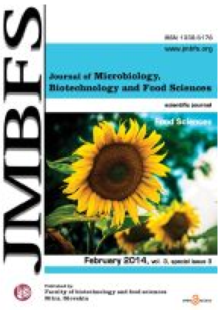

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BEHAVIOR OF CRACKED EGGS AT NON – DESTRUCTIVE IMPACT

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ABSTRACT

The influence of cracks on the dynamical frequency response of eggshells was studied. The non-destructive impact tests of the intact and cracked eggs were performed. Record of impact force time history was enabled by experimental device. Response of eggshell to the impact was described by the surface displacement of the eggshell. This response was measured by the laser interferometry. The force and response were also expressed in the frequency domain using of the fast Fourier transform. Both time and frequency response were affected by the presence of cracks. It was shown that the influence of cracks on the eggshell response was more effectively described in the frequency domain. The frequency response was relatively very sensitive to the position and orientation of cracks. The frequency response function was characterized by many peaks. Five excitation resonant frequency characteristic of signals were extracted based on the difference of frequency domain response signals. Distinction between intact and cracked eggs was enabled by these parameters. Even if some main problems were solved some of them remained unsolved. One of them was the effect of the impacting body r shape. This problem could be effectively solved namely using of numerical methods. In order to describe the response of eggshell response to the non-destructive impact using of the numerical simulation exact description of eggshell shape was performed. This numerical simulation will be subject of forthcoming paper.

Keywords: Eggshell, impact loading, frequency analysis, crack, egg

INTRODUCTION

Egg in the daily human diet is considered to be a cheap source of quality protein (**Papadopoulou *et al.*, 1997; Adesiyun *et al.*, 2006; *Liu et al.*, 2007**). Cracks on eggshell are commonly produced during packing and/or transportation. Cracked eggs are more vulnerable to *Salmonella spp.* and other bacterial infections leading to health hazards(**Adesiyun *et al.*, 2005a; Adesiyun *et al.*, 2005b**).In addition, intact eggs could be contaminated with infected cracked eggs with significant economic loss (**Bain, 1990**).Crack detection in egg sorting and packing industry is usually achieved manually and relies on candling(**Lin, 1995**). Recent researches have shown that it is possible to measure the quality of eggs by analysis of the dynamical frequency response of eggshells (**Cho *et al.*, 2000; Ketelaere *et al.*, 2000**).**De Ketelaere *et al.* (2003)**evaluated several parameters for eggshell measurement. **Jindal and Sritham (2003)** employed ANN (artificial neural network) model combined with acoustic resonance to detect cracked eggs. The mechanical properties of rupture force, specific deformation, rupture energy and firmness was examined (**Altuntas and Sekeroglu, 2008**). It was found that the acoustic response signals of eggs were affected by impacting locations and force (**Nedomova *et al.*, 2009a,b**). Regardless to this effort many problems remain unsolved. Namely more experimental results are needed. This is the main reason for this research which is focused on the influence of an existing crack in hen eggs exposed to light impact on the eggshell response.

MATERIAL AND METHODS

The experimental device described e.g. by **Nedomova *et al.*(2009b)**has been used; schematic of this device is shown in the Figure 1.

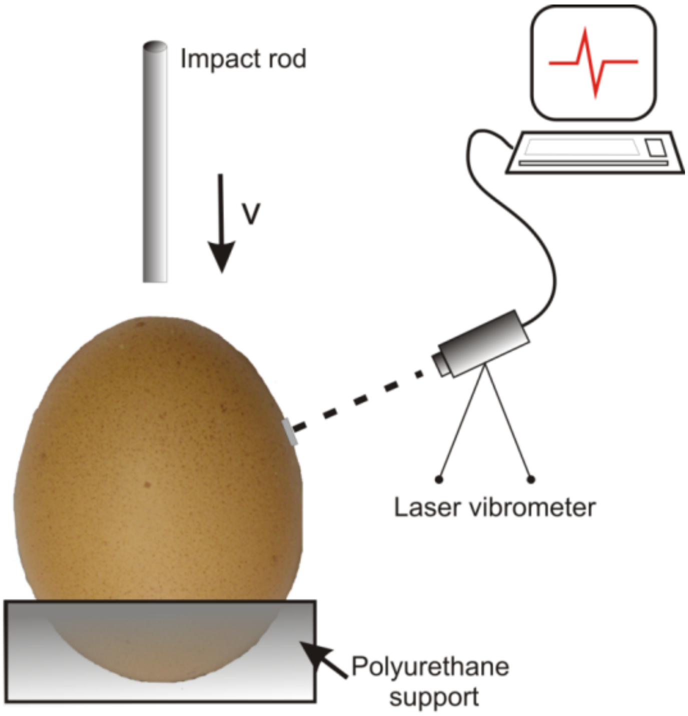


Figure 1 Schema of the impact loading of the egg

This experimental arrangement enables to study the egg's behavior under impact by different bodies accelerated to different velocities. Eggshell response is measured in terms of the eggshell surface displacement. In this research impactors were used in form of flat cylinders and ball. Using of the cylindrical impactor enables to record time history of the impact force. The research investigated the effects of excitation point, egg mass, impact intensity and shell crack on the frequencies response signals.

