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Common failures of ship propulsion shafts

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ABSTRACT

This article aims to provide a critical review of the most common failures of ship propulsion systems as a crucial ship system, with emphasis on fatigue failure. The accent is given on the shaft of marine propulsion systems as a most common point of failures in the entire propulsion system. A general description of failure causes and failure analysis methodology is presented. Several representative case studies summaries for fatigue failure on critical points of the propulsion shaft are described. Torsional vibrations and geometric stress concentrations of the shaft are identified as the most common cause of fatigue failure. The importance of constant monitoring, measurement and data collection of fatigue indicators and indicative events that have influence on fatigue development is emphasized. Methods used in failure analysis are discussed and propositions for improvement are given, especially in terms of using numerical routines in failure prediction.

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1 Introduction

The propulsion system has a pivotal role on board ships. A typical marine propulsion system is comprised of the following main parts: main engine, driving device, marine shaft and propeller as shown in Figure 1. As far as fatigue is concerned, the main engine is a complex unit for itself. It represents a vibrations source (impulse operation) for the entire ship and the propulsion system as well. Here, the propulsion shaft will be discussed more in detail.

The propulsion shaft is subjected to various types of loading during operation, namely torque moment, bending moment, axial thrust force and transversal loads (gravitational and centrifugal forces). The operating environment of the propulsion system is characterized by significant changes in temperatures and humidity, aggressive atmosphere (salt and/or oil mist), long lasting interrupted operating time (several months) and variations in load amplitudes. The risk of failures of the propulsion system additionally increases with the severity of sea and weather conditions as they have a direct effect on the dynamics of the load variation. All of the above has a direct influence on fatigue behaviour and life time of the propulsion shaft.

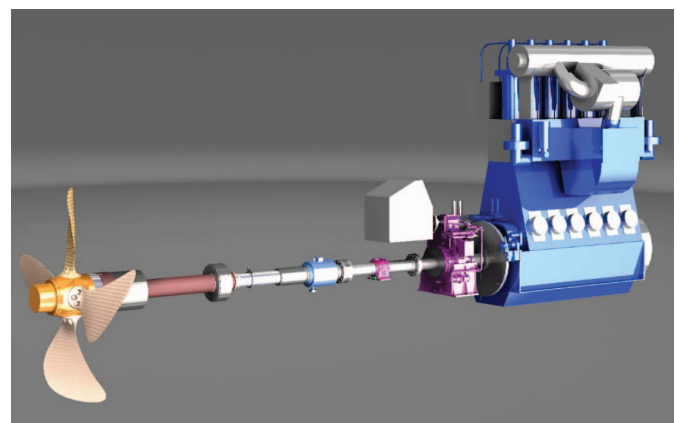


Figure 1 Typical Ship Propulsion System Elements Rendering

Source: (<http://shipmanagementinternational.com/wp-content/uploads/2013/12/wartsila-10.jpg>)

Different types of propulsion (diesel, gas turbine, electrical propulsion motors (diesel-electrical drives), steam turbines etc.) result in different type of vibration load

