Analysis on screw preload condition of acoustic beacon in high water pressure environment

Yang Chen¹, Shichao Dong, Junbo He, Haitao Xiao and Jialu Sun
Dalian Scientific Test and Control Technology Institute, Dalian, China

¹E-mail: 27780709@qq.com

Abstract. The acoustic beacon is mainly assembled by using screw thread couplings between caps and shell. The products are always affected by heavy loads when operating under high water pressure. In this paper, to investigate the influence of screw thread couplings on acoustic beacon strength under deep water condition, the structural stresses and the distributions of the acoustic beacon with different pre-tightening torque of screw thread under particular water pressure is analysed by using finite element method. The variations of stresses which is relative to the pre-tightening torque of screw thread are also analysed and proposed as the form of line chart. The results indicate that the acoustic beacon strength can be improved by increasing the pre-tightening torque of screw thread, and the line chart can be used to determine the most suitable pre-tightening torque while assembling the products.

1. Introduction
The underwater acoustic beacons are mostly used in ocean and some deep-water lake. The reliable structure strength and electronic functions under heavy water pressure are significant technical index for keeping the quality of acoustic beacon products. An eligible underwater acoustic beacon should have small size, light weight, long underwater working life and reliable triggering performance; these are also important design requirements of acoustic beacon product. Therefore, the structure strength under heavy water pressure is essential to be considered in the design process of the product [1-4].

There are many common methods to improve the structural strength of underwater acoustic beacon product. For example, to apply stronger materials for manufacture, to increase the wall thickness of the products and to optimize the product structure etc. [5-6], but some unexpected limitations may exist for the mentioned methods: The variation of material could weaken the conductivity of the acoustic beacon and cause triggering failure in the underwater environment; to increase the wall thickness of the product will enlarge the dimension and weight of the beacon; to optimize the product structure will extend the production cycle unpredictably. Consequently, it is necessary to find more simple and effective methods to guarantee the strength and reliability of acoustic beacon product.

The familiar underwater acoustic beacon always be assembled by screw thread coupling, so how to determine the pre-tightening torque to guarantee structure strength and sealing property is significant for the product reliability. In this paper, the load analysis on acoustic beacon with the consideration of pre-tightening torque of screw thread coupling is proposed; the stresses and relevant distributions of acoustic beacon under the compound effects of water pressure and axial pre-tightening force (derives from pre-tightening torque of screw thread) are investigated by using finite element method [7]. The relationships between the structural strength of acoustic beacon and the pre-tightening torque of screw thread are discussed, and the regulations will be presented according to the analysis results.
2. Basic methodology

2.1. Structure of underwater beacon
The structure of small underwater beacon product is shown as the following Figure 1:

![Figure 1. Appearance and section of beacon products.](image)

The body of the underwater acoustic beacon is mainly composed of a cylindrical tube (housing), two end caps (top cap and bottom cap) and two O-type sealing rings. The end caps are assembled by connecting a pair of pipe threads of M30 into the cylindrical tube (housing). The O-rings are coated with vacuum grease and installed in the gaps between the caps and the housing (see Figure 1). Once the screw is tightened by pre-tightening torque, the O-ring is greatly compressed due to the axial pre-tightening force of screw thread, so the whole inner cavity of the cylindrical tube can be sealed completely. The purpose of sealing is to ensure that the water switch of internal circuit devices can be normally triggered once the beacon touches water, otherwise the device doesn’t work. Some previous applied experience indicates that the top cap is more likely to be damaged under the condition of overload water pressure [8-9], consequently the investigation and relevant analysis in this paper are introduced and discussed on the basis of top cap.

2.2. Load condition and analytical model
For the study, it is assumed that the water pressures on the acoustic beacon are 65/70 MPa, and the whole structure is all stressed under uniform water pressure. Meanwhile, the axial pre-tightening force which derives from pre-tightening torque of screw thread is also loaded on the top cap. The specified load condition of the acoustic beacon is illustrated as Figure 2:

![Figure 2. Load condition of acoustic beacon.](image)

According to Figure 2, it can be seen that the actual load condition on the top cap is very similar to the theoretical model of simply supported beam under uniform load without considering the actual
shape of the top cap. Therefore, the load analysis diagram of the top cap can be simplified to the form as shown in Figure 3:

![Figure 3](image)

**Figure 3.** Equivalent simply supported beam model of upper top cover.

The maximum tensile stress of simply-supported beam and strength criteria can be stated by following Equation (1):

\[
[\sigma] \geq \sigma_{\text{max}} = \frac{M_{\text{max}}}{W}
\]  

(1)

