Experimental study on the failure of tangential anti-loose dowel of ship hydraulic fluid tubing in alternating torque and vibration environment

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Abstract. The internal hydraulic fluid tubing in central shaft is a critical part of pitch adjusting paddle in the ship propulsion system. The failure of screw pairs of internal hydraulic fluid tubing will result in a loss of propulsion. This real accident has happened on a ship. In order to determine the reason for the tangential anti-loose dowel falling out from the screw pairs, 380.5h and 147h alternating torque and vibration environment tests are completed on two samples with difference of manufacturing processing. The result shows that alternating torque and vibration combined stress is the synthesis stress for the dowel falling out from dowel hole. The basic reason is the larger fit clearance between dowel and dowel hole. This clearance is suggested to be manufactured below 0.2~0.3mm, and the value of diameter for piercing outside the dowel hole should be greater than 1.95mm.

1. Introduction

As a kind of advanced ship propulsion system structure, screw pitch of propeller can be changed by rotating paddles around hub by means of the pitch adjusting paddle, so that the controllable thrust force and direction of propeller can be changed [1]. The function failure of screw pitch of propeller would be caused by the clamping stagnation of hydraulic one-way valve [2], hydraulic pump [3], unsuitable of assembly clearance [4], etc. As for the pitch adjusting paddle with pitch adjusting hydraulic cylinder and pitch adjusting action piston in the hub, re-greasing distributor is often placed at the front of the gearbox output shaft. Tail shaft, middle shaft and gearbox output shaft are hollow structures. Dual hydraulic oil tubing can be placed in the hollow structure [5] (Figure 1).

![Figure 1. Dual hydraulic oil tubing structure.](image-url)
Internal hydraulic fluid tubing assembled with several tubing parts in the large ship is always beyond fifty meters. These parts are connected by adjusting ring [6]. Two adjacent tubing parts are connected with the means of screw. Tangential dowel is used to be anti-loosed after fastening the screw connector. After putting tangential dowel into the dowel hole, three piercing will be made by impacting outside the tubing with 1~2mm distance away to the side of dowel hole. Then the material of dowel hole will deform toward the center, which prevents dowel falling out from its dowel hole. Tangential dowel is shown in Figure 2. Losing the looseness-proof function caused by tangential dowel falling out could lead to the screw failure at the internal hydraulic fluid tubing connector. If the oil circuit is destructed by the screw failure, the action of adjust pitch of paddle will not be executed. Finally, propeller is not able to provide the propelling force.

The accident of tangential anti-loose dowel falling out happened in a ship. The real situation of the accident is that tangential dowel fell out from one side of the dowel hole, after that, the dowel had scratched the screw of external tubing for a long time and screw connector failed finally. A short circuit fault is located between the hydraulic oil supply circuit and return circuit, which makes the action of adjusting pitch of paddle ineffective. After this accident, this ship was repaired in the dock. The piece of failed internal tubing was cut down for analysis. The damage of screw pair and the tangential anti-loose dowel could be seen obviously.

In order to analysis the reason about failure of anti-loose dowel falling out more deeply, in this paper, the failure of this tangential dowel falling out is as reference. Through repetition of the experiments for this, the reasons about tangential dowels falling out under different stress environment are studied. The influences of key parameters in the manufacturing process to dowel falling out are analyzed, and some processing suggestions about these parameters are given eventually.

2. Experimental samples of internal hydraulic fluid tubing
Two internal hydraulic fluid tubing samples are cut from the tubing as same type as the failure one in the accident ship. They contain complete screw connector with a brass supporting ring in the middle. The lengths of samples are both 300mm. These samples are shown in Figure 3. The material of tubing is 45 steel. Four fan-shaped grooves at the end of tubing are to load torque using the test fixtures. The dimensions of samples and the position of tangential dowel are displayed in Figure 4. The diameter of dowel is 6 mm and its length is 40 mm. The material of dowel is A1 austenitic stainless steel. For comparison, there are some small parameter differences between the sample 1 and sample 2 in manufacturing processing of the dowel holes and piercings. Related parameters of the real tubing with fault and two experimental samples are all listed in Table 1.
Figure 4. Dimensions of internal hydraulic fluid tubing sample.

| Tubing                  | Diameter of dowel (mm) | Diameter of dowel hole (mm) | Clearance between dowel and dowel hole (mm) | Tightening torque (N•m) | Diameter of piercing outside the dowel hole (mm) |
|-------------------------|------------------------|------------------------------|---------------------------------------------|-------------------------|--------------------------------------------------|
| Real tubing with fault  | 5.92                   | 6.16~6.86                    | 0.24~0.94                                   | 400~600                 | Left: 1.80~2.15 Right: 2.02~2.36                 |
| Sample 1                | 6.00                   | 6.18~6.29                    | 0.2~0.3                                     | 420                     | Left: 1.95~2.03 Right: 2.02~2.05                 |
| Sample 2                | 6.00                   | 6.34~6.39                    | 0.3~0.4                                     | 420                     | Left: 1.22~1.25 Right: 1.19~1.26                 |

