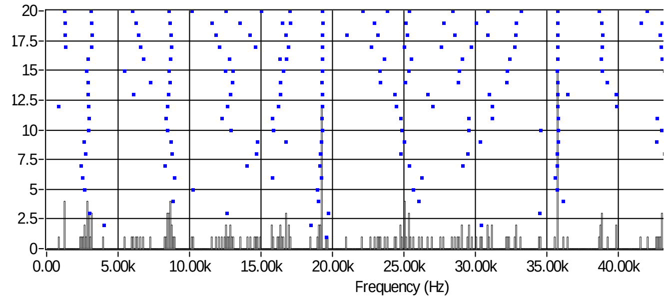

Fig. 8. Output of modal analyses statistical chart with counterfeit 2 euro coin number 2.

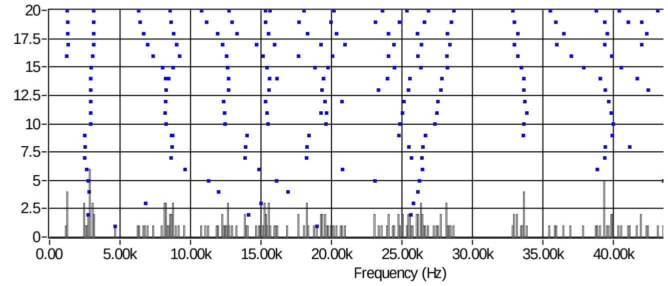

Fig. 9. Output of modal analyses statistical chart with counterfeit 2 euro coin number 3.

The results of the stabilization chart of modal analyses with counterfeit coins are presented in Fig. 7–Fig. 9, where three types of counterfeit coins are examined.

The experimental results of modal analysis with counterfeit euro coins have been given in Table III.

TABLE III. THE RESULTS OF MODAL ANALYSES, BASED ON THE COUNTERFEIT COINS.

Counterfeit 2 euro coin	**Natural frequencies (1; 2; 3), kHz**	**Damping ratio**
Nr. 1	31.1; 13.8; 23.5	-0.387; -0.427; -0.586
Nr. 2	35.7; 19.3; -	-0.66; -0.64
Nr. 3	- ; - ; -	-

The investigated by modal analyses counterfeit 2 euro coins have dissimilar frequencies. Moreover, the stabilisation chart of the last coin (Fig. 9) shows that there is no distinct frequency spectrum in this acoustical signal.

As could be marked, from acoustic signal, spectrum analysis and modal analysis presented before, the results of three types 2 euro coins are totally different from each other and from authentic 2 euro coin.

IV. RESULTS

The experiments have been repeated 10 times with every coin under test. FFT and modal analysis based on acoustic signal processing provide coin validation by signal spectra.

Results of experiments show the efficiency and high accuracy of described method based on acoustic signal for identification of euro coins. Extracted and fixed sets of frequencies and corresponding magnitudes of each euro coin are unique and provide coin validation and recognition.

Taking into account results of proposed acoustic signal processing, the validation of genuine and counterfeit coins based on the spectrum analysis and modal analysis provide counterfeit coin matching with high accuracy.

Using of the proposed approaches, low cost, high speed and accuracy acoustic sensor based solution for euro coin validation can be developed.

V. CONCLUSIONS

In this paper, acoustic signal spectrum analysis methods based on FFT and modal analysis have been proposed, evaluated in Matlab and investigated.

The experiments have been carried out on authentic and counterfeit euro coins, the results and analysis of experiments are presented. The results shows the efficiency of the proposed solution for authentic euro coin detection and validation and counterfeit coin detection.

Further development of presented method could be achieved by combining imaging coin validation unit.

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