轮机维护与修理

Maintenance and Repair Technologies of Marine Machinery

（英文版）

程　东　主编
朱新河　主审

大连海事大学出版社

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Preface

The ability for engineers to maintain and repair the marine machineries is required for the students majoring in Marine Engineering according to "Regulations on Examination, Assessment and Certification of Competence for Seafarers of the People's Republic of China" and STCW Convention, Manila Amendments.

The book is intended to establish the foundations of maintenance and repairing of marine machinery for students majoring in Marine Engineering, and to improve their abilities to solve the problems in this field.

The book is divided into 9 chapters, which include the basic theories of maintenance and failure analysis (including failure and maintenance, tribology, corrosion, fatigue failure, defect detection and fault diagnostics), repairing process and technologies (including mechanical repair methods, electroplating, thermal spray, welding, metal stitching, adhesive, grinding, repairing process, cleaning, dry docking, and testing), overhauling and maintenance of marine machinery (including cylinder cover, cylinder liner, piston, piston ring, crankshaft, bearing, precision coupling, turbocharger, shafting, and propeller), installation and alignment (including diesel engine installation, shafting alignment).

The authors of the book are teachers at Dalian Maritime University. They have worked very intensively together for years in the field of marine engineering. Chapter 1 was written by Fu Jingguo. Chapter 2 was written by Yan Zhijun. Chapter 7 was written by Yu Guifeng. Chapters 3, 4, 5, 6, 8 and 9 were written by Cheng Dong.

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The Authors
2013.6

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Chapter 1
Failure and Maintenance

1.1 Failure

1.1.1 Introduction of Failure

(1) Fault, Failure and Error

Fault is the abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function, as shown in Figure 1.1.

Machinery **failure** can be defined as the inability of a machine to perform its required function. In other words, a failure is the non-fulfillment of a functional requirement.

An **error** is a "discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition".

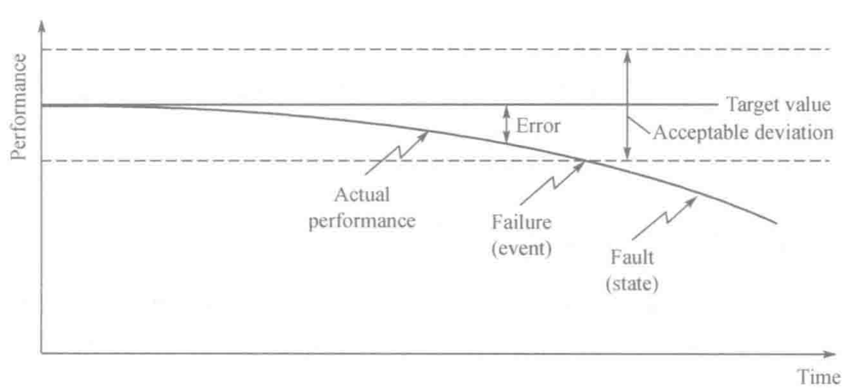

Figure 1.1 Fault, failure and error

(2) **Failure Mechanisms**

Failure mechanisms category related to metal structure components are corrosion, cracking, deformation, embrittlement, fatigue, fracture, friction, and wear.

Understanding of the failure mechanisms enables the manufacturer to take prompt and proper measures for correcting the design and/or manufacturing processes, so that the recurrence of the failure can be prevented.

(3) **Failure Modes**

The term "**failure modes**" refers to the actual manner in which equipment or machine fails, or the way the failure occurs. It is the result of the failure mechanism (cause of the failure mode).

Note that a failure mode is always related to one or more required functions. Sometimes failure mechanisms (e.g., corrosion) are erroneously used as failure modes. Failure modes indicate symptoms of failure, but failure mechanisms represent the course and mechanism for arriving at these symptoms. For example, corrosion is not a failure mode, but might be the cause of a failure mode. However, the failure mechanism may be different for the different failure modes, and the failure mechanisms may vary during the life of the equipment; some failure modes are caused by compound mechanisms instead of just a single mechanism, so it is essential to investigate one factor at a time to determine the true cause.

To help understand this relationship, Table 1.1 examines typical hardware-related equipment failure mechanisms.

Table 1.1 Examples of dominant physical failure mechanisms for hardware

Mechanical loading failure	Wear	Corrosion	Temperature-related failure
• Ductile fracture • Brittle fracture • Mechanical fatigue • Excessive deformation (elastic or plastic)	• Abrasive • Adhesive • Fretting • Corrosive	• Galvanic • Uniform • Stress corrosion cracking • Pitting • Cavitation	• Creep • Metallurgical transformation • Thermal fatigue

1.1.2 Failure Classification

The goal of failure classification is to separate failures into classes, with each class of failures having common symptoms and/or cause. In order to arrive at an appropriate classification, it is necessary to know the important characteristics/attributes of failures.

Failures may be categorized in a number of ways according to the following criterion:

(1) **Based on the Influences on the Shipping Service**

Partial failure without suspend shipping service: The equipment failed due to local failure may be repaired during sailing, without suspend shipping service.

