<u>ISTANBUL TECHNICAL UNIVERSITY ★ FACULTY OF AERONAUTICS AND ASTRONAUTICS</u>

PROACTIVE AND PREDICTIVE MAINTENANCE

GRADUATION PROJECT

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Department of Aeronautical Engineering

Thesis Advisor: Dr. Cemil KURTCEBE

JULY, 2020

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To my family,

FOREWORD

Aviation history is written in blood. Therefore, various measures have been taken to prevent further bloodshed and have been developed and applied from past to present. Security and safety in aviation are the most important factors. For this reason, aircraft should be constantly monitored, except for regular maintenance. These monitoring methods are called predictive maintenance. In my thesis, the development of maintenance from past to present, the types of maintenance and the authorities that provide various controls are explained and what preventive maintenance is and what techniques are it.

I would like to thank my counselor, Dr Cemil Kurtcebe, who has guided me in the process of determining the topic of the thesis, and has not withheld his tolerance and help. Also, I would like to thank Mr. Emrah Usta, who is my chief at Turkish Tecnic, and my colleague, Mr. Yücel Özer, for their knowledge and experience in maintenance, for enlightening me during the thesis process and for helping in determining the thesis topic. I would like to extend my thanks to my family and Esin İpek, who have always been with me during this process.

July 2020 Rüstem YENİLMEZ

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ABBREVIATIONS

AC	**:** Aircraft
AD	**:** Airworthiness Directive
AMM	**:** Aircraft Maintenance Manuel
AOG	**:** Aircraft On Ground
APU	**:** Auxiliary Power Unit
ATA	**:** Ait Transportation Association
CAP	**:** Capability
CDCCL	**:** Critical Design Configuration Control Limitation
CSB	**:** Component Service Bulletin
EASA	**:** European Aviation Safety Agency
ECAC	**:** European Civil Aviation Conference
EO	**:** Engineering Order
FAA	**:** Federal Aviation Agency
FAR	**:** Federal Aviation Rules
FC	**:** Flight Cycle
FH	**:** Flight Hour
FOD	**:** Foreign Object Damage
ICAO	**:** International Civil Aviation Organization
IPC	**:** Illustrated Part Catalogue
ITEM	**:** Illustrated Tool Equipment List
JAA	**:** Joint Aviation Authority
LRU	**:** Line Replacable Unit
M/H	**:** Man Hour
MEL	**:** Minimum Equipment List
MOE	**:** Maintenance Organization Exposition
MRO	**:** Maintenance and Repair Organization
MSG	**:** Maintenance Steering Guide
SB	**:** Service Bulletin
SHGM	**:** Sivil Havacılık Genel Müdürlüğü
SL	**:** Service Letter
SRM	**:** Structural Repair Manual
TC	**:** Task Card
WDM	**:** Wiring Diagram Manual

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PROACTIVE AND PREDICTIVE MAINTENENCE

SUMMARY

Maintenance costs are a major part of the total operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent between 15 and 60 percent of the cost of goods produced. For example, in foodrelated industries, average maintenance costs represent about 15 percent of the cost of goods produced, whereas maintenance costs for iron and steel, pulp and paper, and other heavy industries represent up to 60 percent of the total production costs.

These percentages may be misleading. In most American plants, reported maintenance costs include many nonmaintenance-related expenditures. For example, many plants include modifications to existing capital systems that are driven by market-related factors, such as new products. These expenses are not truly maintenance and should be allocated to nonmaintenance cost centers; however, true maintenance costs are substantial and do represent a short-term improvement that can directly impact plant profitability. Recent surveys of maintenance management effectiveness indicate that one-third—33 cents out of every dollar—of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. When you consider that U.S. industry spends more than $200 billion each year on maintenance of plant equipment and facilities, the impact on productivity and profit that is represented by the maintenance operation becomes clear.

The result of ineffective maintenance management represents a loss of more than $60 billion each year. Perhaps more important is the fact that ineffective maintenance management significantly affects the ability to manufacture quality products that are competitive in the world market. The losses of production time and product quality that result from poor or inadequate maintenance management have had a dramatic impact on U.S. industries'ability to compete with Japan and other countries that have implemented more advanced manufacturing and maintenance management philosophies.

The dominant reason for this ineffective management is the lack of factual data to quantify the actual need for repair or maintenance of plant machinery, equipment, and systems. Maintenance scheduling has been, and in many instances still is, predicated on statistical trend data or on the actual failure of plant equipment. Until recently, middle- and corporate-level management have ignored the impact of the maintenance operation on product quality, production costs, and more important, on bottom-line profit. The general opinion has been "Maintenance is a necessary evil" or "Nothing can be done to improve maintenance costs." Perhaps these statements were true 10 or 20 years ago, but the development of microprocessor- or computerbased instrumentation that can be used to monitor the operating condition of plant equipment, machinery, and systems has provided the means to manage the maintenance operation. This instrumentation has provided the means to reduce or eliminate unnecessary repairs, prevent catastrophic machine failures, and reduce the negative impact of the maintenance operation on the profitability of manufacturing and production plants.

1. INTRODUCTION

Predictive maintenance is not a substitute for the more traditional maintenance management methods. It is, however, a valuable addition to a comprehensive, totalplant maintenance program. Where traditional maintenance management programs rely on routine servicing of all machinery and fast response to unexpected failures, a predictive maintenance program schedules specific maintenance tasks as they are actually required by plant equipment. It cannot eliminate the continued need for either or both of the traditional maintenance programs (i.e., run-to-failure and preventive). Predictive maintenance can, however, reduce the number of unexpected failures and provide a more reliable scheduling tool for routine preventive maintenance tasks. The premise of predictive maintenance is that regular monitoring of the actual mechanical condition of machine-trains and operating efficiency of process systems will ensure the maximum interval between repairs; minimize the number and cost of unscheduled outages created by machine-train failures; and improve the overall availability of operating plants. Including predictive maintenance in a total-plant management program will optimize the availability of process machinery and greatly reduce the cost of maintenance. In reality, predictive maintenance is a condition-driven preventive maintenance program. The benefits that are derived from using predictive maintenance technologies depend on the way the program is implemented. If the predictive maintenance program is limited to preventing catastrophic failures of select plant systems, then that is the result that will be derived; however, exclusive focus on preventing failures may result in a substantial increase in maintenance costs. For example, a large integrated steel mill was able to reduce unscheduled machine failures by more than 30 percent, but a review of maintenance costs disclosed a 60 percent increase. When used properly, predictive maintenance can provide almost unlimited benefits; however, when the scope of the program is artificially limited by the scope or work or restrictions imposed by the plant, the benefits may be substantially reduced.

2. CIVIL AVIATION AUTHORITIES

2.1 JAA

JAA, of which Turkey is a member, is within the body of ECAC; is an organization created to provide standardization in flight safety, aircraft design, production and certification, meeting the airworthiness requirements, aircraft maintenance and operation. Our country also contributes to the efforts to develop and expand the legislation and policies that this organization has established for the establishment of a safe and common civil aviation network on an international platform, under equal competitive conditions.

JAA's activities date back to 1970. The original purpose of the organization, which at that time was called "Joint Airworthiness Authorities", was only to prepare common certification codes of the goods produced by the Avripa Industry for wide body aircraft and engines, especially to meet the needs of international consortia such as Airbus. JAA membership is based on the original signing of the "JAA Agreement" signed in Cyprus in 1990.

The main purpose of JAA is to harmonize the civil aviation rules of the European countries' civil aviation rules in accordance with the ICAO standards, to facilitate the circulation of aircraft, aircraft components, and materials and maintenance personnel among European countries. It is also the creation of common flight safety rules and standards.

Written rules of this association are published as "Joint Aviation Requirements". However, it is not compulsory for all countries that are members of the union to comply with these common aviation rules and it is possible to make different practices in line with the opinions of their national aviation organizations. In other words, JAA's rules do not have any legal sanction power. The Union also strives to ensure compliance of these rules with the US Civil Aviation rules, FAR "Federal Aviation Requirements". Directorate General of Civil Aviation on behalf of the Republic of Turkey, has been a full member of JAA 4 April 2001.

Many of the JARs were converted to IRs after the establishment of EASA. For example, Jar-21 becomes Part-21.

2.2 EASA

The formation of EASA is the final point in the demand that emerged in the European Industry in the 1969s. It all started in 1969 when leaders of the aviation industry understood the importance of cooperation for the future. The European Association of Aerospace Industries (AECMA) was promoted, and JAA was established in 1970 to adopt a common aviation compliance rules. Despite the successful expansion of the JAA system (maintenance, operation, licensing, etc.) and procedural improvements over time, a common system that would be valid across Europe by clearing aviation safety requirements from national differences could not be created in the desired form. The boundaries of JAA membership have expanded, and countries from many parts of the world have become members of JAA. In my opinion, the European Commission was appointed in March 2000 for a new formation in which only the European Union countries will become a member due to Europe's superiority. At the end of this process, on 15 July 2002, EASA was adopted by the European Union council and parliament.

The main regulation aims to establish the competence of the European Union for aviation safety within the existing European Union trends and institutionalization and defines the general organization and duties of EASA. The main objective of the main regulation; To guarantee a high level of aviation safety in Europe. In addition, there are additional targets such as attaching importance to environmental protection, free movement of aviation products and people, improving costs, and supporting member countries.

Taking over the responsibility for the flight operations and the qualifications of the related personnel by EASA is also specified in the main regulation. On the other hand, a new decision of the European Parliament and the Council is needed to take over responsibility for air traffic control and the safety of airports in the long term.

The EASA board of directors is composed of representatives of the 25 European Union member states, the European Commission and the countries with observer status (Switzerland, Bulgaria, Romania). A group of professionals in compliance with the main regulation provides consultancy services to the board of directors. Sometimes, if decisions are controversial, opinions of independent experts are taken. The EASA headquarters is located in Cologne, Germany. The chairman of the board is Paul Riemens. Chief executive officer is Patrick Ky as executive director.Then there are 4 separate departments that work with rule making, certification, quality and standardization, and administrative division headings. AGNA (Advisory Group of National Authorities), which consists of representatives of countries, and SSCC (Safety Standard Consultative Committe), which is composed of representatives of relevant groups, supports the rules making.

2.2.1 Transition from JAA to EASA

EASA member countries; has taken over the authority to issue certificates on aviation products and organizations. In other words, since September 28, 2003, issues such as design, modification, repair, airworthiness order and approval of design organizations have been among the direct responsibilities of EASA. The European commission recommended that EASA's responsibilities be extended to include certification of airline operators in non-European countries. In the transition process, EASA relies on the support of the civil aviation authorities of the countries until they form my own expertise and do these tasks properly. EASA has joined the JAA system, which will continue its development work on operations and team licensing until these issues are taken over by EASA in the future, and will represent the European Union member countries in the JAA organization. JAA member countries will also accept EASA certifications and adopt the same rules to prevent two headings. According to the agreement between the two organizations, EASA will benefit from JAA's expertise and experience. Another important difference of the new system from the old JAA system is that the member states cannot deviate from the common rules, cannot establish additional rules and cannot make agreements with third countries. The main regulation states that the EASA budget will be financed with the assistance from the European Union and the money received from applicants on certification and similar matters. During the first 4 years, the pricing system will be constantly under scrutiny for the correct determination of how much fee will be received from the applications, and the prices of the next year will be determined by studies that will be carried out by considering various parameters every year.

2.3 FAA

FAA is the national civil aviation authority of the USA. It concerns Turkish operators and maintenance organizations in terms of permits to be taken for flights to the USA and maintenance powers for maintenance operations to be carried out on US registered aircraft and similar issues. In 1992, FAA launched a program in which all foreign airlines carrying passengers to the USA evaluate their countries in terms of compliance with international operating and maintenance standards known by ICAO. This program is called "International Aviation Safety Assessment" (IASA). In these audits, the dominance of the civil aviation authority of the country concerned is evaluated. According to the applicable US law, the countries to which the organizations that wish to air transport to the USA are affiliated must apply to the US Department of Transportation (DOT) in order to obtain permission under the Federal Aviation Act. (This law has been re-coded as 49 USC 41302.) Sections 211 and 302 of DOT's economic rules describe the conditions for flight permits to the United States. Certain safety rules to be followed on flights to the United States in accordance with international law are described in 14 CFR Part 129 published by FAA. The 14 CFR Part 129 states that the carrier's Chicago Convention that wishes to carry passengers to the US must meet the safety standards set out in Annex 6 part 1.

2.4 ICAO

As a result of the studies carried out in Chicago in November 1944, in order to make general arrangements for the solution of political and technical problems that occurred in air transportation after World War II; "Chicago Convention on International Civil Aviation", prepared by representatives of 52 countries, opened the signature of countries in Washington on December 7, 1944.