The tangential anti-loose dowels of sample 1 and sample 2 will not fall out from dowel holes by the gravity and small pushing force along the axis direction of dowel. Clearance of sample 2 which between the dowel and dowel hole is larger than the sample 1, and its dowel can slide into the dowel hole which is to verify the influences causing by this clearance.

3. Test conditions and test devices

3.1. Test conditions

According to the working environment of the real internal hydraulic fluid tubing in the ship, there are no circumferential constraints to the tubing. The front of tubing with dowel failure is a supporting ring in the external tubing for locating along the axis of shaft. At the end of the internal tubing, it is placed in the external tubing of the hub with a seal ring. The rotation torque is transmitted through the friction force between internal oil tubing and the external one. There is rotating speed difference between internal and external oil tubing when rotating speed of the shaft system is changed. This rotating speed difference causes alternating torque stress on the internal tubing which also working in the vibration environment. This shaft vibration is caused by the extra vibration dynamic stress of ship propeller shaft and dynamic amplification of resistance force to other structures vibration in the ship stern [7]. This vibration can be related by shaft resonance [8], shaft stiffness, the damping of the shaft and coupling and even the fatigue failure of the reduction gear shaft [9]. The vibration frequency range which can be calculated is based on the rotating speed of tubing [7]. And on this basis of the friction resistance force and mass inertia, the alternating torque is estimate. In order to analyze the performance of the tangential dowel in tubing connector in different stress, test conditions are made and list below.

- The rotation speed with alternating direction of tubing connector is 120rpm±10rpm. Acting times are 2s for accelerating rotation, 2s for decelerating and 6s for keeping rotation speed which is shorter than real ship for saving test time. Three tests with different stress environment are practiced on sample 1 and sample 2 respectively. They are no-load test without resistance torque, 50 N•m alternating torque (Figure 5) load test and 50N•m alternating torque and vibration combined stress tests.
Figure 5. Schematic diagram of alternating rotating and alternating torque load conditions.

- The vibration stress is the reciprocating sine sweep vibration. The vibration frequency range is 5~200 Hz and the acceleration is 0.5 m/s².
- Each test could be ended when tangential dowel falls out from dowel hole. Moreover, the time to the next test condition can be changed by the test results.
- The test conditions of sample 1 and sample 2 are the same. The status of dowels will be checked every 2 h.

3.2. Test devices

The vibration environment is produced by the electromagnetic vibration table. Alternating torque environment is provided by the torque loading devices fixed on the vibration slip table. Programmable drive motor provides rotation speed and torque. Magnetic powder brake produces resistance torque simulating the reverse torque load caused by the inertia of the real long tubing and other resistance force. Characteristics of alternating torque is implemented by changing the rotation status. The magnitude of alternating torque is controlled by the magnetic powder brake. Other devices of the test equipment include the bearings, couplings, fixtures, fasteners, test sample and vibration table (Figure 6).

Figure 6. Test devices of alternating torque and vibration combined stress test.

4. Test result and analysis

The tests are completed in the lab with purified air. The temperature is 18~25°C and the humidity is 40%~70%RH. To sample 1, the test times of test are 70.5h of no-load test, 260h of alternating torque load test, 50h of alternating torque and vibration test. The total test time is 380.5h and the times of alternating torque load is 137 thousand. It shows obvious moving of tangential dowel in dowel hole by...
comparing the photos (Figure 7) before and after. Although nothing happened, the trend of dowel falling out from the right side of dowel was shown.

![Before test](image1.png) ![After test](image2.png)

**Figure 7.** The dowel status of sample 1 before and after all test.

To sample 2, times of test are 77.5 h of no-load test, 27 h of alternating torque load test. At the time of 42.6 h in the alternating torque and vibration test, the tangential dowel fell out from the dowel hole, then the test ended. The total test time of sample 2 is 147 h and the times of alternating torque load is 82 thousand. Deformation of sample 2 dowel is obvious. The status of dowel falling out from the dowel hole is showed in Figure 8 and Figure 9.

