

**Abstract.** One of key ways of assuring a high level of reliability of a ship power plant is to design redundancy of its structural elements, for example redundancy of prime drivers, drivelines etc. This paper deals with issues related to the redundancy as a way increasing dependability of the ship power and propulsion systems. Especially, fundamental characteristics of dependability, major design strategies influencing the reliability, and types of redundancies related to ship power and propulsion systems are presented.

**Keywords:** redundancy, dependability, ship power plant

## INTRODUCTION

Machine operation and maintenance processes always accompanied our civilization as people begun to use machines to support their work. The proper running of these processes required the use of certain knowledge. It is particularly important when we try to design some features into the machine which enable its rational operation and maintenance. The lack of such action may cause negative effects, including economic. This is due to a fact, the machine customer bear only direct investment costs, whereas expenses for the machine operation and maintenance are generally hidden. They can be presented in the form of the so-called 'iceberg model' used to illustrate both direct and hidden factors of some phenomenon, for example psychological, medical etc. (Fig. 1).



**Fig. 1. Machine operation and maintenance expenses as the 'iceberg model'.**

Source: Blanchard et al., 1995

With regard to ship power plants, the operation and maintenance cover all aspects and activities necessary to run them in a safe and more economical manner. It means a set of activities relating to:

- ensuring motion of all systems in a ship power plant supporting its working processes,
- maintaining all systems by carrying out actions necessary for retaining, or restoring a serviceable condition of a ship power plant.

Some manuals distinguish additional activities relating to the operation and maintenance of ship power plants depending on their nature, for example checking, supplying etc.

The ship power plants as every complex technical items can be characterized by principal properties where one of the most important is reliability. One of the key ways of assuring a high level of the reliability is to design redundancy of their structural elements, for example: redundancy of prime drivers, drivelines etc. The reliability and redundancy are strictly connected with development of a dependable system.

This paper deals with issues related to redundancy as a way increasing reliability of ship power plants. Especially, fundamental characteristics of the dependability, the major strategies influencing reliability, and the types of redundancies related to ship power plant are presented.

### DEPENDABILITY AND ITS ATTRIBUTES

In general, the dependability is the ability of a system to deliver its intended level of service to its users. Laprie (Laprie, 1992) distinguished three fundamental characteristics of dependability: attributes, threats, and means.

The attributes of dependability express the properties which are expected from a system. Dependability threats are usually defined in terms of faults, errors, or failures, and a common feature of these three terms is that they give us a message that something went wrong. The difference is that:

- in case of a fault, the problem occurred on the physical level;
- in case of an error, the problem is connected with a human action that produces an incorrect result;
- in case of a failure, the problem occurred on a system level that is a deviation of the system from its intended purpose.

The dependability means are methods and techniques enabling the development of a dependable system. All these characteristics are presented as the dependability tree in Fig. 2.

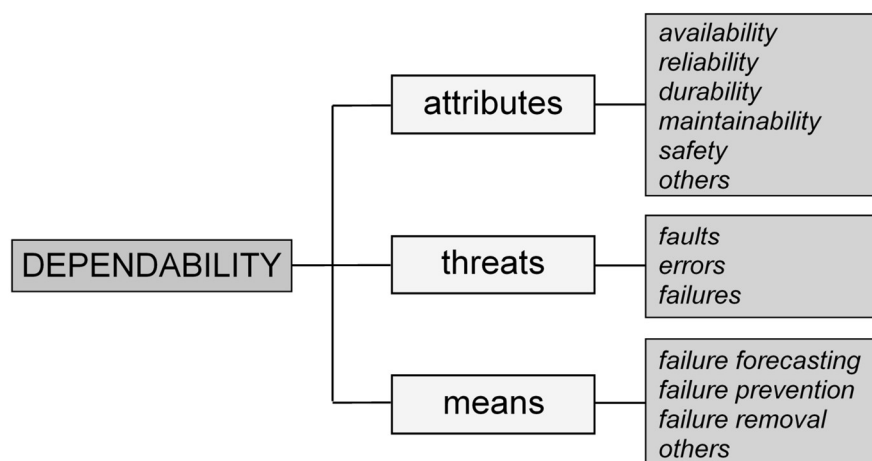


Fig. 2. Fundamental characteristics of dependability.

Source: Laprie, 1992

With regard to ship power plants, the primary attributes are reliability, availability, and safety. Other possible attributes include durability, maintainability, and storability. The definitions of the mentioned attributes exist in current standards (International Electrotechnical Vocabulary, 2006) and (Wydawnictwa Normalizacyjne, 2001).