The purpose of the agreement, also known as the Chicago Convention, is stated in the introduction section; Agreeing on certain arrangements in order for international civil aviation to develop safely and regularly and civil aviation services to be registered on equal opportunities basis and to operate in a sound and economical manner.

In order to achieve the main purpose stated above with article 43 of the mentioned agreement, the establishment of the "International Civil Aviation Organization" ICAO is envisaged; Until the permanent structure was created, the way of working with the name PICAO (Permanent ICAO) was adopted. After 20 months of PICAO, ICAO officially became operational on April 4, 1947, and Montreal was chosen for its headquarters at the invitation of the Canadian government.

ICAO's expenses are mainly covered by the contributions of the member countries. Turkey became a party to the agreements referred to in Law No. 4749 and June 5, 1945 date. As of today, the number of countries that are members of ICAO has reached 193. The objectives of ICAO, set out in Article 44 of the Chicago Convention, are summarized below.

- To ensure safe and regular development of international civil aviation worldwide,
- To support the development and operation of aircraft for peaceful purposes,
- To ensure the development of air corridors, airports and navigation patterns for international civil aviation,
- To meet the needs of the world public for safe, regular, sufficient and economical air transportation,
- To prevent waste of unreasonable competition from economic reasons,
- To fully protect the rights of the country parties and to provide suitable opportunities for each of the countries on international airline management,
- Not to make any difference between the countries,
- To guarantee flight safety in international air navigation.

2.5 SHGM

The first aviation works in our country started in 1912 in Sefaköy, near the present Atatürk Airport, as a facility in 2 Hangars and a small square. The institutional foundations of Turkish civil aviation were laid with the “Turk Tayyare Cemiyeti”, which was founded in 1925 and became the “Turk Hava Kurumu” in the following years.

The first civil air transport was launched in 1933 with a small fleet of 5 aircraft under the name "Turk Hava Postaları ". In the 10th year of our Republic, established under the Ministry of Defense "Havayolları Devlet İşletme İdaresi" to establish civil air transport routes in Turkey and has been appointed to do. In the face of the rapid development of world civil aviation, the great progress in technology, the " Sivil Havacılık Dairesi Başkanlığı" established in the Ministry of Transport in 1954, in order to maintain and maintain our international relations on a regular basis, as the " Sivil Havacılık Genel Müdürlüğü" in 1987, has been reorganized according to. SHGM, which was the main service unit of the Ministry of Transport until November 18, 2005, became financially special by the law about the SHGM organization and its duties, which came into force on this date, and reached its current management structure.

Today, aviation activities in our country are carried out within the framework of the " Türk Sivil Havacılık Kanunu" numbered 2920 and " İdari ve Teknik Yönetmelikler ve Havacılık Talimatları" published in this context.

Our country has become a member of various international organizations in order to follow the international aviation developments closely and to fulfill the requirements of the era in the aviation industry that requires advanced technology and has no borders. Our country became a party to "Chicago Convention on International Civil Aviation", which is the basis of international civil aviation, in 1945 and was among the founding members of ICAO. Our country, which was a founding member of ECAC in 1956, is also a member of EUROCONTORL in the European region. Apart from these, our country, which has various organizations at the regional level, continues its aviation activities in accordance with national and international legislation.

3. REGULATONS

3.1 EASA Part-145

The purpose of this regulation is to regulate the qualifications and procedures and principles regarding the activities that public institutions and organizations and enterprises belonging to real and legal persons should have as an approved maintenance institution for all types of civil aircraft. This regulation covers organizations authorized to provide maintenance services for all types of civil aircrafts or components used in commercial air transport, as well as managers and personnel working in these organizations.

3.2 EASA Part-M

The European Aviation Safety Agency (EASA) is an agency of the European Union with responsibility for civil aviation safety. It carries out certification, regulation, and standardization, and performs investigation and monitoring. It collects and analyses safety data, drafts and advises on safety legislation, and coordinates with similar organizations in other parts of the world.

The objective of EASA Part M is Continuing Airworthiness Requirements. Part M concerns specifically the continuing airworthiness of aircraft and aeronautical products, parts and appliances together with the approval of organizations and personnel involved in these tasks.

3.3 EASA Part-21

That part of the Federal Aviation Administration (FAA)/JARs/European Aviation Safety Agency (EASA) Regulatory System which deals with the approval of aircraft design and production organisations and certification of aircraft, products and related parts.

3.4 EASA Part-66

The European Aviation Safety Agency Implementing Rule (IR) Part 66 is the aviation regulation which defines the conditions by which a maintenance engineer is able to gain (through a company approval) authorisation to work on, certify and release an aircraft into service after a maintenance operation. Licensed engineers are allowed to certify the work that has been carried out on an aircraft and return it to service. There are several categories of licenses which cover different levels and disciplines and a variety of routes exist to achieve them.

4. AIRCRAFT MAINTENANCE AND HISTORY

4.1 Aircraft Maintenance

Maintenance is carried out to repair, restore, fully restore or operate the aircraft's parts, components, systems or integrity; It is the general name given to the activities that consist of works such as service, repair, modification, revision, inspection and due diligence.

If the concept of maintenance is handled on a plane basis; When an aircraft is delivered to an operator, it has been designed and certified to meet basic flight availability and safety rules. The main purpose of the maintenance is to keep the aircraft's performance and reliability within the design limits specified after delivery. For this, it is mandatory to establish and implement an appropriate maintenance program as per the rules. The maintenance program is the program that should be followed in relation to aircraft structure, systems, components and engines, which will ensure that an aircraft designed to carry passengers from one point to another point at a certain level of comfort and reliability, can be kept constantly in flight conditions.

Authorities, aircraft manufacturers and manufacturers of aircraft components, aircraft operators have a say and responsibility in the creation and continuous development of maintenance programs. Aircraft manufacturers are fully responsible for aircraft type certification and product certification alone, design descriptions, and initial MSG-3 analysis drafts. The aircraft operator is obliged to maintain or maintain an acceptable level of aircraft and systems.

4.2 Maintenance History

Aircraft maintenance programs were developed and implemented by technicians in the early aviation history. Because a thought of preventive maintenance to prevent malfunctions in flight did not develop, the technicians determined the requirements for maintenance according to their own experience. Therefore, maintenance programs were quite simple and did not contain analytical elements and were shaped within the framework of the value judgments of technicians.

With the development of the airways that allow new and safe air transport, regulations and the authorities that are the implementers of these regulations started to emerge. Aviation authorities have become not only rule-making, but also institutions that control the reliability and safety of aircraft.

The introduction of large jet planes such as the Boeing 707 and DC-8 drew public attention to the need for safer and more reliable aircraft. From this point on, the program describing how to maintain aircraft has started to be shaped by the company that produces the aircraft. With the intended safety and reliability, the aircraft maintenance concept emerged as replacing and servicing each component at specific time intervals. "As you change more parts, more maintenance is done, making planes safer." philosophy was adopted. After the 1960s, the FAA began to worry more due to the numerous failures in flight and the low reliability of some engine types. A team of representatives from the FAA and aerospace industry realized that planned maintenance had less than anticipated benefit on aircraft engine reliability as a result of their research. The results found revealed the on condition maintenance type to be described in MSG-1/2.

Airplane operation and airline management have reached such a point since the 1970s; The fundamentals of aircraft maintenance have been radically changed to enable the cost discipline needed to survive. We can examine the costs of aircraft operation, purchase costs, direct operation costs, indirect operation costs in three main items. When analyzed based on a long period, it can be seen that the operating expenses are the largest and the most cost-effective group.

Operation expenses can be reduced to 6 categories. These; insurance, rent or depreciation, fuel, team, indirect and direct maintenance expenses. Among these, direct maintenance costs constituted the largest item in the 1970s. As of today, the increase in fuel costs has forced deregulation operators and aircraft manufacturers to develop a new maintenance approach to reduce costs. Due to the differences between the care organizations, indirect care expenses can be very variable. On the other hand, direct maintenance expenses of an airplane are seen as a more systematic and controllable cost item. These expenses are divided into planned and unplanned maintenance expenses, and each category is examined separately for aircraft and engines. Maintenance expenses, which can be examined as materials and workmanship in all categories, can be divided into a wide range of sub-units such as the hour of labor or the cost of labor per flight, the cost of material per flight.

When the airline costs are analyzed historically, the change in direct operating expenses is remarkable. 1960-70-80s draw an increasing graph in terms of fuel costs. When the maintenance expenses are examined in the same time interval, it is observed that the trend is downward. This decline is due to the airways aggressively combating inefficiency in aircraft maintenance. In the 1990s, with the production of a new and efficient aircraft engine and a decrease in fuel prices, fuel costs also tended to decrease; The decrease in maintenance costs also maintained its decreasing direction. When we examine the recent history of aviation, the maintenance schedules of civilian passenger aircraft, and hence the maintenance concepts, met many important concepts.

Maintenance programs applied to airplanes come into force with the approval of the civil aviation authority of the country in which the user is located, in line with the rules and principles stated in the maintenance inspection report and maintenance planning documents published by the aircraft manufacturer and approved by the civil aviation authority of the country where the aircraft is manufactured. Maintenance types and periods to be applied to the aircraft are determined in the maintenance program. The duration of the content of the applied maintenance depends on the type of aircraft under maintenance and the flight time. Regardless of where and how long they are applied, some concepts are generally considered in maintenance practices. These concepts are "hard-time, on-condition and condition monitoring".

In condition monitoring concept, it goes without any planning until the part fails. The failure is given the opportunity to occur, so data is collected and feedback is given. There are no planned maintenance tasks. Any item remains in service until there is a functional malfunction and its reliability is examined by analysis and monitoring programs. The condition monitoring concept is a rarely used maintenance concept because there is not much feedback. It is a suitable maintenance concept for items that do not affect safety in case of malfunction and have high data collection convenience

.In 1968; MSG has developed a planned maintenance decision making process (MSG-1) that targets maximum safety and reliability at minimum cost. Overhaul and on-condition concepts were used in the development of the Boeing 747 planned maintenance program.

In 1970; ATA task force has revised the MSG-1 to include a new concept condition monitoring. The first maintenance programs of the L-1011 vs DC-10 were prepared on this basis.

In 1980; The ATA task force, consisting of authorities, aircraft and engine manufacturers, airlines and the American navy, addressed the shortcomings in MSG-2 and created MSG-3. In MSG-2 concept, all components are selected one by one and maintenance concepts such as hardime, on-condition or condition monitoring are written against them. In other words, the work to be done for all components was determined according to the approaches in these 3 maintenance concepts.

In MSG-3, go down the top, first examine on the basis of the component, and then go down to the lower parts if necessary, gradually go down to the sub-system and finally to the LRU level. There is no need to deal with too many details in MSG-3 with less number of tasks. There is no need to create a task for every little piece. Malfunctions are handled and examined individually. Issues such as whether the malfunction has an operational impact or possibly the consequences if any system malfunctions are being investigated. A task is created for each fault that will reveal this fault. The biggest feature of MSG-3 is the examination of direct faults. The maintenance task vent is given importance in MSG-3, not the maintenance process. In MSG-3, the result is a very detailed task. Because a certain malfunction is taken over and it explores how to fix it. In 1988, the ATA task force revised MSG-3 and made it more useful (MSG-3 Rev1). First maintenance programs of Boeing 777, MD-11 and Airbus A340 were developed. In 1993, ATA revised MSG-3 and included it in its corrosion prevention and control program. In 2001, general visibility and detailed control concepts were redefined with MSG-3 Rev 2001.1 and regional control concept was developed. In 2002; The MSG-3 Rev 2002.1 emphasized the importance of original parts manufacturer recommendations. Fault-tolerant system analysis and non-metal structure analysis were included. In 2003; With MSG-3 Rev 2003.1, failure-tolerant system analysis has been redefined and clarification of security systems and materials has been clarified.