Eggs (*Hisex Brown* strain) were collected from a commercial grading station. Typically, the eggs were a maximum of 2 days old when they arrived at the grading station. The main characteristics of the eggs were evaluated – mass, eggshell thickness, the egg length, L, and the egg width, W. The geometry of the eggshell can be very simply described using the shape index (SI) which is defined as:

$$SI = \frac{W}{L} x100 \quad (\%)$$

The description of the egg's shape has been obtained from digital egg photographs. The application required one measured dimension (the egg length, measured with sliding calipers), and allowed the user to determine any user-defined distance on the photograph from the derived number of pixels per unit length. From the dimensional measures of individual eggs, their contours could be accurately described in Cartesian coordinate system defined by user, by a mathematical equation (**Carter, 1974**). For more details, please refer to the procedure described by **Denys *et al.*(2003)**. Three dimensional egg shapes can be then obtained by revolving the contours 180° about the axis of symmetry. The shape of the eggshell contour can be described using the polar coordinates r, φas:

$$x = r\cos\varphi \qquad y = \sin\varphi$$

where,

$$r(\varphi) = a_o + \sum_{i=0}^{\infty} a_i \cos\left(2\pi\frac{\varphi}{c_i}\right) + b_i \sin\left(2\pi\frac{\varphi}{c_i}\right)$$

The analysis of our data led to the conclusion that the first five coefficients of the Fourier series are quite sufficient for the egg's contour shape description (the correlation coefficient between measured and computed egg's profiles lies between 0.98 and 1).

The knowledge of the equation describing the eggshell contour is necessary namely for the numerical simulation of egg's behavior under different mechanical loading, at numerical simulation of different heat treatment, and also for the determination of the curvature of this curve. The radius of the curvature, R, than plays meaning role at the evaluation of some egg's loading tests (compression test, etc.) – see e.g. **MacLeod *et al.*(2006)**. The data on the eggshell geometry are presented in the Table 1.

Table 1 Eggshell geometry

Values	Mass [g]	Length L [mm]	Width W [mm]	SI [%]	Surface [mm^2]	Volume [mm^3]
Minimum	53.09	52.51	41.48	72.49	6504.94	49333.09
Average	59.64	55.21	43.76	79.29	7024.19	55376.73
Maximum	66.77	58.91	45.84	84.61	7605.10	62363.62
SD	2.73	1.36	0.82	2.31	220.06	2601.27

The values of the radii of the curvature at the main points of the eggshell – see the Figure 2 is reported in Table 2.

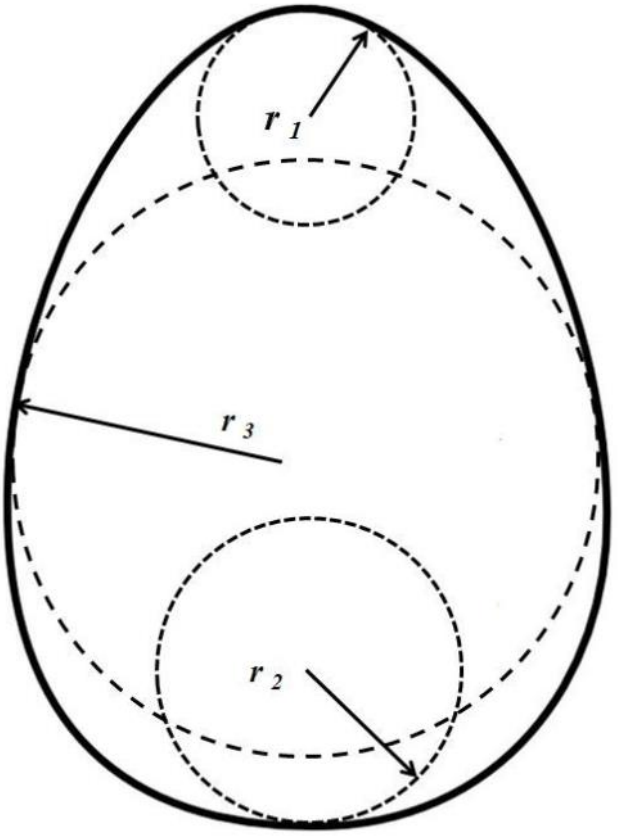


Figure 2 The geometry of an egg for the sharp end (r_1), the blunt end (r_2) and the equator (r_3)

Table 2 Radii of the curvature

Radius of the curvature [mm]	Minimum	Average	Maximum	SD
Sharp end r_1[mm]	11.80	14.99	20.11	1.58
Blunt end r_2[mm]	22.90	33.11	42.14	2.88
Equator r_3[mm]	30.92	38.82	50.81	2.58

Two groups of eggs have been tested. About 100 intact eggs have been selected by the visual inspection. The second group involves eggs with artificially prepared cracks. An initial crack was induced to the eggshells by two weak mechanical impacts close enough to induce a macro-crack oriented mainly along the meridian direction. Eggs were excited by the impact of projectile at three different positions: on the sharp end, on the blunt end and on the equator.

