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POSSIBILITIES TO USE THE EIGENFREQUENCIES TO IDENTIFY COINS

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ABSTRACT— *The acoustic diagnostics is one of the oldest methods for non-destructive control. The present paper, analyzing the recorded sound of a coin, falling on a hard pad or strike with an impulse hammer, defines the first three eigenfrequencies of contemporary coins that are in circulation. (1 BGN 2002, 1EUR 2002, 1 TRL). It is noticeable that the dispersion of the frequencies when measuring a series of coins is the lowest (about 1%) in the Turkish coin, which is the newest coin. On the base of the frequencies measured, Labview-based application is created to identify coins. As the coins are bimetal, the properties of the equivalent thin circular plate model are calculated by FEA using optimization procedure.*

Keywords: coin, eigenfrequency, eigenmode, circular plate, LabView, optimization

1. INTRODUCTUON

The coin is a piece of metal with a determined weight, signed by the legal government. All coins are created with certain technical characteristics. Besides the chemical composition of the alloy, they must comply with a certain weight, diameter and thickness**.** [Mackay J. (2009)].

The acoustic diagnostics is one of the oldest methods for non-destructive control. Even today at lot of railway stations you can see an employee with a hammer in his hand, striking the wheels of the wagons. Acoustic diagnostics is based on a well-known phenomenon that the response of each mechanical system to initial conditions (displacement and/or velocity) is sum of oscillations with specific frequencies, solely dependent on the mass and the stiffness of the system, called natural frequencies (eigenfrequencies). Each eigenfrequency is connected with its corresponding mode of vibration (eigenmode). The method is quick, easy and when using modern technical equipment, it can be easily automated and used for production control (e.g. presence of cracks and other defects, deviation from the shape and the dimensions, etc). Of course, an experimental analysis as well as FEM simulations must be made, in order to define the admission criteria. [Kolarov I. (2012, 2014)].

The solution (1) to determine the natural frequencies f_{mn} of a thin circular plate with free boundary conditions is used. Calculated eigenvalues according to [Leissa A.W. (1969)], for two values of Poisson’s ratio (ν=0.25 and ν=0.33), are shown Table1. In ASTM E1876-09 standard tables for $\lambda_{mn}{}^2$ selection for the first two eigenfrequencies as a function of ν and ratio t/r, based on the work of [J. C. Glandus (1981)] are given. So, the eigenvalues are function of dimensions of the plate and Poisson’s ratio of the material.

$$f_{mn} = \frac{\lambda_{mn}{}^2}{2\pi \cdot r^2}\sqrt{\frac{A}{\rho \cdot t}}, \tag{1}$$

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where $A = \frac{Et^3}{12(1-\upsilon^2)}$ –flexural rigidity of the plate ; λ_{mn}^2-eigenvalues; ρ-density; t-thickness; r –radius of the plate.

Table 1. Eigenvalues for the three lowest eigenfrequencies [Leissa A.W. (1969)]

Poisson's ratio	λ^2_{02}	λ^2_{10}	λ^2_{03}
0.33	5.523	9.084	12.23
0.25	5.513	8.892	12.75

Fig. 1,2 and 3 shows the modes of vibration, corresponding to the three lowest eigenfrequencies of thin circular plate with free boundary condition. The nodal points of the modes are grouped in circles or diameters, respectively marked with indexes "m" and "n", where m-number of nodal circles; **n**-number of nodal diameters. Eigenmode 02: This mode has the lowest natural frequency. The Nodal points are located on two perpendicular diameters. Eigenmode 10: This mode is connected with the second natural frequency. The nodes are located in a circle, with a radius *0.681r*. Eigenmode 03 :This mode is connected with the third natural frequency. The nodes are located on a three diameter.