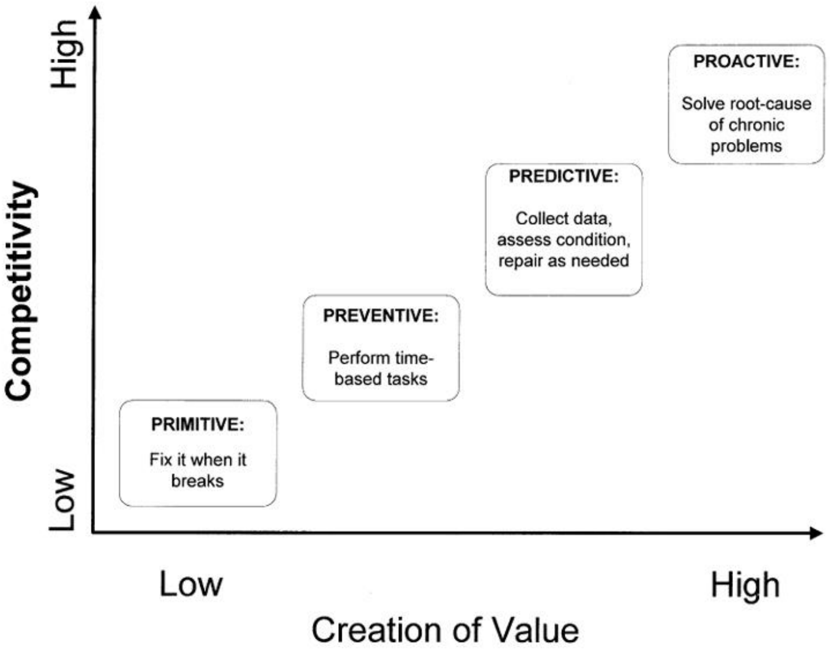


Figure 4.1: Evalution of Maintenance

4.2.1 Maintenance history in Turkey

The beginning of the civil aviation sector in Turkey is based on a Turkish Airlines aircraft maintenance was established May 20, 1933. Article 6 of the founding law for our national airlines established with the law numbered 2186 is as follows:

Article 6: All installations and documents of the State Operations Administration of the Airlines are repaired and repaired at the factories at the Ministry of National Defense, and are sold at the cost price of the spare materials and other military warehouses and warehouses that will be required. These prices are charged to the air budget off-balance chapter on one hand and the same chapter on the other hand. Salary and wages can be employed in this administration with the consent of the National Defense Representative, which is given from the air budget.

Since 1933, the maintenance of State Airlines planes has been carried out in two medium hangars and small workshops scattered around Güvercinlik Square in Ankara, while engine revisions of the planes have been carried out at the “Türk Kuşu Uçak Fabrikası” in Etimesgut. From the originally owned King Bird and ATH-9 aircraft, the maintenance business has been subjected to technology support by foreign companies that manufacture these aircraft, and has continued for a while. However, national facilities built over time have reduced the technical dependence abroad to boast. In the first years, our engineers and technicians trained in countries producing aircraft abroad carried out maintenance and repair works without the need for foreign support. Starting from 1955, maintenance was started in Yeşilköy with a team of 50-60 people.

After the technical department was moved to Yeşilköy, it was restored to new capacity and the technical efficiency in this matter has increased significantly. The Motor Workshop was put into service in 1963 as a new unit, and the electric and electronic workshop in 1972. In 1978, with a new hangar, Turkish Airlines became able to perform all kinds of technical maintenance at its own facilities.

It has become an international maintenance institution that carries out the maintenance of aircraft and components of third parties, apart from its own fleet, by increasing the maintenance capacity with the second hangar, which became operational in 2000. Turkish Airlines Technic, which has a large capacity with its campuses at Sabiha Gökçen and İstanbul Grand Airport, is among the world leaders. In addition, today we are at a time when myTECHNIC has a Turkish aircraft service that will meet the technical needs of Turkish civil aviation, and at the same time, its dependency on maintenance abroad is minimized with one of the region's largest aircraft maintenance and repair hangars, which is capable of maintaining and repairing 4 large-bodied, 8-small-bodied aircraft.

4.3 Maintenance Types

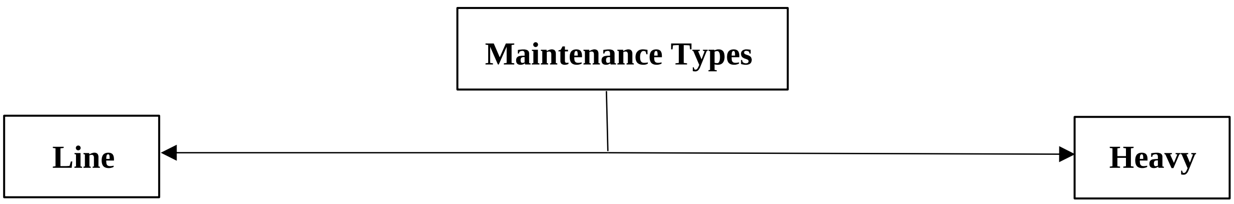


Table 4.1: Maintenance Types

4.3.1 Line maintenance

The line maintenance covers the removal, tooling and sometimes adjustment of external components and motor accessories, which we call LRU. Malfunctions occurring in the engine or components are tried to be eliminated by replacing or repairing these components. Line maintenance personnel are not authorized to interfere with the main parts of the engine or engine components. In addition, operations such as continuous monitoring of the engine, oil and fuel control, visual inspection, monitoring of engine performance are within the scope of the works to be performed by line maintenance personnel.

4.3.2 Heavy maintenance (Revision maintenance)

Revision maintenance includes disassembly, repair, assembly test of the component removed in line maintenance. In revision maintenance, the component is partially or completely removed. Each part is inspected and, if necessary, undergoes repair or testing. Rotating parts are rebalanced after repairs. After all these processes, the parts are given to the assembly. The components must be tested after the assembly process. Revision operations are carried out in revision workshops.

When a component arrives at the revision workshop, it is subjected to several operations depending on the level of failure. These transactions; testing, partial repair, HSI and complete overhaul.

When the engine or component arrives at the workshop, a report is made about the condition of the engine by performing checks such as initial testing, external control, measuring some pressure-vacuum values, oil chip control, rotating part damage control, and boroscope inspection. The transactions and procedures to be applied are determined according to the report issued. These processes are published under the name of workscope.

The engine is partially or completely disassembled to be overhaul until the detected fault area is reached. The dismantled parts are cleaned and prepared for control before passing various controls.

The cleaned parts are passed through some structural control methods according to the relevant manuals. These methods are; boroscope, magnetic particle inspection, FPI, ultrasonic inspection, x-ray inspection, eddy-current inspection. Visual inspection is sufficient for some parts. Some of the structural controlled or visual inspected parts need to be measured.

Parts that have been structurally and dimensionally checked and found active are placed in assembly by arranging an active label. Damaged parts are either repaired or scraped if the amount of damage is outside the repair limits. For parts that can be repaired, an inactive card and a repair form are issued. After these parts are repaired, the active card is also issued. It is not possible and economical for each business to repair every part itself. For this, some parts need to be repaired by organizations that are approved for repair by international civil aviation organizations. These organizations are the DGCA in Turkey, EASA in Europe, and the FAA in the United States. All transactions are made according to the official manuals of the manufacturer companies called vendors. Manuals are books that are subject to change when relevant and revised. Even if some parts are within the limit according to the structural and size control, they should be discarded because of life time.

Especially, rotating parts such as repaired parts, compressor impellers or turbine wheels should be balanced. According to the relevant official manuals, rotating parts are first balanced one by one. Then, these parts are assembled and balanced again in groups. Since gas turbines are high-speed engines, the smallest unbalance will appear as high vibration value during engine operation.

With new, inspected, or repaired active parts, the motor or component is collected again. The measurement clearances specified in the manuals are strictly followed during assembly. This compatibility is certified by technical controllers at various points.

The engine or component, whose repair or assembly is finished, is tested to see if it is doing its job properly. The tested engine or component is ready to be attached to the aircraft.

If the engine or Component is not to be attached to the aircraft immediately, it is stored after various protection methods are taken. Some of the preventive maintenance and storage measures such as protective oil injection to the fuel system, equipping the engine or component with various dehumidifiers, coating some electronic components with electrostatic protectors, and maintaining the amount of moisture in the storage environment.

4.4 Check Types

4.4.1 A check

A check is applied approximately every 400-600 flight hours or 200-300 cycles and varies depending on the aircraft type. It needs about 20-60 man-hours and is usually performed in the hangar. The realization of this control varies depending on the aircraft type, speed, or the number of hours since the last control. A check may be delayed by the airline if certain predefined conditions are met.

4.4.2 B check

B check is performed approximately every 6-8 months. Depending on the aircraft, it takes about 120-150 man-hours and is usually completed within 1-3 days in the airport hangar. A similar repeat schedule applies to control B as well as control A. However, B controls may be included in A controls consecutively.

4.4.3 C check

This is done approximately every 20–24 months or to a certain amount of actual flight time or as defined by the manufacturer. This maintenance check is much more comprehensive than B check and requires most of the aircraft components to be checked. This control leaves the aircraft out of service and is not taken into service until the aircraft is maintained. It also requires more space than A and B controls. Therefore, it is usually carried out in a hangar at a maintenance base. The time required to complete such a check is usually 1-2 weeks, and this effort may require 6,000 man-hours. It has many factors and components, and therefore varies by aircraft category and type.

4.4.4 D check

This is by far the most comprehensive and demanding control for an airplane. Also known as IL or "heavy maintenance visit" (HMV). This check is performed approximately every 6 years. D check where more or less aircraft are separated for inspection and overhaul. Even the paint may need to be completely removed for further inspection on the metal skin of the body. This type of control can usually take 50,000 man-hours and 2 months to complete depending on the aircraft and the number of technicians involved. It also requires the most space in all maintenance checks and should therefore be done on an appropriate maintenance base. The requirements and tremendous effort in this maintenance check make it the most expensive, and the total costs for a single visit result in a good range of million dollar.

Due to the nature and cost of such a check, most airlines especially those with a large fleet have to plan D checks for their aircraft years ago. Usually, old aircraft that are gradually removed from a specific airlines fleet are stored or scrapped after reaching the next D checks due to high costs compared to the aircrafts value. On average, a commercial airplane passes three D checks before retiring. Many MRO stores claim that it is almost impossible to profitably check D. For this reason, only a few of these shops offer D controls.

Given the time requirements of this control, many airlines use this opportunity to make large cabin modifications on the plane, otherwise it takes some time to decommission the aircraft without the need for control. This includes new seats, entertainment systems, carpets, etc. May be included.

4.4.5 Ramp check

By definition, a ramp check is surveillance of an airman, operator, or air agency during actual operations at an airport or heliport. It's conducted by FAA to ensure that you are conducting flights safely and in compliance with regulations. Although generally friendly and straightforward, some result in counseling or correction letters and in the worst case scenario, enforcement actions against the pilot.

A ramp check may occur when an inspector observes unsafe operations in a traffic pattern or ramp area or is notified by ATC of an unsafe operation. They can also occur randomly as part of FAA's normal surveillance. The latter is what is typical of most non-commercial ramp checks.

4.4.6 Transit check

Between flights, a line mechanic performs a transit check of the airplane at the airport ramp. This includes a walk-around inspection of the airplane for obvious damage, required servicing, correction of discrepancies, and operational tasks specified for the airplane. Qualified ground personnel or the flight crew performs a visual preflight walk-around of the airplane, and the flight crew completes a preflight checklist from the flight deck. Together, these precautions should help ensure the airworthiness of the airplane.

4.4.7 Daily check

The daily check, or service check, is performed after the last flight of the day and before the first flight the next day. This usually lasts for about 45 minutes per airplane, and a set of maintenance crew may have to inspect up to seven airplanes every night. The tasks involves the check of fire extinguishers (both in the cargo hold and engines), interior and exterior aircraft lights, cockpit annunciators, fault messages, exterior visual inspection for foreign object damage (FOD) and bird hits, hydraulic pumps for leakage, control surfaces, and wheels and tyres for wear. Part of the check is the downloading of the digital flight data recorder (DFDR), which gives a comprehensive time-stamped data log of every flight parameter, and every essential system that mandates monitoring. This DFDR data is sent to the flight safety department, where the data is analysed. Exceedences are detected, and the concerned flight crew are called for an enquiry if the exceedences are a concern and require justification.

4.5 Maintenance Classification

4.5.1 Unscheduled maintenance

Maintenance is a process that starts with the manufacture of a system, a machine. The concept of maintenance management may differ from business to business. The "run to failure" maintenance method can be used in enterprises where the maintenance concept is not developed. This understanding is the logic of repair when the system breaks down. This maintenance management is called unplanned maintenance. This method is a very expensive solution and it is a method that prevailed in ancient times. Today, the necessity and importance of planned maintenance is accepted by even the smallest and simplest businesses. Systems can become inoperable even if planned maintenance is performed. Because every substance has a lifetime. Planned maintenance and periods of failures will be diluted.