RESULTS AND DISCUSSION

In the first step cracks in the eggshell have been introduced by the impact of the aluminum bar (200 mm length, 6 mm in diameter). The velocity of the bar has been given by the height of the fall, h. Some examples of induced cracks are presented in the Figure 3.

Figure 3 Examples of the cracks

The orientation of cracks was multifarious. So it is hard to provide a scheme which can represent most styles of crack on the surface of eggs.

The next point of the research has been focused on the response of the eggshell to the impact of the aluminum bar. The bar had different velocities, *v*, given by the different height, *h*, of the bar fall. The dependence of the bar velocity on the height, *h*,is plotted in the Figure 4.

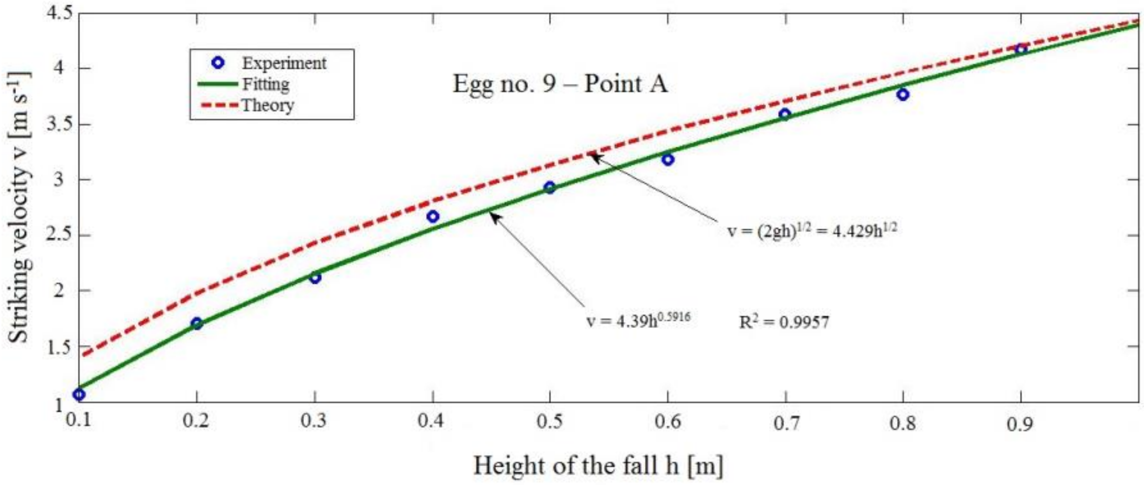


Figure 4 Striking velocity *vs.* height of the bar fall, broken line corresponds to the theoretical dependence

An example of the experimental record of the forces at the point of contact between bar and egg is shownin the Figure 5. It has been found that the shape of the force – time function reflects the eggshell damage. If the eggshell is non – damaged the shape of this function is nearly “half – sine”. The origin of the eggshell damage is connected with an abrupt in this dependence.