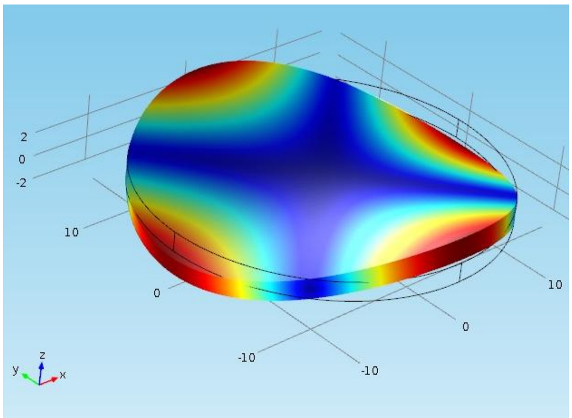

Fig. **1**Eigenmode **02** of a thin circular plate

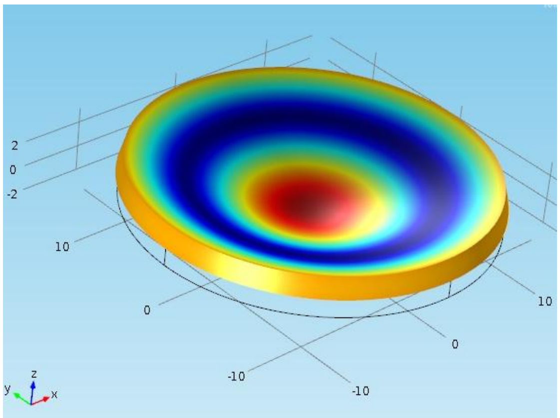

Fig. **2** Eigenmode **10** of a thin circular plate

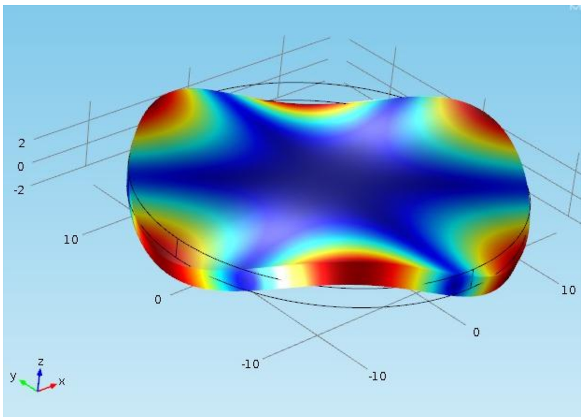

Fig. 3 Eigenmode 03 of a thin circular plate

The present study is a stage of the developing an application for acoustic identification of coins in circulation. For this purpose it is necessary to determine experimentally the natural frequencies of the

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coins and to provide empirical values of the elastic constants, so that the eigenfrequencies can be obtained by using a model of a coin like a thin circular plate.

2. MATERIALS AND METHODS

For the present experiment coins in circulation of „1 BGN“ 2002, „1 EUR“ 2002, „1 TRL” are used, fig.4. Turkish coins are started to mint at 2009. For the experiment coins from years 2010, 2013, 2014 are used. The coins are bi-color, similar in terms of composition, size and weight, Table2. The yellow outer ring is made of copper brass alloyed with Ni. The inner white circle is made of cupronickel, except for the 1EUR coin which has sandwich structure, with middle layer made of pure Ni plated from both sides with Cu-Ni layers. Because of this this coin can be attracted by a magnet.

Fig. 4. General view of the studied coins

Table 2. Dimensions, weight and alloy of the studied coins as per catalogue data

Coin	D, mm	t, mm	m, g	Alloy *outer ring,* *inner circle*
1 BGN (2002)	**24.5**	**1,9***	**7.0**	**Cu-Zn-Ni, 75Cu-25Ni**
1 EUR (2002)	**23.25**	**2.33**	**7.5**	**75Cu-5Ni-20Zn 75Cu-25Ni -Ni - 75Cu-25Ni**
1 TRL (2014)	**26.15**	**1.9**	**8.2**	**81Cu-4Ni-15Zn 75Cu-15Ni-10Zn**