While \([\sigma]\) is the permissible tensile stress, \(\sigma_{\text{max}}\) is the maximum actual tensile stress of top cap, \(M_{\text{max}}\) is the maximum bending moment of top cap, \(W\) is section modulus. According to Figure 3, the maximum bending moment of top cap can be calculated as:

\[
M_{\text{max}} = \frac{Q_p \pi D^3}{8} - F_0 D
\]  

(2)

The screw pre-tightening force can be calculated according to pre-tightening torque as [10]:

\[
T_0 = \frac{F_0}{2} \left[ d_2 \tan(\varphi_v + \phi) + \frac{2}{3} f_c \frac{D^3 - d_0^3}{D^2 - d_0^2} \right]
\]  

(3)

In the equation:  
- \(T_0\) — Screw pre-tightening torque;  
- \(F_0\) — Screw pre-tightening force;  
- \(D\) — Diameter of top cap;  
- \(d_0\) — Diameter of bolt hole;  
- \(f_c\) — Friction coefficient between contact surfaces;  
- \(d_2\) — Minor diameter of thread;  
- \(\varphi_v\) — Equivalent frictional angle;  
- \(\phi\) — Lead angle of thread;

For the threads of M10-M64, an approximate algorithm as following can be used [10]:

\[
T_0 = 0.2dF_0
\]  

(4)

While \(d\) is major diameter of screw thread.

The Equations (1) ~ (4) indicate that the tensile stress of top cap under water pressure is relevant to the screw pre-tightening torque. Equations (3) and (4) state the screw pre-tightening force is directly proportional to the rate at the torque; Equation (2) states the maximum bending moment of top cap
will be decreased on condition that the screw pre-tightening force increase, and the actual tensile stress of top cap will also be decreased. On the basis of service condition and strength requirement, the actual stress (including tensile stress and shear stress) of acoustic beacon under water pressure must be less than the allowable stress (or extreme stress) of the material, consequently it shall be effective to reduce actual stress by increasing screw pre-tightening torque.

3. The simulating analysis

3.1. Finite element model

The geometric model of the underwater acoustic beacon was created by Solidworks software and then imported into ANSYS-Workbench for structural finite element analysis, and the actual stress of the upper end cover under the combined action of water pressure and screw joint preload was calculated. The finite element model used for analysis and the load boundary conditions are shown in the following Figure 4 after the pre-processing steps such as meshing and loading:

![Finite element model of acoustic beacon](image)

(a) geometry  (b) mesh  
(c) load conditions

Figure 4. Finite element model of acoustic beacon.

3.2. Stress analysis

The beacon model is defined as aluminium alloy (density $2.7 \times 10^3$ kg/m$^3$, elastic modulus 70 GPa), the model is meshed by first-order hexahedral elements, and the type is solid185. The analysis results of
the tensile stress (Mises stress) and shear stress of the top cap are shown in the following figures. The loaded water pressure is set to $70\,\text{MPa}$ and the pre-tightening torque is set to $25\,\text{N}\cdot\text{m}$.

![Image](image1.png)

Figure 5. Tensile stress of top cap ($T_0 = 25\,\text{N}\cdot\text{m}$).

![Image](image2.png)

Figure 6. Shear stress of top cap ($T_0 = 25\,\text{N}\cdot\text{m}$).

The contour results which are illustrated in Figure 5 and Figure 6 indicate that the root of the screw should be the region of stress concentration under the integrated effects of water pressure and pre-tightening force. The maximum tensile stress and shear stress of the top cap are $628.04\,\text{MPa}$ and $361.07\,\text{MPa}$. According to the mechanical performance of the material, the extreme tensile strength is $626\,\text{MPa}$, and the shear strength should be $500\,\text{MPa}$ approximately. It presents that the tensile stress has exceeded the extreme tensile strength, but the shear stress is less than the limit significantly. The distribution and values of actual stress indicate that the root of the screw must be destroyed due to the water pressure because the strength of the acoustic beacon doesn’t achieve the requirement. To keep the current structure and improve the strength, it should be effective to increase the screw pre-
tightening torque on the basis of mentioned equations, which means it is important to assign appropriate screw pre-tightening torque while assembling the acoustic beacon product.