4.5.2 Scheduled maintenance

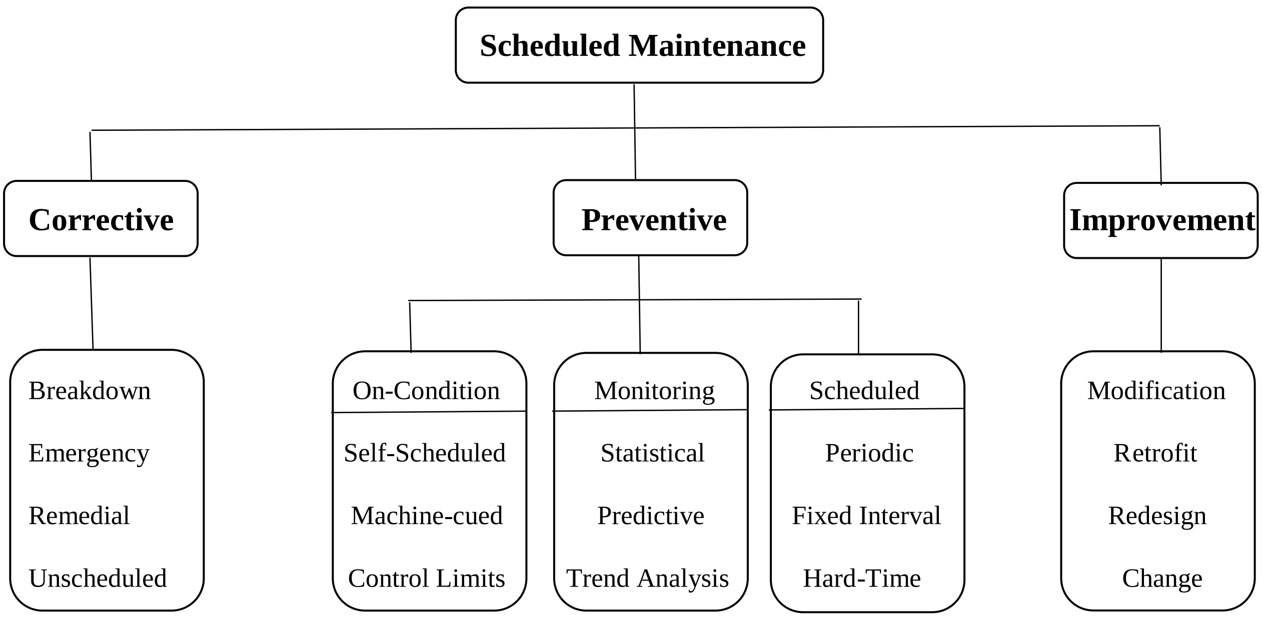


Table 4.2: Scheduled Maintenance

4.5.2.1 Improvement maintenance

In order to increase maintenance periods and increase component reliability, manufacturers are in constant research. Feasible ones from the research and development activities are put into use immediately. It is implemented in the form of improvement maintenance, modification, retrofit program and so on. It is an important phase and the cornerstone of care.

4.5.2.2 Corrective maintenance

Corrective maintenance is a whole set of operations after a malfunction or an incident. The aim of corrective maintenance is to bring the engine back to safe and healthy operation as soon as possible. How to do these corrective actions is done by looking at the relevant repair manuals. Special tools may be required for corrective maintenance. Corrective maintenance operations can be carried out by following the steps of servicing, repair and replacement of components, more complex repairs, repairs performed in private workshops, respectively.

4.5.2.3 Preventive maintenance

Preventive maintenance is a complete systematic process to keep the engine or component running with maximum safety. The maintenance program covers servicing and periodic maintenance. Servicing operations are; controls performed before the first flight of the day are pre-flight controllers, post-flight controls, the controls performed after the last flight of the day. Periodic controls are; This is a set of operations such as visual inspection at regular intervals, control of filters, chip control in magnetic plugs, taking oil and fuel samples for analysis.

The basis of preventive maintenance is “hardtime maintenance”, “on-condition and condition monitoring maintenance”. In time-based hard time maintenance, maintenance periods are carried out according to the time periods determined by the manufacturer and user enterprises. On-condition based maintenance is one of the wide maintenance method decisions of the method. It is a type of maintenance obtained by continuous monitoring of many data of the component or engine. By looking at the deviation values of the data, the engine or component is intervened long before the malfunction and the malfunction is eliminated. This saves considerable time and maintenance costs.

4.6 Maintenance Documents

Aircraft maintenance and troubleshooting operations are bound by international rules and it is clearly determined which documents will be used during these processes. Although two separate authorities (FAA-EASA) are dominant in world civil aviation, the rules they set and the documents they want to use are very similar in a day. Sometimes names or comments differ slightly.

Documents used in aircraft maintenance are:

Maintenance planning document: It is the document published by the manufacturer that includes how to plan maintenance for different aircraft models and which style cards should be applied during maintenance.

Aircraft maintenance manual (AMM): It is the document prepared and approved by the manufacturer for reference of every test and control performed on the aircraft during the line and upper maintenance. In some cases, revision may come. Operators should apply controls and tests to be applied on all types of aircraft on compenant and air frame control surfaces according to this document.

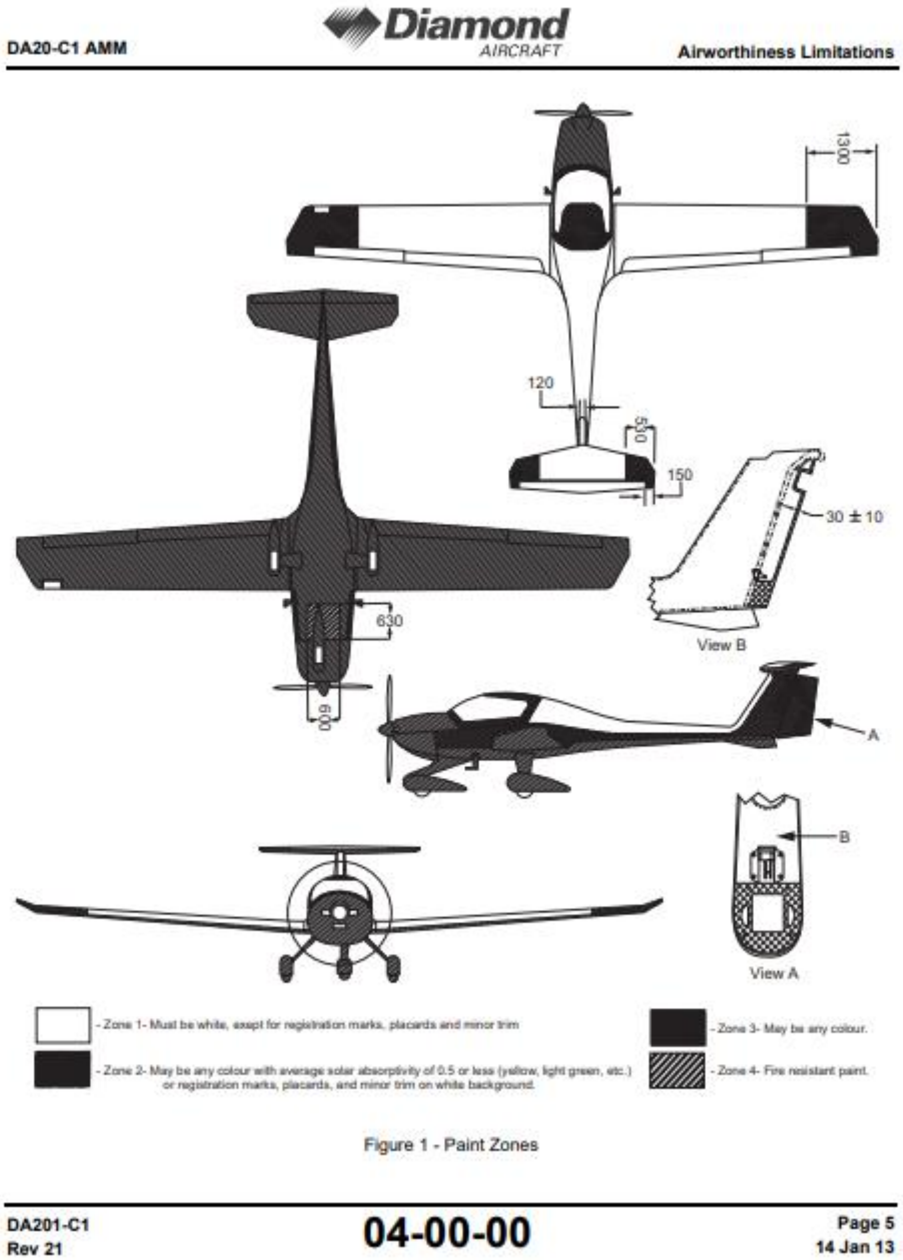


Figure 4.2: Aircraft Maintenance Manual

Task card (TC): It is the version of the work or controls to be performed on the aircraft as a template, taking AMM as reference.

Structural repair manual (SRM): Documents containing on-board repairs to be referenced in subjects such as lightning damage, bird strikes and cracks related to structural damages. Contains 51 to 57 ATA chapters.

American Airlines, Inc.

Date: 02/08/2006 : Time: 13:01:42
Software Release: 2.9.0 SP10 1024
REV 25, Nov. 10/2005

BOEING 737-800
Structural Repair Manual

GENERAL - Structural Classification

1. Applicability
   A. This subject is applicable to the primary and secondary structure of the airplane.
2. General
   A. This section gives the Principal Structural Elements (PSEs) and Secondary Structure of the airplane. This can be used to find the classification of major and minor repairs.
   B. Refer to Structural Classification Diagram, Figure 1/GENERAL for the classification of structures.
   C. Refer to Primary and Secondary Structures of the Airplane, Figure 2/GENERAL for the identification of the primary and secondary structures of the airplane.
      (a) Refer to the and tables that follow for the specified primary structures PSE and non-PSE components, and secondary structures:
         (1) Paragraph 5./GENERAL and Table 1/GENERAL - Doors
         (2) Paragraph 6./GENERAL and Table 2/GENERAL - Fuselage
         (3) Paragraph 7./GENERAL and Table 3/GENERAL - Nacelles and Pylons
         (4) Paragraph 8./GENERAL and Table 4/GENERAL - Stabilizers
         (5) Paragraph 9./GENERAL and Table 5/GENERAL - Wings
   D. The Principal Structural Elements (PSE's) given in this subject agree with the Maintenance Review Board Report (MRBR), Boeing Document M-7360-D541.

      NOTE: If the data between this SRM and the MRB Report is different, refer to the MRB Report over the SRM.

   E. Repairs to PSEs in the wing, nacelle and pylon structures as given in Table 3/GENERAL and Table 5/GENERAL are required to be evaluated for damage tolerance capability.

Figure 4.3: Structural Repair Manual

Illustrated part catalog (IPC): It is the document that expresses the part numbers by showing them with pictures and that will be looked and referenced when any part or component is to be changed on the plane. It tells you about the alternatives of parts, which aircraft can be used, the manufacturer, where to go for detailed information. It is published by the manufacturer like AMM and is one of the indispensable documents of aircraft maintenance.