*****-*an average result, based on the measurement of the coin thickness at different points*

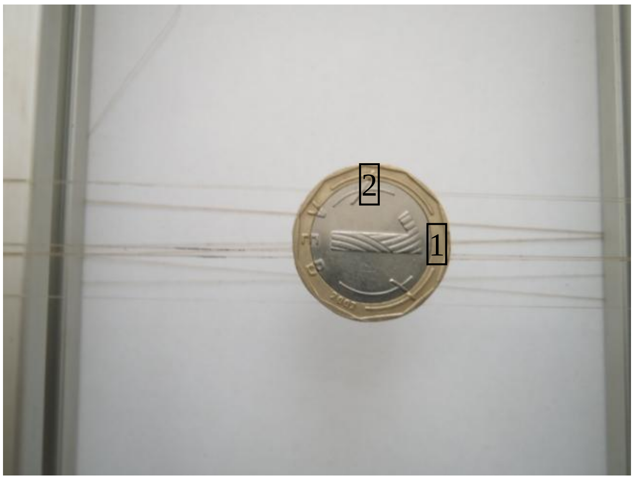
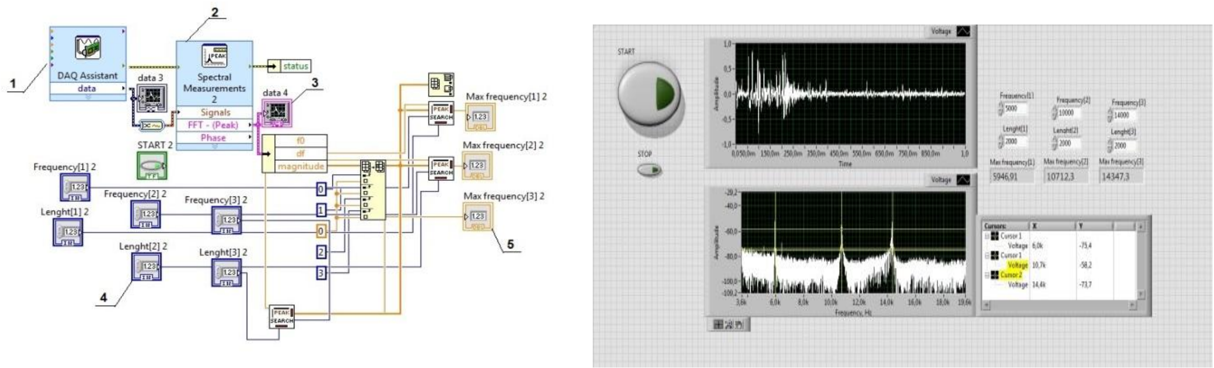


Fig. 5. Positioning the coin for eigenfrequency experiment (1,2 –impact points)

To determine the eigenfrequencies, the coins are laid on elastic threads (fig.5) and strike with an impulse hammer (hardened steel ball on a flexible rod). The sound signal, recorded with the help of a microphone, is processed by a computer and is presented as an amplitude-frequency spectrum. For the purposes of the present study, an RTF sound level meter, working with a condenser microphone with an external polarization, is used. The analog output signal is digitalized by a NI6216 module (16bit ADC "National Instruments"). The sampling frequency is set to 150kHz.

Labview-based application is developed to obtain eigenfrequency values. The block diagram and the front panel are shown on fig.6. Block (1) identifies the measuring channel, followed by a block for Fourier transformation (2). Then the controls for fixing the areas for peak search, corresponding to the respective eigenfrequency, come. When the "START" button is pressed sound signal with a specified duration (1s) is recorded and transformed to frequency spectrum. On the front panel the graphs of the signal in the time and frequency domains, as well as the obtained eigenfrequencies, are displayed.



1 – a module to identify the sound-level meter; 2 – a module, based on FFT; 3 – a graph; 4 – controls; 5 – indicators.

Fig. 6 – Block diagram (left) and front panel (right) of the Labview application for coins identification by their eigenfrequencies

3. RESULTS AND DISCUSSION

3.1. Measured eigenfrequencies

The obtained eigenfrequencies are shown on fig.7. On a base of this results mean and standard deviation are calculated, Table 3 (mean values are given with a dotted line on fig.7). According to the general rule that the eigenfrequencies are determined by the stiffness to mass ratio, it can be seen that, the coin with the highest thickness (1 EUR) has the highest set of eigenfrequencies.

