Finite Element Method and Its Applications to Study the Dynamic Behavior of Biological Systems

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Abstract— **In this paper, natural frequencies of human blood cells are obtained with help of ANSYS software. The objective of finding the natural frequencies is to prevent resonance which occurs when frequencies due to external medicines match with natural frequencies of organs of human body. Though properties of blood cell are keep on varying, properties required for analysis such as young's modulus (E), poison's ratio, mass density are taken within their range. Modal analysis is first carried out to yeast (bacteria) cell as a case study, natural frequencies and mode shapes are obtained and also compared with experimental values available in the literature [1] and the error obtained in frequency is around 9 %. Then, modal analysis is extended to Erythrocyte (biconcave shape) human blood cell to determine thirty mode shapes and natural frequencies. Finally, harmonic analysis is done to know at what frequency resonance is occurring. By preventing resonance bursting of a blood vessel in the brain and coronary arteries leading to heart can be prevented.**

Keywords—Human Blood cell,Modal Analysis,Hramonic Analysis;

I. INTRODUCTION

For the past few decades, tremendous research efforts have been made to find natural frequencies of living cells. It is apparent the mechanical properties of the living cells and particularly the natural frequencies are highly related to health condition of cells. Natural frequencies of spherical cells made up of yeast cell (bacteria) are explained by Marjan Molavi, Ali Bonakdar, Ion Stiharu [1]. Saccharomyces Cerevisiae commonly known as baker's yeast or budding yeast is one of the major model organisms that have been under intense study for many decades. Yeasts are single cell (unicellular) Fungi and almost spherical shape. A spherical shape of cell is considered because many cells and bacteria have a spherical shape. The thickness of the shell is small as compared with the cell radius and the shell is regarded as a simple elastic membrane. The frequency of the natural oscillations of spherical cell can be obtained by modeling the spherical cell by using finite element method. In order to describe the mechanical behavior of the cell, we should simplify the complex structure of cell and reduced its model to simple model; containing the relevant structural parts of the cell.

Three-dimensional finite element modal analysis for fluid filled spherical cells is carried out two times; one time considering the elastic modulus of 0.6 MPa and the second time considering the elastic modulus of 110 MPa for cell membrane. At first, a sphere shell with elastic modulus of 0.6 MPa and radius 4.5 μm is considered. The thickness of the sphere is 0.1 μm. Both sphere and shell are modeled as linear elastic materials. The elastic modulus of membrane is kept constant at 0.6 MPa. The Poisson's ratio of 0.499 is considered for the membrane and all degrees of freedom are constrained at the bottom. The modal analysis is performed and natural frequencies are obtained.

The human red blood cell with a biconcave shape and an average diameter of about 8μm has a typical life span of 120 days during which it circulates through the human body nearly half a million times [2]. During the course of its circulation, it undergoes severe elastic deformation as it passes through narrow arteries whose inner diameter is smaller than 3μm.

Geometry of human blood cell is explained by Rie HUGUCHI and Yosinori Kanno [3]. The analysis of biological networks and introduction to cell biology is explained by Roded Sharan, Moran Cabili and Elad Donsky [4]. The basic unit of life is the cell and all living creatures are made of cells which are small membrane-bounded units filled with a concentrated aqueous solution of chemicals, the cytoplasm. Each cell is an independent entity, capable of creating copies of itself by growing and dividing into two identical daughter cells. The complete characteristic of an organism is carried by each of its cells. This hereditary information is stored within the DNA molecule. In higher multicellular organisms, each cell carries the same DNA content, storing the complete biological information essential for life. Organisms can be divided into two classes:

- Prokaryotes - organisms whose cells do not contain a nucleus. These are simple unicellular organisms such as bacteria and archaea.
- Eukaryotes - organisms whose cells' DNA is stored within a nucleus and also contain other inner membrane elements the eukaryotes include more complex multicellular organisms such as plants, animals and fungi. However, they also include unicellular organisms such as yeast and amoebas.

Modeling of biological cells was described by Reddy on his paper on computational engineering science [5]. Cells have long been observed to respond physiologically to external forces. The first step towards understanding the behavior of the cell is to comprehend its mechanical response to external mechanical stimuli. Through suitable experimental and theoretical formulations the mechanical properties are derived by a number of researchers. The material properties derived from experimental methods have found to vary by orders of magnitude even for the same cell type, which is primarily attributed to the stimulation process, and the theoretical model used in interpreting the data. This drawback can only be overcome by the development of a sound mathematical framework correlating the material of the cell with the evaluation of the experimental data. Here, such a framework is developed through a computational modeling of the cell and is used to interpret results from currently wide spread experimental procedures.

