RISK CRITERIA FOR SEA-GOING SHIPS ARISING FROM THE OPERATION OF THE MAIN ENGINES' CRANKSHAFT – CONECTING ROD – PISTON SYSTEMS

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Abstract

In the article the risk criterion for sea-going ships arising from the operation of the main engines' crankshaft – connecting rod – piston systems is proposed. This criterion is based on the procedures recommended in the Formal Safety Assessment method developed under the auspices of International Maritime Organization (IMO). First of all the collective risk criterion for ship has been proposed. In the next step, the share of the main engines' crankshaft – connecting rod – piston systems, as the causes of marine accidents has been estimated. Then the risk criteria for ships arising from operation of those systems have been created. Additionally the reliability requirements for main engine components have been established.

Key words: *risk criterion, ship, main engine, crankshaft – connecting rod – piston system.*

1. Introduction

Safety in shipping is the object of interest of many people professionally connected with this branch of transportation, but also of the general public, because every one of us can be a passenger on the watercraft or we can be affected by an accident at sea for example in the case of environmental disaster caused by the loss of the ship's hull integrity or ship sinking.

Special responsibility for the safety in shipping is laying on the ship designers, ship builders, ship owners and crew members. Marine accidents and disasters can cause a loss of human life, serious damage in the environment and of course in every case financial loss.

There are numerous rules governing the principles of proper design, construction, operation and disposal of vessels. The examples of that are the rules of classification societies, international conventions on safety in navigation and protection of the marine environment. However, all those norms and regulations are of deterministic character. Still there are no widely used probabilistic rules in shipping, as it take place in inland nuclear power plants, chemical industry and some sectors of aviation.

Attempts to non - deterministic approach to the issue of safety at sea are undertaken. In particular it can be observed since 1997, when under the auspices of the International Maritime Organization the maritime community began to develop the method of Formal Safety Assessment.

In this article the special attention of the author is focused on the unreliability of main engines' crankshaft – connecting rod – piston systems components. Damage or failures of these elements

can lead to the need of reducing the main engine output power or in some cases to the need of stop main engine during sea travel. It can directly lead to the marine accident or disaster, especially under the difficult conditions of navigation.

Hence the idea: to create the risk criterion for a ship as a whole and the risk criterion arising from the operation of the main engines' components. These criteria are based on ALARP risk acceptability criteria concept. ALARP means that risk level should be as low as reasonably practicable. The proposed risk criteria relate to health and life of human beings and also losses of an economical and ecological nature.

2. Individual and societal risk criteria in maritime transportation

The definitions of individual and societal risk are given in [4]. Individual risk is the frequency at which an individual may be expected to sustain a given level of harm from realization of specified hazards. Societal risk is the relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards.

As it has been already stated above, risk criteria are built using principles of ALARP concept widely described in the literature, for example in [1, 2, 3, 4, 5]. To build ALARP based risk criterion it is necessary to divide the risk spectrum area into three parts. To do that, two limits of risk have to be established: the lower limit of risk and the upper limit of risk. The area below the lower limit of risk is an acceptable risk area. The area above the upper limit of risk is an unacceptable risk area. The area between those two limits (ALARP region) is the subject of judgment between the risk and benefits and between possibility to reduce the risk level and costs of such reducing.

If the risk is in the acceptable area we needn't take any action to reduce the risk. If the risk is in the unacceptable area the object of interest (ship) can't be used as the mean of transportation, it is necessary to take steps to reduce the level of risk. In the ALARP region we should try to reduce the risk as far as it is reasonably justified and possible in practice. Individual risk criteria (frequency of loss of life by individual) proposed for ships are as follows [2, 5]:

- maximum tolerable risk for crew members 10^{-3} annually,
- maximum tolerable risk for passengers 10^{-4} annually,
- maximum tolerable risk for public ashore 10^{-4} annually,
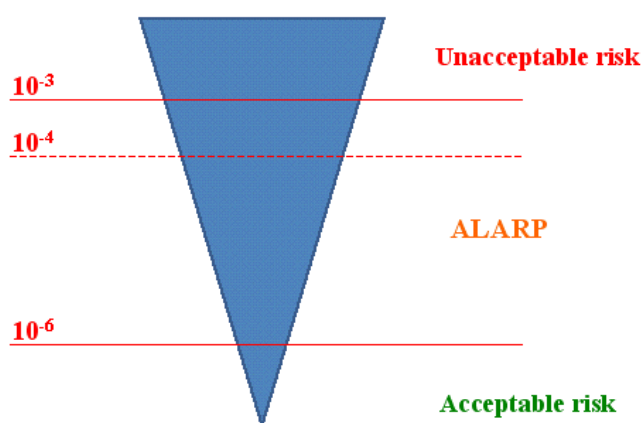- negligible risk 10^{-6} annually.