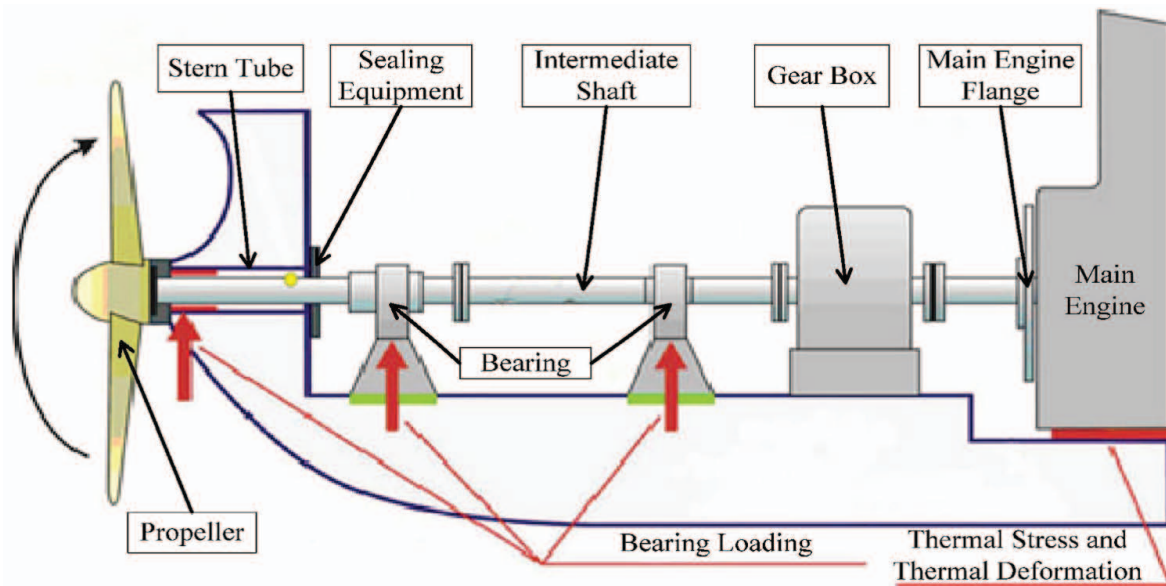


Figure 2 Propulsion System Elements and Loads Schematics [1]

due to different types of excitation forces. The most widespread type of marine vessels propulsion system is the diesel engine propulsion system, which is characterized by significant vibrations and fluctuation of vibration excitation forces caused by intermittent explosions of the gas in the engine cylinders. The dominant form of vibration is torsion vibrations. The characteristics of the propulsion shaft torsion vibrations are system dependent and have a strong correlation to the natural frequencies vibrations of the shaft.

Torsion vibrations in ship propulsion systems are of great importance and are addressed by various ship classification societies by defining criteria for shaft dimensioning in order to prevent fatigue failure and local deformations [2-5].

2 Failure causes

In general, shaft fatigue failure are caused by wear, corrosion effects, material imperfections, poor material quality, overloads, stress concentration and impact loads, all of which reduce the fatigue strength of shafts. The most frequent failure cause of propulsion shafts on board ships are the extreme torsion vibrations caused by main diesel engines. Lower level loads that are sufficiently low in comparison with the nominal design values can cause fatigue failure that will occur at stress concentration areas on the shaft (fillets, chamfers, keyholes etc.) due to the dynamic nature of the shaft load.

The torque moment is the dominating load in conventional, diesel low speed engine propulsion systems. Nevertheless, the discrete number of propeller blades, elastic couplings, connections of the shaft elements and misalignment of the shaft can cause pulsations of the load even in steady sailing conditions. The amplitude of pulsation varies according to actual sea conditions, changes of

hull hydrodynamic resistance and propeller submersion. The maximum torque loads usually occur on stop ship instantly requirement. The parameters that can increase the torsion vibration of the propulsion shaft are coupling stiffness, shaft stiffness, coupling damping and shaft damping.

Along the torsion load, ship propulsion shaft are also loaded by a bending moments due to gravitational effects. The two types of loads combined results in multiaxial stress. The variation of the load conditions during exploitation can have a significant variation in comparison to design values. The shaft is submitted to variable cyclic torsional-bending loads which can trigger high cycle fatigue mechanisms.

Typical marine propulsion shaft failures are to be studied systematically based on experimental testing during actual investigation. The comprehensive results collected by such investigations should comprise a knowledge database for engineers and students alike.

3 Methodology of failure analysis

Classification societies prescribe procedures and the basic equations for the verification of the load carrying capacity for shafts as S-N based methodology for fatigue life assessment [6]. These procedures are somewhat simplified in order to better fit typical shaft designs in marine applications, such as marine propulsion and auxiliaries on board ships and mobile offshore units. Axial loads are neglected due to the fact that the dominant stresses are torsional and bending stress.

