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ANALYSIS OF SHIP SHAFT LINE COUPLING BOLTS FAILURE

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Abstract

The ship propulsion shaft line is one of the most critical ship components having big influence on a ship safety. Because of that, there is well known need for proper shaft line survey either by ship crew, ship owner technical services as well as by classification society surveyors. One of the most dangerous and frequent kind of shaft line failures, especially on old ships, is a fatigue break of the collar coupling bolts. It usually causes the loss of the possibility to use the main propulsion system. In case of the bad weather and severe sea conditions it can lead even to the ship loss. The paper presents some data on failure statistics that was observed to shaft lines and propulsion system machinery. Furthermore, analyses of causes and generation mechanism of the mentioned fatigue breaks of the collar coupling bolts is presented.

Keywords *: ship propulsion system, shaft line, alignment, failure*

1. INTRODUCTION

Ship machinery equipment failures and in particular propulsion systems are quite frequent cases during ship operation. Failures in shafting are also important figure in all machinery failures. An example of specific failure is breaking of coupling bolts in main propulsion shaft collars.

However, that type of machinery damage is not very frequent, the failure itself is potentially very dangerous as it could lead to the loss of control over propulsion and manoeuvrability of the ship. That situation could result further in severe losses like the ship and cargo and possibly environmental disaster. A severe see conditions can multiply potential damages and turn them from local to global scale that could finally be very costly and ship operator or owner could be taken to court.

The risk of ship failures is much higher in worse sea conditions due to dynamic nature of propulsion system with diesel engine as it operates with shaft overloading by torque and bending moments and resultant load pulsation.

Underneath, there are given some examples of the above mentioned failures and related discussion of damages in the analysed shaft joints for the two specific types of propulsion systems.

a)

Failure statistics in shipping for years 1996-2000 [1] according to insurance companies							
Failure reason	**Heavy weather**	**Contact**	**Collision**	**Grounding**	**Machinery**	**Fire/Explosion**	**Other**
	3%	**9%**	**21%**	**20%**	**31%**	**6%**	**10%**

b)

Machinery claims by cost in period 1998-2004 [1] according to insurance companies						
Failure place	**Main engine**	**Steering gear**	**Aux. engine**	**Boilers**	**Propulsion**	**Other**
	43%	**10%**	**20%**	**31 %**	**23%**	**2%**

Fig. 1 Failure statistics in shipping according to data collected by insurance companies: a) Failure Statistics for 1996-200, b) (Machinery claims by cost 1998-2004) [1].

Type of ship	**Number of shaft alignment failures**
Bulk carrier	3
Chemical carrier	1
Container carrier	1
General cargo carrier	3
Offshore supply vessel	43
Oil carrier	7
Passenger vessel	1
Special purpose vessel	15
Tug	32
Yacht	7
Source: ABS	

Fig. 2 Alignment related failure statistics [2].

2. The main types of loading in shaft-line joints

In a typical ship propulsion system, there are the following types of load that are generated during the propulsion system operation:

- Torque moment;
- Bending moment
- Axial thrust force
- transverse loads that consists of gravity force of the shaft line system components and inertial and centrifugal forces.

The influence of the listed above loads on the strength and durability of the shaft line joints depends on the type of the main propulsion diesel engine and the shaft line construction. We analyse two the most popular types of the ship propulsion systems.

2.1. Conventional propulsion system with low speed reversible diesel engine and fixed pitch propeller

In the conventional propulsion system the dominating load is torque moment. Due to the shaft connection of the diesel engine with shafts and propeller without highly elastic couplings and due to the low engine diesel speed (even for steady sailing conditions – ahead) there are pulsations of the load. The reason for this is a limited number of propeller blades as well as the number of engine heads. The amplitude of pulsation values depends mainly on actual sea conditions and changes of ship hull resistance and propeller submersion that results from action of waves. It must be pointed out, that maximal load due to torque occurs in case of the requirement to stop ship instantly. The change of the engine rotation direction, which takes relatively short time, leads to substantial increase of the nominal torque (could be even doubled) during the procedure of the engine reverse manoeuvre.It could be clearly observed in the Fig 3 presenting characteristic curves of the propulsion system during this maneuver.

