Thesis for the Degree of Doctor of Philosophy

An Implementation of Risk Based Inspection for Elevator Optimum Maintenance

by

Seung-Tae Park

UR Interdisciplinary Program of Mechanical Engineering,

The Graduate School

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최적의 유지보수를 위한 엘리베이터 위험기반 검사의 실행

Advisor: Prof. Bo-Suk Yang

by

Seung-Tae Park

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Approved by:

Chairman: Prof. Ki-Woo Nam

Member: Prof. Byung-Hyun Ahn | Member: Prof. Seon-Jin Kim

Member: Dr. Seon-sun Lee | Member: Prof. Bo-Suk Yang

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Chapter III Elevator Fault Analysis and Life Cycle Assessment

p	number of pole
n	rotor speed
n_s	synchronous speed
s	slip

Chapter IV New Concept of Performance Measurement and Evaluation

B	ball roller diameter
$BPFO$	ball pass frequency of outer race
$BPFI$	ball pass frequency of inner race
BSF	ball spin frequency
C	penalty term
d	degree of polynomial
D	average distance
f	frequency
f_b	broken rotor bars frequency
f_{brg}	bearing frequency
f_e	supply frequency
f_{ec}	eccentricity fault frequency
f_i	character frequency of inner race
f_o	character frequency of outer race
f_r	rotating frequency
f_t	turn-fault frequency

f_v	characteristic vibration frequency
FTF	fundamental train frequency
n	rotor speed
n_s	synchronous speed
P	pitch diameter
p	number of pole
q	joint feature sets
s	slip

Greek symbols

α	condition patterns
δ	evaluation criterion
γ	kernel parameter
λ	parameter for quadratic-programming
ρ	mean all features

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Abstract

This dissertation presents an investigation of risk management, elevator risk assessment and reduction methodology, elevator fault analysis and life cycle assessment based on studying and surveying about the elevator component replacement life cycle. It also provides the elevator performance management development as well as elevator evaluation criteria to apply the condition prognosis and the inspection/maintenance. The risk management by RBI method gives the proposed guidance for optimal risk-based inspection/maintenance.

Elevator maintenance is very important to decide the best solution of the management about the inspection periodic, replacement time and evaluation method. The fault feature of elevator is obtained from studying, diagnosing and surveying the elevator component cycle assessment in the site.

The replacement life cycle of elevator component was surveyed through the elevator maker and the maintenance company, also the design cycle life was studied through the literature and maker design documents. The replacement life

cycle of the elevator component was proposed through the effective data by comparing and analyzing the domestic maker, elevator world data and survey data through the makers and the maintenance company.

The evaluation of ride quality and rotating machinery are the important techniques when maintaining elevator. Through the development of performance measurement device, it is possible to prognosis the condition of the characteristic features which indicate the fault event, and feature representation is a process where the features are calculated on time domain, frequency domain and waterfall function. The proposed evaluation criteria are conducted by the statistical analysis on the measured value of ride quality and vibration of traction machine. Thus it is necessary to use the analysis as performance assessment standards. If such standards are exceeded, the causes need to be analyzed through FFT analysis. It is deemed that the measurement and analysis on elevator ride quality and vibration of traction machine in combination with prevention maintenance and prediction maintenance would guarantee the higher stability and reliability. The reliability of Dr. Elevator system has been evaluated by Korea Research Institute of Standards and Science through experimental work that used the measured frequencies are 2.5, 5, 10, 20, 40, 63, 80 Hz, and the maximum relative standard uncertainty and tolerance range are 0.054% and under 5%, respectively. Dr. Elevator is validated by applying it to diagnosis and predicts the elevator fault cases of car resonance, rail installment, reducer fault, bearing fault, unbalance, misalignment and guide roller vibration etc.

This work studied the risk assessment by using the elevator accident and breakdown statistics data based on FMEA techniques and we tried an implementation of risk based inspection for the elevator maintenance in the site. This study has carried out the risk based inspection for elevator and has proposed the method on how to prevent elevator safety accident and make the premium management and maintenance.

