Biological Characteristics of Eggshell and Its Bionic Application

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Abstract

This paper discusses macro-geometrical, micro-geometrical and biomechanical features of eggshell, and proposes its inspiration for bionic design of submersible pressure hull. The results show that eggshell has excellent bionic performance on the weight-strength ratio, the span-thickness ratio, the aesthetic characteristics, the distribution of material and so on. The pressure endurance of the eggshell under uniform pressure is quite remarkable. Bionic design based on eggshell structure can effectively coordinate variable features of deep-sea pressure hull such as strength, stability, reserve buoyancy, streamline shape, space utilization in the crust and occupant comfort.

Key words: Macro-geometrical features; Micro-geometrical features; Biomechanical features; Eggshell; Submersible pressure hull

INTRODUCTION

With the evolution of creatures in nature, the shell structures, including eggshell, skull, sea shell, spiraling shell and so on, have good performance on pressure endurance in order to meet the demand for survival. Eggshell is the most effective bearing structure among them because of its high-level properties such as weight-strength ratio, span-thickness ratio, aesthetic characteristics and reasonable distribution of material (Wong, 2005). Eggshell is the superior bionic model conforming to the dome principle as it uses the minimal material but achieves sufficient strength and stability without additional strengthening support (Ar, Rahn, & Paganelli, 1979).

The structure of eggshell is widely imitated in architechture/buildings, such as ST Peter's Basilica in Rome, the Hagia Sophia in Constantinople, Sydney Opera House in Australia, Monument to the Martyrs of Baghdad in Iraq, Swiss Re Building, the Cybertecture Egg in Bombay, International Convention Centre in Liuzhou, China, Henan Provincial Art Centre and National Centre for the Performing Arts (Retrieved from website [1])(Figure 1).

Exbury egg was designed by PAD studio, the SPUD group and the artist Stephen Turner, and they ultilize the ship manufacturing techniques and local material to build this egg-shaped space containing a bed, a table, a small stove and a wet room (Figure 2). It can be treated as a residence for the living, a laboratory for studying the tide and also a center of collection including both storage and showcase. Exbury egg is under the influence of 730 times tide a day and the exposure of 365 days, which lead to the growth of verdigris on the underwater structure, and bleaching of wooden part upside of the water. The boat is installed in the "cradle", and fluctuates due to the tide (Retrieved from website[2]).

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[1] http://baike.sogou.com/v36728.htm
  http://baike.sogou.com/v2265240.htm
  http://baike.sogou.com/v61229.htm
  http://www.mlm114.com/comnews/7413/29316.shtml
  http://baike.sogou.com/v76021500.htm
  http://fashion.sina.com.cn/l/ds/2013-11-05/062926997.shtml
  http://baike.sogou.com/v66731284.htm
  http://baike.sogou.com/v684927.htm
  http://baike.sogou.com/v154330.htm
  http://www.exburyegg.org/
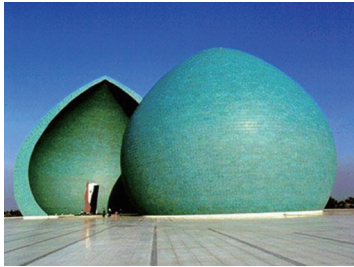[2] http://www.exburyegg.org/

St Peter's Basilica in Rome

The Hagia Sophia in Constantinople

Sydney Opera House in Australia

Monument to Martyrs of Baghdad in Iraq
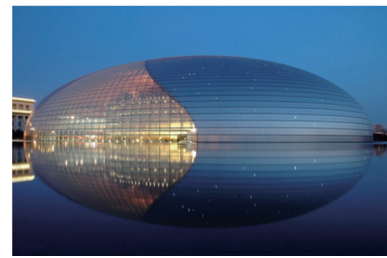

30 St. Mary Axe/Swiss Re Building

The Cybertecture Egg in Bombay

International Convention
Centre in Liuzhou China
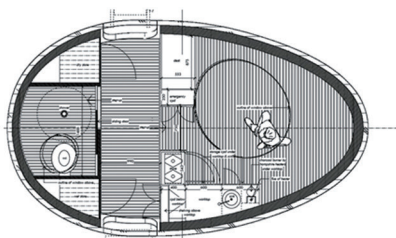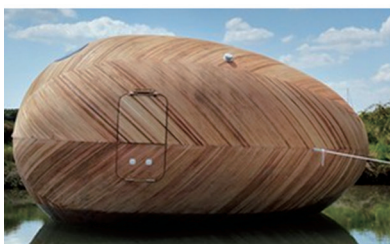