Even though marine propulsion shafts are exposed to a wide spectrum of loads, just a few of the dominating load cases need to be considered i.e. start to full load to stop cycles (low cycle fatigue, $N < 10^4$), reversed bending and torsional vibration during continuous operation cycle (high cycle fatigue, $N > 3 \times 10^6$), transient condition and

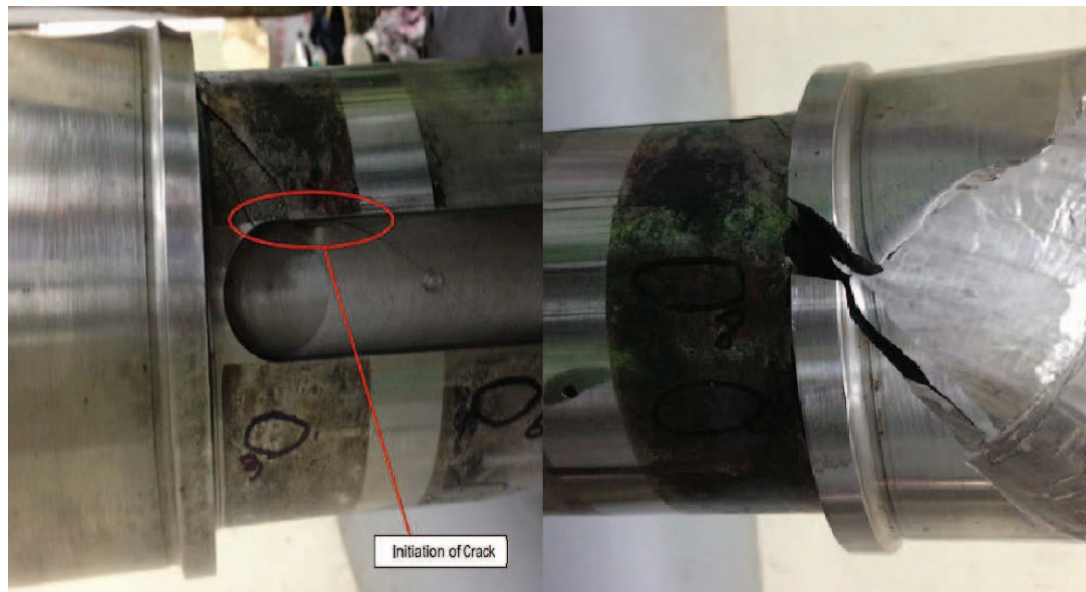


Figure 3 The Characteristic Torsional Failure Crack Shape [8]

passing through barred speed ranges cycle (direct coupled propulsion plants) and reversing when crash stop cycle.

Failure analysis is performed as a Root Cause Analysis (RCA) taking into account all possible causes in three main groups, namely design, process and operation phase of the shaft life cycle. The stresses that caused the failure can be mechanical, thermal or due to corrosion effects. The fracture itself can exhibit characteristic of brittle, ductile or fatigue fracture.

Marine propulsion systems reliability is performed based on Fault Tree Analysis (FTA) method which takes into account the systems main components (main engine, transmission equipment, shafting and propeller) reliabilities individually [7], [1]. Although, this method can assess the reliability of the comprehensive marine propulsion system in a determined period of time, it lacks in reliability predictions in the entire life span of the system.

The failure analysis procedure should be comprised of failure description, a record of failure history (describing the nominal state of the system/structure as defined in the design phase, the actual working condition before the failure, frequencies of load variations etc.), stating a failure hypothesis (presuming the mechanisms of failure based on preliminary inspections), instrumental analysis (defining an investigation plan, collecting samples, testing and analysis, simulation etc.), description of investigation results and statement of failure cause (or causes).

If the instrumental analysis and investigation can exclude thermal stresses, corrosion effect and material mechanical properties as a cause of failure, fatigue remains as the most probable failure culprit. Chemical composition analysis, micro-structural characterization, fractography, hardness measurements, and finite element simulation are common procedures used during fatigue fracture analysis.

The knowledge obtained during fatigue fracture case studies analysis must serve as an aid in predicting and finding possible faults in the propulsion system before the final fatigue rupture to enable the highest possible reliability of such an important ship system. The reliability of the propulsion system directly results in safer navigation and reduced operating cost of ships.