In broad terms:

- reliability is the probability of a component (or an entire system) to operate under designated operating conditions up to an assigned time,
- durability is the probability that a component is not permanently lost after a failure,
- maintainability is the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources,
- availability is the probability of a component (or an entire system) to operate under designated operating conditions at a designated time or cycle, and it is used extensively in the power plant engineering,
- storability is the probability that a component (or an entire system) is capable to be stored for a considerable time without loss of usability,
- safety is the likelihood of a component (or an entire system) to maintain – throughout its life cycle – an acceptable level of risk that may cause major damage to the system or its environment.

Safety can be considered as an extension of reliability, namely reliability with respect to failures that may create safety hazards. From the reliability point of view, all failures are equal. For safety considerations, failures are partitioned into fail-safe and fail-unsafe ones. The safety is required in safety-critical applications where a failure may result in human injury, loss of life, or environmental disaster. Examples are trains, automobiles, avionic system and of course – the ship power plants.

The relationship between dependability and its attributes are presented in Fig. 3.

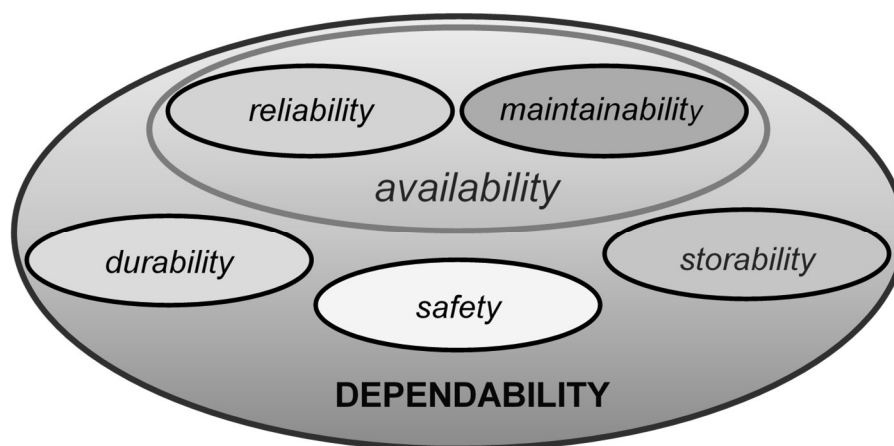


Fig. 3. The relationship between dependability and its attributes.

## APPLICATION OF REDUNDANCY IN SHIP POWER AND PROPULSION SYSTEMS

### Types of redundancies

In general, reliability is a measure of the system ability to perform its required function, in adequate manner for a given period. With regard to ship power and propulsion systems, the high reliability is required in situations when it is expected to operate without interruptions as in case of a ship propulsion during maneuverings to avoid danger of collision, or when maintenance of a diesel engine cannot be performed because one piston-cylinder system cannot be accessed during engine works.

It is obvious that it is almost impossible to achieve an absolute reliable system because it is not possible:

- to predict all factors influencing the system and their actual magnitudes,
- to have the complete knowledge regarding the types of processes running in the system,
- to eliminate of all material defects, manufacturing errors etc.

The reliability engineering distinguishes the following major strategies influencing reliability: fault tolerance and fault avoidance.



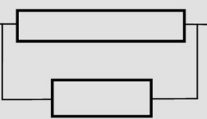
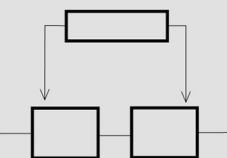
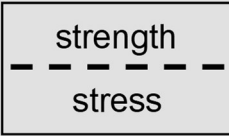
The fault tolerance is a system design characteristic associated with the ability of a system to continue operating after a component failure has occurred. It is implemented by having design redundancy and a fault detection response capability.

The fault avoidance is the design and operations characteristic that allows the system respond to component failures in a way sufficient to meet task requirements. This usually involves operational workarounds and the use of components in ways that were not originally intended. The mentioned strategies essentially come down to the use of different reliability structures (Kilinski, 1979). These, in turn, are associated with various types of redundancy in relation to what is necessary to ensure its proper operation. The redundancy was found as being the best type of solution in the detailed design stage of a ship power plant. We can control a reliability level through by application of:

- structural redundancy – introducing to its structure so-called reserve components, without which it can work; it is a mean of raising its reliability level,
- functional redundancy – its selected elements are able to perform separate functions; in case failure of any elements the others take over to perform this function within a predetermined range (sometimes with a little worse performance),
- parametric redundancy – design features (geometric, material, dynamic) of its selected components providing the higher properties (for example material strength) than it is potentially necessary to perform given functions.