I. Introduction

1. Background

The advent of high-rise buildings in modern cities requires high-speed elevator systems to provide quick access within the buildings. These buildings require that elevators run at speeds faster than ever before. To meet this requirement, elevators achieve the super high speed of 1010 m/min, and handles capacity loads from 900 to 2000 kg.

Elevators have various mechanical structures according to the rating speed and the maximum load capacity. Generally elevators have three principal mechanical parts: the traction machine, the cage, and the counterweight. The traction machine is installed in a machine room, which is located on the top of a building, and composed of the traction motor, the main sheave, and the breaker. The counterweight is used to balance with the cage and connected to the second sheave of the traction machine through a moving pulley. The compensation rope and sheave are utilized to eliminate the weight difference of both side ropes according to the cage position [1].

Building owners and managers have their work cut out when it comes to ensuring that those rides are uneventful. Proper installation and ongoing maintenance and inspection are a must. Long-time continuous usage increases fault-occurrence probability, which requires troubleshooting quickly [2]. To assess the reliability and efficiency of the elevators a maintenance program is a significant part of overall elevator system. The safe and reliable operation of the elevator is of paramount importance to the owners, the management company and, ultimately, to the tenants and visitors who travel throughout these buildings daily. The target of elevator maintenance is as follows:

- Prolong equipment life
- Improve equipment safety and reliability
- Reduce the cost of major repairs
- Minimize the inconvenience of equipment downtime

Since the early 1910s when the elevator was introduced, the Korean elevator industry has its remarkable growth with 2,000,000 housing constructions in 1990 as well as in 1986 Seoul Asian games and 1988 Seoul Olympics. Currently, about 360,000 elevators are working in Korea which is ranking 9th in the world.

Meanwhile, the number of people who have been rescued by 911 rescue team, owing to elevator accidents, reaches the second-highest level following traffic accidents. The data by the National Statistics Office on elevator accidents shows that there were 90 and 97 accidents in the year of 2006 and 2007, respectively. These accidents are increasing annually as indicated in Table 1.1 [3].

Table 1.1 The number of accident and installation

Year	Total number of installation	Number of accident	The incidence of accident (%)	Accident number per 10,000 persons
1998	159,230	28	0.0176	1.76
1999	174,261	12	0.0069	0.69
2000	190,187	22	0.0116	1.16
2001	208,497	28	0.0134	1.34
2002	231,562	16	0.0069	0.69
2003	259,850	40	0.0154	1.54
2004	289,808	25	0.0086	0.86
2005	314,495	42	0.0134	1.34
2006	336,311	90	0.0268	2.68
2007	359,098	97	0.0270	2.70

There is a need for new technical solutions to lessen the safety accidents and break-down. It has to be provided as a technical guide to promote the progressive and selective maintenance and improvement of the safety of existing elevator. So, the ageing elevators should be made more effective, safer, more reliable and more comfortable through effective maintenance and improvement [4].

Therefore, the aim of this research is to develop the performance measurement device, to decide the performance evaluation criteria as classifying the defect kind through the test of elevator tower, also the diagnosis in the site using the developed device (Dr.Elevator). There is need to survey the life cycle of elevator parts through the elevator accidents data and fault and to analysis the fault characteristic of elevator main parts to maintain elevator more economic and safe. So finally, the aim is to develop the optimum maintenance guide of elevator and to implement in the site. The result is respected to reduce the probability of breakdowns and accidents of elevator, and be much safer to elevator users [5, 6].

2. Motivation of This Research

Machines are critical part in industry. Industrial machines are complex and consist of many components that could potentially fail. The issue of reliability and robustness of machines has received a deep attention from researchers and practitioners maintenance. There has been an increased interest in machine condition monitoring because of the potential benefits to be obtained from reduced maintenance costs, improved operating efficiency, increased machine reliability and availability

Elevator accidents increase gradually every year in Republic of Korea. Elevator consists of many components that will be degraded the operating condition and could be failed due to wear and fatigue during the operating time.