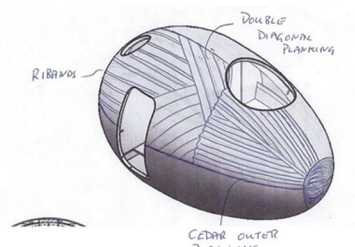Henan Provincial Art Centre in China

National Centre for the
Performing Arts in China

Figure 1
Buildings With Eggshell's Bionic Structure

Internal space

Plane graph

Conceptual design

Figure 2
Exbury Egg

This paper will discuss macro-geometrical, micro-geometrical and biomechanical features of the eggshell, and will propose its inspiration for bionic design of submersible pressure hull.

1. MACRO-GEOMETRICAL FEATURES OF EGGSHELL

Eggshell is a thin-walled rotation structure satisfying the gaussian curve with multi-focus. That is to say it is generated by a generatrix (meridian) revolving around an axis of rotation. Every point on the eggshell has two radiuses of curvature in the direction of warp and weft, and two finite arc line according to the two radiuses is perpendicular to each other (Babich, 1993; Retrieved from website[3]). Because the eggshell shapes of birds and poultry are different, the geometrical features are generally described by the shape parameters and shape functions.

1.1 Shape Parameters

Eggshell shape parameters include: the major axis L, minor axis B, mean diameter D_g, sphericity Φ, surface area S, volume V, shape index SI, elongation λ, thickness δ, thickness index TI, weight M, etc. There are approximate mathematical relationship between the characteristic parameters (Osborne & Winters, 1977; Marcé-Nogué et al., 2013; Nedomová & Buchar, 2014; Nedomova et al., 2009). For example:

$$D_g = \left(LB^2\right)^{\frac{1}{3}},$$

$$\phi = \frac{D_g}{L} \times 100\%,$$
$$S = \pi D^2{}_g,$$
$$V = \frac{\pi}{6}LB^2,$$
$$SI = B/L \times 100\%,$$
$$\lambda = L/B,$$
$$TI = L \times B/M.$$

1.2 Shape Functions

Shape functions of eggshell are primarily established in Cartesian coordinates and Polar coordinates. There are six kinds of related mathematical functions:

(a) N-R Function

In 2001 and 2002, N-R goose eggshell function was established by Narushin VG and Romanov MN based on the Cartesian coordinates (Nedomova et al., 2009):

$$y = \pm \sqrt{L^{\frac{2}{n+1}} x^{\frac{2n}{n+1}} - x^2} \quad , \quad n = 1.057 \left(\frac{L}{B}\right)^{2.372}. \tag{1}$$

Wherein x is the coordinate along the major axis, y is the displacement along the minor axis.

(b) Upadhyaya Function

In 1986, Upadhyaya bird eggshells function was established by Upadhyaya SK based on the Cartesian coordinates (Upadhyaya et al., 1986):

$$\frac{x^2}{a^2} + \frac{y^2}{\left(b + x\tan\theta\right)} = 1 . \tag{2}$$

Wherein a is semi-major axis, b is semi-minor axis, and θ is the egg-shape angle (Figure 3).
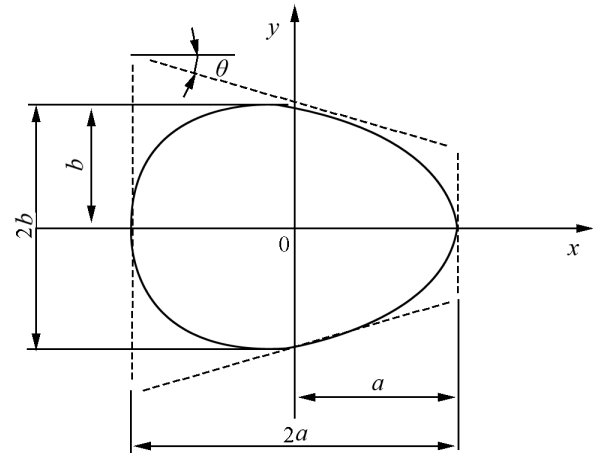

Figure 3
The Curve of Upadhyaya Function

(c) Brandt Function

In 1983, Brandt biological eggshell function was established by Brandt GV based on the Cartesian coordinates (Babich, 1993):

$$y = \frac{\sqrt{3}}{2} \sqrt{x(2-x) \left[1 - \frac{\beta^2}{(1+x)^2}\right]}. \tag{3}$$

Wherein β is a curvature parameter of plane (Figure 4).