Types of the mentioned redundancies with their characteristics are presented in Table 1.

**Table 1.**  
**Types of the redundancies with their characteristics.**

Type of redundancy	Graphical representation	Characteristics
STRUCTURAL REDUNDANCY		<i>a system consists of a base component and a reserve component - it works correctly if at least one component is not fails</i>
FUNCTIONAL REDUNDANCY		<i>a component performs its own functions in a system – in case of this component fails, its functions is realized by other component which is not designated perform this function</i>
PARAMETRIC REDUNDANCY		<i>a value of one of component parameters is higher than it is necessary to perform given functions in a system (strength, preload etc.)</i>

### The structural redundancy

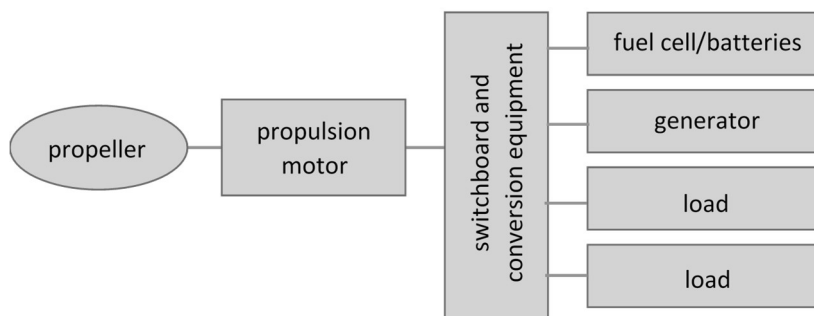
The structural redundancy in power and propulsion systems permits redistribution of a function to its reserve component in case of failure of the key component. This ability of the plant to generate power over and above the current demand is expressed as reserve capacity. We can distinguish two types of reserves:

- cold reserve is that reserve capacity, which is available for service but normally not ready for immediate loading, for example, one of few diesel generators that can be pressed into service if demand increases,
- hot reserve is that reserve capacity, which can be made available quickly for example emergency generator ensuring the essential machinery and system suffering a blackout.

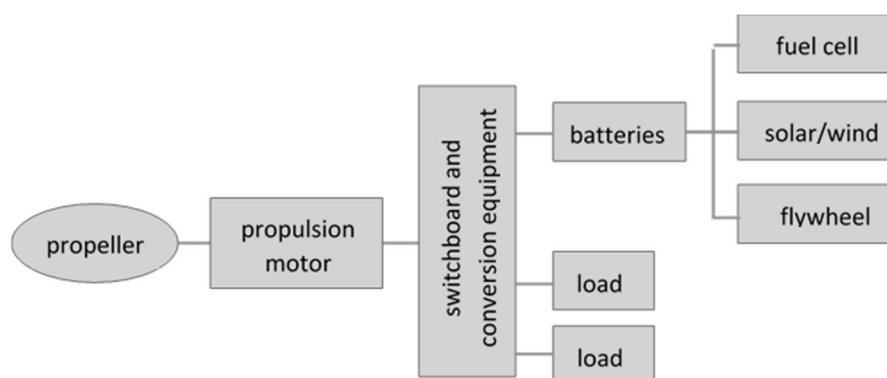
An example of the structural redundancy in a ship power plant is the installation more main engines. Each of the engines should then be able to deliver the required power. In case when one of the engines fails, there is still enough power to navigate the ship safely to its destination.

Having more engines available, it is possible to monitor them closely and to shut one off if it gives strange values from the diagnostic instruments. This might prevent the biggest failures.

a)



b)



**Fig. 4. Examples of ship hybrid electric power systems:  
a) energy storage technologies; b) energy generation technologies**

Source: (American Bureau of Shipping, 2017)

In case of application of a diesel-electric propulsion, generator sets are used to generate the required power, both for propulsion and auxiliary purposes. Due to the multiple engine redundancy this concept is said to have high reliability. When one of the generator set fails the other set will have enough power to navigate the ship into port on a lower speed. The engines can be placed anywhere in the ship and be connected to the propellers by cables. If this type of propulsion will be used, the failures in the main engine and the diesel generators will overlap. Today hybrid propulsion systems have been put in operation on several ship concepts. As a rule, hybrid electric power systems support compliance with the new rigorous MARPOL Annex VI pollution regulations required in environmentally sensitive areas. They, using stored energy as a backup for the main power source, allow shipowners to increase safety in response to emergency situations where all main power is lost, or in situations such as explosive natural gas buildups where use of internal combustion engines would not be considered safe (American Bureau of Shipping, 2017).