Sustaining their condition or avoiding their failure leading to stoppage of elevator is of vital importance to be taken into consideration. Risk-based inspection (RBI) and maintenance has been progressively received much interest for their potential benefits as mentioned in the previous section. Hence, the development of risk management for elevator inspection and maintenance based on fault diagnosis and risk-based inspection are the motivation of this research.

3. Research Objectives

This research focuses on the development of an integrated risk management system for elevator and risk-based inspection and maintenance as stated in the introduction section, this research objectives are to develop the performance evaluation of elevator and to implement risk-based inspection for elevator maintenance. The main objectives of this research are as follows:

- To develop the performance measurement and evaluation methodology of elevator using Dr. Elevator.
- To apply the Dr. Elevator (elevator performance measurement device) in the site and classify the defect kind and evaluation criteria
- To determine the life cycle of elevator component using the survey of maintenance and manufacture.
- To apply the risk assessment of accident statistics and break-down data by failure mode and effect analysis (FMEA) method.
- To develop the effective maintenance guide of elevator for using Dr. Elevator diagnosis device and RBI system.
- To implement the Risk-Based Inspection for the optimum maintenance.

4. Research Method and Approach

In order to achieve the objectives of this research, the following methods have been adopted:

- Performance measurement and evaluation device development that consists of the elevator ride quality in car and rotating machinery parts in machine room.
- Survey of maintenance and manufacturers about elevator component life cycle.
- Elevator accident statistical analysis in Republic Korea and breakdown data for three year in the maintenance site by FMEA analysis method
- Implementing the performance assessment of elevator in the site to decide the fault frequency feature and performance assessment criteria.
- Studying the feasibility of elevator component fault to develop the effective maintenance guide.

5. Contribution of This Research

The main contribution of this research is developing the elevator performance measurement and evaluation device, applying the Dr. Elevator in the site and classifying the defect kind and evaluation criteria. Several other significant contributions of the developed risk management of elevator are as follows:

- The ability to obtain the optimal features for fault classification using Dr. Elevator by the ride quality in the car and rotating machinery parts in the machine.
- The developed system was successfully applied in real application to diagnose and detect the faults of elevator system based on vibration.

- The component replacement life cycle of elevator was successfully applied in real application by studying the fault characteristic and surveying the component life cycle of the makers and the maintenance company.
- By implementing the proposed RBI process, the elevator maintenance is ensure that significant risks are identified and appropriate action taken to minimize them as much as is reasonably possible. So it result in less downtime, and greater revenues, also the fatal accidents could be prevented.

6. Organizational Overview of This Dissertation

Based on aforementioned aims and objectives of this research, this dissertation is outlined as follows.

Chapter 1 introduces the background and motivation behind this research. It also describes the main objectives and contributions of this research and outlines an overview of this dissertation.

Chapter 2 outlines the preliminary literature review and maintenance management knowledge, risk management, elevator risk assessment and reduction methodology.

Chapter 3 reviews and studied the elevator fault analysis and life cycle assessment.

Chapter 4 presents new concept of performance measurement and evaluation. It outlines the description, composition, basic specification, analysis function of the system, and also the reliability of the system has been proved by Korea Research Institute of Standards and Science. To study the elevator fault features, Dr.Elevator is used to analyze the vibration and frequency waveform, and they were verified through elevator diagnosis in real site. It includes the proposed standards by performance assessments of elevator. Furthermore, it describes the case studies of performance assessment about fault prognosis in real site.

Chapter 5 applies Risk-based inspection of elevator. It addresses statistic analysis of elevator accident and breakdown and elevator breakdown parts data by FMEA method. Finally, it addresses the proposed guidance for optimal risk-based maintenance.

Chapter 6 gives several conclusion based on the results obtained in this research. This chapter also recommends some directions for further research in the future.

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II. Preliminary Review

1. Introduction

Maintenance management techniques have been through a major process of metamorphosis over recent years. Today, the maintenance process has been provoked by the increase in complexity in manufacturing processes and variety of products, growing awareness of the impact of maintenance on the environment and safety of personnel, the profitability of the business and quality of product [1]. There is a paradigm shift in implementing maintenance strategies like condition-based maintenance (RBM) has been emphasized. The development of maintenance philosophies is shown in Fig. 2.1 [2]. This figure reveals that maintenance policies are evolved over time and can be categorized as first, second, third and recent generations.

