Investigations on Natural Frequencies of Individual Spherical and Ellipsoidal Bakery Yeast Cells

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Abstract: In this paper, a Finite Element (FE) modal analysis is employed to estimate the natural frequencies of individual spherical and ellipsoidal cells (Bakery Yeast cell). It is apparent that the mechanical properties of the living cells and particularly the natural frequencies might be related to the health condition of cells, and therefore a comprehensive analysis is carried out to determine the natural frequencies of individual cells. The natural frequencies and corresponding mode shapes are determined using COMSOL software for specific type of cell whose elastic properties of cell have been measured experimentally. The results obtained from the finite element modal analysis of an individual cell are compared to the latest reports available on the natural frequencies of the Bakery Yeast cell.

Keywords*:* Spherical Cells; Ellipsoidal Cells; Natural Frequency; Bakery Yeast Cells

1. Introduction

Cell as a fantastic representation of biology encapsulates life in its elemental form. By understanding the behaviour of a cell, one is able to distinguish many of the complexities of living organisms [1]. In contrast with most material systems, the mechanical behaviour of a living cell cannot be characterized simply in terms of fixed properties, as the cell structure is a dynamic system that adapts to its local mechanochemical environment. Cells have diverse capabilities and express themselves through different shapes. Some cells, like certain varieties of bacteria, are not much more than inflated bags invented more than two centuries ago. Others, such as nerve cells have branched structures at each end connected by an arm [2]. Studies have been done to find the connections between mechanical responses and biological functions of different organs and tissues and a lot of efforts have gone into the area of cells in order to obtain a better understanding of cell mechanical properties. Cell mechanical properties could be defined as the study of the relationship between forces and deformation when these are applied. According to this definition, measurements of cell mechanics will reflect basically the properties of cell stiffness and viscoelasticity. In some diseases, the mechanical properties of individual cells are altered. For instance, in blood cells, changes in cell mechanical properties can have profound effects on the cell’s ability to normally flow through the blood vessels, since increased stiffness impedes progress of cells through small capillaries [3].

It is apparent the mechanical properties of the living cells and particularly the natural frequencies are highly related to the health condition of cells. The biological condition of the cell is associated with the frequency of the natural phenomenon of oscillation because the biological condition of the cell is related to the balance among various properties and exchange with the surrounding media of nutrients and toxins. Although the physical and mechanical properties of cells like size, shape and especially wall stiffness, are highly important in determination of the health condition of cell; the absolute determination of these properties of all biological system, which are complex, might not always be necessary. Very often only a comparison between two different oscillation frequencies is needed to conclude changes in size, shape or stiffness due to change in biological properties.

Free oscillations of spheres have been the area of interest for a long time. Lamb [4] obtained the equations governing the free vibration of the solid sphere and Chree [5] subsequently developed these equations rather than in Cartesian co-ordinates in the more convenient spherical co-ordinates. Sato *et al*. [6]

studied the vibrations of solid spheres and provided extensive numerical results. The free vibration behaviour of multi-layered hollow spheres is studied by Jiang *et al.* [7] and they provided tabular results for a number of cases studied. Lampwood *et al.* [8] also described the vibrations of solid and hollow spheres in his book on oscillations of the Earth.

Engin [9] developed a model of the human head consisting of a spherical shell filled with in viscid fluid using the thin-shell theory. Investigation on the vibration of a fluid-filled shell is carried out by Advani *et al.* [10]. Guarino *et al.* [11] looked at the frequency spectra of a fluid-filled sphere, both with and without a central solid sphere. For the head impact modeling, the multi-layered spherical shell with liquid core of relevance to head impact is modeled by Young [12]. He found the free vibration of spheres composed of inviscid compressible liquid cores surrounded by spherical layers. Resonance frequencies of the red blood cells is studied by modeling the cells as isotropic elastic shell filled with and surrounded by viscous fluid [13].

Natural frequencies of biological cells based the elastic properties of cellular materials is developed by Zinin *et al.* [14]. The results obtained by Zinin *et al.*, have complex forms and only simple approximations are obtained for red blood cells. Following these observations, Zinin *et al.* [15] numerically analyzed the spectra of the natural oscillations of different types of cell and bacteria. Further investigation on the mechanical properties of spherical cell led to detection of the cell wall vibration by Pelling *et al.* [16, 17]. They detected the free vibrations of a specific spherical cell with Atomic Force Microscopy (AFM). By using this method the distinct periodic nanomechanical motion of Bakery Yeast cells is measured. The periodic motions in the range of 0.8 to 1.6 *kHz* with amplitudes of 1-7 *nm* is reported by Pelling *et al.* using a very low stiffness cantilever with AFM [16,17].