Figure 4
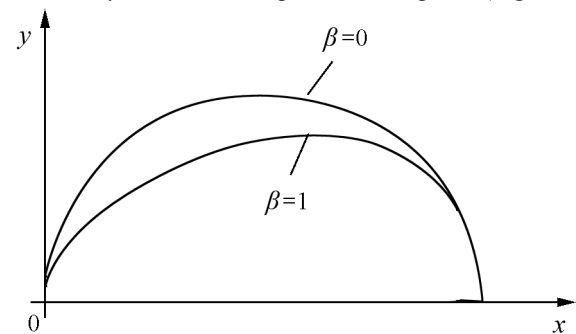**The Curve of Brandt Function**

(d) Lebedv Function

In 1982, Lebedv eggshell function was established by Lebedv JS based on Cartesian coordinates (Sumec et al., 2010):

$$y = \sqrt{3x(2-x)(1-\beta^2/(x+1)^2)}$$

$$\beta = \frac{c}{a} \quad \beta \in \left(0.76 \sim 0.86\right). \tag{4}$$

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[3] http://shodhganga.inflibnet.ac.in/bitstream/10603/1231/9/09_chapter%201.pdf

Wherein a is half big coordinate, and c is the distance between two main points (Figure 5). β selected from 0.76 to 0.8 is suitable for the characteristics of eggs, and got from 0.8 to 0.85 is good for the features of bird eggs.
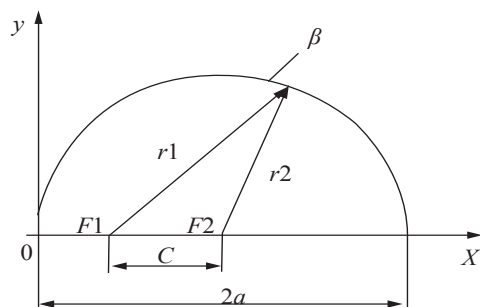

Figure 5
The Curve of Lebedv Function

(e) N-J Function
In 2014, NJ goose eggshell function was established by Nedomova S and Buchar J based on Polar coordinates (Nedomová & Buchar, 2014):

$$x = r\cos j, \ \ y = r\sin j,$$

$$r = a_0 + \sum_{i=1}^{i=\infty} [a_i \cos(iw\varphi) + b_i \sin(iw\varphi)]. \quad (5)$$

Wherein a_0, a_i, b_i, w can be achieved from experimental data by using the Fourier transformation.

(f) Jaroslav Function
In 2010, Jaroslav eggshell function was established by Jaroslav based on Polar coordinates (Buchar, Nedomová, & Severa, 2010):

$$x=\gamma \cos \phi, \ y=\gamma \sin \phi , \qquad r(\varphi) = \sum_{i=1}^{i=n} p_i \varphi^i. \quad (6)$$

Wherein, p_i was achieved by fitting the experimental data.

1.3 Method for Measuring Geometrical Parameters of Eggshell

The main geometric parameters of the eggshell contain length, width, shape index, sphericity and so on. The length and width can be measured with a vernier caliper. Shape index can be obtained through the calculation of ratio of length and width. The thickness can be measured by the digital microscope or a Vicker's Image Splitter attached to microscope. Among them, digital microscope measures the by using a bending bar reaching into the interior through stoma of eggshell. The thickness measured by this method contains the cell membrane thickness, although the result remains an error. A Vicker's Image Splitter attached to microscope can be operated in micron scale working environment, which can separate the cell membrane from the shell surface, the result is more accurate than the former. Sphericity can be measured by projection method involved in the equation, $\frac{127A}{D^2}$, where

A is projected area of eggshell, and D is the maximum diameter of projection obtained under projecting the eggshell along a plane parallel to the axis of rotation (Tung, 1967; Abanikannda & Leigh, 2012; Narushin et al., 2004). Besides, the eggshell can be directly obtained by 3D scanning technology, such as American three-coordinate measuring machine CIMCORE MODEL5124. It can accurately position coordinates of each point on the whole model with high accuracy.

In terms of the corresponding practice, Abanikannda studied on the geometrical size of egg, including measuring the mass of eggshell by a digital weighing scale with high sensitivity and the thickness of eggshell by a vernier caliper (Abanikannda & Leigh, 2012). Rasali measured length and width of eggshell by a caliper and thickness of eggshell by a micro caliper (Rasali et al., 1993). Narushin measured mass, length and circumference by an electronic scale, a vernier caliper and a tap respectively (Narushin et al., 2004). Tung measured the sphericity of eggshell by projection method (Tung, 1967). Ren Yilin measured the three-dimensional image model of eggshell by using Image Acquisition System (Ren, 2007).