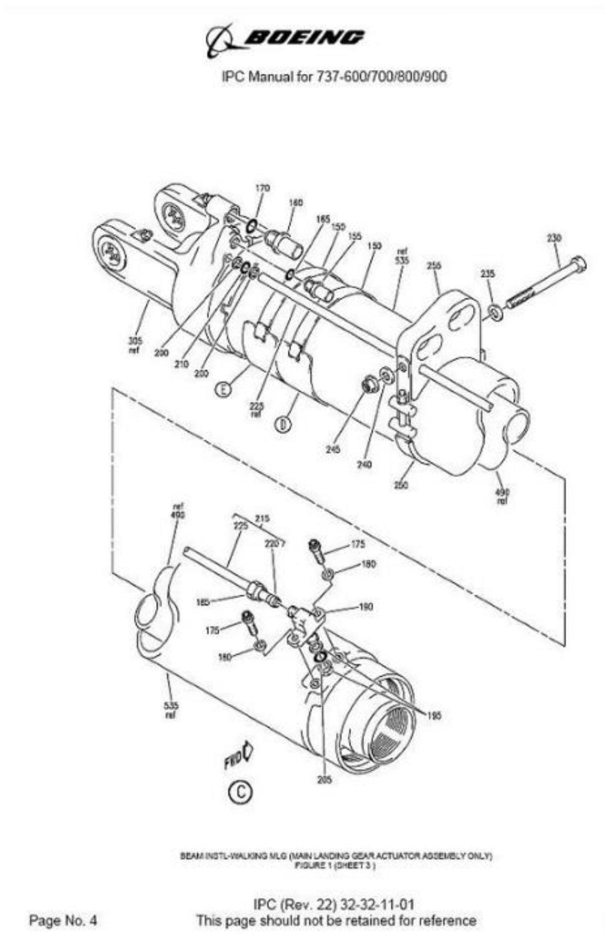


Figure 4.4: Illustrated Part Catalog

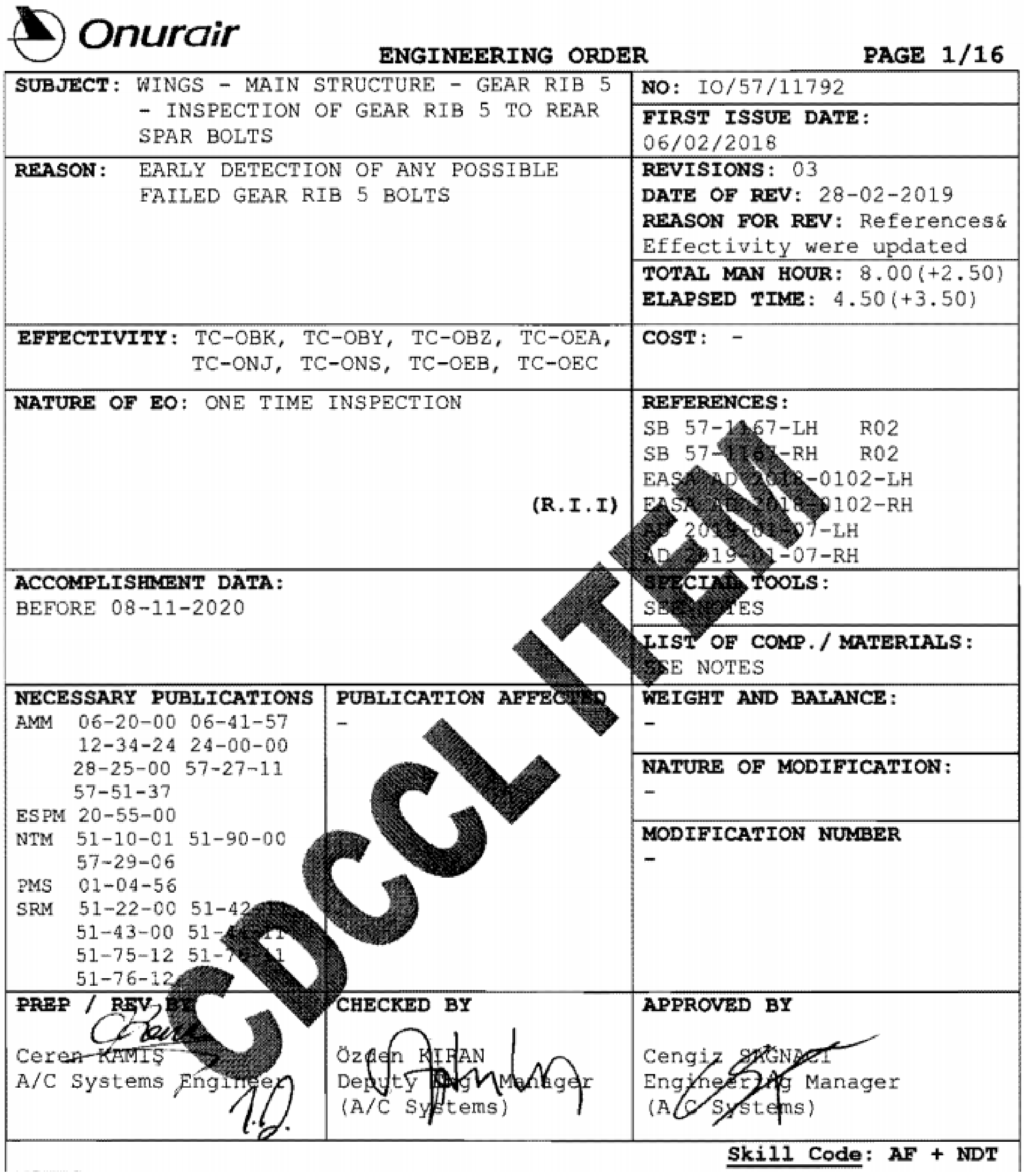
Ilustrated tool equipment list (ITEM): This document contains tools that make it easy to do some work during maintenance. It writes which tools should be used for which jobs in AMM. It also has the manufacturer and all the numbers in ITEM. It is a document prepared by the aircraft manufacturer.

Service bulletins (SB): Documents prepared by the manufacturer based on issues such as accident, feedback of the operators, design updates made, and are published by evaluating them with degrees such as mandatory or recommendation. It is directly related to the aircraft. In terms of application priority; it can be alert, recomended, desirable or optional.

Component service bulletin (CSB): Documents prepared by the manufacturer based on issues such as accident, feedback of the operators, design updates made, and are published by evaluating them with degrees such as mandatory, recommendation or recommendation. It is directly related to the component.

Service letters (SL): It is called minor SB. Producer publications and application requirements are strictly absent.

Engineering order (EO): SB, AD, SL based on the document based on simplification by the operator or MRO, followed by writing down for follow-up. It does not go beyond the documents it references.



Onurair

ENGINEERING ORDER PAGE 1/16

SUBJECT: WINGS - MAIN STRUCTURE - GEAR RIB 5 - INSPECTION OF GEAR RIB 5 TO REAR SPAR BOLTS		**NO:** IO/57/11792 **FIRST ISSUE DATE:** 06/02/2018
REASON: EARLY DETECTION OF ANY POSSIBLE FAILED GEAR RIB 5 BOLTS		**REVISIONS:** 03 **DATE OF REV:** 28-02-2019 **REASON FOR REV:** References& Effectivity were updated **TOTAL MAN HOUR:** 8.00(+2.50) **ELAPSED TIME:** 4.50(+3.50)
EFFECTIVITY: TC-OBK, TC-OBY, TC-OBZ, TC-OEA, TC-ONJ, TC-ONS, TC-OEB, TC-OEC		**COST:** -
NATURE OF EO: ONE TIME INSPECTION (R.I.I)		**REFERENCES:** SB 57-1167-LH R02 SB 57-1167-RH R02 EASA AD 2018-0102-LH EASA AD 2018-0102-RH AD 2019-01-07-LH AD 2019-01-07-RH
ACCOMPLISHMENT DATA: BEFORE 08-11-2020		**SPECIAL TOOLS:** SEE NOTES **LIST OF COMP./ MATERIALS:** SEE NOTES
NECESSARY PUBLICATIONS AMM 06-20-00 06-41-57 12-34-24 24-00-00 28-25-00 57-27-11 57-51-37 ESPM 20-55-00 NTM 51-10-01 51-90-00 57-29-06 PMS 01-04-56 SRM 51-22-00 51-42-[illegible] 51-43-00 51-[illegible] 51-75-12 51-7[illegible]1 51-76-12	**PUBLICATION AFFECTED** -	**WEIGHT AND BALANCE:** - **NATURE OF MODIFICATION:** - **MODIFICATION NUMBER** -
PREP / REV BY Ceren KAMIŞ A/C Systems Engineer	**CHECKED BY** Özden KIRAN Deputy Eng Manager (A/C Systems)	**APPROVED BY** Cengiz SAĞNAÇI Engineering Manager (A/C Systems)
		Skill Code: AF + NDT

CDCCL ITEM

Figure 1.5: Engineering Order

Airworthiness directives (AD): This is the document issued by the airworthiness authorities. It is the airworthiness directives that are mandatory to apply in a period of time.

Approved maintenance manual (AMP): It is the document that is approved by the airline or operator and is made by MPD. An airline must be approved when performing any MRO maintenance.

Wiring diagram manual (WDM): It is the document that shows where all the cables on the plane come from and which component is related.

Trouble shooting manual (TSM): It is a guiding manual for the troubleshooting of aircraft. It is published by the manufacturer in the light of experiences and feedback from airlines. It aims to eliminate the fault in the shortest time and in the most efficient way by revealing the most probable cause of the fault by evaluating the data of a fault. This manual is sometimes not a separate manual, but can be found in sections within AMM, or it can be used as a manual with a different name. For example, the name of Boeing aircraft is FIM (Fault Isolation Manual).

System schematics manual (SSM): It is the document that shows the general operation of aircraft systems and their relations with each other in schemes without going into much detail. Electrical information is predominant. It is very useful for system monitoring and fault solutions.

Master minimum equipment list (MMEL): It is the document that explains whether the aircraft can fly safely with an inactive system or equipment, and under what conditions and how long it can fly. It is prepared by the manufacturer and approved by the civil aviation authority of the country in which it is located.

Minimum equipment list (MEL): Master MEL'in müşteriye göre özel hale getirilmiş şeklidir. Bu dökümandaki şartlar Master MEL'den daha sıkı olabilir, ancak daha hafif ya da esnek olamaz. Uçağın uçurulduğu ülkenin sivil havacılık otoritesi tarafından onaylanır.

No technical objection (NTO): Sometimes the operator consults the manufacturer and asks for an opinion when there is a problem open to interpretation of the aircraft or engine. The experts of the manufacturer are examined in detail and the opinions of the manufacturer, including whether or not the aircraft can be flown, when and if so, and under what conditions. If the view is positive, this is an NTO. Regarding the engines, this article may be called CDR.

Configuration deviation list (CDL): It is the document that explains whether the aircraft can fly safely with missing parts or parts, what measures or processes should be available if it can fly, and what kind of restrictions may come. Sometimes it can be found together with DDPG (Dispatch Deviation Procedures Guide), and sometimes as a part in FM (Flight Manual).

5. PROACTIVE AND PREDICTIVE MAINTENANCE

5.1 Definition of Predictive Maintenance

Predictive maintenance has many definitions. To some workers, predictive maintenance is monitoring the vibration of rotating machinery in an attempt to detect incipient problems and to prevent catastrophic failure. To others, it is monitoring the infrared image of electrical switchgear, motors, and other electrical equipment to detect developing problems. The common premise of predictive maintenance is that regular monitoring of the actual mechanical condition, operating efficiency, and other indicators of the operating condition of machine-trains and process systems will provide the data required to ensure the maximum interval between repairs and minimize the number and cost of unscheduled outages created by machine-train failures.

Predictive maintenance is much more, however. It is the means of improving productivity, product quality, and overall effectiveness of manufacturing and production plants. Predictive maintenance is not vibration monitoring or thermal imaging or lubricating oil analysis or any of the other nondestructive testing techniques that are being marketed as predictive maintenance tools. Predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of plant equipment and systems to optimize total plant operation. Acomprehensive predictive maintenance management program uses the most costeffective tools (e.g., vibration monitoring, thermography, tribology) to obtain the actual operating condition of critical plant systems and based on this actual data schedules all maintenance activities on an as-needed basis. Including predictive maintenance in a comprehensive maintenance management program optimizes the availability of process machinery and greatly reduces the cost of maintenance. It also improves the product quality, productivity, and profitability of manufacturing and production plants. Predictive maintenance is a condition-driven preventive maintenance program. Instead of relying on industrial or in-plant average-life statistics (i.e., mean-time-to-failure) to schedule maintenance activities, predictive maintenance uses direct monitoring of the mechanical condition, system efficiency, and other indicators to determine the actual mean-time-to-failure or loss of efficiency for each machine-train and system in the plant. At best, traditional time-driven methods provide a guideline to “normal” machine-train life spans. The final decision in preventive or run-to-failure programs on repair or rebuild schedules must be made on the basis of intuition and the personal experience of the maintenance manager. The addition of a comprehensive predictive maintenance program can and will provide factual data on the actual mechanical condition of each machine-train and the operating efficiency of each process system. This data provides the maintenance manager with actual data for scheduling maintenance activities. Apredictive maintenance program can minimize unscheduled breakdowns of all mechanical equipment in the plant and ensure that repaired equipment is in acceptable mechanical condition. The program can also identify machine-train problems before they become serious. Most mechanical problems can be minimized if they are detected and repaired early. Normal mechanical failure modes degrade at a speed directly proportional to their severity. If the problem is detected early, major repairs can usually be prevented. Predictive maintenance using vibration signature analysis is predicated on two basic facts: all common failure modes have distinct vibration frequency components that can be isolated and identified, and the amplitude of each distinct vibration component will remain constant unless the operating dynamics of the machinetrain change. These facts, their impact on machinery, and methods that will identify and quantify the root cause of failure modes are developed in more detail in later chapters.