In order to describe the mechanical behaviour of the cell a numerical study could be proficient. A numerical study of the natural vibrations of cell may be based on a simplified cell model, the "shell model" [18]. Within the shell model, a cell is assumed to have a spherical or ellipsoidal shape of few micron radiuses. For the shell model considering the simplifications, the motion of the cell is composed of the motion of three components: the internal fluid, cell nucleus and the cell wall [18]. Both spherical and ellipsoidal shapes of the cell are assumed for two reasons. First, recently, the mechanical behaviour of spherical cells has received attention because resonance vibrations of spherical Bakery Yeast cell wall have been detected by AFM. Second, many calls and bacteria indeed have a spherical or ellipsoidal shape. We, recently, studied the natural frequency of fluid filled spherical Bakery Yeast cell without nucleus [19]. Our study was based on the properties reported by Zinin *et al.* [15]. We couldn't analyze the spherical and ellipsoidal cells containing nucleus with the approach that we presented in our report [19].

In this work, we present a FE method which enables us to characterize the natural frequency of cells with different shape and mechanical properties. The aim of this work is to determine the natural frequencies of spherical and ellipsoidal Yeast cells. To this end, a comprehensive finite element modal analysis of cell is carried out and the influence of the cell shape as well as the existence of nucleus is investigated.

2. Materials and methods

Bakery Yeasts are single cell and almost spherical shape. All of the material within cell, exclusion of its nucleus, is defined as the cytoplasm. The cell is filled with cytoplasm, which is a watery solution of enzymes, proteins and ions. Wall around the whole cell, the nucleus and the vacuole are the main parts of the cell that are illustrated in Figure 1. Bakery Yeasts are 3–15 μm in diameter with a cell wall thickness of 100–1000 *nm* [16].

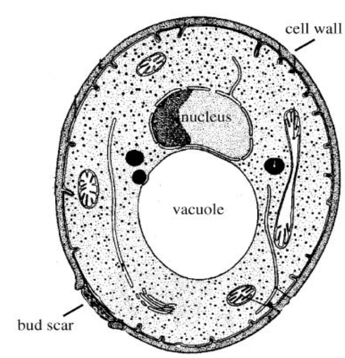


Figure 1. Internal structure of Bakery Yeast cell [20].

This study considers the simplified models under linear conditions of Yeast cells. The frequency of the natural oscillations of cells can be obtained by modeling the cell by employing FE analysis in COMSOL software. In order to describe the mechanical behaviour of the cell, the complex structure of cell was simplified to a simple model; including the relevant structural parts of the cell (Wall, Cytoplasm and Nucleus).

We made the assumption of two spherical and ellipsoidal shapes for biological cell to estimate the natural frequencies of the specific type of cell. Recently, the mechanical behaviour of Yeasts has been detected by AFM and Young's modulus of E=0.75 *MPa* has been reported [16, 21].

To compare the natural frequencies of a sphere and ellipsoidal cells, three-dimensional Finite Element modal analysis is carried out in COMSOL for spherical and ellipsoidal cell, both with and without nucleus. The element type used for the numerical analysis for this model is Argyris shell which is simple but sophisticated 3-node triangular element for computational simulations of isotropic and elastic shells.

3. Analysis

3.1. Finite Element Analysis of Spherical cell without nucleus

The spherical cell model has a maximum diameter of 9 microns. The elastic wall of the cell has a thickness of 200 *nm* [16]. The cytoplasm stiffness has the magnitude of 10^4 N/m^2 based on results presented by Adams [22]. Both cytoplasm and cell wall are modeled as linear elastic materials. The elastic modulus of cell wall is kept constant at 0.75 *MPa*. The Poisson's ratio of 0.499 is considered for the wall. The boundary condition which is considered for this analysis is zero-value displacement constraints on one node at the cell bottom. Table 1 shows the natural frequencies obtained from modal analysis of spherical Bakery Yeast cell.

Table1. Natural frequency (N. F.) for the four spheroidal mode of vibration of spherical Bakery Yeast cell.

Order	n=1	n=2	n=3	n=4
N. F. (*KHz)*	143.552	299.207	402.951	510.345

The correspondent spheroidal modes of vibration for the first, second, third and forth natural frequencies, expressed in Table 1, are shown in Figure 2.