2. MICRO-GEOMETRICAL FEATURES OF EGGSHELL

For common birds, birds, insects, reptiles, and some marine animals, their eggshell is mostly thin and porous. There are mainly four layers including the cuticle layer, the crystalline layer, the mammillary layer and the membrane fiber respectively from outside to inside. The cuticle layer is the outermost part surrounding shell and mainly composed of calcium carbonate (Figure 6). Its structure is basically continuous. Its surface is smooth and its thickness is small. The crystalline layer is a kind of board strip crystal structure which is formed by the internal mammillary layer diffusing to the cuticle layer. Its thickness is bigger than the former. The mammillary layer is the inner layer of eggshell, which the crystal grows from. It's generally emulsion structure. Microstructures of the crystalline layer and mammillary layer are shown in Figure 7. The membrane fiber, in the interior of the shell, is made up of reticular fiber protein, and its microstructure is shown in Figure 8. The microstructure of layers of eggshell can be obtained by observing air-dried eggshell with gold foil through scanning electron microscope. Besides, shell crystal morphology, orientation, size and orientation relation of the adjacent grain can be obtained by X ray diffraction analysis, scanning electron microscopy and transmission electron microscopy (Alejandro et al., 2006; Zhang et al., 2005; Zhang et al. 2005).

In addition, eggshell has porous structure, which should be the results of balance promotion of gas exchange for prevention of water loss. Its pore width
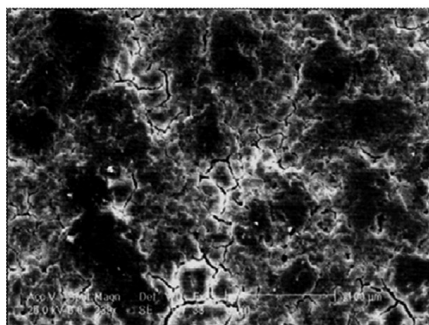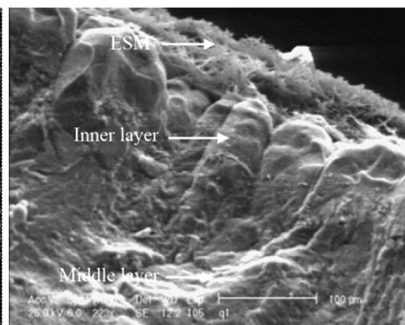
Figure 6
Cuticle Sheet

Figure 7
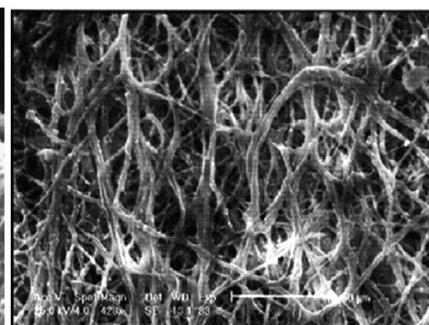**Crystalline Sheets and**
Mammillary Sheets

Figure 8
Membrane Fibres

is generally not more than a few microns (Zhang et al., 2005). It can be found by scanning electron microscope, pores on the surface of eggshell can be divided into three categories: balanced pores, gradient pores and mixed pores. Compared with other structure, pore structure can get the maximum space under the same circumstances (Zhang et al., 2005).

Zhang Jianzhong studied the microstructure characteristics of eggshell and its bionic applications (Zhang et al., 2005). Alejandro studied the arrangement direction and size of eggshell microstructure by x-ray diffraction (Alejandro et al., 2006). Darvizeh studied on the morphology and structure characteristics of the microstructure of eggshell by using scanning electron microscopy (Darvizeh et al., 2013). Riley carried out quantitative research on the microstructure of eggshell by computed tomography (Riley et al., 2014).