Fig. 1. Individual risk criteria for crew members and passengers on ships

Societal risk criteria are created to limit the risk from ships to whole groups of people containing crew members, passengers, and even local communities, which may be affected by ship

activities. According to [5] these criteria are used to limit the risks of catastrophes affecting many people at the same time. The criteria are given in the form of FN diagrams. F - means an annual frequency of N or more fatalities, N - means a number of fatalities. The diagrams are divided into three areas of risk: intolerable risk, ALARP, negligible risk. The examples of such risk criteria are given in Fig. 2.

Fig. 2. FN curves for bulk carriers, container vessels and tankers shown together with risk evaluation curves [5]

As we can see above the historical data gives us FN curves for most examined ships in the ALARP region. More about the individual and societal risk criteria for ships one can find in [4, 5].

3. Set of risk criteria proposed for sea-going vessels

All the above presented risk criteria are related only to the loss of life. In this section the author's proposals of risk criteria for ships are presented. The graphical form of the criteria (three in one) is shown in Fig. 3.

Those criteria relate to health and life of human beings and also to losses of an economical and ecological nature. They were built using principles of risk assessment for the inland industrial plants, extensively described in [3]. The criteria are similar to those proposed on the forum of the International Maritime Organization and developed for the case of loss of human life. The similarity arises from the fact that IMO decision-makers also relied on procedures developed for land based installations.

To create a risk criterion is necessary to build a risk matrix. The risk matrix should contain the frequency of hazardous events per year and the potential consequences of the dangerous incident. In addition both of them (frequency and consequences) should be quantified. In the first step the quantification was made with the use of linguistic values. The frequency of hazardous events was identified by the following values: very often, often, quite often, occasionally, seldom, very seldom, almost never. The potential consequences of hazardous events are defined as follows: catastrophic, significant, moderate, small, minor.

The next, very difficult but also very important step is to convert the linguistic values into numerical values. It was decided, that the frequencies of hazardous events will be convert into numerical values in accordance with the rules described in [3]. The frequencies of hazardous events per year in accordance with these guidelines are:
-    very often   frequency of occurrence more than 10^{-1} per year,

-	often	frequency of occurrence from 10^{-1} to 10^{-2} per year,
-	quite often	frequency of occurrence from 10^{-2} to 10^{-3} per year,
-	occasionally	frequency of occurrence from 10^{-3} to 10^{-4} per year,
-	seldom	frequency of occurrence from 10^{-4} to 10^{-5} per year,
-	very seldom	frequency of occurrence from 10^{-5} to 10^{-6} per year,
-	almost never	frequency of occurrence less than 10^{-6} per year.

Determination of numerical values of the potential consequences of hazardous events is very debatable. A certain amount of financial losses for one ship owner may be a little fraction of his income. For another ship owner it can be very significant. That is why categories of losses should be developed with taking into account the individual situation of the owner of the ship, the type of the ship, the value of the cargo, the navigation area, etc.

It doesn't mean that's impossible to propose universal risk criteria. Such an attempt was made in this study. The three categories of losses were taken into account: loss of human life, financial losses and ecological losses.

The biggest problem, of course, is a reasonable scaling of the size of losses. The taxonomy of the losses is presented below with the explanation why such numerical values were established. It is worth noting, that in the risk analysis we use quite often order of magnitude rather than precise numbers to express the value of losses.

Frequencies of hazardous events per year			Potential consequences of hazardous events				
			Minor	Small	Moderate	Significant	Catastrophic
Very often	> 10^{-1}						
Often	10^{-1} - 10^{-2}					Intolerable risk	
Quite often	10^{-2} - 10^{-3}						
Occasionally	10^{-3} - 10^{-4}				ALARP		
Seldom	10^{-4} - 10^{-5}						
Very seldom	10^{-5} - 10^{-6}		Negligible risk				
Almost never	< 10^{-6}						
Human losses			Only injuries	1 or more	10 or more	100 or more	1000 or more
Oil spills			10 tons or more	100 tons or more	1000 tons or more	10 000 tons or more	100 000 tons or more
Financial losses			1000 $ or more	10 000 $ or more	100 000 $ or more	1 000 000 $ or more	10 000 000 $ or more

Fig. 3. The proposal of set of risk criteria for sea-going vessel

Human losses. The greatest number of people, even a few thousand (for example 4000 people) can stay aboard a luxury cruise ship. So as the result of accident at sea, in the most pessimistic scenario, may lose life several thousand people. Therefore the scale of fatalities will start from thousands of victims and will be vary by an order of magnitude. The scale will be than as follows: thousands of victims, hundreds of victims, tens of victims, individual victims, only injuries.