3.3. Data comparisons

The analysis with the water pressure of 65 MPa is also carried out according to identical processes. To research the relationship between the screw pre-tightening torque and actual stress, the finite element analysis is necessary to be carried out multiple times to investigate the actual stress of top cap with various screw pre-tightening torque. The following Table 1 lists the relevant stress results:

| Screw pre-tightening torque (N·m) | P = 70 MPa |  | P = 65 MPa |  |
|-----------------------------------|------------|---|------------|---|
|                                   | Tensile stress (MPa) | Shear stress (MPa) | Tensile stress (MPa) | Shear stress (MPa) |
| 0                                 | 638.55     | 367.03 | 593.26     | 341 |
| 5                                 | 636.44     | 365.84 | 591.15     | 339.81 |
| 10                                | 634.33     | 364.64 | 589.04     | 338.61 |
| 15                                | 632.23     | 363.45 | 586.95     | 337.42 |
| 20                                | 630.14     | 362.26 | 584.85     | 336.23 |
| 25                                | 628.04     | 361.07 | 582.76     | 335.04 |
| 30                                | 625.96     | 359.88 | 580.68     | 333.85 |
| 35                                | 623.88     | 358.68 | 578.6      | 332.65 |
| 40                                | 621.8      | 357.49 | 576.53     | 331.46 |
| 45                                | 619.73     | 356.3  | 574.96     | 330.27 |
| 50                                | 618.58     | 355.11 | 574.08     | 329.08 |
| 55                                | 617.69     | 353.92 | 573.19     | 327.89 |
| 60                                | 616.81     | 352.72 | 572.31     | 326.69 |
| 65                                | 615.92     | 351.53 | 571.42     | 325.5 |
| 70                                | 615.04     | 350.34 | 570.54     | 324.31 |
| 75                                | 614.15     | 349.15 | 569.65     | 323.12 |
| 80                                | 613.27     | 347.96 | 568.77     | 321.93 |
| 85                                | 612.38     | 346.76 | 567.88     | 320.73 |
| 90                                | 611.49     | 345.57 | 567        | 319.54 |
| 95                                | 610.61     | 344.38 | 566.11     | 319.06 |
| 100                               | 609.72     | 343.54 | 565.23     | 318.78 |

According to the stress data in Table 1, the line chart which can describe the relationship between the actual stress and screw pre-tightening torque can be concluded as following:

Figures 7 and 8 indicate that the tensile stress and shear stress under different water pressure are both inversely proportional to screw pre-tightening torque basically, the tensile stress has a slight inflection point when the torque is 45 N·m approximately. The figures also indicate the tensile stress will exceed the extreme tensile strength of the material (626 MPa) under the water pressure of 70 MPa if the screw pre-tightening torque doesn’t reach to 30 N·m, but the torque is not significant any more under the lower water pressure of 65 MPa; the shear stresses are all significantly less than extreme shear strength (500 MPa) no matter how large the water pressure is. The phenomena state that the
most possible mechanism of the structure failure of the acoustic beacon should be the tensile fracture under water pressure, and it is only necessary to concern the pre-tightening torque if the water pressure is heavy enough; the shear strength of the structure is safe enough and not necessary to be noticed frequently, so the significance of the line chart of tensile stress is similar to S-N curve of material. Furthermore, the tensile stress line chart also shows that the minimum pre-tightening torque for ensuring the structure strength under the water pressure of 70 MPa should be 30 N·m, the reliability of the acoustic beacon product should be improved significantly by guaranteeing enough pre-tightening torque while assembling the screw. In addition, the line chart is also significant for searching the prescribed minimum of pre-tightening torque according to the particular allowable stress with various safety factor requirements.

Figure 7. The relationship between tensile stress and screw pre-tightening torque.

Figure 8. The relationship between shear stress and screw pre-tightening torque.
The tensile stress with pre-tightening torque of 30 N·m under the water pressure of 70 MPa can also be calculated. According to the geometry of the top cap, the diameter D is 32 mm, section modulus W is 1152.65, the pitch diameter of thread of M30 is 29.026 mm, so the tensile stress of top cap should be:

$$\sigma = \frac{M_{\text{max}}}{W} = \frac{70 \times 3.142 \times 32^3 - 30000 \times 32}{0.2 \times 29.026} / 1152.65 = 638.1 \text{ (MPa)}$$

The data in Table 1 indicate that the related finite element result is 625.96 MPa, the difference between the two results is:

$$\frac{638.1 - 625.96}{625.96} \times 100\% \approx 2\%$$

3.4. Empirical validation

A Hydrostatic pressure test can be carried out to validate proposed discussions. To divide 80 underwater acoustic beacon specimens into two groups equally, each 10 of 40 specimens in each group are assembled with the pre-tightening torque of 20, 30, 40 and 50 N·m (the screw pre-tightening torque can be guaranteed by torque wrench). The specimens of group 1 are loaded by the water pressure of 65 MPa, and the specimens of group 2 are loaded by the water pressure of 70 MPa, all specimens will be loaded for 5 minutes. After the empirical validation, data regarding the failure of specimens are listed in following Table 2.

| Water pressure | Group 1 | Group 2 |
|----------------|--------|--------|
|                | 65MPa  | 70MPa  |
| Test duration  | 5 min  | 5 min  |
| The number of specimens | 10 | 10 |
| Screw pre-tightening torque (N·m) | 20 | 30 |
| Normal | 10 | 10 |
| Structural failure | 0 | 5 |