Predictive maintenance using process efficiency, heat loss, or other nondestructive techniques can quantify the operating efficiency of nonmechanical plant equipment or systems. These techniques used in conjunction with vibration analysis can provide maintenance managers and plant engineers with information that will enable them to achieve optimum reliability and availability from their plants. Five nondestructive techniques are normally used for predictive maintenance management: vibration monitoring, process parameter monitoring, thermography, tribology, and visual inspection. Each technique has a unique data set that assists the maintenance manager in determining the actual need for maintenance. How do you determine which technique or techniques are required in your plant? How do you determine the best method to implement each of the technologies? How do you separate the good from the bad? Most comprehensive predictive maintenance programs use vibration analysis as the primary tool. Because most normal plant equipment is mechanical, vibration monitoring provides the best tool for routine monitoring and identification of incipient problems; however, vibration analysis does not provide the data required on electrical equipment, areas of heat loss, condition of lubricating oil, or other parameters that should be included in your program.

5.2 Predictive Maintenance Techniques

Avariety of technologies can, and should be, used as part of a comprehensive predictive maintenance program. Because mechanical systems or machines account for most plant equipment, vibration monitoring is generally the key component of most predictive maintenance programs; however, vibration monitoring cannot provide all of the information required for a successful predictive maintenance program. This technique is limited to monitoring the mechanical condition and not other critical parameters required to maintain reliability and efficiency of machinery. It is a very limited tool for monitoring critical process and machinery efficiencies and other parameters that can severely limit productivity and product quality. Therefore, a comprehensive predictive maintenance program must include other monitoring and diagnostic techniques. These techniques include vibration monitoring, thermography, tribology, process parameters, visual inspection, ultrasonics, and other nondestructive testing techniques. This chapter provides a brief description of each of the techniques that should be included in a full-capabilities predictive maintenance program for typical plants. Subsequent chapters provide a more detailed description of these techniques and how they should be used as part of an effective maintenance management tool.

5.2.1 Vibration analysis and monitoring engine performance

Because most plants consist of electromechanical systems, vibration monitoring is the primary predictive maintenance tool. Over the past 10 years, most of these programs have adopted the use of microprocessor-based, single-channel data collectors and Windows based software to acquire, manage, trend, and evaluate the vibration energy created by these electromechanical systems. Although this approach is a valuable predictive maintenance methodology, these systems' limitations may restrict potential benefits.

Computer-based systems have several limitations. In addition, some system characteristics, particularly simplified data acquisition and analysis, provide both advantages and disadvantages.

While providing many advantages, simplified data acquisition and analysis can also be a liability. If the database is improperly configured, the automated capabilities of these analyzers will yield faulty diagnostics that can allow catastrophic failure of critical plant machinery. Because technician involvement is reduced to a minimum, the normal tendency is to use untrained or partially trained personnel for this repetitive function. Unfortunately, the lack of training results in less awareness and knowledge of visual and audible clues that can, and should be, an integral part of the monitoring program.

Most of the microprocessor-based vibration-monitoring systems collect singlechannel, steady-state data that cannot be used for all applications. Single-channel data are limited to the analysis of simple machinery that operates at relatively constant speed.

Although most microprocessor-based instruments are limited to a single input channel, in some cases, a second channel is incorporated in the analyzer; however, this second channel generally is limited to input from a tachometer, or a once-per-revolution input signal. This second channel cannot be used for vibration data capture.

This limitation prohibits the use of most microprocessor-based vibration analyzers for complex machinery or machines with variable speeds. Single-channel data acquisition technology assumes the vibration profile generated by a machine-train remains constant throughout the data acquisition process. This is generally true in applications where machine speed remains relatively constant (i.e., within 5 to 10 rpm). In this case, its use does not severely limit diagnostic accuracy and can be effectively used in a predictive maintenance program.

Most of the microprocessor-based instruments are designed to handle steady-state vibration data. Few have the ability to reliably capture transient events such as rapid speed or load changes. As a result, their use is limited in situations where these changes occur. In addition, vibration data collected with a microprocessor-based analyzer are filtered and conditioned to eliminate nonrecurring events and their associated vibraion profiles. Anti-aliasing filters are incorporated into the analyzers specifically to remove spurious signals such as impacts or transients. Although the intent behind the use of anti-aliasing filters is valid, their use can distort a machine’s vibration profile.

Because vibration data are dynamic and the amplitudes constantly change, as shown in Figure 5.1, most predictive maintenance system vendors strongly recommend averaging the data. They typically recommend acquiring 3 to 12 samples of the vibration profile and averaging the individual profiles into a composite signature. This approach eliminates the variation in vibration amplitude of the individual frequency components that make up the machine’s signature; however, these variations, referred to as beats , can be a valuable diagnostic tool. Unfortunately, they are not available from microprocessor-based instruments because of averaging and other system limitations.

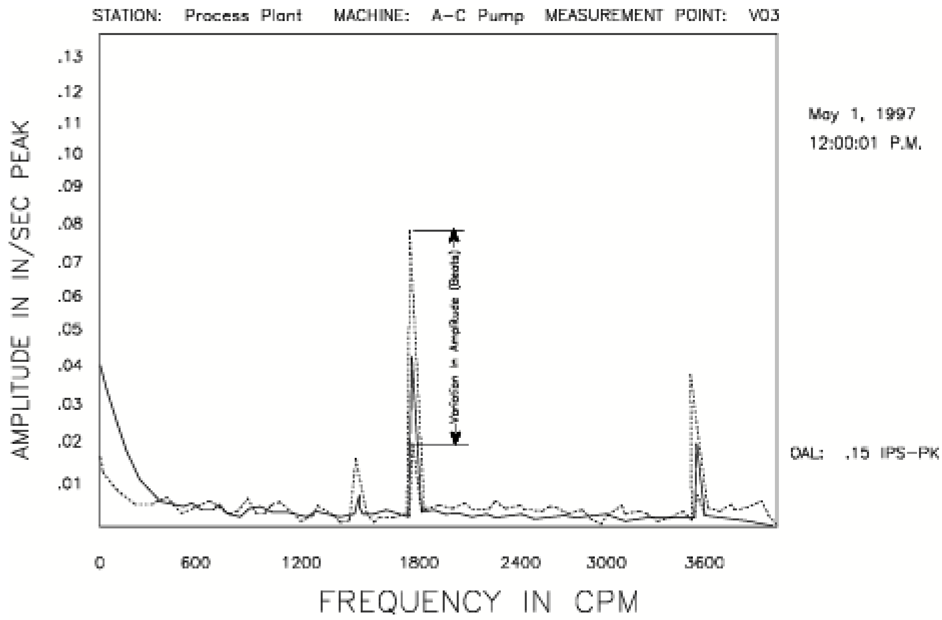


Figure 2.1: Frequency-Amplitude Graph

The most serious limitations created by averaging and the anti-aliasing filters are the inability to detect and record impacts that often occur within machinery. These impacts generally are indications of abnormal behavior and are often the key to detecting and identifying incipient problems.

Most predictive maintenance programs rely almost exclusively on frequency-domain vibration data. The microprocessor-based analyzers gather time-domain data and auto matically convert it using Fast Fourier Transform (FFT) to frequency-domain data. A frequency-domain signature shows the machine’s individual frequency components, or peaks.

While frequency-domain data analysis is much easier to learn than time-domain data analysis, it cannot isolate and identify all incipient problems within the machine or its installed system. Because of this limitation, additional techniques (e.g., time-domain, multichannel, and real-time analysis) must be used in conjunction with frequencydomain data analysis to obtain a complete diagnostic picture.

Many of the microprocessor-based vibration-monitoring analyzers cannot capture accurate data from low-speed machinery or machinery that generates lowfrequency vibration. Specifically, some of the commercially available analyzers cannot be used where frequency components are below 600 cycles per minute (cpm) or 10Hz.

Two major problems restricting the ability to acquire accurate vibration data at low frequencies are electronic noise and the response characteristics of the transducer. The electronic noise of the monitored machine and the “noise floor” of the electronics within the vibration analyzer tend to override the actual vibration components found in low-speed machinery.

Analyzers especially equipped to handle noise are required for most industrial applications. At least three commercially available microprocessor-based analyzers are capable of acquiring data below 600 cpm. These systems use special filters and data acquisition techniques to separate real vibration frequencies from electronic noise. In addition, transducers with the required low-frequency response must be used.

All machine-trains are subject to random, nonrecurring vibrations as well as periodic vibrations. Therefore, it is advisable to acquire several sets of data and average them to eliminate the spurious signals. Averaging also improves the repeatability of the data because only the continuous signals are retained.

Typically, a minimum of three samples should be collected for an average; however, the factor that determines the actual number is time. One sample takes 3 to 5 seconds, a four-sample average takes 12 to 20 seconds, and a 1,000-sample average takes 50 to 80 minutes to acquire. Therefore, the final determination is the amount of time that can be spent at each measurement point. In general, three to four samples are acceptable for good statistical averaging and keeping the time required per measurement point within reason. Exceptions to this recommendation include low-speed machinery, transient-event capture, and synchronous averaging.

Many of the microprocessor-based vibration-monitoring systems offer the ability to increase their data acquisition speed. This option is referred to as overlap averaging . Although this approach increases speed, it is not generally recommended for vibration analysis. Overlap averaging reduces the data accuracy and must be used with caution. Its use should be avoided except where fast transients or other unique machine-train characteristics require an artificial means of reducing the data acquisition and processing time.

When sampling time is limited, a better approach is to reduce or eliminate averaging altogether in favor of acquiring a single data block, or sample. This reduces the acquisition time to its absolute minimum. In most cases, the single-sample time interval is less than the minimum time required to obtain two or more data blocks using the maximum overlap-averaging sampling technique. In addition, single-sample data are more accurate.

Table 5.1 describes overlap-averaging options. Note that the approach described in this table assumes that the vibration profile of monitored machines is constant.

Overlap,%	**Description**
0	No overlap. Data trace update rate is the same as the block-processing rate. This rate is governed by the physical requirements that are internally driven by the frequency range of the requested data.
25	Terminates data acquisition when 75% of each block of new data is acquired. The last 25% of the previous sample (of the 75%) will be added to the new sample before processing is begun. Therefore, 75% of each sample is new. As a result, accuracy may be reduced by as much as 25% for each data set.
50	The last 50% of the previous block is added to a new 50% or half-block of data for each sample. When the required number of samples is acquired and processed, the analyzer averages the data set. Accuracy may be reduced to 50%.
75	Each block of data is limited to 25% new data and the last 75% of the previous block.
90	Each block contains 10% new data and the last 90% of the previous block. Accuracy of average data using 90% overlap is uncertain. Since each block used to create the average contains only 10% of actual data and 90% of a block that was extrapolated from a 10% sample, the result cannot be representative of the real vibration generated by the machine-train.

Table 5.1: Overlap Averaging Options

Perhaps the most serious diagnostic error made by typical vibration-monitoring programs is the exclusive use of vibration-based failure modes as the diagnostic logic. For example, most of the logic trees state that when the dominant energy contained in a vibration signature is at the fundamental running speed, then a state of unbalance exists. Although some forms of unbalance will create this profile, the rules of machine dynamics clearly indicate that all failure modes on a rotating machine will increase the amplitude of the fundamental or actual running speed.

Without a thorough understanding of machine dynamics, it is virtually impossible to accurately diagnose the operating condition of critical plant production systems. For example, gear manufacturers do not finish the backside (i.e., nondrive side) of gear teeth. Therefore, any vibration acquired from a gear set when it is braking will be an order of magnitude higher than when it is operating on the power side of the gear.

Another example is even more common. Most analysts ignore the effect of load on a rotating machine. If you were to acquire a vibration reading from a centrifugal compressor when it is operating at full load, it may generate an overall level of 0.1 ips-peak. The same measurement point will generate a reading in excess of 0.4 ips-peak when the compressor is operating at 50 percent load. The difference is the spring constant that is being applied to the rotating element. The spring constant or stiffness at 100 percent load is twice that of that when operating at 50 percent; however, spring constant is a quadratic function. A reduction of 50 percent in the spring constant will increase the vibration level by a factor of four.

To achieve maximum benefits from vibration monitoring, the analyst must understand the limitations of the instrumentation and the basic operating dynamics of machinery. Without this knowledge, the benefits will be dramatically reduced.

The greatest mistake made by traditional application of vibration monitoring is in its application. Most programs limit the use of this predictive maintenance technology to simple rotating machinery and not to the critical production systems that produce the plant’s capacity. As a result, the auxiliary equipment is kept in good operating condition, but the plant’s throughput is unaffected.

Vibration monitoring is not limited to simple rotating equipment. The microprocessor-based systems used for vibration analysis can be used effectively on all electromechanical equipment no matter how complex or what form the mechanical motion may take. For example, it can be used to analyze hydraulic and pneumatic cylinders that are purely linear motion. To accomplish this type of analysis, the analyst must use the time domain function that is built into these instruments. Proper operation of cylinders is determined by the time it takes for the cylinder to finish one complete motion. The time required for the cylinder to extend is shorter than its return stroke. This is a function of the piston area and inlet pressure. By timing the transient from fully retracted or extended to the opposite position, the analyst can detect packing leakage, scored cylinder walls, and other failure modes.