4 Case studies

4.1 Shaft keys

The geometry of the ends of keyways represents a stress concentration factor in the cases of torque transmission through shaft keys for dynamic vibrational loads. Faulty machining of shaft key elements (key groove, keyway and key) geometry, inadequate run out radii or material imperfection can be root causes of torsional fatigue failure in shaft keys. The characteristic torsional failure indicator is the crack pattern that initiates at the end of the keyway and propagates in a 45° rotational direction in a helical shape, shown in Figure 3.

Various case studies [8, 9] have shown that inadequate torsional vibration calculation parameters (shaft elements stiffness and damping, natural frequencies, safety factors) and a subsequent poor design of the shaft's keyway cause failures. In this case a root cause analysis has been made by the analytical stress calculation process MIL G 17859D and VDI 3822 standards. A FEM model has been used in order to verify the existing fracture characteristics and causes.

4.2 Fillets

Fillets, tapers and chamfers in the shaft geometry also represent geometrical stress concentrations. Inadequate design of these elements can lead to fatigue failure. Case

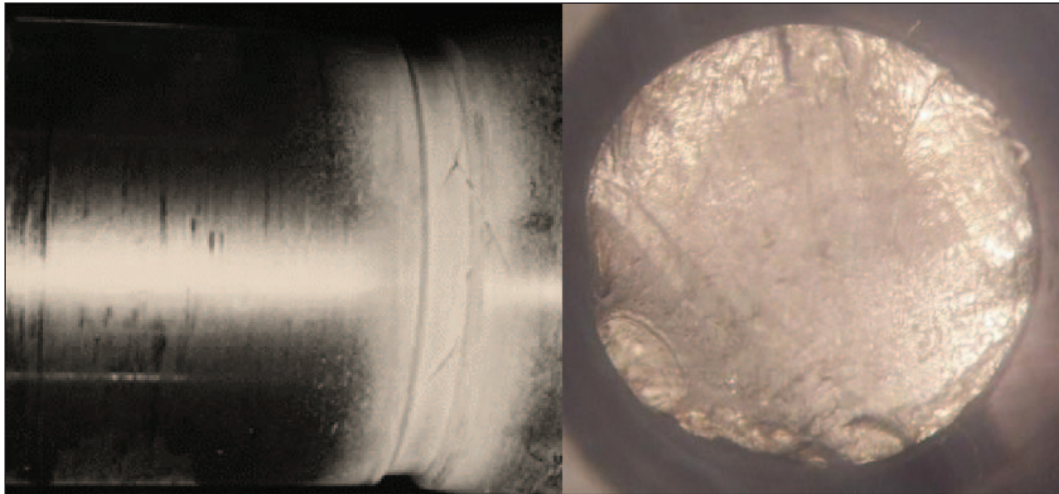


Figure 4 Shaft Fillet Failure Crack Shape [10]

studies of fractures initiated at this elements [10], [11] show fatigue due to cyclic torsional-bending load, with a crack that originates in multiple points on fillet shoulders on the shaft, gradually reducing the load bearing area of the shaft as it grows, and finally resulting in a sudden failure during overload as shown in Figure 4. The analysis for this case study has been comprised of chemical composition analysis, micro-structural characterization, fractography, hardness measurements, and finite element simulation.

4.3 Spline joints

The alternatives to shaft key joints are spline joints which are press fitted to other shaft elements. The analysis of spline joint failure [12] has shown that the press fitting of the joining elements can cause surface deformation which in turn causes surface cracks formation. Cracks usually start on the spline teeth at the shaft junction zone, Figure 5. Torsion fatigue caused by fluctu-

ating stress promotes crack growth and propagation. Inhomogeneity of the shaft material can additionally assist crack propagation.

In this case, a visual and macroscopic inspection has been performed, followed by material chemical analysis, hardness measurement, optical and scanning electron microscope (SEM) microstructure analysis with X-ray dispersive analysis of particles under the SEM.