In the present paper, modal analysis is first carried out to spherical cell made up of baker's yeast or budding Yeast as a case study. First and second natural frequencies and mode shapes of bacteria cell is shown in the Figures 1 and 2 respectively. First and second natural frequencies obtained are 139387 Hz and 145843 Hz respectively and these values compared with experimental values available in the literature [1] and the error obtained was 9 %. Therefore, numerical analysis is applied through ANSYS software and it is safely adopted to human blood cell (biconcave shape) to determine natural frequencies and harmonic analysis to find at what frequency resonance is occurring. Blood cell is modeled in ANSYS based on geometry available in literature [3]. It has an average diameter of 8 µm.

II. MODAL ANALYSIS OF YEAST CELL

Yeasts are single cell (unicellular) fungi and almost spherical shape. A spherical shape of cell is considered because many cells and bacteria have a spherical shape and the required properties are given in Table 1. The frequency of the natural oscillations of spherical cell can be obtained by modeling the spherical cell by using finite element method. Three dimensional finite element modal analysis for fluid filled spherical cells is carried out two times. That is by considering one time the elastic modulus of 0.6MPa and the second time the elastic modulus of 110MPa. Elements used in the present work are Quadratic 4 node 42 and Brick 8 node 45.

Table 1: Mechanical properties of yeast cell

S.No	Mechanical property	Numerical value
1	Young's modulus(E)	0.6MPa
2	Mass density (ρ)	998 Kg/m^3
3	Radius of sphere®	4.5µm
4	Poisson's ratio(1/m)	0.499

The first and second mode shapes and natural frequencies are shown in Figures 1 and 2 respectively. First natural frequency is obtained at 139387Hz and second natural frequency is identified at 145843 Hz.

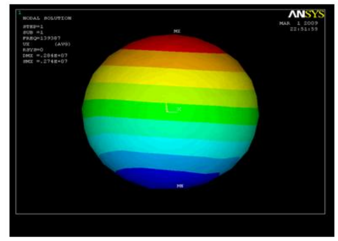

Figure 1 First mode shape of YEAST cell

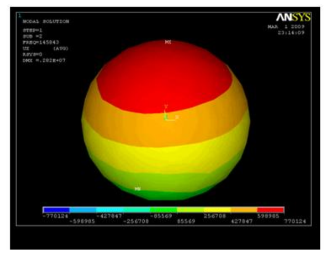

Figure 2 Second mode shape of YEAST cell

III.MODAL ANALYSIS OF HUMAN ERYTHROCYTE BLOOD CELL (BICONCAVE SHAPE

Human blood cell was modeled in ANSYS based on geometry available in literature is shown in Figure 3. Black lancozos mode extraction method is used to obtain 30 mode shapes and natural frequencies. Input parameters required for modal analysis is shown in Table 2.

Table 2: Mechanical properties of Human Blood cell

Serial number	Mechanical property	Numerical value
1	Young's modulus (E)	886 N/m^2
2	Mass density (ρ)	1090 Kg/m^3
3	Radius®	8 µm
4	Poisson's ratio(1/m)	0.49 to 0.5

Biconcave shape blood cell (erythrocyte) modeled in ANSYS with elements used in the present work are Quadratic 4 node 42 and Brick 8 node 45 and blood cell is constrained as shown in Figure 4.

Biconcave shape modelled in ansys

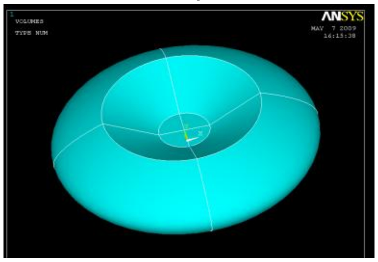

Figure3 Geometrical models of Biconcave Shape Blood cell

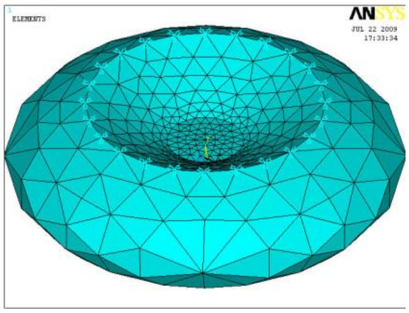

Figure 4 FEM Model and Constraints of Biconcave shape blood cell

IV.HARMONIC ANALYSIS OF BLOOD CELL

For harmonic analysis, frequency range is taken as 0 to 150000 Hz and average blood pressure of human being 90 mm of Hg is converted into equivalent load of 1.3948*E-9 N and is given as sinusoidal input to blood cell which is applied randomly at node number 973. Type of harmonic solution used is full and number of sub steps taken are 100. Stepped boundary condition is used. Graphs between amplitude and frequency, stresses versus frequency are obtained. Eleven peaks are identified in the plot between amplitude and frequency