Vibration monitoring must be focused on the critical production systems. Each of these systems must be evaluated as a single machine and not as individual components. For example, a paper machine, annealing line, or any other production system must be analyzed as a complete machine not as individual gearboxes, rolls, or other components. This methodology permits the analyst to detect abnormal operation within the complex system. Problems such as tracking, tension, and product-quality deviations can be easily detected and corrected using this method.

When properly used, vibration monitoring and analysis is the most powerful predictive maintenance tool available. It must be focused on critical production systems, not simple rotating machinery. Diagnostic logic must be driven by the operating dynamics of machinery not simplified vibration failure modes.

The proof is in the results. The survey conducted by Plant Services in July 1999 indicated that less than 50 percent of the vibration-monitoring programs generated enough quantifiable benefits to offset the recurring cost of the program. Only 3 percent generated a return on investment of 5 percent. When properly used, vibration-based predictive maintenance can generate return on investment of 100:1 or better.

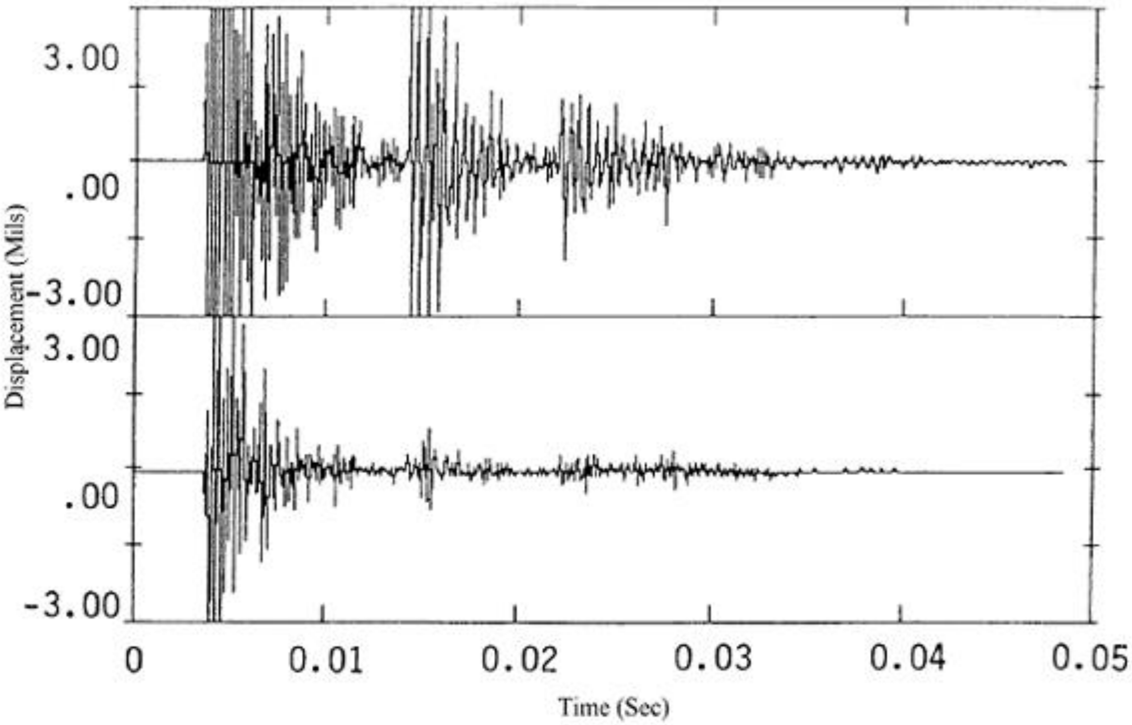


Figure 5.2: Vibration Profile

5.2.2 Termograph analysis

Thermography is a predictive maintenance technique that can be used to monitor the condition of plant machinery, structures, and systems, not just electrical equipment. It uses instrumentation designed to monitor the emission of infrared energy (i.e., surface temperature) to determine operating condition. By detecting thermal anomalies (i.e., areas that are hotter or colder than they should be), an experienced technician can locate and define a multitude of incipient problems within the plant.

Infrared technology is predicated on the fact that all objects having a temperature above absolute zero emit energy or radiation. Infrared radiation is one form of this emitted energy. Infrared emissions, or below red, are the shortest wavelengths of all radiated energy and are invisible without special instrumentation. The intensity of infrared radiation from an object is a function of its surface temperature; however, temperature measurement using infrared methods is complicated because three sources of thermal energy can be detected from any object: energy emitted from the object itself, energy reflected from the object, and energy transmitted by the object. Only the emitted energy is important in a predictive maintenance program. Reflected and transmitted energies will distort raw infrared data. Therefore, the reflected and transmitted energies must be filtered out of acquired data before a meaningful analysis can be completed.

Variations in surface condition, paint or other protective coatings, and many other variables can affect the actual emissivity factor for plant equipment. In addition to reflected and transmitted energy, the user of thermographic techniques must also consider the atmosphere between the object and the measurement instrument. Water vapor and other gases absorb infrared radiation. Airborne dust, some lighting, and other variables in the surrounding atmosphere can distort measured infrared radiation. Because the atmospheric environment is constantly changing, using thermographic techniques requires extreme care each time infrared data are acquired.

Most infrared-monitoring systems or instruments provide filters that can be used to avoid the negative effects of atmospheric attenuation of infrared data; however, the plant user must recognize the specific factors that affect the accuracy of the infrared data and apply the correct filters or other signal conditioning required to negate that specific attenuating factor or factors.

Collecting optics, radiation detectors, and some form of indicator are the basic elements of an industrial infrared instrument. The optical system collects radiant energy and focuses it on a detector, which converts it into an electrical signal. The instrument's electronics amplifies the output signal and processes it into a form that can be displayed.

Three types of instruments are generally used as part of an effective predictive maintenance program: infrared thermometers, line scanners, and infrared imaging systems.

Infrared thermometers or spot radiometers are designed to provide the actual surface temperature at a single, relatively small point on a machine or surface. Within a predictive maintenance program, the point-of-use infrared thermometer can be used in conjunction with many of the microprocessor-based vibration instruments to monitor the temperature at critical points on plant machinery or equipment. This technique is typically used to monitor bearing cap temperatures, motor winding temperatures, spot checks of process piping temperatures, and similar applications. It is limited in that the temperature represents a single point on the machine or structure; however, when used in conjunction with vibration data, point-of-use infrared data can be a valuable tool.

Line scanners provides a one-dimensional scan or line of comparative radiation. Although this type of instrument provides a somewhat larger f ield of view (i.e., area of machine surface), it is limited in predictive maintenance applications.

Unlike other infrared techniques, thermal or infrared imaging provides the means to scan the infrared emissions of complete machines, process, or equipment in a very short time. Most of the imaging systems function much like a video camera. The user can view the thermal emission profile of a wide area by simply looking through the instrument’s optics.

A variety of thermal imaging instruments are on the market, ranging from relatively inexpensive, black-and-white scanners to full-color, microprocessor-based systems. Many of the less expensive units are designed strictly as scanners and cannot store and recall thermal images. This inability to store and recall previous thermal data will limit a long-term predictive maintenance program.

Point-of-use infrared thermometers are commercially available and relatively inexpensive. The typical cost for this type of infrared instrument is less than $1,000. Infrared imaging systems will have a price range between $8,000 for a black-andwhite scanner without storage capability to over $60,000 for a microprocessor-based, color imaging system.

Training is critical with any of the imaging systems. The variables that can destroy the accuracy and repeatability of thermal data must be compensated for each time infrared data are acquired. In addition, interpretation of infrared data requires extensive training and experience.

Inclusion of thermography into a predictive maintenance program will enable you to monitor the thermal efficiency of critical process systems that rely on heat transfer or retention, electrical equipment, and other parameters that will improve both the reliability and efficiency of plant systems. Infrared techniques can be used to detect problems in a variety of plant systems and equipment, including electrical switchgear, gearboxes, electrical substations, transmissions, circuit breaker panels, motors, building envelopes, bearings, steam lines, and process systems that rely on heat retention or transfer.

5.2.3 Tribology analysis

Tribology is the general term that refers to design and operating dynamics of the bearing-lubrication-rotor support structure of machinery. Two primary techniques are being used for predictive maintenance: lubricating oil analysis and wear particle analysis.

Lubricating oil analysis, as the name implies, is an analysis technique that determines the condition of lubricating oils used in mechanical and electrical equipment. It is not a tool for determining the operating condition of machinery or detecting potential failure modes. Too many plants are attempting to accomplish the latter and are disappointed in the benefits that are derived. Simply stated, lube oil analysis should be limited to a proactive program to conserve and extend the useful life of lubricants. Although some forms of lubricating oil analysis may provide an accurate quantitative breakdown of individual chemical elements—both oil additive and contaminants contained in the oil—the technology cannot be used to identify the specific failure mode or root-cause of incipient problems within the machines serviced by the lube oil system.

The primary applications for lubricating oil analysis are quality control, reduction of lubricating oil inventories, and determination of the most cost-effective interval for oil change. Lubricating, hydraulic, and dielectric oils can be periodically analyzed using these techniques to determine their condition. The results of this analysis can be used to determine if the oil meets the lubricating requirements of the machine or application. Based on the results of the analysis, lubricants can be changed or upgraded to meet the specific operating requirements.

In addition, detailed analysis of the chemical and physical properties of different oils used in the plant can, in some cases, allow consolidation or reduction of the number and types of lubricants required to maintain plant equipment. Elimination of unnecessary duplication can reduce required inventory levels and therefore maintenance costs.

As a predictive maintenance tool, lubricating oil analysis can be used to schedule oil change intervals based on the actual condition of the oil. In midsize to large plants, a reduction in the number of oil changes can amount to a considerable annual reduction in maintenance costs. Relatively inexpensive sampling and testing can show when the oil in a machine has reached a point that warrants change.

Wear particle analysis is related to oil analysis only in that the particles to be studied are collected by drawing a sample of lubricating oil. Whereas lubricating oil analysis determines the actual condition of the oil sample, wear particle analysis provides direct information about the wearing condition of the machine-train. Particles in the lubricant of a machine can provide significant information about the machine's condition. This information is derived from the study of particle shape, composition, size, and quantity.

Two methods are used to prepare samples of wear particles. The first method, called spectroscopy or spectrographic analysis , uses graduated filters to separate solids into sizes. Normal spectrographic analysis is limited to particulate contamination with a size of 10 microns or less. Larger contaminants are ignored. This fact can limit the benefits that can be derived from the technique. The second method, called ferrographic analysis , separates wear particles using a magnet. Obviously, the limitation to this approach is that only magnetic particles are removed for analysis. Nonmagnetic materials, such as copper, aluminum, and so on that make up many of the wear materials in typical machinery are therefore excluded from the sample.

Wear particle analysis is an excellent failure analysis tool and can be used to understand the root-cause of catastrophic failures. The unique wear patterns observed on failed parts, as well as those contained in the oil reservoir, provide a positive means of isolating the failure mode.

Three major limitations are associated with using tribology analysis in a predictive maintenance program: equipment costs, acquiring accurate oil samples, and interpretation of data.

The capital cost of spectrographic analysis instrumentation is normally too high to justify in-plant testing. Typical cost for a microprocessor-based spectrographic system is between $30,000 and $60,000. Because of this, most predictive maintenance programs rely on third-party analysis of oil samples.

In addition to the labor cost associated with regular gathering of oil and grease samples, simple lubricating oil analysis by a testing laboratory will range from about $20 to $50 per sample. Standard analysis will normally include viscosity, flash point, total insolubles, total acid number (TAN), total base number (TBN), fuel content, and water content. More detailed analysis, using spectrographic, ferrographic, or wear particle techniques that include metal scans, particle distribution (size), and other data can cost more than $150 per sample.

Amore severe limiting factor with any method of oil analysis is acquiring accurate samples of the true lubricating oil inventory in a machine. Sampling is not a matter of opening a port somewhere in the oil line and catching a pint sample. Extreme care must be taken to acquire samples that truly represent the lubricant that will pass through the machine's bearings. One recent example is an attempt to acquire oil samples from a bullgear compressor. The lubricating oil filter had a sample port on the clean (i.e., downstream) side; however, comparison of samples taken at this point and one taken directly from the compressor's oil reservoir indicated that more contaminants existed downstream from the filter than in the reservoir. Which location actually represented the oil's condition? Neither sample was truly representative of the oil's condition. The oil filter had removed most of the suspended solids (i.e., metals and other insolubles) and was therefore not representative of the actual condition. The reservoir sample was also not representative because most of the suspended solids had settled out in the sump.