Important failure with little suspend shipping service: The equipment lost the function due to serious failure, and the shipping service has to be suspended to get rid of failures in a short period of time. The suspending time for cargo ships is less than 6 hours, 2 hours for passenger ships.

Complete failure with long suspend shipping service: It's a catastrophic failure and costs a long time to repair. In this case, the ship is unseaworthy, and has to be repaired in a shipyard. For example, the cracked crankshaft, tailshaft or intermediate shaft, the broken propeller, or ship's hull.

(2) **Based on the Failure Causes**

Primary failure (inherent weakness failure): Failures due to inherent weakness of the component or system and occurring while the item is being correctly used.

Secondary failure: Failures of the function of a component as a result of failures occured elsewhere.

(3) **Based on the Failure Process**

Sudden failure: Failures which could not have been anticipated.

Gradual failure: Failures which are progressive in nature and could have been anticipated. Over time a system's operating performance and/or accuracy may degrade and exceed its specified tolerances and/or operating parameters.

Random failure: Failures which occur suddenly and at random during the anticipated useful life of a component or system due to the causes not related to age. They are non-predictable by both system designers and operators.

(4) **Based on Detectability**

Evident failure: Failures which will become evident to operators under normal circumstances.

Hidden failure: Failures not evident to the crew or operator during the performance of normal duties. However, most of these failures can be detected by inspections or tests performed by maintenance personnel.

(5) **Based on the Characters**

Human failure: Almost all failures are caused by human factors. There are two main types of human failure: errors and violations. A human error is an action or decision which was not intended. A violation is a deliberate deviation from a rule or procedure.

Nature related failure: Failures caused by nature related factors, deteriorated environment, such as bad weather.

As with the causes of failure, they can also be subdivided into only two categories. **Catastrophic failures** are sudden and complete. **Incipient failures** are partial and usually gradual. In all but a few instances, there is some advanced warning as to the onset of failure; that is, the vast majority of failures pass through a distinct incipient phase.

Deficiencies in the original design, material or processing, improper assembly, inappropriate maintenance, and excessive operational demands may all cause premature failure.

1.1.3 Frequency of Failure

Anecdotal and statistical data describing the frequency of failures can be summarized in a curve with failure rate on the vertical axis and time on the horizontal axis. Because of the shape of this failure rate curve, it has become widely known as the "bathtub" curve. Figure 1.2 shows a typical bathtub curve, which is applicable to an individual machine or population of machines of the same type.

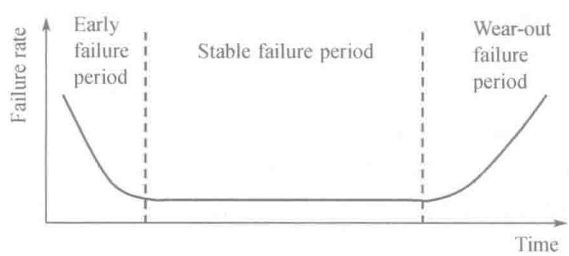

Figure 1.2 The bathtub curve

The bathtub curve consists of three periods:

(1) Early Failure Period

The beginning of a machine's useful life is usually characterized by a relatively high rate of failure and a gradual decline in the number of failures over time.

These failures are referred to as "wear-in" failures. This region is known as the Early Failure Period (also referred to as **Infant Mortality Period**, **Burn-In Period**, **Break-In Period**, or **Debugging Period**).

They are typically due to such things as design errors, manufacturing defects, assembly mistakes, installation problems and commissioning errors.

The remedial actions in this period could be debugging, running-in, replacing the components with defects. As the causes of these failures are found and corrected, the frequency of failure decreases.

(2) **Stable Failure Period**

Once the early failures have been eliminated, the failure rate stabilizes at an extremely low level, but latent failures may reveal themselves at random over a long time and thus their number does not decline to zero. The failures that do occur mainly happen randomly or unpredictably, and the failure rate is almost constant.

This period of a machine's life is called the **Stable Failure Period** (also called the **Normal Wear Period, Random Failure Period or Intrinsic Failure Period**) and usually makes up most of the life of a machine. There should be a relatively low failure rate during the normal wear period when operating within design specifications. The constant failure rate level is called the **Intrinsic Failure Rate**.

Some of the causes of failures in this region include insufficient design margins, incorrect use environments, undetectable defects, human error and abuse, and unavoidable failures (i. e., ones that cannot be avoided by even the most effective preventive maintenance practices).

(3) **Wear-out Failure Period**

As a machine gradually reaches the end of its designed life, the frequency of failures again increases. This is the **Wear-out Failure Period**. These failures are called "wear-out" failures.

This gradually increasing failure rate at the expected end of a machine's useful life is primarily due to metal fatigue, wear mechanisms between moving parts, corrosion, inadequate or improper preventive maintenance, limited-life components and incorrect overhaul practices.

Wear-out period failures can be reduced significantly by executing effective replacement and preventive maintenance policies and procedures.

