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Estimate of the fatigue life of the propulsion shaft from torsional vibration measurement and the linear damage summation law in ships

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ABSTRACT

Most ships use a diesel engine for the propulsion system. Since a diesel engine is operated by the force of the cylinder from the explosion of the gas, the torsional vibration from the fluctuation torque is bigger than that of other types of engines, such as gas-turbine and electrical propulsion motors. Therefore, the propulsion shafts in ships frequently fail due to the extreme torsional vibration from diesel engines. Ships that require high power and revolution speed usually have V-type, 4-stroke diesel engines and reduction gears to increase the output torque. Therefore, a robust design of the shaft is required for this type of vessel. In this research, the fatigue stability and life cycles of the shaft are estimated with Soderberg's safety evaluation method and the linear damage summation law based on the torsional vibration data. When estimating them, non-standard sailing conditions such as starting the engine and zigzag maneuvers are included in addition to normal sailing conditions such as straight maneuvers.

1. Introduction

Diesel engines are widely used as low-speed propulsion engines on ships. Since diesel engines operate from the explosive force of the cylinder connected to the crank shaft, the vibratory torque of the diesel engine is larger than that of other types of engines such as gas turbines and electric motors. Ships that require high speed and torque usually use V-type, 4-stroke, high-speed engines, and reduction gear is adopted in order to obtain high torque. The propulsion shaft of this type of engine can fracture due to the high torque and speed. Many studies have been conducted on shaft fractures due to dynamic loads at high-stress areas such as the fillet, chamfer, and keyway.

Okubo et al. (1968) performed the torsional fatigue test with 2 different test keyway shaft specimens with various fillet radiuses of the key and the keyway and suggested stress concentration factors. The test results showed that the stress concentration factor of the end of the key was larger than that of the keyway. In addition, the researchers suggested the stress concentration factor of the keyway could be modified by decreasing the rigidity caused by the addition of the keyway to the shaft. Pedersen (2010) suggested shaping the fillet of the keyway in a super ellipse and found from finite element analysis (FEM) that the stress concentration factor was reduced about 50% compared to the circular fillet. Bhaumik et al. (2002) investigated the fracture of the stage helical gearbox of a low-speed hollow shaft transmitting the engine load through the key and keyway and used visual inspection and a scanning electron microscope (SEM) to find that fracture was caused by torsional fatigue. He reported that the fracture of the shaft was caused by the small fillet radius under specification, improper machining, and MnS included in the material lattice. JianPing, and Guang (2008) reported the fracture of the gear shaft of the extruder. By measuring the torsional vibration of the gear shaft, they found the root cause of the fracture was the extreme static load and verified it with finite element analysis and Goodman fatigue criteria. Parida et al. (2003) studied the root cause of fatigue fracture for the keyway of the ball and race-type coal pulverizer and, using SEM analysis and mechanical tests such as the tensile and Charpy impact tests, found that the fracture was caused by anon-standard heat treatment process that reduced the endurance and toughness of the material. Goksenli and Eryurek (2009) investigated the fracture of the drive shaft of the elevator with a keyway and estimated the fracture was caused by the combined effect of repetitive torsion and a bending load. The stability of the shaft was evaluated with the Goodman criteria, and the life cycle of the shaft was estimated with the SN curve reflecting the mean stress, and the fatigue limit, which includes shaft size changes and surface modification factors, was recalculated. In the investigation, the fracture was caused by the stress concentration at the small fillet at the end of the

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keyway, and the researchers suggested corrective actions to increase fillet radius at the keyway, which was verified with FEM analysis. Han et al. (2012) investigated the root cause of the fracture of the coupling that connects the gas turbine and the reduction gear in a ship. In the investigation, the fracture was not caused by the misalignment of the shaft itself but by the independent movement of the gas turbine and reduction gear supported by the independent resilient mounting system when the ship was sailing in rough seas. Therefore, a corrective action was suggested to add horizontal mounts that can reduce the movement of the gas turbine and reduction gear. In these studies, the shaft fractured frequently in the industrial field, and had various root causes such as design error, manufacturing error, extreme operating conditions, and other external causes. Ma and Wang (2006) researched the propeller shaft for the high speed craft whose material is SUS630. He found out that the fracture of the propeller shaft was caused by pitting corrosion and the life cycle was reduced about maximum 27%. Arisoy et al. (2003) reported the fracture of the 17–4 ph precipitation hardening stainless steel propeller shaft installed in a sailboat working in marine environment. He found out that the fracture of the propeller shaft was broken because the stress corrosion cracking which is progressed transgranulary in the martensitic matrix was occurred in the propeller shaft under the serious vibratory torque. Fonte et al. (2011) performed the failure analysis of two helical gear wheels of a ducted azimuth thruster. Through SEM (scanning electron microscope), it can be found out that the fracture was caused by fatigue and the root cause of this fatigue fracture is the inappropriate lubricating of the gear shaft.