Proper methods and frequency of sampling lubricating oil are critical to all predictive maintenance techniques that use lubricant samples. Sample points that are consistent with the objective of detecting large particles should be chosen. In a recirculating system, samples should be drawn as the lubricant returns to the reservoir and before any filtration occurs. Do not draw oil from the bottom of a sump where large quantities of material build up over time. Return lines are preferable to reservoir as the sample source, but good reservoir samples can be obtained if careful, consistent practices are used. Even equipment with high levels of filtration can be effectively monitored as long as samples are drawn before oil enters the filters. Sampling techniques involve taking samples under uniform operating conditions. Samples should not be taken more than 30 minutes after the equipment has been shut down.

Sample frequency is a function of the mean-time-to-failure (MTTF) from the onset of an abnormal wear mode to catastrophic failure. For machines in critical service, sampling every 25 hours of operation is appropriate. For most industrial equipment in continuous service, however, monthly sampling is adequate. The exception to monthly sampling is machines with extreme loads. In this instance, weekly sampling is recommended.

Understanding the meaning of analysis results is perhaps the most serious limiting factor. Results are usually expressed in terms that are totally alien to plant engineers or technicians. Therefore, it is difficult for them to understand the true meaning, in terms of oil or machine condition. Agood background in quantitative and qualitative chemistry is beneficial. At a minimum, plant staff will require training in basic chemistry and specific instruction on interpreting tribology results.

5.2.4 Visual inspection

Visual inspection was the first method used for predictive maintenance. Almost from the beginning of the Industrial Revolution, maintenance technicians performed daily “walkdowns” of critical production and manufacturing systems in an attempt to identify potential failures or maintenance-related problems that could impact reliability, product quality, and production costs. Avisual inspection is still a viable predictive maintenance tool and should be included in all total-plant maintenance management programs.

5.2.5 Non destructive analysis

Ultrasonics, like vibration analysis, is a subset of noise analysis. The only difference in the two techniques is the frequency band they monitor. In the case of vibration analysis, the monitored range is between 1 Hertz (Hz) and 30,000Hz; ultrasonics monitors noise frequencies above 30,000Hz. These higher frequencies are useful for select applications, such as detecting leaks that generally create high-frequency noise caused by the expansion or compression of air, gases, or liquids as they flow through the orifice, or a leak in either pressure or vacuum vessels. These higher frequencies are also useful in measuring the ambient noise levels in various areas of the plant.

As it is being applied as part of a predictive maintenance program, many companies are attempting to replace what is perceived as an expensive tool (i.e., vibration analysis) with ultrasonics. For example, many plants are using ultrasonic meters to monitor the health of rolling-element bearings in the belief that this technology will provide accurate results. Unfortunately, this perception is invalid. Because this technology is limited to a broadband (i.e., 30kHz to 1MHz), ultrasonics does not provide the ability to diagnosis incipient bearing or machine problems. It certainly cannot define the rootcause of abnormal noise levels generated by either bearings or other machine-train components.

As part of a comprehensive predictive maintenance program, ultrasonics should be limited to the detection of abnormally high ambient noise levels and leaks. Attempting to replace vibration monitoring with ultrasonics simply will not work.

5.2.6 Other techniques

Numerous other nondestructive techniques can be used to identify incipient problems in plant equipment or systems; however, these techniques either do not provide a broad enough application or are too expensive to support a predictive maintenance program. Therefore, these techniques are used as the means of confirming failure modes identified by the predictive maintenance techniques discussed in this chapter.

Electrical testing

Traditional electrical testing methods must be used in conjunction with vibration analysis to prevent premature failure of electric motors. These tests should include:

- Resistance testing

Resistance is measured by using an ohmmeter. In reality, an ohmmeter does not directly measure resistance; it measures current instead. The scale of the meter is calibrated in ohms, but the meter movement responds to current. The amount of current supplied by the meter is very low, typically in the rage of 20 to 50 microamperes. The meter functions by applying its terminal voltage to the test subject and measuring the current in the circuit.

For practical purposes, although resistance testing is of limited value, some useful tests may be performed. A resistance test will indicate an open or closed circuit. This can tell us whether there is a break in a circuit or if there is a dead short to ground.

It is important to remember that inductive and capacitive elements in the circuit will distort the resistance measurements. Capacitive elements will appear initially as a short circuit and begin to open as they charge. They will appear as open circuits when they are fully charged. Inductive elements will appear initially as open circuits, and the resistance will decrease as they charge. In both cases, the actual charging time is tied to the actual resistance, capacitance, and inductance in the circuit in question. It still requires five time constants to charge capacitors and inductors. It is also important to remember that when disconnecting the meter from the circuit that there are now charged capacitive and inductive elements present, so due caution must be observed when disconnecting the test equipment.

Resistance testing is of limited value for testing coils. It will detect an open coil, or a coil shorted to ground. Resistance testing will most often not detect windings that are shorted together or weak insulation.

- Megger testing

In order to measure high resistances, a device known as a mega-ohmmeter can be used. This instrument differs from a normal ohmmeter in that instead of measuring current to determine resistance, it measures voltage. This mode of testing involves applying relatively high voltage (500 to 2,500 volts, depending on the unit) to the circuit and verifying that no breakdown is present. Generally, this is considered a nondestructive test, depending on the applied voltage and the rating of the insulation. This method of testing is used primarily to test the integrity of insulation. It will not detect shorts between windings, but it can detect higher-voltage–related problems with respect to ground.

- HiPot testing

HiPot (high potential) testing is a potentially destructive test used to determine the integrity of insulation. Voltage levels employed in this type of test are twice the rated voltage plus 1,000 volts. This method is used primarily by some equipment manufacturers and rebuilding facilities as a quality assurance tool. It is important to note that HiPot testing does some damage to insulation every time it is performed. HiPot testing can destroy insulation that is still serviceable, so this test is generally not recommended for field use.

- Impedance testing

Impedance has two components: a real (or resistive) component and a reactive (inductive or capacitive) component. This method of testing is useful because it can detect significant shorting in coils, either between turns or to ground. No other nonintrusive method exists to detect a coil that is shorted between turns.

- Other techniques

Other techniques that can support predictive maintenance include acoustic emissions, eddy-current, magnetic particle, residual stress, and most of the traditional nondestructive methods. If you need specific information on the techniques that are available, the American Society of Nondestructive Testing (ANST) has published a complete set of handbooks that provide a comprehensive database for most nondestructive testing techniques.

6. CONCLUSIONS AND RECOMMENDATIONS

A survey of 500 plants that have implemented predictive maintenance methods indicates substantial improvements in reliability, availability, and operating costs. The successful programs included in the survey include a cross-section of industries and provide an overview of the types of improvements that can be expected. Based on the survey results, major improvements can be achieved in maintenance costs, unscheduled machine failures, repair downtime, spare parts inventory, and both direct and indirect overtime premiums. In addition, the survey indicated a dramatic improvement in machine life, production, operator safety, product quality, and overall profitability.

Based on the survey, the actual costs normally associated with the maintenance operation were reduced by more than 50 percent. The comparison of maintenance costs included the actual labor and overhead of the maintenance department. It also included the actual materials cost of repair parts, tools, and other equipment required to maintain plant equipment. The analysis did not include lost production time, variances in direct labor, or other costs that should be directly attributed to inefficient maintenance practices.

The addition of regular monitoring of the actual condition of process machinery and systems reduced the number of catastrophic, unexpected machine failures by an average of 55 percent. The comparison used the frequency of unexpected machine failures before implementing the predictive maintenance program to the failure rate during the two-year period following the addition of condition monitoring to the program. Projections of the survey results indicate that reductions of 90 percent can be achieved using regular monitoring of the actual machine condition.

Predictive maintenance was shown to reduce the actual time required to repair or rebuild plant equipment. The average improvement in mean-time-to-repair (MTTR) was a reduction of 60 percent. To determine the average improvement, actual repair times before the predictive maintenance program were compared to the actual time to repair after one year of operation using predictive maintenance management techniques. The regular monitoring and analysis of machine condition identified the specific failed component(s) in each machine and enabled the maintenance staff to plan each repair. The ability to predetermine the specific repair parts, tools, and labor skills required provided the dramatic reduction in both repair time and costs.

The ability to predict machine-train and equipment failures and the specific failure mode provided the means to reduce spare parts inventories by more than 30 percent. Rather than carry repair parts in inventory, the surveyed plants had sufficient lead time to order repair or replacement parts as needed. The comparison included the actual cost of spare parts and the inventory carrying costs for each plant.

Prevention of catastrophic failures and early detection of incipient machine and systems problems increased the useful operating life of plant machinery by an average of 30 percent. The increase in machine life was a projection based on five years of operation after implementation of a predictive maintenance program. The calculation included frequency of repairs, severity of machine damage, and actual condition of machinery after repair. Acondition-based predictive maintenance program prevents serious damage to machinery and other plant systems. This reduction in damage severity increases the operating life of plant equipment.

A side benefit of predictive maintenance is the automatic ability to monitor the meantime-between-failures (MTBF). These data provide the means to determine the most cost-effective time to replace machinery rather than continue to absorb high maintenance costs. The MTBF of plant equipment is reduced each time a major repair or rebuild occurs. Predictive maintenance will automatically display the reduction of MTBF over the life of the machine. When the MTBF reaches the point that continued operation and maintenance costs exceed replacement cost, the machine should be replaced.

In each of the surveyed plants, the availability of process systems was increased after implementation of a condition-based predictive maintenance program. The average increase in the 500 plants was 30 percent. The reported improvement was based strictly on machine availability and did not include improved process efficiency; however, a full predictive program that includes process parameters monitoring can also improve the operating efficiency and therefore productivity of manufacturing and process plants. One example of this type of improvement is a food manufacturing plant that decided to build additional plants to meet peak demands. An analysis of existing plants, using predictive maintenance techniques, indicated that a 50 percent increase in production output could be achieved simply by increasing the operating efficiency of the existing production process.

The survey determined that advanced notice of machine-train and systems problems had reduced the potential for destructive failure, which could cause personal injury or death. The determination was based on catastrophic failures where personal injury would most likely occur. Several insurance companies are offering premium reductions to plants that have a condition-based predictive maintenance program in effect. Several other benefits can be derived from a viable predictive maintenance management program: verification of new equipment condition, verification of repairs and rebuild work, and product quality improvement.

Predictive maintenance techniques can be used during site acceptance testing to determine the installed condition of machinery, equipment, and plant systems. This provides the means to verify the purchased condition of new equipment before acceptance. Problems detected before acceptance can be resolved while the vendor has a reason—that is, the invoice has not been paid—to correct any deficiencies. Many industries are now requiring that all new equipment include a reference vibration signature provided with purchase. The reference signature is then compared with the baseline taken during site acceptance testing. Any abnormal deviation from the reference signature is grounds for rejection, without penalty of the new equipment. Under this agreement, the vendor is required to correct or replace the rejected equipment. These techniques can also be used to verify the repairs or rebuilds on existing plant machinery.

Vibration analysis, a key predictive maintenance tool, can be used to determine whether the repairs corrected existing problems and/or created additional abnormal behavior before the system is restarted. This ability eliminates the need for the second outage that is often required to correct improper or incomplete repairs.

Data acquired as part of a predictive maintenance program can be used to schedule and plan plant outages. Many industries attempt to correct major problems or schedule preventive maintenance rebuilds during annual maintenance outages. Predictive data can provide the information required to plan the specific repairs and other activities during the outage. One example of this benefit is a maintenance outage scheduled to rebuild a ball mill in an aluminum foundry. The normal outage, before predictive maintenance techniques were implemented in the plant, to completely rebuild the ball mill was three weeks, and the repair cost averaged $300,000.

The addition of predictive maintenance techniques as an outage-scheduling tool reduced the outage to five days and resulted in a total savings of $200,000. The predictive maintenance data eliminated the need for many of the repairs that would normally have been included in the maintenance outage. Based on the ball mill's actual condition, these repairs were not needed. The additional ability to schedule the required repairs, gather required tools, and plan the work reduced the time required from three weeks to five days.

The overall benefits of predictive maintenance management have proven to substantially improve the overall operation of both manufacturing and processing plants. In all surveyed cases, the benefits derived from using condition-based management have offset the capital equipment costs required to implement the program within the first three months. Use of microprocessor-based predictive maintenance techniques has further reduced the annual operating cost of predictive maintenance methods so that any plant can achieve cost-effective implementation of this type of maintenance management program.

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