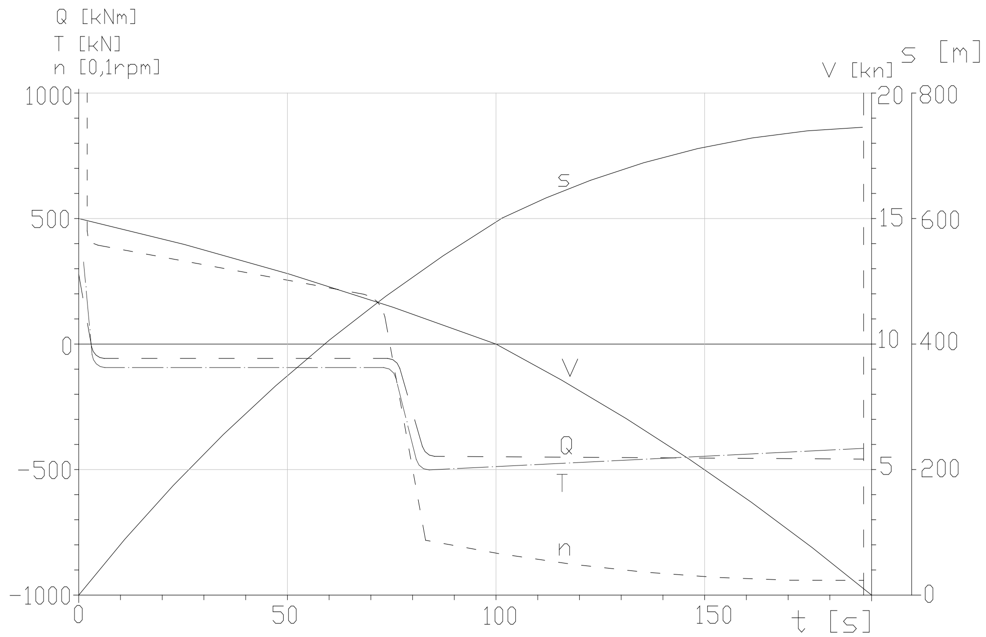


Fig. 3 Characteristic curves of major parameters of a propulsion system composed of diesel engine – constant pitch propeller during "crash stop" of the sea ferry at speed V=15 knots (7,7 m/s).
Legend: n – propeller rpm; s – breaking distance; Q – torque moment at propeller shaft; T – thrust; V – vessel speed; t – time. [3]

The change of rotation direction of the shaft is accompanied not only by torque moment overloading and moment direction change but also by change of the thrust force direction.

As a consequence, the force that pressed shaft collars by means of coupling bolts is decreasing. The frictional moment that takes vital part of maximal torque moment decreases accordingly.

Other important issue is the increase of possibility of mutual displacement of the shaft collar joints. The same risk could appear during main engine reverse on shallow water or in the area of floating ice when the propeller blade could hit bottom or other obstacle. The probability of the discussed displacement of collars and the relative sag and gap are dependant on the initial tension force of coupling bolts and the fit force of the bolts

In case there will appear displacement of the shaft collars under load than the new position of collars will have no advantages for normal working conditions and sailing with “ahead speed”. The reason is the decrease or even disappearance of participation of the cylindrical surfaces of fitted bolts in bearing of the torque moment. Appearance of overloading by torque or presence of bending moment could lead to additional movement of coupled collars in the direction of original position. Taking into consideration of the dynamics of that displacement and resulting micro-deformations and wearing of contacting surfaces we can assume that new position is not to be exactly the same.

Having in mind longer operational time, we can observe repeating action as previously described.

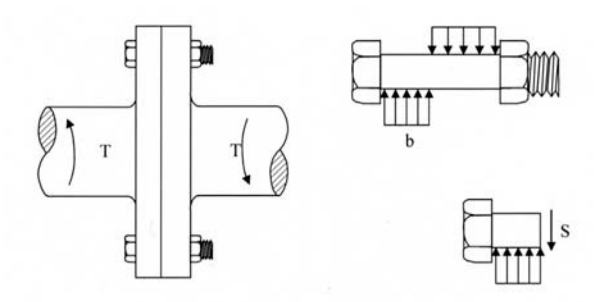
It is for sure, that with each displacement of shafts collars the probability of next displacements grows and grows also the value of movements and wearing rate of the contacting surfaces.