V. RESULTS AND DISCUSSIONS

With the help of modal analysis thirty natural frequencies and mode shapes of erythrocyte (biconcave shape) blood cell, are taken into consideration and are given in table 3. Point of load application is shown in Figure 5.

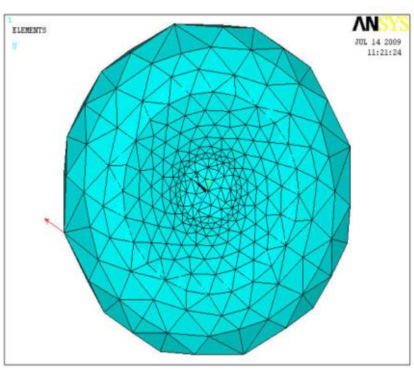

Figure 5 Point of Load Application On the Blood Cell

Table 3 Mode shapes and Natural Frequencies of Blood Cell

Serial number	Frequency(Hertz)
1	36241
2	37710
3	39049
4	51013
5	55922
6	59904
7	66554
8	67886
9	81891
10	84290
11	86247
12	86280
13	92225
14	94700
15	100480
16	108190
17	109520
18	116090
19	117820
20	118410
21	120590
22	121170
23	122900
24	125540
25	140090
26	144440
27	145600
28	148090
29	158340
30	159790

Harmonic response of human blood cell when it is subjected to average blood pressure of 90 mm of Hg (equivalent force =1.3948*E-9) is shown in the Figure 6. Here amplitude is expressed in meters and frequency in Hertz.

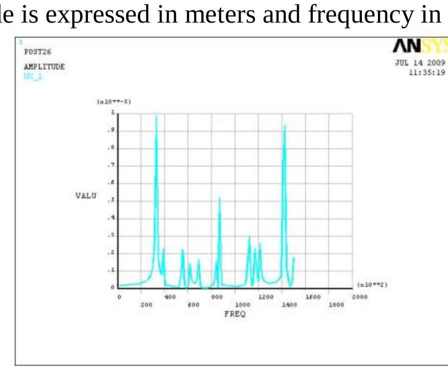

Figure 6 Harmonic Response of Human Blood Cell

Eleven peaks are observed in the graph.

1. First peak is the highest which occurs at a frequency of 36241Hz (i.e. at first mode shape)
2. Second peak is found at a frequency of 40000 Hz which is close to 3^{rd} mode shape.
3. Third peak is observed at a frequency of 55000Hz is nothing but 5^{th} mode shape.
4. Fourth peak is obtained at a frequency of 62000 Hz which is approximately equal to seventh mode.
5. Fifth peak occurred at a frequency of 70000 Hz which is approximately equal to eighth mode shape.
6. Sixth peak is found at a frequency of 85000 Hz which is close to tenth mode shape.
7. Seventh peak is observed at a frequency of 88000 Hz which is approximately equal to 12^{th} mode shape.
8. Eighth peak is obtained at a frequency of 112000Hz which is approximately equal to seventeenth mode.
9. Ninth peak is occurred at a frequency of 118000 Hz which is close to 20^{th} mode shape.
10. Tenth peak is observed at a frequency of 122000Hz which is 23^{rd} mode shape.
11. Eleventh peak is found at a frequency of 142000 Hz which is approximately equal to 26^{th} mode shape.

Variations of stresses versus frequency are shown in Figure 7 and it is expressed in N/m^2 and Hertz respectively. Von - Misses stresses are shown in Figure 8. Mode shape of blood cell corresponding to the highest peak (1^{st} mode shape) is shown in Figure 9 and mode shape corresponding to 2^{nd} highest peak is shown in Figure 10.