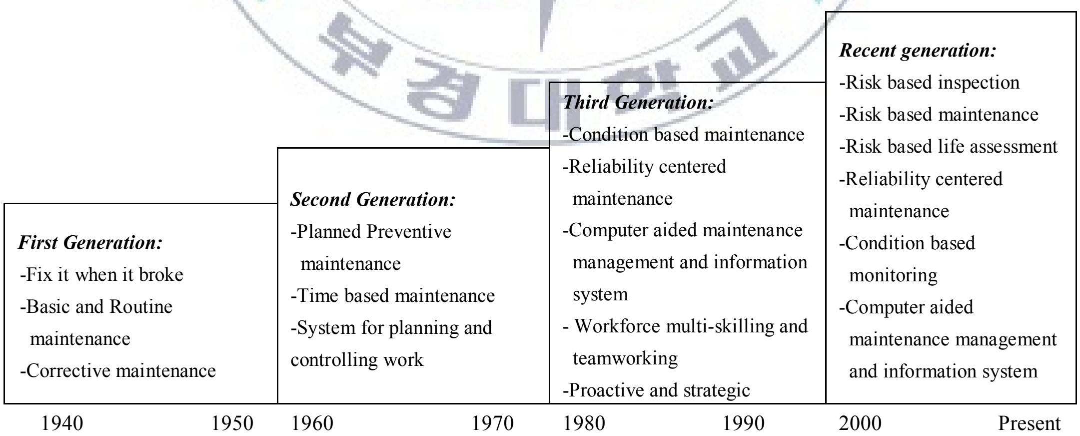

Fig. 2.1 Development of maintenance philosophies.

2. Review of Maintenance Management

General maintenance mission is mainly as follows:

- To preserve the functions of our physical assets throughout their technologically useful lives
- To the satisfaction of their owners, of their users, and of society as a whole
- By selecting and applying the most-effective techniques
- By managing failures and their consequences
- With the active support of all the people involved

A maintenance strategy provides as follows:

- A fixed, long-term reference for congruency and changing decision criteria
- A structure for relationships between maintenance environment variables
- Base-lining opportunities
- Ensures continuity
- A clearly mapped growth path to maintenance process maturity
- It identifies the "Right" things that needs doing, and presents a clear choice.
- Accelerated learning opportunity

The development of maintenance philosophies is divided by four generation as shown in Fig. 2.1.

2.1. First Generation

First generation typically belongs to the time before the World War 2. Industries were not very highly mechanized. Equipment was simple and redesigned which made them reliable and easy to repair. Machines were operated until they broke down and no way to predict failures. Typical maintenance practices were basic and routine maintenance, reactive breakdown service (fix it when it broke), corrective maintenance [3].

2.2. Second Generation

Second generation belongs to the time period in between the Second World War and the late 1970s. Industries become more complex with great dependency on machines. Maintenance cost became higher than other relative operating cost. Maintenance policies adopted were planned preventive maintenance, time-based maintenance, system for planning and controlling work. This period was criticized for imposing quite often unnecessary treatments, which disrupted normal operations, and also induced malfunctions due to missed operations [3].

2.3. Third Generation

The maintenance strategies within 1980 and 2000 are termed as third generation policies. This generation is typically characterized by continued growth in plant complexity, accelerating use of automation, just-in-time production system, rising demand for standard of product and service quality, more tight legislation on service quality. Condition based maintenance (CBM), reliability centered maintenance (RCM), and computer aided maintenance management were adopted for maintenance during this period.

2.4. Recent Generation

In 1990s, risk-based inspection and maintenance methodologies started to emerge, and gain popularity beyond 2000, highly characterized by the inception of risk-based inspection and maintenance in addition to RCM and CBM. Up to 2000, maintenance and safety were treated as separate and independent activities [4]. An integrated approach incorporating maintenance and safety is appropriate mean for optimizing plant capacity, as safety and maintenance are not mutually exclusive functions. Overall objective of maintenance process is to increase the probability of operation and optimize the total life cycle cost without compromising safety or environmental issues. Inspection and maintenance planning based on risk analysis minimizes probability of system failure and its consequences. It helps management in making correct decisions concerning investment in maintenance and related fields.