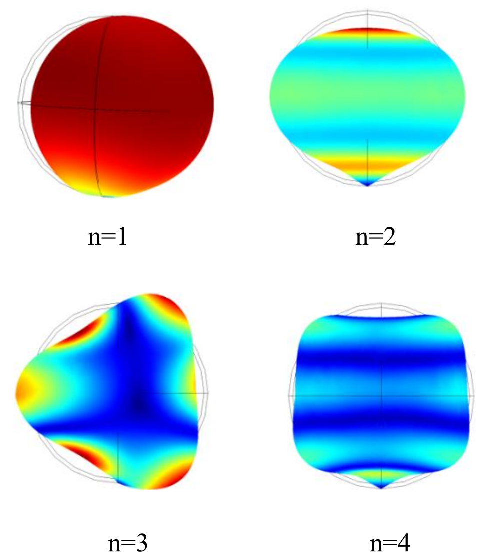


Figure 2. Mode shapes for the spheroidal modes of vibration for spherical Bakery Yeast cell.

3. 2. Finite Element Analysis of Spherical cell with nucleus

To observe the effect of other organelles of cell on the natural frequencies, the problem has been solved for fluid filled sphere containing the nucleus as shown in Figure 3. The nucleus, which has an important fraction of total cell volume and occupies 7-8% of the cell volume, is considered 4 μm in diameter [23]. The Young's modulus of cell nucleus is considered 10^5 N/m^2 since it is believed to be about an order of magnitude stiffer than surrounding cytoplasm.

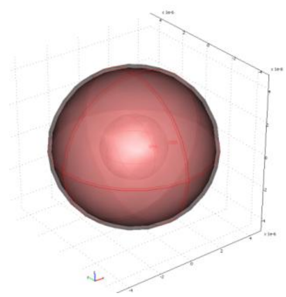


Figure 3. Model of spherical cell with nucleus.

The modal analysis is performed and natural frequencies are obtained as shown in Table 2.

Table 2. Natural frequency (N. F.) for the four spheroidal mode of vibration of spherical Bakery Yeast cell with nucleus.

Order	n=1	n=2	n=3	n=4
N. F. *(KHz)*	141.866	330.885	424.161	525.759

Figure 3 shows spheroidal modes of vibration for the first, second, third and forth natural frequencies.

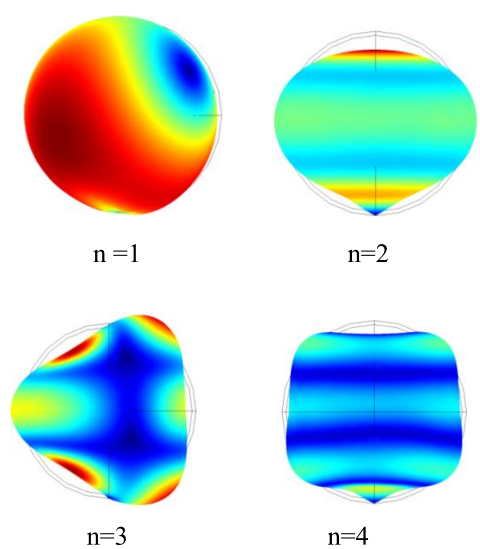


Figure 3. Mode shapes for the spheroidal modes of vibration for spherical Bakery Yeast cell with nucleus.

The attitude of a spherical cells containing nucleus indicates a small reduction in the first resonant frequency and increase in the second, third and forth resonant frequency.

3. 3. Finite Element Analysis of Ellipsoidal cell without nucleus

The ellipsoidal shape of yeast cell is analyzed this part to find out the effect of cell shape on the natural frequencies of cell. The equatorial and polar radiuses of the ellipsoid are considered 4.5 μm and 6.172 μm, respectively, to have the same volume for both spherical and ellipsoidal cell. The mechanical properties of wall, cytoplasm and nucleus of the proposed model are those which are considered for spherical cell in the previous analysis. Numerical results are computed for ellipsoidal cell without nucleus. The results are presented in Table 3.

Table 3. Natural frequency for the four spheroidal mode of vibration of ellipsoidal Bakery Yeast cell without nucleus.

Order	n=1	n=2	n=3	n=4
N. F. *(KHz)*	137.971	303.546	411.872	510.619

Spheroidal modes of vibration of elastic Ellipsoidal Bakery Yeast cell without are shown in Figure 4.

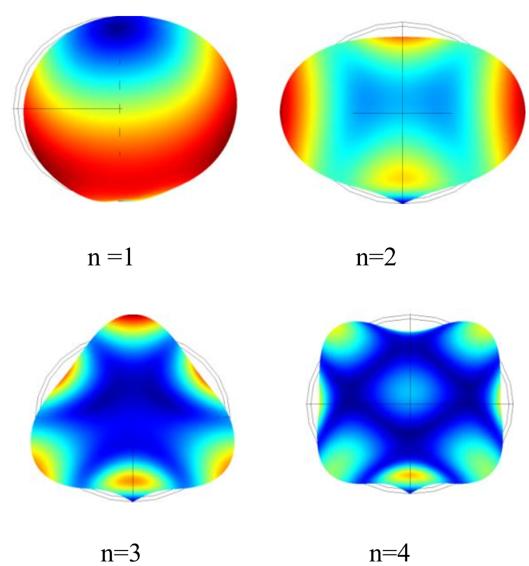


Figure 4. Mode shapes of ellipsoidal Bakery Yeast cell without nucleus.