4.4 Bolted Connections

Bolted connections are used in collar coupling of shaft elements and in propeller blades connections. Changes of the shaft rotation direction result in torque moment overloading and direction change as well as thrust force direction change. The resulting effect is a dynamic load on collar coupling bolts in a longer operating time [13] which can result in fatigue failure. The fretting that occurs on adjacent connecting surfaces in these cases creates micro notches that develop into fatigue cracks with the direction

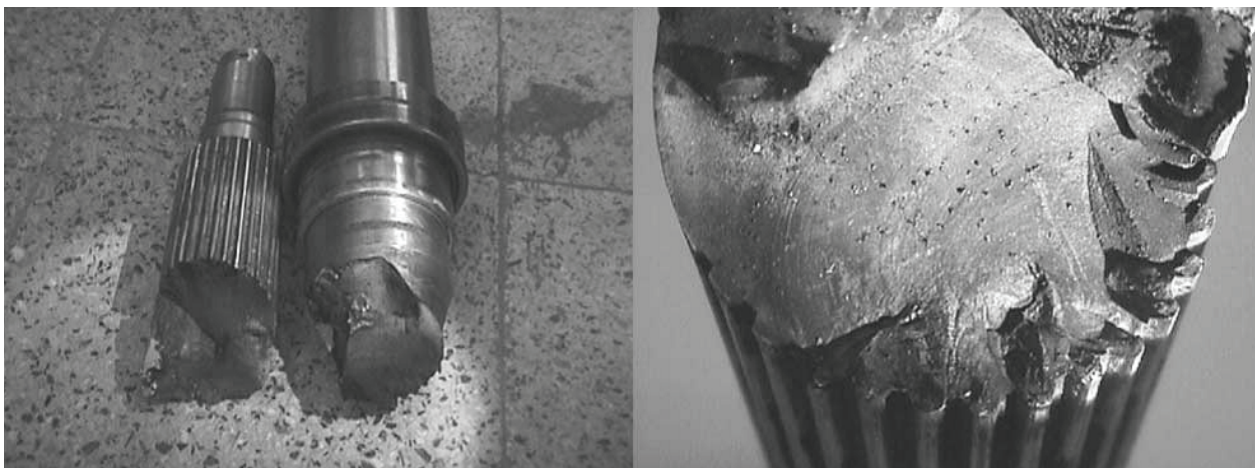


Figure 5 The Characteristic Torsion Failure Crack Propagation Shape (45° angle) [10]



Figure 6 Fatigue Indicative Fretting on Surfaces [13]

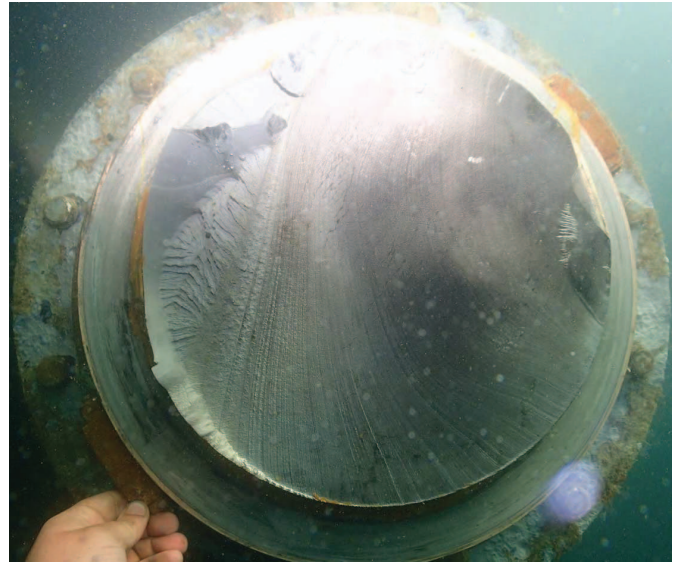


Figure 7 Uniaxial Fatigue Failure Crack Shape [15]

of failure growth in planes angled from 35° to 60° which is not characteristic of pure torsion fatigue failures. The analysis has shown that the coupling bolts are subjected to an increasing bending moment which contributes to fatigue crack growth. The experimental research and numerical calculation done in this case study proved the hypothesis of variable bending stress in the coupling as the failure cause.