3. BIOMECHANICAL FEATURES OF EGGSHELL

3.1 Mechanical Analysis

Egg is a kind of complex biological structure, including air chamber, viscous liquid (formed by egg yolk and albumen), and shell. Eggshell provides embryo with an external skeleton support. On the one hand, it has enough strength to support the embryo itself and maternal weight, ensuring the safety of embryos in the process of the incubation. On the other hand, the strength of the eggshell should be moderate, so the embryo can successfully hatch after incubation (Ar et al., 1979). It can be seen that the loading conditions of eggshell can be divided into two kinds: One is the uniform pressure, resisted by in-plane stress of the eggshell, which is the most ideal loading state for eggshell; another is the concentrated load making eggshell bear local bending stress, which leads to the yield and ultimately the failure of eggshell (Woelke, 2005). The distance between an arbitrary point in the shell and middle plane is far less than the arc diameter of the eggshell, which means the thickness of the shell is far less than the radius of curvature of surface arc, so eggshell is a kind

of thin shell structure. Due to this state, its mechanical properties are relevant to thickness, size, shape, material and other factors (Nedomova et al., 2009). From a biological perspective, the factors affecting eggshell strength generally have nutritional and non-nutritive factors. The non-nutritive factors include catagory, age, temperature, physiological stress of birds or poultry. The nutritional factors include calcium, phosphorus, magnesium, vitamin D3, salt, vitamin c and so on (Wang & Wang, 2003). From the micro perspective, the eggshell is a kind of biological ceramic material with the best mechanical properties (Alejandro et al., 2006).

3.2 Research Status of Biomechanical Features

A group of international and domestic researches on eggshell strength have been conducted, and these studies focused on egg safety under concentrated load in the process of production, transport and sell (Voisey & Robertson, 1969). Early in 1955, Brooks working in the university of Cambridge published a paper entitled "the Strengh of the eggshell of the hen's egg" in the journal *Nature*. He discussed the relationships between strength, geometrical parameters, material hardness and the chemical composition when eggshell is under concentrated load. Studies showed that eggshell shape has smaller influence on the strength of the eggshell. However, hardness of eggshell is relevant to its strength and it presents a linear trend across the shell. If the shell becomes softer, the hardness will be greater. Besides, the area of eggshell fragmentation is related to its hardness value. The rigidity of outer layer of eggshell equals mild steel, and the hardness of inner layer is equivalent to marble (Brooks & Hale, 1955). Then, some studies showed that anti-crushing ability along vertical axis of eggshell is strong, and the anti-crushing ability along the horizontal axis is weak. Under the same loading conditions, the stress and deformation of the waist are higher than those of both ends, and the thicker eggshell can withstand the greater stress. Under the same deformation conditions, eggshell on the long axis direction can carry more load (Wang, 2013). Besides, many more similar studies show that there are some positive correlation between strength of eggshell

and its thickness, curvature, mass ratio. And intensity of eggshell is also influenced by porous nature, the thickness of eggshell membrane, mineral content of eggshell and protein matrix (Ren et al., 2007). However, egg's weight, egg's shape index and the number of pores have little influence on the strength (Brooks & Hale, 1955).

Finite element analysis method has become the mainstream approach which is used to study pressure characteristic of eggshell research. Coucke Studied the relationship between geometrical parameters and static stiffness of eggshell with method of finite element method, and studies showed that thickness of eggshell has a greater influence on the static stiffness, and that the dynamic stiffness is highly affected by the shape factor (Coucke et al, retrieved from website [39]). Darvizeh studied the strength and deformation of eggshell under the uni-directional force by using the numerical method (Darvizeh et al., 2013). Buchar studied dynamic properties of eggshell under dynamic concentrated load with numerical methods (Buchar, Nedomová, & Severa, 2010). Perianu studied dynamic mechanical properties of egg in structural acoustic behavior and hydro-mechanic properties of internal liquids with FEM (Eissa & Alghannam, 2011). Jordi studied dynamic impactive mechanical properties of eggshell with variable velocity and different energy (Marcé-Nogué et al., 2013). Eissa studied modal mechanical properties of eggshell under different vibration frequency (Eissa & Alghannam, 2011). In China, Jiao Hongjie studied static stress and buckling modal characteristics of eggs correponding with a single static load (Jiao et al., 2009). Jiangsong studied static stress of eggshell under different load (Jiang et al., 2009).

3.3 Biomechanical Test Method of Eggshell

3.3.1 Hardness Test

The vickers hardness tester can be used to measure hardness with tiny indentation technique. A short strip sample can be fetched along the equator edge of eggshell which is removed from the cell membrane and the cuticle. The sample is installed on the epoxy next burnished by fine sand paper. It uses aluminum oxide lapidary wheels to carve the projection shape of the eggshell along the direction of the equator. It uses a square-based diamond pyramid to exert a force on a quarter in the edge, the length of the indentation diagonal can be obtained by using the ocular micrometer on the Tukon tester measure (Tung, 1967).

