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Failure analysis of crankshafts used in maritime V12 diesel engines

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ABSTRACT

Maintenance of equipment requires constant monitoring of the components that constitute a mechanical system, as well as the monitoring of the conditions of service, among others.

One first indication of failure in a crankshaft is given by the low-pressure value of the lubrication circuit. This is mainly due to the accumulation of debris in the lubrication channels, which causes the oil filters to be clogged. As such, this will cause poor lubrication of the crankshaft, which can consequently cause its catastrophic failure, and frequently originates damage propagation to other components of the engine, namely crankcase, bearing shells, connecting rods, pistons and other mechanical parts.

In the 4-stroke internal combustion maritime V12 diesel engine herein studied, there has been a frequent failure of crankshafts. The seven cases of failure of the crankshafts reported in the last 25 years are presented in the paper and several causes of failure were listed. From those, the influence of initial imperfections in the material was discussed in the article, as well as the influence of the loadings applied to the crankshaft. Hence, the theoretical dimensioning of the crankshaft was firstly assessed assuming the conservative Soderberg criterion and the crankshaft model was then analysed using the Finite Element Method, during a complete combustion cycle, at several stress concentration regions. The Rainflow cycle counting method was applied to determine the stress cycles induced during functioning and a stress-life equation was then used to estimate the fatigue lifespan of the crankshaft. Additionally, a modification to the crankshaft's geometry was suggested and a significant reduction of the induced stresses was obtained.

1. Introduction

Internal combustion engines have a great importance in the daily life of humanity, and its manufacturers constantly seek to design new models with greater power, lower fuel consumption and lower emissions of greenhouse effect gases. It is in the transport industry that the use of internal combustion engines is most evident due to the need to displace people and goods. If one looks closely, an internal combustion engine works due to a perfect working relationship between its components, each of which with a great engineering complexity. One of these mechanical parts is the crankshaft, whose main function is to convert the linear movement of the pistons into rotational movement transmitted to the shaft. The crankshaft is supported by several bearing journals and crankshaft rotation occurs due to the torque generated by the connecting rods that connect pistons to the crankshaft at crankpin journals, which are eccentric in relation to the longitudinal axis of the crankshaft. It is also worth mentioning the existence of lubrication channels

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that run inside the crankshaft in order to lubricate and cool the crankshaft journals and the crankpin journals.

Hence, crankshaft is an important mechanical part in all types of engines employed in applications like aircraft, reciprocating compressors, marine engines, car engines, as well as diesel generators [1], and diesel engines used in power plants and to marine propulsion are especially sensitive to outage events [2]. Nevertheless, a study conducted for diesel engines up to 2 MW revealed that failures per year related to engine crankshaft are low [2], although they involve high mean stoppage time to perform corrective maintenance. In fact, in case of a crankshaft failure, the repair cost frequently includes not only that of the crankshaft itself, but also the cost of other parts, such as connecting rod, piston, cylinders, bearings, as well as the lengthy time period required for repair, mainly because of the crankshaft location inside the engine [3].

An extensive literature survey of crankshaft failures [1] reported the following root causes for failure:

- Wrong machining and grinding processes during manufacturing.
- Cracks produced at stress concentration due to the combined effect of mechanical (bending and torsion) and thermal fatigue loads.
- Torsional vibrations.
- Surface contact which resulted into excess of pitting or spalling.
- Fatigue cracks may propagate through residual stress in the fillet regions.
- Improper assembly, or
- Improper lubrication.

Moreover, Yu and Xu [4] reported a crankshaft failure that occurred due to the initiation of a fatigue crack in a stress concentration region where the absence of a hardened layer due to nitriding was noticed. In fact, it is well known that surface hardening by nitriding can raise the fatigue strength of the material [4]. A similar case was reported in [5], in an induction hardened cast crankshaft, in which a crack propagated from a non-hardened fillet region and from the periphery of graphite nodules. The absence of the hardened material and the presence of free graphite and nonspheroidal graphite in the fillet region made fatigue strength decrease and led to failure in a shorter time than the normal usage life [5]. Nevertheless, for heavy-duty applications solid-forged crankshafts predominate [6] instead of using cast iron. More recently, Cevik and Gurbuz [7] evaluated the effect of fillet rolling on the fatigue behaviour of a crankshaft. They found that induced compressive residual stresses provide a significant improvement in the fatigue strength of the component.

In addition, according to [8], there are three features almost universal regarding fatigue failure of engineering components and structures, hence related with crankshafts, namely in-service failures are almost always high-cycle fatigue failures, crack invariably initiates at stress-concentration and are essentially linear-elastic events, whereas any plasticity will be restricted to a very localised region near the notch discontinuity. In Fonte et al. [9], a crack was found at the crankpin web-fillet and fatigue was the dominant failure mechanism; the root cause of failure was, accordingly with the authors [9], probably a poor design and a deficient assembling of the crankshaft. In another study [10], a failure analysis of two damaged crankshafts was presented and in both cases a crack grew from the crankpin-web fillet, being the crankpin web-fillets the critical zones where the cracks can initiate. Ktari et al. [11] carried out a failure investigation on three cases of failed diesel engine crankshafts made up of forged carbon steel; all failures were due to fatigue, and crack initiation occurred due to the high stress concentration on fillet radius and the unusual friction on bearing journals. Witek et al. [12] also studied a crankshaft's failure of a diesel engine; these authors carried out a numerical analysis of the crankshaft using the Finite Element Method and found that the main reason of premature fatigue failure was probably the large alternating bending stresses applied to a small crankpin fillet radius (notch effect).

Another study, [13], considered crankshaft failures, either at crankshaft journal or at crankpin journal. According with [13], crankshaft bearing failures are either caused by mechanical or tribological failure and among the later mainly due to abrasive (60%), adhesive (19%) or surface (11%) fatigue wear. In relation to abrasive wear, this type of failure would be due to oil contamination with wear products or with foreign particles [13]; concerning adhesive wear, that would be caused by low oil viscosity, by insufficient oil supply, by oil film breakdown (overload, vibrations) or insufficient clearance (poor design, fault assembly), while surface fatigue wear could be due to insufficient fatigue strength of lining material, or to misalignment, or due to the application of loads that exceeds the fatigue strength of the materials [13].

2. Materials and methods

2.1. Description of the propulsion system under study

The internal combustion maritime engines are mostly diesel powered. This is because this type of engine has a much higher compression ratio than that of gasoline engines, thus ensuring a higher torque at low engine speeds, which is ideal for overcoming the inertia caused by the high displacement of the ships.

In the case herein studied, the propulsion of the vessels is a Combined Diesel or Gas system (CODOG), with two lines of shafts, each with a 4-stroke supercharged diesel engine of 3600 kW of maximum power at 1200 rpm, one General Electric LM 2500 gas turbine, a Renk Tacke gearbox and an associated Escher Wyss variable pitch propeller. The CODOG system allows to have only one engine type delivering power to the shaft at a time, and not simultaneously.

Each diesel engine is composed by 12 cylinders arranged in "V" in the block (Fig. 1a), with a unit capacity of 11.63 dm^3, and V cylinders of the two engine's banks, namely A and B (Fig. 1a), are linked to the same crankpin journal of the crankshaft (Fig. 1b). The two engines in operation allow a maximum speed of 19 knots, corresponding to 60% of the maximum speed of the ship, and the firing