Financial losses. As the basis of financial losses it was taken the cost of purchasing of a typical vessel. The most expensive cargo ships cost is tens of millions of dollars (luxury passenger cruiser costs even hundred millions of dollars). So the scale of financial losses will be like this: tens of millions of dollars, millions of dollars, hundreds of thousands of dollars, tens of thousands of dollars, thousands of dollars. Of course in the event of total loss of the ship, the financial loss will be higher than the current value of the ship (value of the cargo, compensation payment etc.).

Ecological losses. Environmental losses depend on the type of vessel and the cargo. It is therefore hard to offer a universal measure of potential damage in the environment. So, as the example, the environmental risk measure for crude oil tankers has been proposed, in the form of the potential size of the oil spill. The largest tankers operated nowadays in the sea are able to carry hundreds of thousands of tons of cargo onboard one vessel. Such volume was taken then as the upper limit of oil spill.

4. Risk criteria arising from the operation of the main engines' crankshaft – connecting rod – piston systems

First of all let's try to determine a participation of the failure events of crankshaft – connecting rod – piston systems as the causes of accidents at sea. Because it was impossible to collect statistical data, by the author, directly showing the participation of such systems as the causes of accidents - an attempt was made to estimate the value according the indirect data.

In the article [6] the principal causes of ship accidents are as follows: deck officer error 26 %, crew error 17 %, shore error 9 %, pilot error 5 %, eng. officer error 2 %, structural failure 9 %, equipment failure 9 %, mechanical failure 5 %, under investigation 6 %, other 12 %.

According to this report the unreliability of mechanical systems is the cause of 5 % of all marine accidents.

Looking at the research results published in [7] we can find out, that the average number of the loss of propulsion event by the container vessel, equipped with direct propulsion system (no reduction gear), is m = 2.5 times per year with a standard deviation σ = 1.1325 times per year. The same research team has established and published in [7] the share of main participants in the loss of propulsion event probability: fuel oil subsystem p_1 = 0.1330; sea water cooling subsystem p_2 = 0.0437; low temperature fresh water cooling subsystem p_3 = 0.0395; high temperature fresh water cooling subsystem p_4 = 0.0620; starting air subsystem p_5 = 0.0853; lubrication oil subsystem p_5 = 0.0687; cylinder lubrication oil subsystem p_6 = 0.0446; electrical subsystem p_7 = 0.1876; main engine p_8 = 0.1987; remote control subsystem p_9 = 0.1122; propeller and shaft line p_{10} = 0.0247.

The above results show, that for the direct propulsion system, the main engine's failure share is approximately 20 % in the all causes of loss of propulsion.

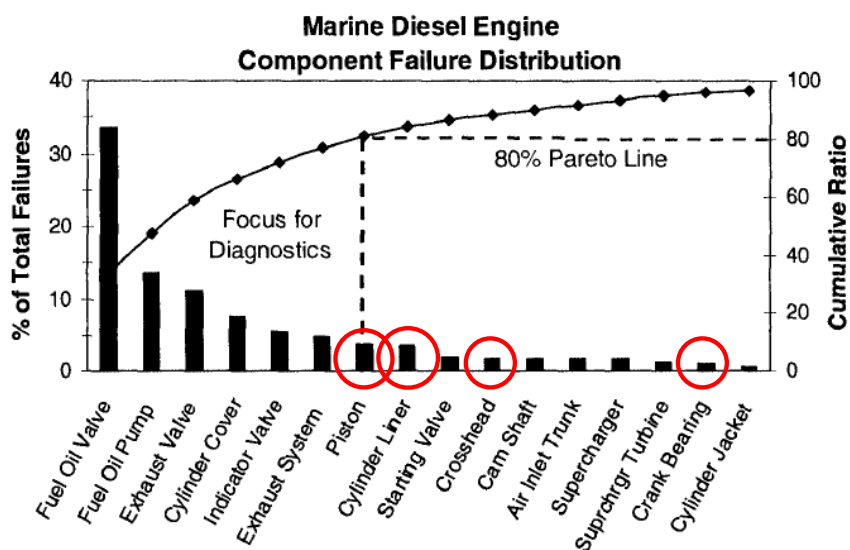Marine diesel engine component failure distribution is given in Fig.4.