3.3.2 Material Parameters Test

The elastic modulus and possion's ratio is obtained from the computing standard of material properties of curved surface published by America Society of Agricultural Engineers. In this literature the elastic modulus is measured by using auto-testing instrument with the method of compression test of biological materials. For example, the Instron Universal Testing apparatus

compresses the whole eggshell unless the compression reach to the prepared value. Nextly, the reaction and deformation of the eggshell can be measured, which can be used in the equation of calculating the elastic modulus referring to the former literature (ASAE, 2003).

The density can be measured by the density gradient column mathod. Firstly, the eggshell is put into a density gragient tube containing two solutions with different density. Nextly, when the sample is balanced and still, the height of the center of the sample is recorded. Lastly, the density is calculated according to the standard curve.

3.3.3 Pressure Endurance Test

The test has two different methods including hydraulic circuit test and static pressure test (Figures 9 and 10).

(a) Hydraulic circuit test

Method: Oil pressure in the transparent container equals the inlet pressure of overflow valve and the overflow valve controls outlet pressure of hydraulic pump. Thus, the pressure in the transparent container can be controlled by adjusting the overflow valve. The eggshell is fixed in a transparent container. Finally, the change of eggshell under different oil pressure is recorded with a high-speed camera.

Advantages: Oil pressure can be controlled real-time and accurately. The device is automatic and effective.

Disadvantages: The workplace needs to meet high demand. The device dismantling is complicated and it costs highly.
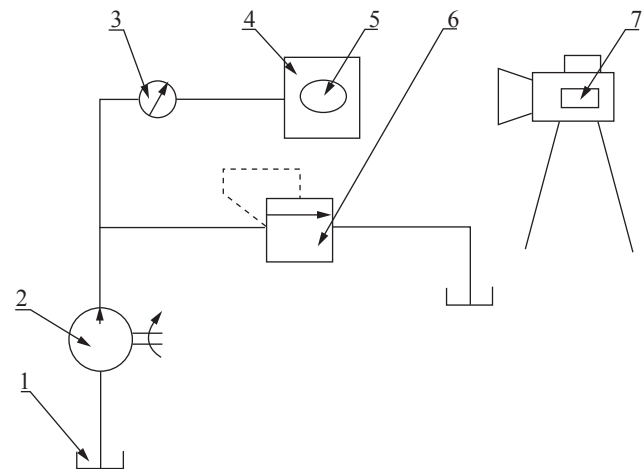

Figure 9
The Hydraulic Circuit of Eggshell Pressure Characteristic
1. Oil Tank, 2. Hydraulic Pump, 3. Pressure Gage, 4. Transparent Container, 5. Egg, 6. Overflow Valve, 7. High-Speed Cameras

(b) Static pressure test

Method: Liquid pressure of transparent container is changed by adding the weight on the pushrod or pushing it manually. The change of liquid pressure is displayed on the pressure sensor. and the eggshell is fixed in a transparent container. Finally, the change of eggshell under different pressure is recorded with a high-speed camera too.

Advantages: The philosophy is simple and reliable. Low requirement is needed for the workplace. Components disassembling are easy and the device is low cost.

Disadvantages: Due to lack of the automation, the method is less effective. Meanwhile, the liquid leakage occurs more easily.
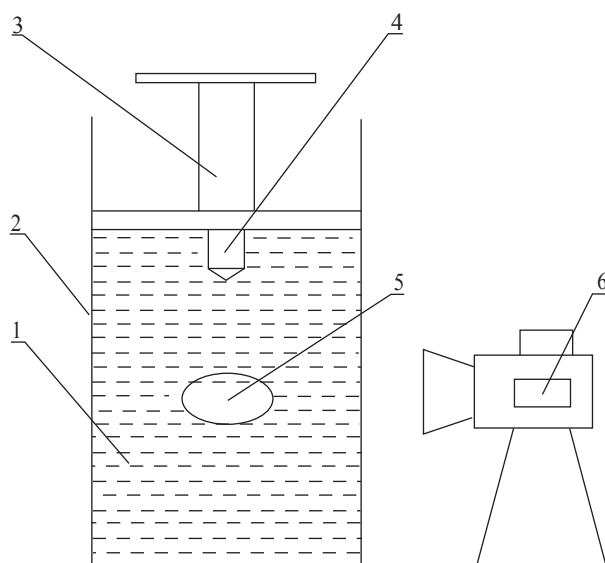