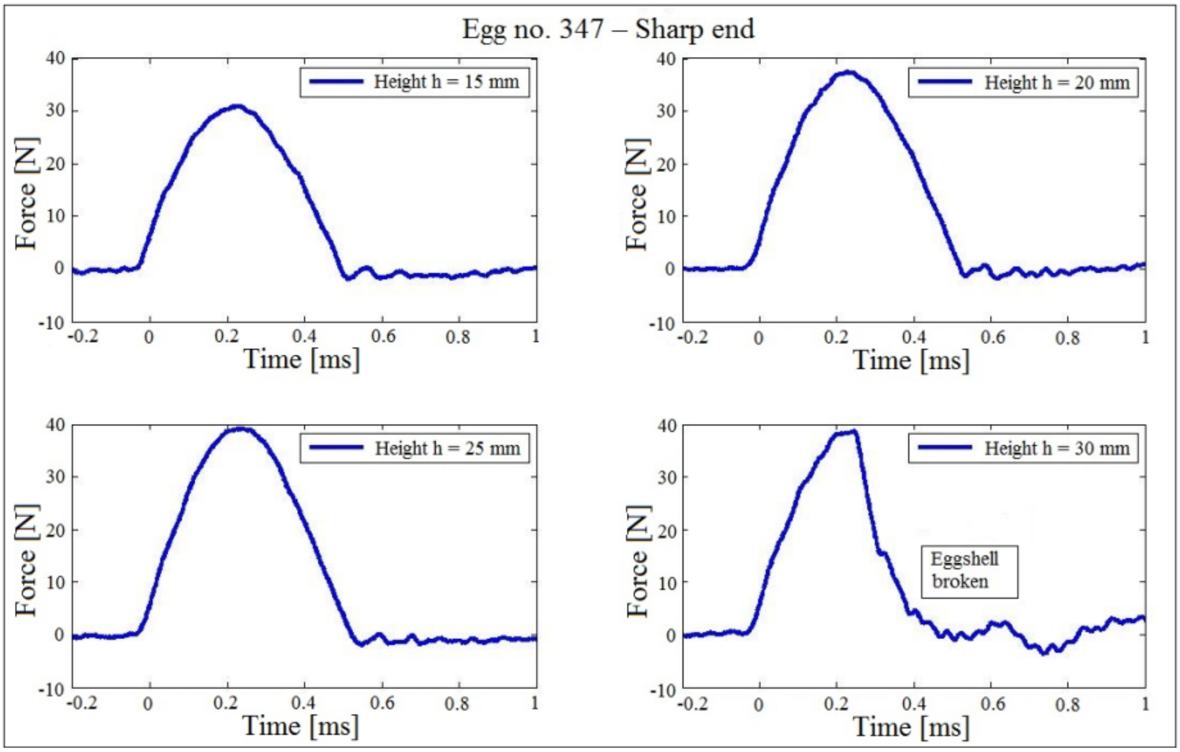


Figure 5 Experimental records of the force at the point of the bar impact

The time history of the eggshell surface displacement is shown in the Figure 6. The origin of the damage leads to significant increase in peak value of this displacement.

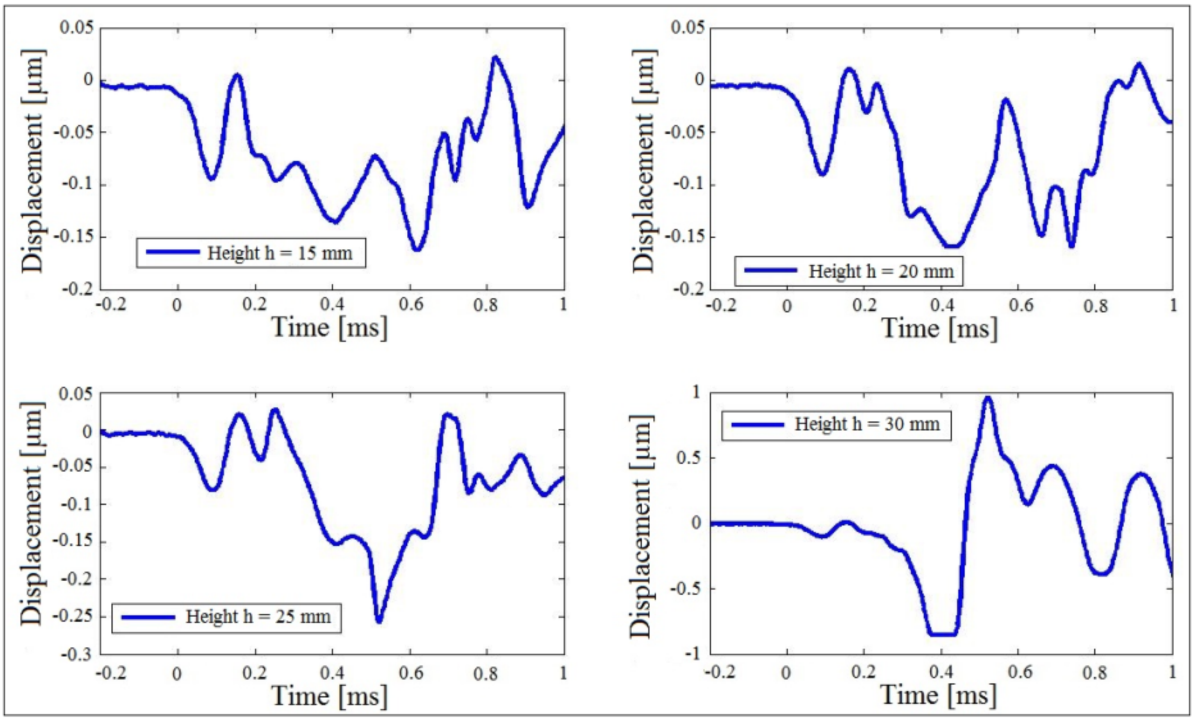


Figure 6 Experimental records of the surface displacements on the equator

The response of the eggshell can be also described in the frequency domain. This procedure is based on the Fourier transform technique – see e.g. **Stein and Shakarchi (2003)** for a review.

For a continuous function of one variable *f (t)*, the Fourier Transform *F (f)* is defined as:

$$F(\omega)=\int_{-\infty}^{+\infty} f(t)e^{-i\omega t}dt.$$

and the inverse transform as:

$$f(t)=\int_{-\infty}^{+\infty} F(\omega)e^{i\omega t}d\omega$$

where *F* is the spectral function and ω is the angular frequency.

The same procedure can be used for the Fourier transform of a series x (k) with N samples. This procedure is termed as the discrete Fourier Transform. A special kind of this transform is Fast Fourier Transform. This procedure is part of the most software packages dealing with the signal processing. The transform into the frequency domain will be a complex valued function, that is, with magnitude and phase:

$$F(\omega)=\mathrm{Re}(F)+i\,\mathrm{Im}(F),$$
$$amplitude=\sqrt{\mathrm{Re}(F)+\mathrm{Im}(F)},$$
$$phase=\arctan\left[\frac{\mathrm{Im}(F)}{\mathrm{Re}(F)}\right].$$

An example of the frequency dependence of the amplitude of the spectral function (force) is shown in the Figure 7. One can see that the most significant are frequencies well below about 2000 Hz.