Fig. 4. Marine diesel engine component failure distribution [8]

Components like: piston, cylinder liner, crosshead, crank bearing together are responsible for about 15 % of the main engine failure events.

Based on all the data given above, the share of the main engines 'crankshaft – connecting rod – piston systems as maritime accidents causes can be estimated like this: mechanical failure as the cause of accident 5 %, main engine as the cause of loss of propulsion by ship 20 %, selected components of the main engine as the cause of engine failure 15 %.

So, finally the share is $0.05 \cdot 0.20 \cdot 0.15 = 0.0015 = 0.15$ %.

Failures of the main engines' crankshaft – connecting rod – piston systems, assuming the correctness of the above considerations, have a small part in maritime accidents. However we shouldn't ignore them, because in each case they generate high costs connected with the repair of the engine and exclusion the ship from the operation.

The risk criterion for ships arising from operation of the main engines 'crankshaft – connecting rod – piston systems can be build with the help of the criteria given at Fig. 2. The goal is to not overstep the limits of frequencies of hazardous events involving a ship per year. As we can see the limits are 10^{-3} per year between negligible risk area and ALARP region and more then 10^{-1} per year between ALARP region and intolerable risk area.

Assuming that the considered elements of the main engine are responsible for 0.15 % of the marine accidents, the risk criteria for them should take the following form:

If the frequency of hazardous events for a ship caused by the elements per one year period of time:
- is lower or equal to $0.0015 \cdot 10^{-3}$ then the risk is negligible;
- is between $0.0015 \cdot 10^{-3}$ and $0.0015 \cdot 10^{-1}$ then we should make a risk analysis according to ALARP principle;
- is higher than $0.0015 \cdot 10^{-1}$ then the risk is intolerable.

Safety is a value itself. The need to take care of safety doesn't require justification. In order to improve the safety we can't ignore components of the main propulsion engines. Efforts should be made to improve their reliability in the future to a higher level than today and do not allow to reduce their quality. So, it is worthy to think about creating the relevant requirements of reliability of such elements. But the requirements need to be realistic.

Therefore, as the starting point of reliability level should be taken the mean time to failure of engine components, achieved by the leading manufacturers on the market today. The mean time to failure should be increased in the future. The proposal of reliability requirements for the future components is given in Fig. 5.
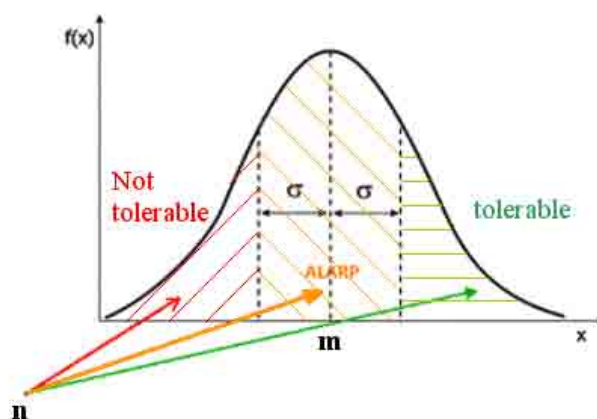

Fig. 5. Proposal of reliability requirements for the future main engines' components

m – the mean time to failure of component used today,
σ – standard deviation of the mean time to failure of component used today,
n – mean time to failure of component to be used in the future,

Following the example of ALARP risk criterion, the proposition of the author is: do not use in the future components with the mean time to failure shorter then $m - \sigma$; for components with the mean time to failure between $m - \sigma$ and $m + \sigma$ try to rise the reliability level, if it is economically justified; for components with the mean time to failure longer then $m + \sigma$ assume that their reliability is sufficient and doesn't require any action to improve it.

5. Final remarks

The considerations made above show, that the share of the main engines' crankshaft – connecting rod – piston systems as a cause of maritime accidents is relatively low. It is worthy to note, that not all of their failures ends with the disaster in the sea. But each serious failure of those elements generates very serious economical costs.

The "safety culture" requires that everyone in his own sphere of responsibility is obligated to take care for safety. Need to take care for safety is not negotiable. Fact that other factors (especially human factor) have a greater impact on the level of risk doesn't relieve the engine manufacturers and designers of ship power plants from responsibility for the safety of maritime transportation.

The aim is to minimize all risk factors. Effective risk management requires appropriate risk measures, procedures for determining the risk and risk criteria. That is why in the article a set of risk criteria, taking into account risk of loss of life, economical risk, and ecological risk has been proposed by the author.

However, the subject has not been closed. Conducted considerations may serve as the basis for further discussion.

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