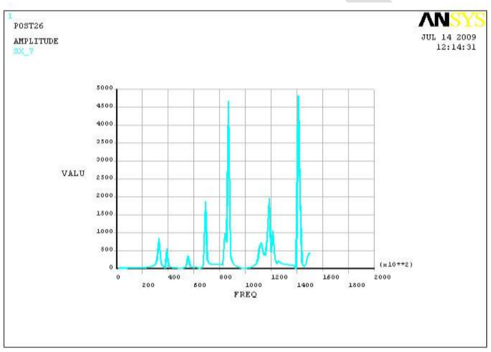

Figure 7 Stresses Induced In the Blood Cell

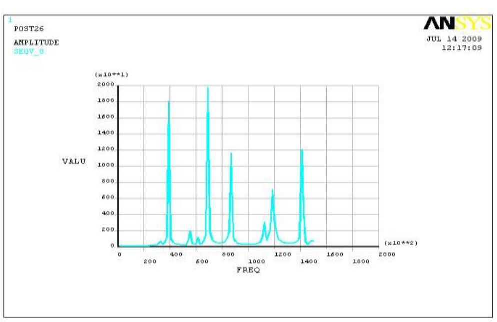

Figure 8 Vonmises Stresses

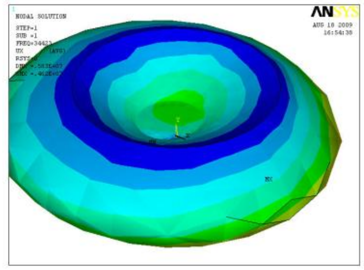

Figure 9 Mode shape of blood cell Corresponding to highest peak

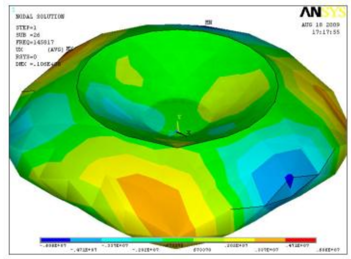

Figure 10 Mode shape corresponding to 2^{nd} highest peak

VI. CONCLUSIONS

1. Second natural frequency of yeast (bacteria) cell obtained by using ANSYS software is compared with experimental values given by Zinin et al [1]. Frequency obtained from the present analysis is 145843 Hz and that of Zinin et al [1] was 160000 Hz and the observed error is around 9 %.
2. From harmonic analysis of blood cell, the maximum amplitude of 0.98*E-5 m occurs at a frequency of 36241 Hz which is the first natural frequency of blood cell. Resonance can be prevented by ensuring frequencies occurring due to external inputs should not match with first natural frequency of blood cells.
3. Maximum vonmises stress of magnitude 19500 N/m^2 occurs at a frequency of 67886 Hz which is the 8th natural frequency of human blood cell.

REFERENCES

[1] Marjan Molavi, Ali Bonakdar, Ion Stiharu, ASME 2008 Summer Bioengineering Conference(SBC 2008) June 25-29, SBC2008-192869, determination of natural frequencies of spherical cells.

[2] Igor V. Pivkin* and George Em Karniadakis+, Physical Review Letter 101,118105 (2008), Accurate Coarse-Grained Modeling of Red Blood Cells.

[3] Rie HIGUCHI and YOSINORI KANNO,JSME International Journal ,Series A, Vol. 49,No. 3,2006, Finite element method analysis of deformation of human red blood cells.

[4] Roded Sharan, Moran Cabili and Elad Donsky, October 26,2006, Analysis of Biological Networks: Introduction to Cell Biology.

[5] J. N. Reddy, 51st congress of Indian society of theoretical and applied mechanics (istam) december18-21,2006, computational engineering science: the third scientific Methodology for the 21st Century and Beyond.

[6] Gerard b.nash and stuart egginton, Biological journal 174,109-122(1993), Comparative rheology of human and trout red blood cells.

[7] M. Dao, C.T. Limb, S. Suresh, Journal of the Mechanics and Physics of Solids 51(2003) 2259-2280, Mechanics of the human red blood cell deformed By optical tweezers.

[8] Wing Kam Liu , Yaling Liu , David Farrell , Lucy Zhang , X. Sheldon Wang , Yoshio Fukui , Neelesh Patankar , Yongjie Zhang , Chandrajit Bajaj , Junghoon Lee , Juhee Hong , Xinyu Chen , Huayi Hsu, SCIENCE DIRECT, Computation Methods Appl.Mech.Engrg.195(2006) 1722-1749, Immersed finite element method and its applications to biological systems.