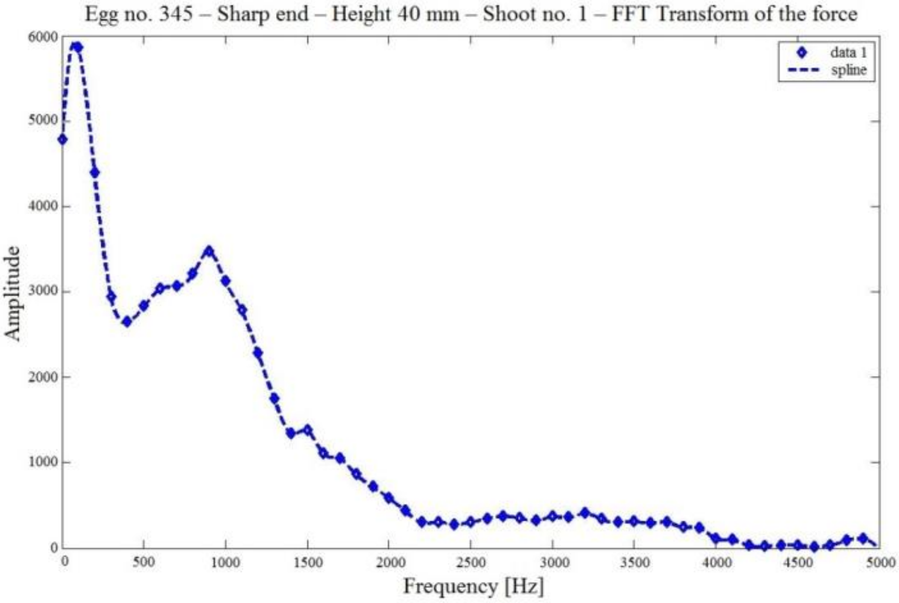


Figure 7 Amplitude spectrum of the force – time record

Example of the amplitude obtained for the displacement is displayed in the Figure 8.

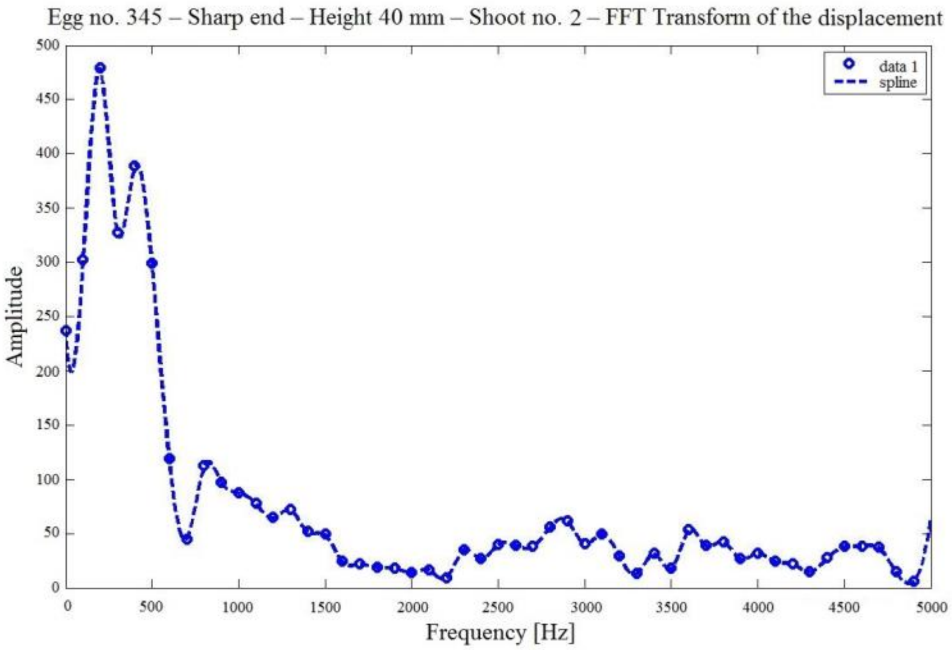

Egg no. 345 – Sharp end – Height 40 mm – Shoot no. 2 – FFT Transform of the displacement

Figure 8 Amplitude spectrum of the surface displacement – time record

The amplitude exhibits a maximum. The corresponding frequency is denoted as the dominant frequency. This frequency plays dominant role at the evaluation of the mechanical stiffness of many fruits and eggshell. Its value depends on the excitation intensity (i.e. on the height of the bar fall).

In order to describe the mechanical properties of the tested materials using the response functions, one must use some assumptions about material behavior. The simplest model represents the linear elastic body. The real body, e.g. egg, can be represented by single degree of freedom system as shown in the Figure 9.