Figure 10
Static Pressure Test of Eggshell Pressure Characteristic
1. Liquid, 2. Transparent Container, 3. Piston Push Rod, 4. Pressure Sensor, 5. Egg, 6. High-Speed Cameras

4. THE INSPIRATION TO THE DESIGN OF PRESSURE HULL

Life science is a source of technological innovation, and bionic design is an important way of innovative design. The content of the bionic design covers mechanical bionics, molecular bionics, energy bionics, information and control bionics, etc.. In 1960, the first international bionic conference was held in the United States, which marked that bionics was born truly as an independent discipline. Since 2006, China has held four international conferences on biomimetic engineering in support of Ministry of Science, Natural Science Foundation and Jilin University, which marked that bionics had become domestic research hotspot. In recent years, numerous studies in the field of bionics have showed that the new bionic product with better performance and higher demand can be achieved by studying on typical creatures living in certain environments by means of studying on its surface morphology, microstructure, surface material, state of motion, etc.. The world's first nuclear submarine "Nautilus" was developed by the United States by imitating the working way of Nautilus, which floats by drainaging water and sinks by absorbing water (Brodbeck, 2014).

The various submersibles with different operating purposes have developed rapidly with the accelerating pace of ocean development. The submersibles are mainly used for oil exploration and development, scientific research, exploitation of mineral resources, military exploration, salvage, etc.. What was clearly stated by "The notice of State Council on the issuance of the national marine economic development 'Twelfth Five Years' Plan" is that ocean exploration technology and deep-sea research should be strengthened to support the construction of basement and production of deep-sea equipment. Diving equipment is important to ocean exploration and deep-sea research. The pressure hull, as an important part of the submersible, plays a role in protecting the normal work of internal equipment and safety of personnel in the process of diving. Its weight accounts for 1/4-1/2 total weight of submersible. The pressure hull design has a significant impact on buoyancy reserve capacity, hydro-dynamic characteristics, space utilization, occupant comfort and other properties of the submersible.