Technologies used to deliver electric power in the hybrid propulsion systems can be divided into two wide categories: energy storage technologies, and energy generation technologies. The first type of technologies includes batteries (Lithium-ion batteries), capacitors (super capacitors and hybrid capacitors) and flywheel energy storage. The second type of technologies includes fuel cells, solar and wind power. Examples of ship hybrid electric power systems are presented in the form of block diagrams in Fig. 4a and b.

#### **The functional redundancy**

The functional redundancy enables the use of power and propulsion systems using the additional function of its base components, which in the original design intention were not designed to fill them. A classic example of this type redundancy is the use of Lunar Module



Aquarius of the Apollo 13 space mission. It played an unexpected role in saving the lives of the three astronauts after an oxygen tank in the Service Module ruptured. This module served as a 'lifeboat' for the astronauts during their return to Earth.

With regard to the ship power and propulsion systems, the SOLAS convention requires the redundancy of its component by means of regulation II-1/26.2 (International Maritime Organization, 2014), which states that: '*Special consideration shall be given to the reliability of single essential propulsion components and may require a separate source of propulsion power sufficient to give the ship a navigation speed, especially in the case of unconventional arrangements*'

In the conventional oil tankers, a power and propulsion system consists of a single main engine driven a fixed pitch propeller. In some solutions of their ship power plants, shaft generators can be additionally installed. A concept taking into account the mentioned SOLAS regulation is based on the assumption that this generator can work also as an electric motor driven the propeller, and which has a separate source of sufficient electric power (Fig. 5).

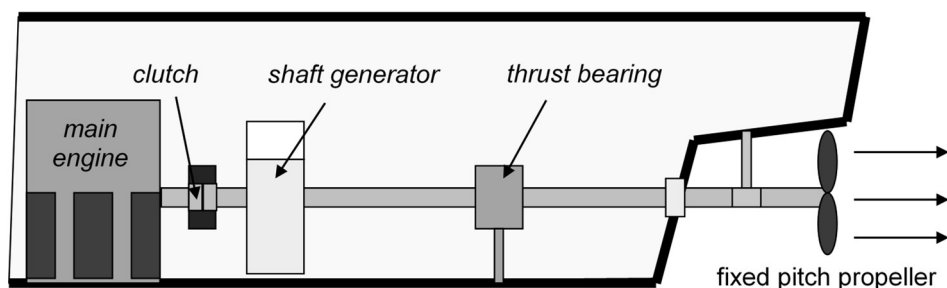


Fig. 5. Ship power and propulsion system with shaft generator.

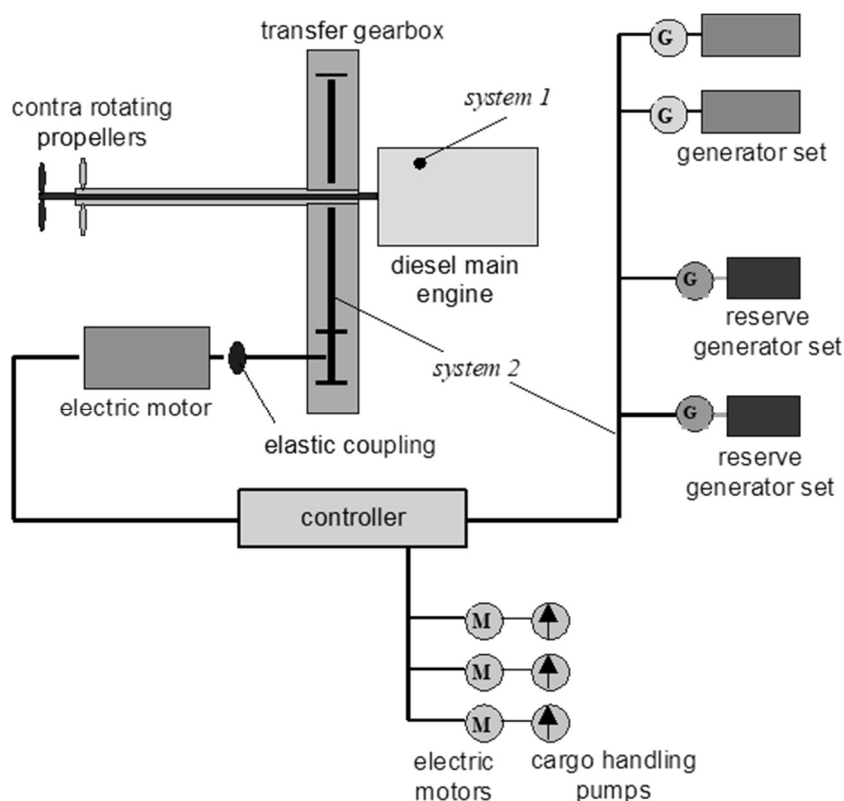


Fig. 6. Power and propulsion system of oil tanker with contra rotating propellers