The presented wearing process that exists where micro displacements of adjacent surfaces are known as fretting. As a result of fretting the creation of micro notches that further could develop into fatigue cracking. With the increase of wearing area and value of collars displacements, the bolts linking the collars are subjected more to bending, that also accelerates fatigue up to final breaking. The breaking of one bolt, leads to the increase of loading of the remaining bolts and further breaks of collar bolts up to total lost of the shaft integrity. The view of shaft collar where fitted bolts were broken is presented in Fig 4.

Fig.4. An example of failure of the shaft collars and fitted bolt holes in the propulsion shaft [4].

The case of coupling bolts, failure in the propulsion shaft line has been described in paper [1]. It took place on the small tanker during engine reversing and ship moving astern. The all, eight bolts coupling bolts linking collars of intermediate and propeller shaft were broken and consequently it resulted in the lost of ship propulsion and manoeuvring abilities. Fig. 5a and b presents more details of that case with indication of the bolts cross-sections and their position in the shaft collar.

a)



b)

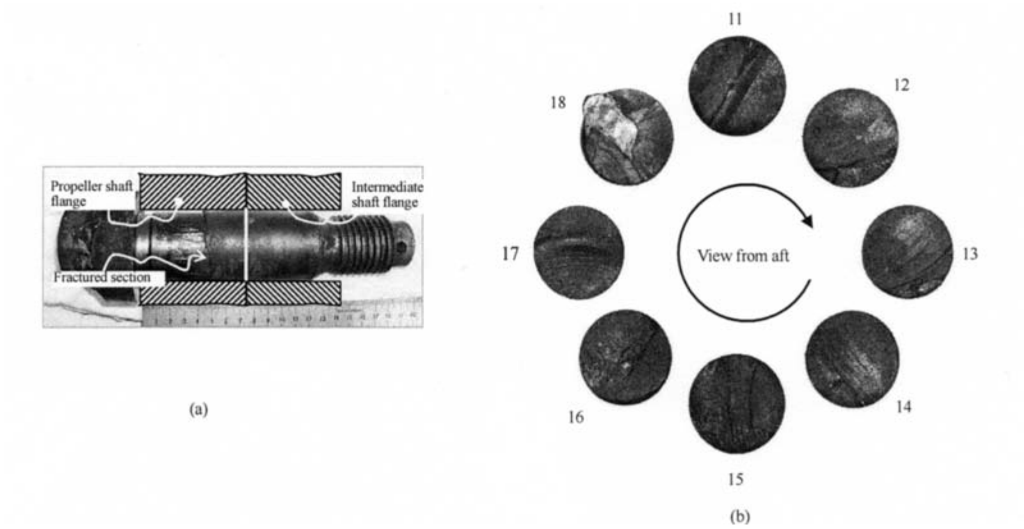


Fig. 5. a) Bolted connection of the shaft collars and collar with broken bolt, b) View of the fatigue cross-section with original position of the broken bolts in the shaft collar [5].

The specific feature of the presented cross sections is direction of failure growth, that according to the authors of the reference [5] is angled 35° to 60° from the action line of the shear force. The publication do not contain the explanation of the phenomena.

We must point out the one more important issue of the discussed failure - the plane of fracture is not lying in the shear plane of the bolt but is located in the fitted area of shaft collar holes. It means that creation of fatigue fracture is result of variable bending stresses in coupling bolts. The hypothesis was further proofed by experimental research and calculation with using of numerical methods as is presented in Fig 6.