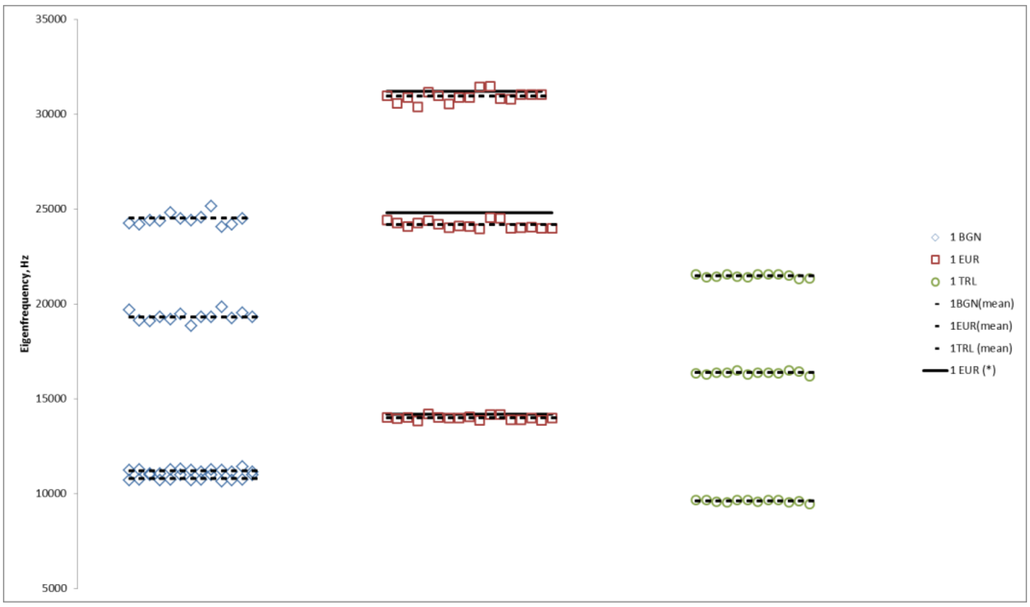


Fig. 7 The obtained eigenfrequencies of the studied coins
**-eigenfrequency of 1 EUR coin from [Gavrijaseva, A. et al. (2015)]*

Eigenfrequencies of 1 EUR are similar to these shown in [Gavrijaseva, A. et al. (2015)]. At one and the same thickness the BGN has higher set of eigenfrequencies compared to the TRL, due to its lower weight. For the 1 BGN coin two f_{02}' s peaks are detected, fig.8, which is an indication for anisotropy of material properties and/or influence of coin protuberance. For the 500 yen coin [Oshida, T et al. (2015)] found out the same phenomena. They first apply annealing heat treatment and later milling operation to remove the protuberance, but the two f_{02}' s peaks are still appears. Since, experiments with changing the impact point (1,2 fig.5) results in different amplitude ratio of peaks , it can be stated that the deep protuberance of the coin is the major reason.

Table 3. Mean and standard deviation, of the measured eigenfrequencies *

Coin / Eigenfrequencies		**1 BGN**	**1EUR**	**1 TRL**
f_{02}, kHz	**Mean (μ)**	**10.8 / 11.2**	**14.0**	**9.63**
	St. Dev. (s)	86.9	96.7	52.2
f_{10}, kHz	**Mean (μ)**	**19.3**	**24.2**	**16.4**
	St. Dev. (s)	291	160	73.5
f_{03}, kHz	**Mean (μ)**	**24.5**	**30.9**	**21.5**
	St. Dev. (s)	297	256	80.9