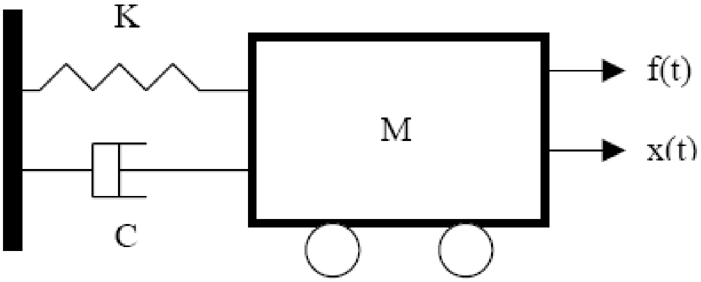


Figure 9 Single degree of freedom system

Mathematical representation of a single degree of freedom system is expressed in equation:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \tag{1}$$

where M = mass, C = damping, K = stiffness, f = external force, x = displacement.

Transferring this time domain into frequency domain, Equation (1) becomes:

$$\left[-M\omega^2 + iC\omega + K\right]X(\omega) = F(\omega) \tag{2}$$

or

$$Z(\omega)X(\omega) = F(\omega) \tag{3}$$

The inverse of Equation (2) or (3) gives the frequency response function (FRF) of the system. $H(\omega)$:

$$X(\omega) = H(\omega)F(\omega) \tag{4}$$

Equation (4) relates the system response X(ω) to the forcing function and the FRF can be defined as

$$H(\omega) = \frac{X(\omega)}{F(\omega)}$$

The frequency response function (sometimes called as transfer function) plays significant role in the extracting of the modal parameters of the tested body. The procedure can be found i.e. in **Coucke *et al.*(2003)**.

In this paper we limit the consideration on some qualitative features of this FRF function. An example of the amplitude of the transfer function is shown in the Figure 10.

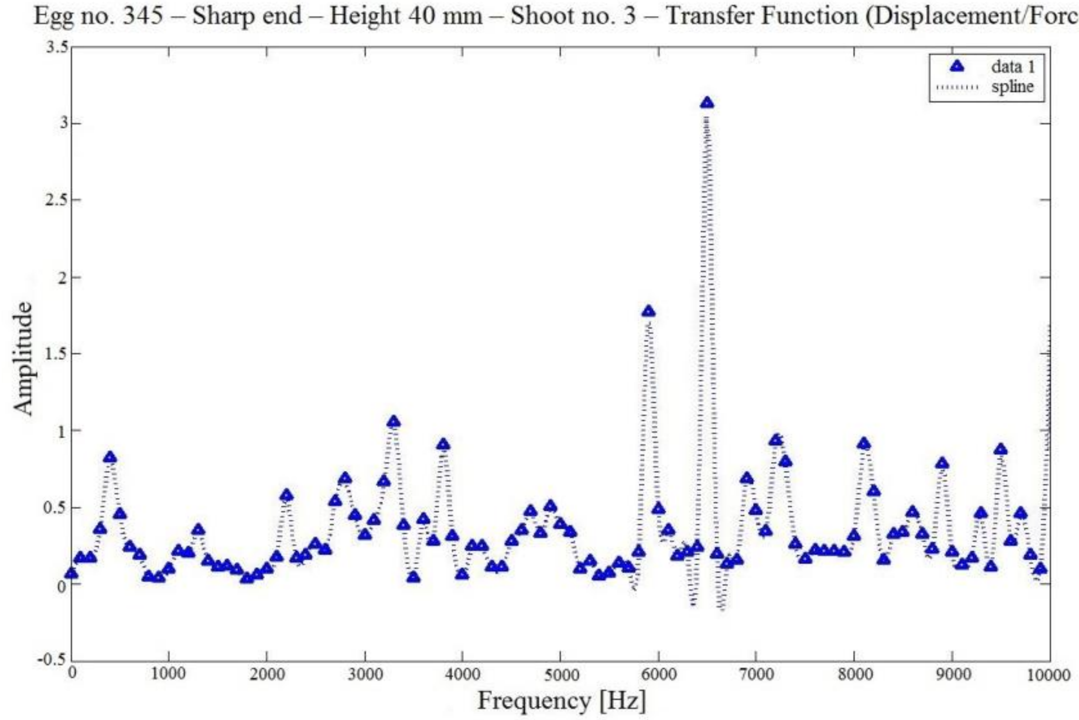


Figure 10 Example of the transfer function amplitude

In the next step the same experiments have been performed on the eggs with induced cracks.The results show that the presence of cracks may affect the surface displacement by the increase in the displacement amplitude. This increase depends on the distance of the crack from the point of the excitation – see the Figure 11.