Active pressure hull can be divided into spherical structure, cylindrical structure and ellipsoid structure, as shown in Figure 11. Among them, spherical shell has the advantages of high strength, good stability, low coefficient of buoyancy, high utilization rate of material, but it has the disadvantages of low utilization rate of space and poor hydro-dynamic characteristics. It is mainly used in deepwater submersibles. Cylindrical shell has the characteristic of easy processing, high utilization rate of space, good hydro-dynamic characteristic, but its weaknesses include high coefficient of buoyancy, low utilization rate of material and high bending stress (it needs to be strengthened internally). It is generally used in diving submersibles. Ellipsoidal shell is a compromise of spherical shell and cylindrical shell. In addition, the pressure hull also includes droplet structure with good hydro-dynamic characteristics, as well as ring structure which have a characteristic of bearing strong pressure, but at the expense of other properties. They are both not widely used (Cheng, 2012; Pan, 2010; Fathallah et al., 2014; Burcher & Rydill, 1994). However, the existing pressure hull can not realize the effective coordination of these properties, which caused the bottleneck to develop deep-sea submersible. The eggshell can resist uniform external pressure by producing the in-plane stress, which means that eggshell has superior characteristics to bear pressure. Pressure hull is the shell structure, and it must meet the requirements of strength, stability, reserve buoyancy capability, streamline shape, space utilization and occupant comfort. Obviously, eggshell can provide effective biological information for deep-sea pressure hull design, the function mapping relationship among eggshell, the pressure hull and submersible is shown in Figure 12.
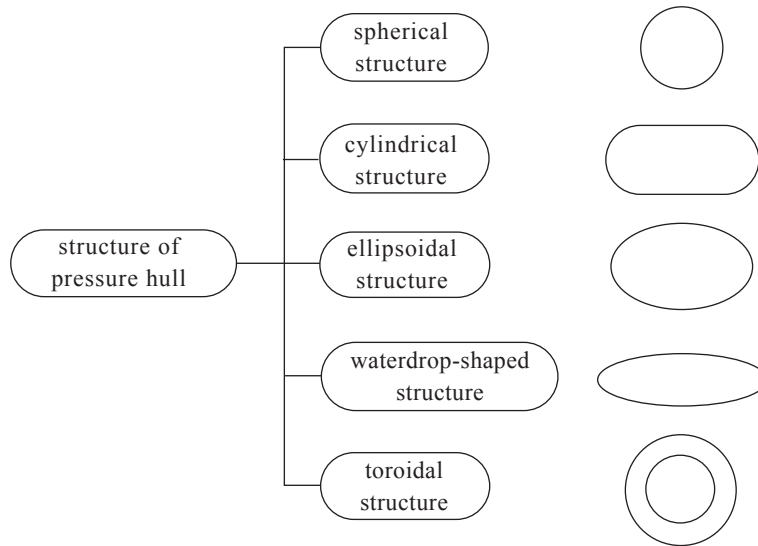
Figure 11
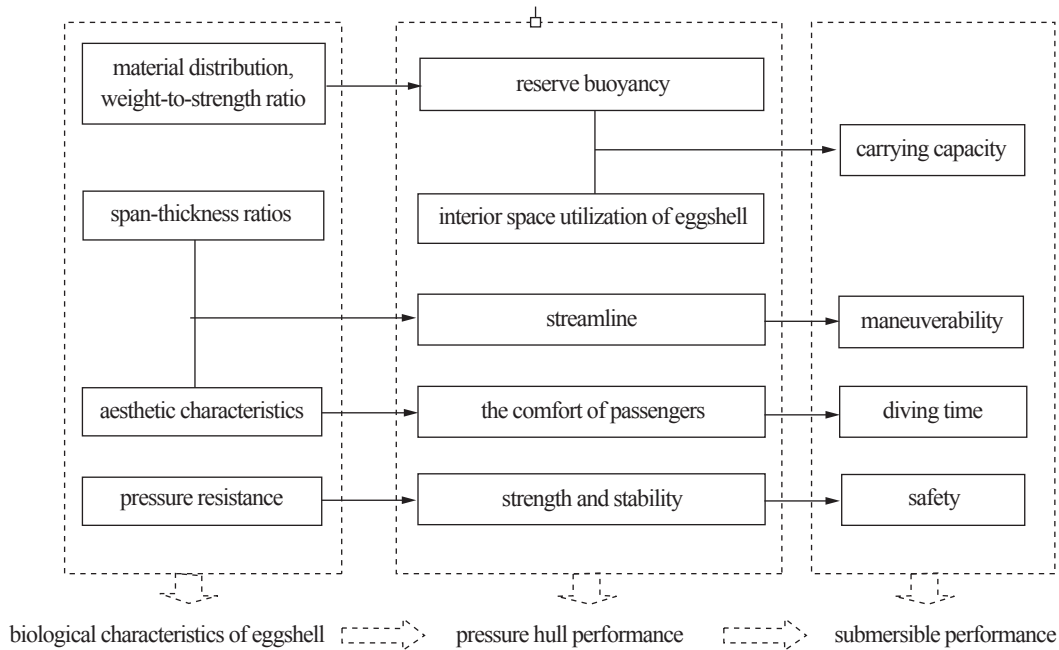**Structural Classification Diagram of Existing Pressure Hull**

Figure 12
Schematic Diagram of Performance Mapping for Eggshells, Pressure Hull and Submersuble

CONCLUSION

Eggshell has good bionic features including weight-strength ratio, span-thichness ratio, esthetics characteristics, distribution of material and so on. From the macro-geometrical perspective, eggshell is a thin-walled rotation structure satisfying the Gaussian curve with multi-focus, and is generated by a generatrix (meridian) revolving around an axis of rotation. This generatrix is expressed by using N-R function, Upadhyaya function, Brandt function, Lebedv function, N-J function, Jaroslav function and so on. From the micro-geometrical perspective, there are mainly four layers including the cuticle layer, the crystalline layer, the mammillary layer and the membrane fiber respectively from outside to inside. Eggshell has porous structure, which should be the results of balance promotion of gas exchange with prevention of water loss. Its mechanical properties are relevant to thickness, size, shape, material and other factors. Under uniform pressure, the eggshell has good ability to bear. Pressure hull based on the imitating of the eggshell can well meet the requirements of strength, stability, reserve buoyancy capability, streamline shape, space utilization and occupant comfort. However, the researches so far have the following problems:

(a) The characterics of the pressure endurace and modes of instability is lack, as well as the influence of the material and geometrical parameters on it.

(b) Eggshell belongs to the thin-wall rotating shell, and the strength and stability are quite important content. Mechaical theory on eggshell under the uniform pressure is not found. Submesible pressure hull under deep water is working in severe environment and during long diving time. It increases the demand of the strength, stability, reserve buoyancy capability, streamline shape, space utilization and occupant comfort. However, this problem is lack of the deep research on considering all of thses features.

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