The bathtub curve is often modeled by a piecewise set of three hazard functions:

$$y(t)=\begin{cases} c_0-c_1t+\lambda, & 0\leqslant t\leqslant c_0/c_1 \\ \lambda, & c_0/c_1<t<t_0 \\ c_2(t-t_0)+\lambda, & t_0<t \end{cases} \tag{1.1}$$

While the bathtub curve is useful, not every product or system follows a bathtub curve hazard function. There are at least six different failure patterns that equipment might experience (see Figure 1.3):

Pattern A—Bathtub: Infant mortality, then a constant or increasing failure rate, followed by a distinct wear-out zone.

Example: overhauled reciprocating engine.

Pattern B—Traditional Wear-out: Constant or slowly increasing failure rate followed by a distinct wear-out zone.

Example: reciprocating engine, pump impeller.

Pattern C—Gradual Rise with no Distinctive Wear-out Zone: Gradually increasing failure rate, but no distinct wear-out zone.

Example: gas turbine.

Pattern D—Initial Increase with a Leveling off: Low failure rate initially, then a rapid increase to a constant failure probability.

Example: complex equipment under high stress with test runs after manufacture or restoration such as hydraulic systems.

Pattern E—Random Failure: Constant failure rate in all operating periods (random failure).

Example: roller/ball bearings.

Pattern F—Infant Mortality: High infant mortality followed by a constant or slowly rising failure rate.

Example: electronic components.

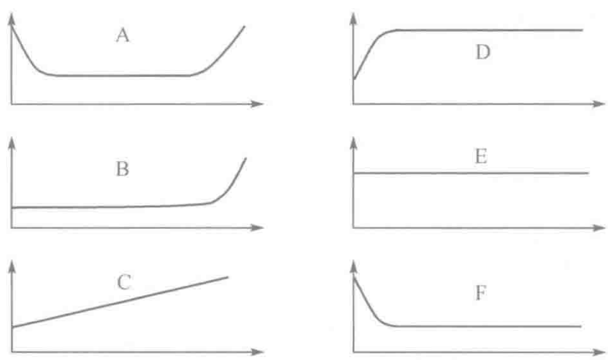

Figure 1.3 Six different failure patterns

1.1.4 Human Error in Shipping

A modern ship is comprised of many elements (systems), each of which has a varying degree of effect on the overall performance of that ship. Over the last 40 years or so, the shipping industry has focused on improving ship structure and the reliability of ship systems in order to reduce casualties and increase efficiency and productivity. Today's ship systems are technologically advanced and highly reliable. Yet, the maritime casualty rate is still high. Why?

It is because vessel is a typical integrative system of marine machinery and seafarers. The integrated reliability of a vessel consists of the intrinsic reliability of marine machinery and ship's hull and the reliability of seafarers. The ship structure and system reliability are a relatively small part of the safety equation. Although many of these systems may be fully automated, they still require a degree of human intervention (e.g., set initial tolerances or respond to alarms). Also, the nonautomated systems may require direct human inputs for their operation and maintenance, humans to interact with other humans, etc. The maritime system is a *people* system, and human errors figure prominently in casualty situations. Needless to say, as humans are not one hundred percent reliable, the past experiences indicate that in the shipping industry around 80% of all accidents are rooted in human error.

Human error may be defined as the failure to perform a specified task (or the performance of a forbidden action) that could lead to disruption of scheduled operations or result in damage to property and equipment. Human error may be classified into six categories: design, assembly, inspection, installation, operation, and maintenance.

There are various consequences of human error. They may vary form one task to another or one set of equipment to another. Furthermore, a consequence can range from minor to severe (e.g., from a short delay in system performance to a major loss of property and lives).

Often, a deficiency in engineering ethics is found to be one of the root causes of an engineering failure, and human errors are often blamed on "inattention" or "mistakes" on the part of the operator. However, an accident generally occurs as a result of a combination of multiple causes, and these human errors are also symptomatic of deeper and more complicated problems in the total maritime system. The three largest problems were fatigue, inadequate communication and coordination, and inadequate technical knowledge. Others include faulty standards, policies, or practices, poor maintenance and organization, poor environment, poor design, lack of situation awareness and complacency.

1.2 Maintenance

Maintenance is defined as a set of organized activities that are carried out in order to keep an item in its best operational condition with minimum cost required.

Maintenance has a greater purpose than simply looking after plant and machinery. If that was all that was necessary then maintainers would only ever fix equipment and do servicing. In today's competitive world, maintenance has grown into the need to manage plant and equipment over the operating life of a business' asset. It is seen as a subset of Asset Management, which is the management of physical assets over the whole life cycle to optimize operating profit.

There are at least six key factors required of maintenance to achieve its purpose of helping to get optimal operating performance. These are to reduce operating risk, avoid plant failures, provide reliable equipment, achieve least operating costs, eliminate defects in operating plant and maximize production.

Maintenance strategies can be divided into two major categories: **preventive** and