3.4. Finite Element Analysis of Ellipsoidal cell with nucleus

The nucleus which the volume of 7% of the cell volume is assumed for the ellipsoidal cell as it was considered for the previous analysis. Numerical results are computed for ellipsoidal cell with nucleus (Figure 5) and the natural frequencies are presented in Table 4.

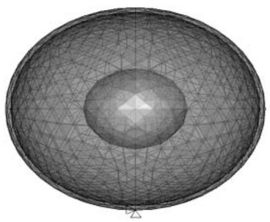
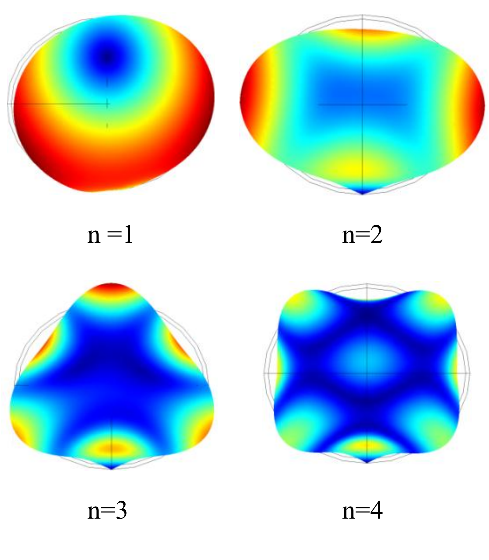


Figure 5. Ellipsoidal shape of cell with nucleus

Table 4. Frequencies of four spheroidal modes of vibration of ellipsoidal Bakery Yeast cell with nucleus.

Order	n=1	n=2	n=3	n=4
N. F. *(KHz)*	137.734	334.053	435.465	524.076

Spheroidal modes of vibration of Ellipsoidal Bakery Yeast cell with nucleus are shown in Figure 6.



n =1 n=2

n=3 n=4

Figure 6. Mode shapes of ellipsoidal Bakery Yeas cell with nucleus.

4. Discussion

The study of cell oscillations in cell biology provides valuable information about the situation of cellular processes and health condition of cell. Oscillations of cell may simply reflect the mechanical properties of a cell. This characteristic may represent possible diagnostic signatures that may be used to monitor cellular response to changes in physiological conditions and exposure to certain drugs. From this point of view, in this study, we determined the natural frequencies and mode shapes of Yeast cells in both spherical and ellipsoidal shapes. We applied a shell model for a biological cell to estimate the quality of the natural vibrations of the specific types of cell. The natural frequencies of spherical Yeast cells which were obtained through our analysis have huge differences with those were obtained by Pelling *et al.* [16, 17]. Comparison of natural frequencies obtained from FE modal analysis of a spherical cell including nucleus and elastic modulus of 0.75 *MPa* with those obtained by Pelling *et al.* shows that the frequency of the resonance oscillations of the Yeast cells is much higher than 0.8-1.6 *kHz* which is reported by Peilling *et al*. [16, 17]. It is believed that the resonances detected by Pelling using AFM are not related to the mechanical resonances of cell vibration. Latest report on the values of second natural frequency of Yeast cell, relates the second natural frequency of 160 *KHz* to the spherical Yeast cell with radius of 5 micron and Young's modulus of 0.6 *Mpa* [15]. Although it is not that much far from our work but based on our analysis, we believe that the natural frequency of Yeast cell should be higher that the value reported by Zinin *et al.* [15].

In This work, in addition to spherical shape of Yeast cell, an analysis was done for ellipsoidal Yeast cell and the results for natural frequencies were compared.

5. Conclusion

Natural frequencies obtained from FE modal analysis of a spherical cell shows that the frequency of the resonance oscillations of the Yeast cells is much higher than 0.8-1.6 *kHz* which is reported by Peilling *et al*. [16, 17]. Comparison of the results for both sphere and ellipsoidal cell shapes shows that, there are no significant changes in natural frequencies of Yeast cell due to changes in the shape of cell. The resonance frequencies of cells are more dependent to the size of cell and the functional elements in cell like nucleus very little influence the natural frequencies of cell.

6. References

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