In this study, effective experimental evaluations of shaft safety for torsional vibration are described with the input shaft of the reduction gear connected to the diesel engine. The torsional vibration was measured directly with a strain gauge and a telemetry system. The life cycles under the measured stress conditions were estimated using rain flow cycle counting and the linear damage summation law, and the results were compared to a standard stability evaluation method such as the Soderberg criteria. In this investigation, transient and non-standard ship sailing conditions such as zigzag maneuvers and engine starting were also examined in order to evaluate the safety of the shaft.

2. Measurement of the torsional vibration

2.1. Measurement setup

The fatigue stability is generally dependent on the static as well as alternating stress. The static stress of the propulsion shaft is caused by the mean torque of the engine and the alternating torque of it is caused by the vibratory torque of the engine. Since a diesel engine is operated by the force of the cylinder from the explosion of the gas, the vibratory torque of the diesel engine is bigger than that of the other type of engines such as gas turbine and electric motor. The alternating stress as well as the vibratory torque of the shaft system is called torsional vibration and it should be restricts to avoid torsional fatigue failure. The torsional vibration can be measured and evaluated by the elector torsiograph, laser torsiograph, strain gauge and so on. In this research, the vibratory torque of the reduction gear input shaft connected to the diesel engine was measured with a full bridge shear strain gauge and a telemetry module as shown in Fig. 1, and the rotating speed (rpm) of the shaft was measured simultaneously. The telemetry system is consists of the transfer and receiver module. The full bridge shear strain gauge is connected to the transfer module through the Wheatstone bridge and the strain data is transferred to the receiver module as shown in Fig. 1(b). The data

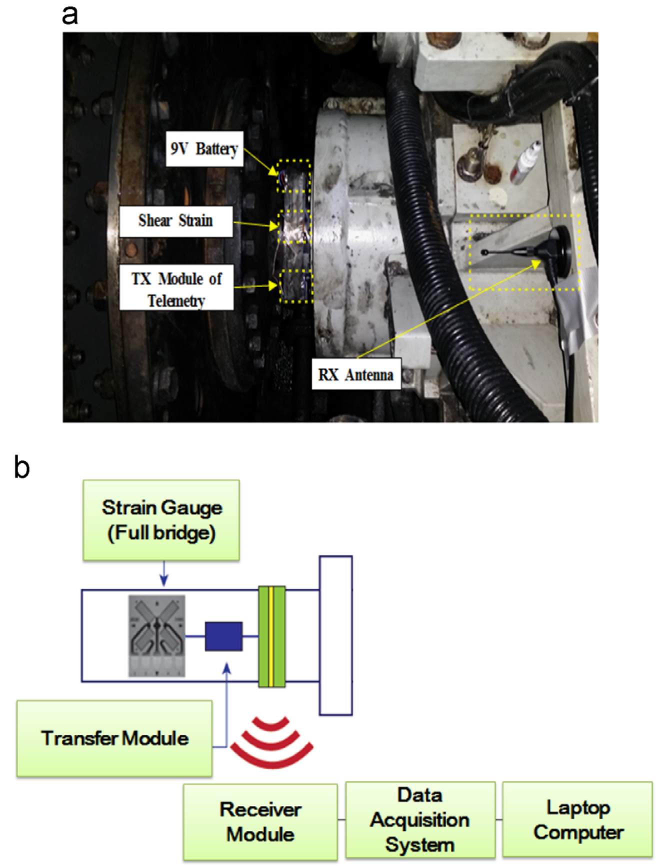

Fig. 1. Telemetry system measuring TV, (a) test setup, (b) schematic diagram of the telemetry system.

Table 1
Test system.

Test system	Maker	Model
FFT Analyzer	B&K	Pulse 3053-B12/0
Strain gauge	MM	CEA-06-250US-350
Telemetry	Binsfeld engineering Inc.	TT 10K-LP
Tachometer	Monarch instrument	ROLS-P

from the receiver module was collected with a data acquisition system. The specifications of the strain gauge, telemetry module, and data acquisition system are shown in Table 1.

2.2. Measurement of torsional vibratory torque and engine vibration

Since the exhaust pipe of the diesel engine discussed in this research is installed near the free surface of the sea as shown in Fig. 2, the torsional vibratory torque can be increased when the back pressure varies more than the specified limit because of variations in the draft line, for example, in rough seas. This kind of design of the exhaust line for the diesel engine is usually applied to the special ship such as naval vessel.

Changes in the torsional vibration of the engine caused by changes in the back pressure have been studied for submarines in snorkeling conditions (Mann, 2011; Hield, 2011). Studies showed that the torsional vibration varied according to the wave height and period because the exhaust pipe of the diesel engine is located under the free surface.

Figs. 3 and 4 show the torsional vibratory torque during straight maneuver sailing conditions as well as zigzag maneuver