Bolted connections of propeller blades and the shaft are often in a cathodic protection environment. Hydrogen inclusions in the material and variable stress conditions can cause crack nucleation and propagation, finally causing a failure [14]. Fractographic analysis, chemical analysis, micro hardness tests, slow strain rate test, microstructure analysis and finite element analysis have been performed in this case.

4.5 Propeller hub

Abnormal performance of the propeller by way of one non-performing malformed blade can generate a uniaxial force which fluctuates once per rotation in a consistent transverse direction across the shaft. The fluctuating force generates a couple which can cause fatigue failure of the propeller hub [15]. Uniaxial type of failure is characterized by a fatigue fracture with a single origination point that progresses across the shaft from the side where the force is being applied and results in the final overload failure occurring on the opposite side from the fluctuating force.

Visual inspection, detail axis alignment measurements, microscopic metallurgical examination, hardness measurements and ultrasonic scanning have been used during the analysis.

4.6 Shaft misalignment

Proper shaft line alignment is very important in order to avoid vibration load generation. Thermal loads gener-

ated in the main engine can produce misalignments in the engine shaft [16, 17] what, in turn, produces vibrational load to the propeller shaft. Existing engines producers' thermal deformation models may be too simple to cover the entire temperature span an engine experiences during exploitation, so the need for specialized software arises [18]. Due to the complexity of thermal deformation processes, numerical modelling seems necessary.

5 Discussion

The propulsion shaft is a major machinery component on a ship propulsion system, and as such, its design should ensure a sufficient fatigue safety factor using representative methods (Goodman, Soderberg, and Gerber methods). The design procedure and calculation must be compliant to the classification society's rules. The main idea is to make a real marine propulsion system that can enable an efficient, reliable, safe, durable and low cost performance throughout its entire life cycle.

The examination of cases of fatigue fractures must serve as a basis for the design as well as maintenance and operation of propulsion shafts. When the causes and mechanisms for typical fatigue failures are well known, tell tail effects or manifestations of ongoing fatigue failure processes can be identified before the final rupture, so that corrective or repair measures can be implemented to avoid the failure itself.

There are several parameters that can have a significant influence on vibrations and fatigue described above. The calculations done in the design phase often differ from actual values in a real system during exploitation. Parametric studies can be conducted by variation of the influencing parameters in order to predict possible future failures or determine the cause of the existing fatigue failures through numerical calculations/simulations and collected measurement results.

Steady operation of the main propulsion engine, a suitable control of the shaft line alignment, well maintained elements of the propulsion shaft and data collection for important events and measurements of fatigue indication parameters during navigation of the ship are key enablers of a safe and economic long lasting operational life of the ship propulsion system.

As shown, the majority of the ship propulsion fatigue failure analysis nowadays applies visual, analytical and mechanical inspection methods in the attempt to identify fatigue failure causes after the event has occurred. The working and load conditions for ship propulsion systems are stochastic in nature and intensely dependant on weather conditions at sea as well as influences on loads defined by required sailing parameters. The complexity of fatigue failure analysis accentuates the need for numerical simulation of possible catastrophic fatigue failures during the entire lifetime span of the ship propulsion system. If the ship structure, the propulsion system and the possible influence of different ship elements as vibration sources for the propulsion shaft, coupled with the relevant data collected during maintenance procedures are numerically modelled then a tool for fatigue failure prediction can be developed. The ability to predict failures would greatly improve the safety of ships exploitation.

6 Conclusion

Common failures of ship propulsion systems have been summarized and described. Constant load variation changes resulting in fluctuating torsional vibrations coupled with geometrical high stress concentration areas have been identified as main causes of fatigue failure of propulsion shafts. As poorly designed geometric shapes of specific shafting elements connections are shown to be the starting points of fatigue crack formation, special attention must be given to their dimensioning during design. Constant monitoring, measurement and data collection of fatigue indicators and indicative events that have an influence on fatigue development is very important in order to form a knowledge base that can serve as basis for current design and maintenance procedures improvement.

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