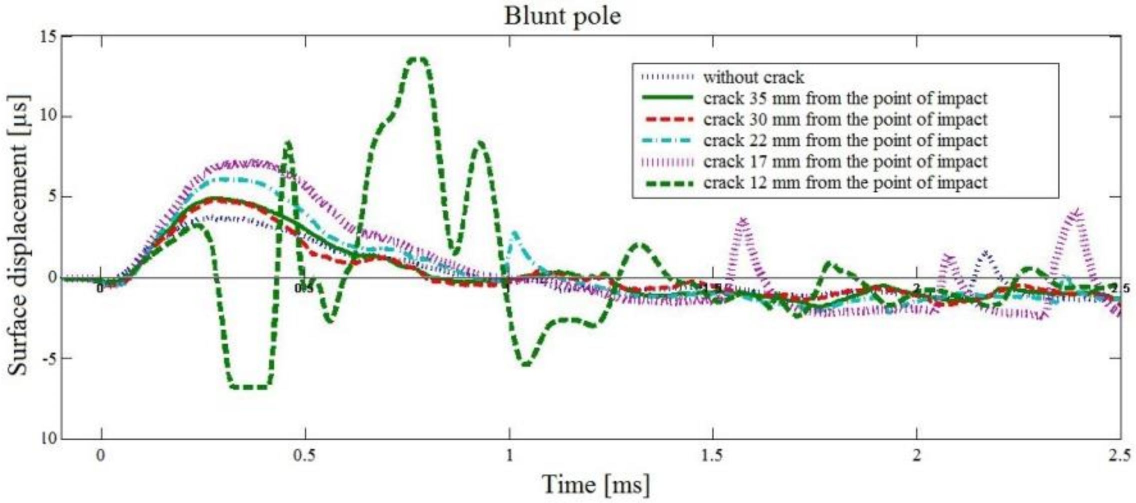
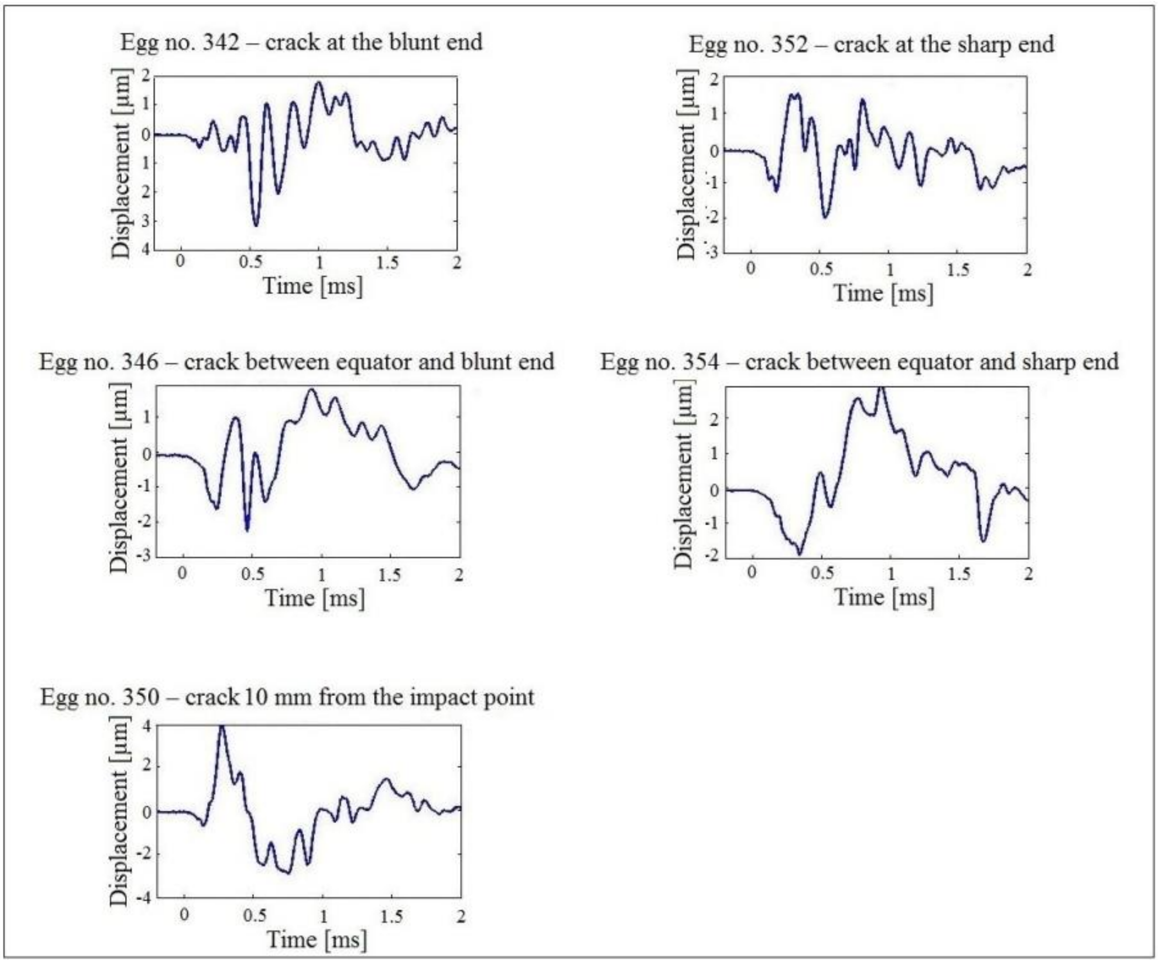


Figure 11 The effect of the crack distance on the eggshell distance, eggs have been loaded at the blunt end, height of fall h = 30 mm, distance is measured along the meridian

The effect of the crack position also plays meaning role as shown in the Figure 12.