The hydrostatic pressure test results indicate that there are total 8 specimens of group 2 damaged, and the specimens of group 1 are all intact, the phenomena validates that the safety of specimens will be higher under light water pressure. Furthermore, the distribution of specimens’ failure also presents that the most of damaged specimens are the ones with the pre-tightening torque of 20 N·m and 30 N·m, and the failure rate of the specimens with the pre-tightening torque of 20 N·m is the highest. The reason of the situation can be explained on the basis of Figure 7, the actual tensile stress of damaged specimens must exceed the tensile strength of the material, and the pre-tightening torque is too weak to improve the structural strength. The specimens with larger pre-tightening torque (40 N·m and 50 N·m) present better reliability, the phenomena are accordant to the results of theoretical analysis well.

4. Conclusions

In this paper, a structural strength analysis is carried out to establish the finite element model of the underwater acoustic beacon, and to calculate the structural stresses and distributions of the top cap under water pressure conditions of 65 MPa and 70 MPa. The analysis results indicate that the tensile stress of top cap with the pre-tightening torque of screw thread 25N·m has exceeded the tensile strength of material; the tensile stress distribution indicates the region with high stress concentration should be the root of screw thread. The situation means the stress concentration region of top cap is likely to be damaged by the water pressure of 70 MPa if the pre-tightening torque of screw thread is 25 N·m, but the top cap should be safe with any pre-tightening torque of screw thread under the water pressure of 65 MPa. According to further stress analysis with the consideration of various pre-
tightening torque, the results demonstrate that the actual stress (including tensile stress and shear stress) of the top cap in the water pressure environment is related to the pre-tightening torque of the thread applied when assembling the products, and the relationship presents linear decreasing function.

The line chart regarding the relationship between the stresses of top cap and pre-tightening torque can be used to decide the most suitable pre-tightening torque for acoustic beacon product assembling with the consideration of particular water pressure. Above discussions have demonstrated that the actual stresses of the top cap under the water pressure can be changed effectively by adjusting the pre-tightening torque of the screw thread, the torque must be applied enough to ensure the structural stresses are less than allowable stress of the material if the water pressure is significantly heavy. In this study, the minimum pre-tightening torque should be \(30 \, \text{N}\cdot\text{m}\) under the water pressure of \(70 \, \text{MPa}\) because the relative structural tensile stress (625.96 MPa) is almost the extreme tensile strength of material (626 MPa), but any pre-tightening torque is acceptable for structural strength of the acoustic beacons which work under the water pressure of 65 MPa. The empirical validation also indicates the samples with higher pre-tightening torque is more reliable than others under water pressure of 70 MPa. The proposed line chart and the method to decide pre-tightening torque can improve the reliability of the product structure effectively, and they are definitely significant for optimizing the structure design and determining the important characteristics of the underwater acoustic beacon products.

References

[1] Yang Song, Zhang Qiong, Qu Yuanxin, et al. 2015 The application of underwater acoustic beacon in rescue and salvage Electronic Publishing House 4 14

[2] Qu Jiasheng and Yang Song 2012 The design and implementation in portable underwater acoustic beacon detection and orientation equipment Ship Science and Technology 34 4

[3] Qu Jiasheng, Han Hui and Yang Shanshan 2019 A Design of The Underwater Acoustic Beacon Detection and Location Method IOP Conference Series Materials Science and Engineering 612 4

[4] Qu Jiasheng and Wang Jiaxin 2019 Electronic A design and implementation of beidou technology for the rescue of the drowning personnel at sea Measurement Technology 42 19

[5] Zhang Li, Feng Kun, Gou Chao, et al. 2019 Failure tests and bearing performance of prototype segmental linings of shield tunnel under high water pressure Tunnelling and Underground Space Technology 2019 92

[6] Ding Wengi, Gong Yifan, Qiao Yafei, et al. 2020 Experimental investigation on mechanical behavior of segmental joint under combined loading of compression-bending-shear Tunnelling and Underground Space Technology 2020 98

[7] Zhang Yuelin, Jin Jian, Hou Hailiang, et al. 2019 The buckling strength of plexiglass protective shield under static water pressure Engineering Failure Analysis 2019 99

[8] Wagner H N R, Hühne C, Zhang Jian, et al. 2019 Geometric imperfection and lower-bound analysis of spherical shells under external pressure Thin-Walled Structures 2019 143

[9] Wagner H N R, Hühne C, Zhang Jian, et al. 2020 On the imperfection sensitivity and design of spherical domes under external pressure Pressure Vessels and Piping 2020 179

[10] Yang Kezhen, Cheng Guangyun, Li Zhongsheng, et al. 2013 Fundamentals of mechanical design Higher Education Press Edition 6 145