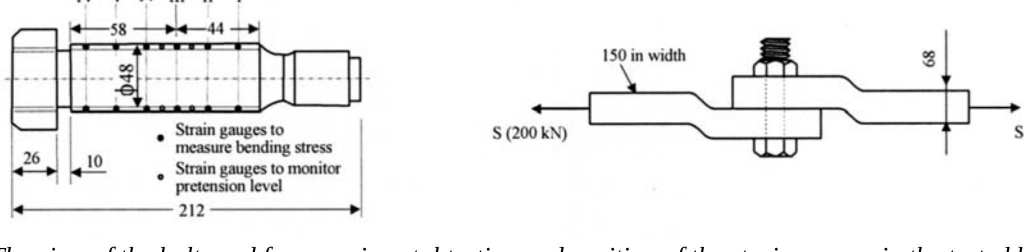


Fig. 6. The view of the bolt used for experimental testing and position of the strain gauges in the tested bolt [5]

The experiment included the measurement of stresses in the fitted area of the bolt using strain gauges technique. Strain gauges were placed in two shallow grooves cut along the bolt and located at 180 arc in the plane of the load action. The gauges were fitted in pairs – one opposite another in six cross-sectional planes as it is presented in the Fig. 6. The final testing was carried out for five different values of pretension ranging from 0 to 0,55 R_e of the bolt material and for three different clearance values of the bolt: 0,16 mm clearance, 0,007 interference and 0,013 interference. Tensioning force has been varied in the range of 150 – 250 kN.

The results of the research, showed that highest bending stress exists in the long fitted area of the bolt outside of the shear plane. The lowest value that stress was found to be in case of highest bolt tensioning and tight interference. On the other hand, there is no evidence that the experiments has not been carried out to initiate fatigue breaking of the bolts. Lack of that testing did not allow to check, whether direction of the fatigue fracture growth rate is in agreement with the shear load acting on the bolt.

It could be stated, that the directional deflection of the fracture growth direction and shear load direction is also result of the bending moment of the shaft. The reason for that is that described failure took place in the joint of propeller and intermediate shaft, where bending moment are taking highest values, even in a correctly assemblies and aligned shaft line. The explanation is in a fact of substantial loading of the shaft line tail by dynamically rotating ship propeller and typical plain bearing solutions.

Due to the necessary radial clearance, plain bearings do not protect the shaft against deflection and deviation from the theoretical shaft line axis. It means, that bolts joining and fixing shaft collars will be loaded additionally by axial force, variable in value. The variation of that force results not only from loading by the propeller mass but also from non uniform hydrodynamic pressure field that is passed by the propeller blades during every rotation. Moreover, in case of big ships or hulls having low stiffness, substantial shaft line bending load may appear as a result of ship hull deformation on waves, particularly important in high sea states, when displacement of the bearing axis takes place, as it is presented in Fig. 7.

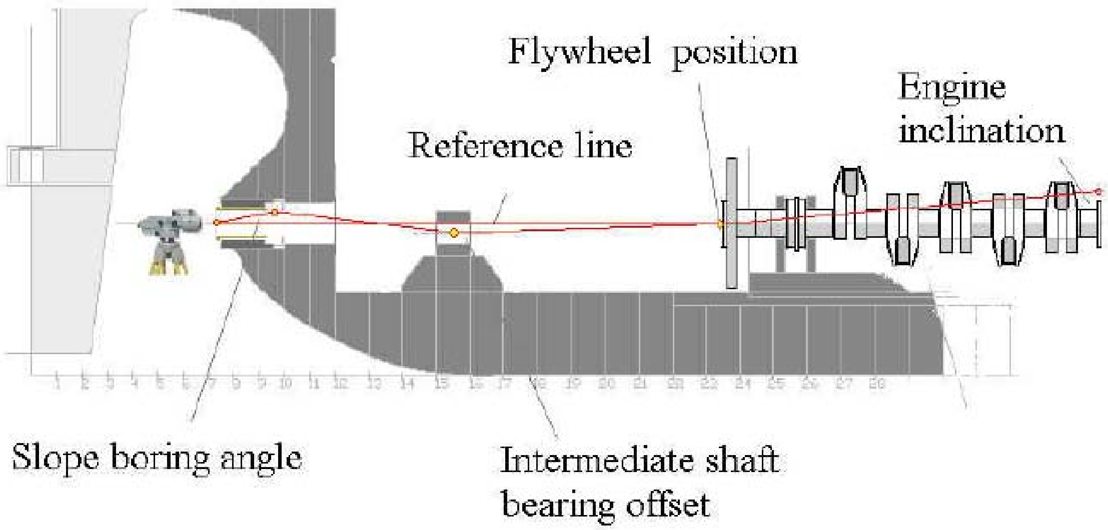


Fig.7. Positioning the Bearings to Actual Design Values [2].