Egg no. 342 – crack at the blunt end

Egg no. 352 – crack at the sharp end

Egg no. 346 – crack between equator and blunt end

Egg no. 354 – crack between equator and sharp end

Egg no. 350 – crack 10 mm from the impact point

Figure 12 The effect of crack position on the eggshell response, eggs have been loaded at the equator (h = 20 mm), displacement was recorded at the equator, 90° from the point of impact

The presence of the cracks also affects number of oscillations in the displacement – time record. Our results suggest that this number increases with the crack length. The orientation of the crack plays also meaningful role.

The frequency response function is characterized by many peaks. The first peak frequencies (maximal magnitude value of frequency domain signal) of intact eggs were prominent and generally appeared in some place round 2900 Hz. In addition, the differences among the first peak (f1), second peak (f2), and third peak (f3) were remarkable (f1, f2, f3) mean of the first, second and third maximal magnitude value of frequency domain signal, respectively). In contrast, eggs with cracks have heterogeneous frequency response signals and their peak frequencies were disperse and not prominent. Differences between first peak f1, second peak f2, and third peak f3 were much smaller than that of intact eggs. It could be explained by the difference of stiffness of the intact and cracked eggs. Differences in response signals between intact and cracked eggs were remarkable when the distance of impacting location and crack was less than about 30 degrees. Very similar results have been reached by **Sun *et al.* (2013)**where five frequencies characteristic were suggested. They were: mean of the amplitude values (X_1), value of first peak frequency (X_2), index of first peak frequency (X_3), mean of magnitude values from top three peak frequency (X_4) and standard of magnitude values from top three peak frequencies respectively (X_5). Values of these parameters are given in the Table 3.

Table 3 Parameters of the frequency spectrum

Parameter	Intact egg	Cracked egg
X_1	120 - 165	140 - 190
X_2	260 - 320	200 - 280
X_3	420 - 650	480 - 760
X_4	370 - 420	410 - 460
X_5	58 - 135	42 - 95

The next analysis of the obtained results led to the conclusion that the resonance frequency domain and the dominant frequency were dependent on the relative position of the excitation point towards the location of the crack on the shell. This is illustrated in the Figure 13.

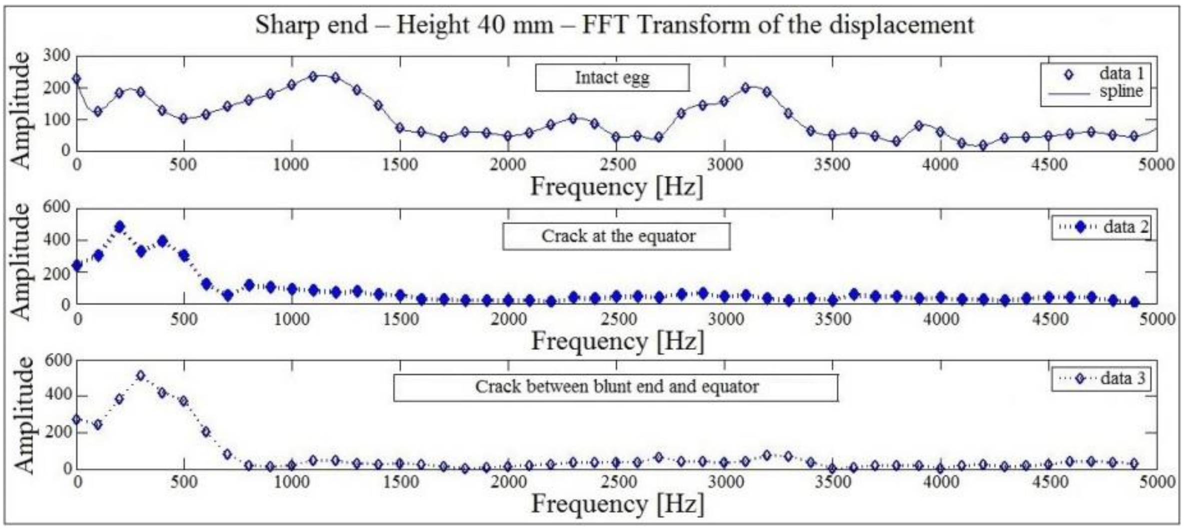


Figure 13 The effect of the crack position on the eggshell frequency response, egg loaded at the sharp end

The excitation resonance frequency characteristic of the cracked egg may be consistent with that of the intact egg, if the detection point is far from the position of the crack.

CONCLUSION

In this paper was studied the possibility of the detection of eggshell crack based on eggshell impulse response. A system for the detection was developed. It has been shown that the main information on the effect of cracks has been obtained using of the signal frequency analysis. The research showed that the proposed method is suitable for the crack detection. The main factors affecting the detection reliability were identified. The results sufficiently indicate that the cracked eggs can be effectively detected by impact measurement system coupled with a fast signal processing.

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