*****number of measured coins n= 15*

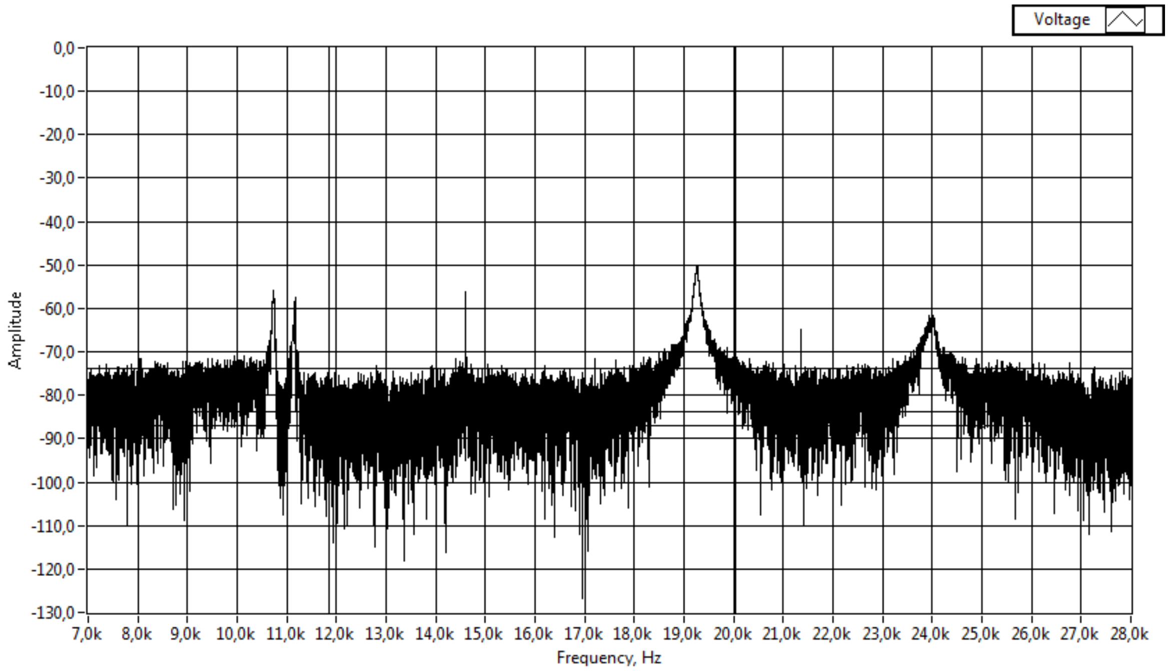


Fig. 8. Amplitude –frequency spectrum for 1BGN coin

3.2 Labview-based software application for coins identification

Calculations shows that for the newest coin (the TRL), the lowest deviation of the frequencies is observed. For the BGN and the EUR the deviation is higher, probably due to the fact that they have been in circulation for a longer period of time. Setting the search intervals as mean ±3*St.Dev the LabView app is rearranged with a Boolean indicator on the front panel, fig.9, showing whether the frequencies of the examined coin fall within the set intervals, i.e. whether the coin is genuine. Such application can be used for example in vending machines coin discriminators [Carlosena, A. et al. (2007)], [Oshida, T et al. (2015)]. To test this app coins are dropped on a hard surface.

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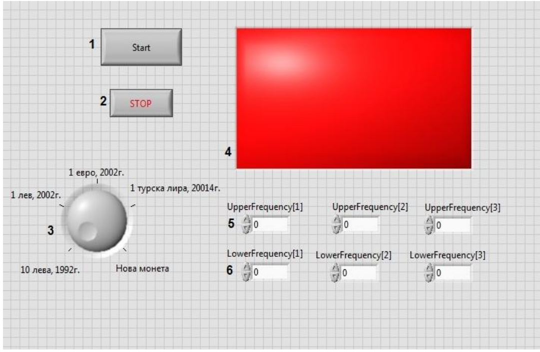

Fig.9 Front panel of a *LabView* application for coins identification

3.3 Approximate values of the elastic constants of the material for analytical determination of the eigenfrequencies

In order to calculate an eigenfrequencies of a coin using simple model of free circular plate, formula (1), one have to determine empirical values for the material properties (E, ρ, ν) and eigenvalues. For coin modeling following approach was suggested in [Dimitrov, D.M. et all (2013)] for gold coins and in [Suzuki, M. (2008)] for Japanese 500 yen coins. Density of the coin can be measured by Archimedes' method or calculated by mixtures rule. The equivalent uniform thickness of a model is obtained by adjusting the weight same as the real coin weight. Elastic constants (E, ν) can also be preliminary obtained by mixtures rule and then adjusted to fit measured frequencies using optimization procedure. For this procedure FEA software "Comsol Multiphysics" is used. As a starting values of E=120GPa and ν=0.35 are used. Optimization procedure minimizes the objective function (2) using Nelder-Mead optimization method. Results for the measured by Archimedes' method densities, calculated equivalent thickness, elastic constants and eigenfrequencies and eigenvalues are given in Table 4.

$$G = \min\left\{\sum\left[f_{mn} - f_{mn}(\exp)\right]^2\right\}, \qquad (2)$$

where f_{mn} -calculated by FEA eigenfrequency.

Table 4. Values for the density, thickness, Young's module E, Poisson's ratio ν and the eigenfrequencies and eigenvalues of equivalent circular plate calculated by FEM

Coin	ρ, kg/m^3	t_{eq}, mm	E, GPa	ν	f_{02} kHz	f_{10} kHz	f_{03} kHz	λ^2_{02}	λ^2_{10}	λ^2_{03}
1 BGN (2002)	8910	1.666	139.5	0.35	11.9	19.3	24.5	4.446	7.774	10.102
1 EUR (2002)	8860	1.994	129	0.359	13.8	24.2	30.9	4.254	7.471	9.555
1 TRL	8820	1.686	133	0.327	9.60	16.5	21.8	5.581	9.573	12.692

4. CONCLUSION

The first three eigenfrequencies of similar bi-color coins in circulation 1BGN (2002), 1

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EUR(2002) and 1 TRL are determined. The lowest are the frequencies of the TRL, followed by the BGN and the highest are those of the EUR coin. It is noteworthy that the dispersion of the results in measuring a series of coins is the lowest (about 1%) in the TRL, which is the newest coin. It can be concluded that with the increase of the number of years in circulation, the dispersion of the frequencies will also increase. On the basis of the measured frequencies, Labview-based application for acoustic identification of coins is developed.

To calculate the eigenfrequencies of these coins using the equivalent thin circular plate model, following empirically obtained values for the properties of the material E=129-139GPa, ρ=8800-8900kg/m3, ν=0.32-0.36 can be used.

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