It can be assumed, that the listed above factors were reasons for the change of the resultant bearing load plane acting on the bolts in the shaft coupling and the observed deflection of the fatigue facture growth up direction.

2.2. Propulsion system with low speed diesel engine and controllable pitch propeller (CPP)

Propulsion systems with CPP experience much better conditions of loading of the collar coupling bolts by torque. The torque keeps constant direction and overloads (if exist) are lower and are not so frequent, practically only during instant stopping manoeuvre or in case the propeller blade hits an obstacle. On the other hand, the loading of the shafts and their joints by the bending moment grows up. There are two reasons for that. First, the mass of the propeller is higher comparing fixed pitch propeller. Secondly, the intermediate shaft coupled with the propeller shaft named camshaft do not have bearing in the hull but is hanging on the propeller shaft and a intermediate shaft. Moreover, it is loaded additionally by oil distribution box, which is used to introduce oil from the fixed hydraulic supply unit to the servo-motor located usually inside the propeller hub. Consequently, the mass of shaft assembly and hydraulic components for pitch control are also additional source of the bending moments. It must be pointed out, that the loads in such case are relatively simple for numerical calculations and propulsion system designers are able to provide suitable strength to the shaft line.

The worse situation exists with accidental and non predictable loads that originates during ship operation. Some possible sources that we can list are: deflections of ship hull due to action of waves, bending of the shaft or loss of bearings alignment that possibly could be result of repair, maintenance services done for machinery or machinery equipment replacement that could took place on every ship.

As an example, the shaft bending or bearing that is not aligned correctly with the shaft line axis could generate shaft bending loads leading to the permanent change of shaft geometry and in a consequence it will result in variable loading of the coupling bolts in shaft line collars. In the worse case, the coupling bolts could be broken by the fatigue. A characteristic feature of that type of failure is that it could have place during normal sailing conditions and quite probably not all the bolts could fail at once. Most frequent situation will be the case where the highest loaded bolt could break first or failure will happen to two neighbouring bolts. Consequently, the stiffness of the shafts joint will be decreased and bending stresses in other bolts will be lowered due to bending. An example of bolts destruction due to that type of failure a partly presented in the Fig 8. The contact area of the collars as well as fitted bolts and their holes were worn substantially. It is non disputable in that case, that failure was accompanied by mutual displacements of mating parts as well as by fretting.

Fig. 8. The view intermediate shaft collar with broken bolts and fractures cross-section of the failed bolts with nuts. [4]

3. Conclusion

The problem of fitted bolts failure in coupling collars of the main propulsion shaft line originates in a complex stress condition during the real ship drive system operation. The possible failure of that type is more probable in case of older ships, that are in operation for more than 15-20 years. Breaking of the fitted bolts in the shaft line collars is potentially very dangerous event and its avoidance is possible due to proper control over propulsion system in ship operation. Suitable control of the shaft line alignment using the proper tools should be used as obligatory diagnostic procedure in case of detection certain abnormal behavior of shaft line i.e. excessive wearing of intermediate bearings, accelerated stern bearing clearance growth, bearings foundation structure or its weld cracks or shaft vibrations that were not observed during earlier ship operation. The cost of potential failure of that type could be very high and resultant repair could take several weeks.

Due to the fact, that providing the continuity of survey over ship machinery requires repeatable observations and follow on analysis of the observed events during the propulsion system operation. It is very important to note and record all that events as they may have possible influence on abnormal behavior of the shaft line. The biggest number of observations can be done by the machinery crew, providing they have suitable training and basic knowledge regarding shaft line problems during operation. The instrumentation for propulsion system or shaft monitoring is almost not available for majority of ships that are currently in operation. Due to financial reasons it will be probably very rarely used in case of older ships. The availability of the dedicated propulsion monitoring systems in future may be much wider and we can expect that there will be more data collected regarding the shafting behavior or failures and the data collected could be suitable for propulsion shaft line failure analysis, if such will be required.

In case of shaft line failure of the similar type as the cases described above, we recommend to gather sufficient details (including broken bolts and nuts) and also all other evidence immediately after failure as that could be very helpful for determination of the optimal repair technology and for taking corrective measures for ship safety due to elimination of the failure source.

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