Source: International Maritime Organization, 1995

Another interesting concept has been proposed for the power and propulsion system of oil tanker with contra rotating propellers (International Maritime Organization, 1995). This concept of the functional redundancy assumed the use of other independent energy sources of a ship power

plant to drive contra rotating propellers (Fig. 6). In the classic arrangement of contra rotating propellers, the both propellers are driven by a single main engine, whereas power distribution is realized by means of the transfer gearbox. Pumps of oil tankers are driven by other independent diesel engines or steam turbines. The power generated by these power sources is used only during cargo handling procedures. The proposed concept based on the use of this power also to vessel propulsion.

### The parametric redundancy

The parametric redundancy should ensure the potentially higher strength of power and propulsion system components than it is necessary to achieve given functions. It is associated with the variance of all physical phenomena, including manufacturing processes, environment interactions etc.

In the description of these phenomena, the probability distributions are used, where some uncertainties always appear on their underparts for example: extremely large and small values of stresses, temperatures, pressures, etc. Therefore, the design of these components should take into account the factor of safety. In the engineering mechanics, this a term describes the load carrying capacity of an element beyond the expected or actual loads. Graphical interpretation of the parametric redundancy for strength of ship machinery components is presented in Fig. 7.

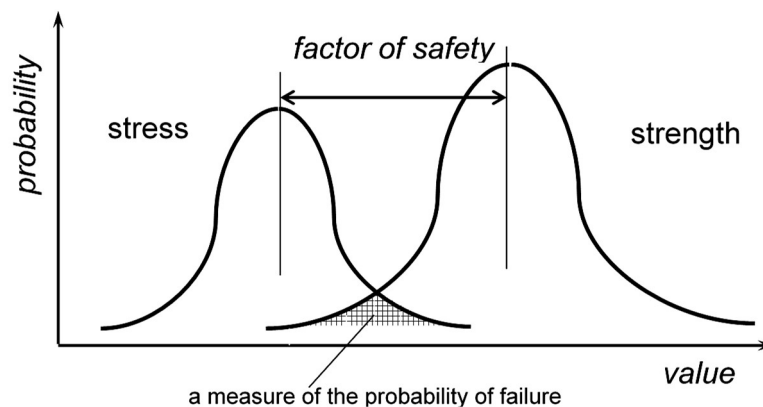


Fig. 7. Graphical interpretation of the parametric redundancy for strength of ship machinery components.

Let us consider this type of redundancy taking into account a propeller shaft. Propeller shaft breaks rarely occur, nevertheless the probability always does exist. The dimensioning takes place according to the regulations of classification societies, which do not differentiate between themselves. Based on empirical formulas, a minimum diameter is specified depending on output, revolutions, type of power and propulsion system, material selection, etc. But these formulas do not take into account many other factors.

From one side, the propeller shaft loads can be increased rapidly due to:

- its torsional and axial vibrations excited by the main engine and by the blade impulses of the propeller,
- the resonance conditions by engine and propeller-lateral exciter frequencies,
- the phase position of the propeller blades with regard to the crankshaft,
- the axial and bending vibrations excited by the free-hanging propeller.

All these factors acting together increase the propeller shaft stress, which is reflected in right underparts of the stress probability distribution (Fig. 7).

From the other side, the propeller shaft can be manufactured with the extreme small values of its properties influencing its strength, but which still are within the ranges of their allowable ones.

To these properties we can include:

- seizes of the propeller shaft,
- quality of material (structure, roughness, yield strength etc.).

These factors, in turn, decrease the propeller shaft strength, which is reflected in left underparts of the strength probability distribution (Fig. 7).

If both the additional loads and the extreme small values of its properties meet together in any propeller shaft than the likelihood of propeller shaft breaks could appear. As a rule, assertion of the necessary value of the factor of safety requires formal supervision carried out by classification societies. An example of this kind of requirement can be provisions of Polish Ship Registry classification (PRS) related to design of ship power system (Polski Rejestr Statków, 2018).

## CONCLUSION

The redundancy was found as being the most effective way to increase reliability in the detailed design stage of ship power plants. There is a possibility to control their reliability level through by application of structural, functional, and parametric redundancies. Applications of this kind of solutions in ship power plants are supported by the provisions of the IMO and classification societies.

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