![The position of dowel falling down](image3.png) ![Dowel of sample 2](image4.png) ![Unused dowel](image5.png)

**Figure 8.** Status of the sample 2 dowel after three kinds of stress environment tests.

![The left side](image6.png) ![The right side](image7.png)

**Figure 9.** Measuring of diameters of sample 2 dowel with failure of falling out from hole.

Figure 8 shows that there is a serious deformation of ample 2 dowel. When the tangential dowel fell out from dowel hole, it touched and extruded the inner surface of external oil tubing, which resulted in a large bending torque. This deformation was caused by this bending torque. The dimeters of sample 2 dowel are 6.05mm (almost same as dimeters before test) and there is no obvious wear around the sides of dowel after tests from Figure 9.
During the test of sample 2, the distance from the left side of dowel to the position outside the dowel hole has been measured every 8–12 h, which is to detect the status of dowel if it moved along the direction of dowel axis. 15 values of this distance are list in the Table 2 and the variation curve is shown in Figure 10. There is an obvious axial movement of tangential dowel according to the result.

**Table 2.** Distance from left side of dowel in sample 2 to the position outside the dowel hole.

| Order number | Distance (mm) | Order number | Distance (mm) | Order number | Distance (mm) |
|--------------|---------------|--------------|---------------|--------------|---------------|
| 1            | 28.1          | 6            | 29.7          | 11           | 28.86         |
| 2            | 29.7          | 7            | 28.5          | 12           | 28.1          |
| 3            | 28.5          | 8            | 28.18         | 13           | 29.1          |
| 4            | 28.1          | 9            | 28.8          |              |               |
| 5            | 28.1          | 10           | 28.1          |              |               |

**Figure 10.** Variation curve of the distance from the left side of dowel in sample 2 to the position outside the dowel hole.

**Table 3.** Test results comparison of sample 1 and sample 2.

| Sample       | Total test time (h) | Number of alternating stress (times) | Result                                           |
|--------------|---------------------|--------------------------------------|-------------------------------------------------|
| Sample 1     | 380.5               | 137 thousand                         | Tangential dowel moved with an obvious distance. |
| Sample 2     | 147                 | 82 thousand                          | Tangential dowel fell out suddenly.             |

The process of dowel falling out has not been found during the test. Based on Figure 9 and Table 2, this failure of tangential dowel falling out is not the type of cumulative damage. It happened suddenly.

According to the result above, the alternating torque with vibration environment produce the special environment with reciprocating centrifugal force and vibration acceleration. Small movement deviation of tangential dowel from the center position in dowel hole will lead to great centrifugal force, the tangential dowel would fall out from the hole in the additional vibration environment at the same time. So, this combined stress is the synthesis stress to sample 2 which has larger fit clearance between dowel and dowel hole.

The test results comparing sample 1 and sample 2 are list in Table 3. The test time of sample 2 is much shorter than sample 1 and the number of alternating torque stress is much less than sample 1, but sample 2 repeated the failure of tangential dowel falling out successfully.

The result shows that the process of tangential dowel falling out. Because of the larger fit clearance between dowel and dowel hole, small contact area and deformation of piercing, the dowel moves more
easily in the dowel hole in the alternative load and vibration environment. This moving action produces shock force acting on the piercings. The tangential dowel will break through the piercing after a long time. Then the tangential dowel slide out of the dowel hole and fall out finally.

5. Conclusions and suggestions
By study of tests about tangential dowels in different stress situations, we have the following conclusions and suggestions.

1) Sample 2 with larger fit clearance between dowel and dowel hole repeated the failure of tangential dowel falling out. As a comparison, the failure did not happen on the sample 1 with a smaller clearance even in the longer test time and more alternating load times.

2) Failure of tangential dowel falling out is not the type of cumulative damage. It happened all at once.

3) The synthesis stress leading to the failure of tangential dowel falling out is alternative torque and vibration combined stress. Reference [10] discuss the structure failure because of shaft resonance caused by positions of tubing supports. But the research result in this paper shows that alternative torque stress on the shaft is one more important reason.

4) The process of tangential dowel falling out when the dowel slide away from the center position in dowel hole, great centrifugal force caused by the eccentricity will make the tangential dowel slide out from the hole in the alternative torque and vibration combined stress environment.

5) Larger fit clearance of sample 2 between dowel and dowel hole is the basic reason for the failure of tangential dowel falling out. The centrifugal force and vibration caused by the alternative torque and vibration combined stress is externally generated. Manufacturing process should be improved or managed more strictly. Interference fit should be ensured or the clearance between tangential dowel and dowel hole should not be larger than 0.2~0.3mm. Diameter of piercing is suggested to be larger than 1.95mm.

6) Design of anti-loose of screw connector with tangential dowel in internal hydraulic fluid tubing should be improved. Welding or self-locking structure can be considered.

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