3. Risk Management

Risk is inherent part of business and public and life. Dynamic market relations increase the uncertainty of the environment where business and public organizations work. Keeping high competitiveness requires the organizations to start initiatives that may have different possible outputs. The possibility of these outputs occurring determines the risk in organizations' activity. Risk covers all aspects of organizational activities and its main aim is to help all other management activities to reach the organization' aims directly and efficiently. Risk management is a continuous process that depends directly on the changes of the internal and external environment of the organization. In reality the changes in the environment require continuous attention for identification and control of risks [5].

3.1 Sources of Risk

Different definitions and classifications can be used in managerial practice. A classification may use physical, social and economic sources. But an in-depth investigation of the problem of risk identification may need classification that can cover all types of risk in more detail. Therefore the sources of risk can be represented depending on the environment in which they arise as follows:

- Physical environment
- Social environment
- Political environment
- Operational environment
- Legal environment
- Legal environment
- Cognitive environment

1) Physical Environment

The physical environment is an important source of risk. Natural disasters like earthquakes, storms, flooding, landslides, etc. lead to serious losses. The environmental influence on the people and people's influences on the environment are important aspects of this source of risk. The physical environment can be a source of profitable opportunities, for example real estate as an investment, or appropriate climate for agriculture business or tourism.

2) Social Environment

The changes in people' values, human behavior and state of social structures are another source of risk. Civil unrest, social riots and strikes are events underlining the importance of the social environment as a source of risk. The level of worker skills and loyalty to the organization determine to a large extent the success of the organization. The difference in social values and culture, for example, in many countries the equal opportunities of minorities lead to faster development.

3) Political Environment

The political environment is an important source of risk in all countries. The ruling party can affect organizations in different ways, for example by cutting aid to some industry branches or protecting some branch or region, by implementing strict rules about the environment, etc. The political environment is a more complex and important source of risk in an international aspect. The difference in the ruling system raises different attitudes and policies toward business. For example, foreign investment might be confiscated, or taxation systems might change significantly, which will hurt the investor's interests. The political environment can present opportunities as well, for example the change in the political system and transfer to the market economy in Bulgaria.

4) Operational Environment

Operational activities of the organization create risk and uncertainty. For example, damage in installation or production processes might result in fiscal injuries of workers. Unfavorable working conditions can threaten both the physical and mental health of the workers. The formal procedures of hiring or firing employees may generate a legal problem. The manufacturing processes may produce harm to the environment. In this case the organization is a source of risk. The international business can suffer from risks in the transport system. The operational environment also provides opportunities, because the results of organizational activities improve the level of life and work of the people.

5) Economic Environment

The economic environment usually is hardly influenced by the political environment in al single country, but the globalization of the market creates a market that is greater than a single market and needs to be considered separately. Although a particular activity of the government can affect the international capital market, the control of the market is impossible for a single government. Examples of sources of risk generated from the economic environment are, in a global aspect, economic recession and depression, and at a local level, interest rate, credit policy, etc.

6) Legal Environment

The legal environment creates risk and uncertainly in business. The legal system creates risk by disparity of current or new laws to the environment. In the international domain, complexity increases because of the variation of legal standards in different countries and can lead to conflict among the partners. The legal system creates opportunities also by stabilizing the society and, due to that, organizations know the restrictions in their work. The legal system provides also a protection of rights as author's right, copy right, unemployment protection.

7) Cognitive Environment

The risk manager's ability to reveal, understand and assess risk is not perfect. The difference between perception and reality for different people is an important source of risk for an organization. The cognitive environment is a big challenge to the risk manager. The questions of how to assess the effect of the uncertainty on the organization and how to understand whether the perception of risk is real are considered. The Chernobyl accident and a lot of production accidents caused by carelessness and human factors are clear examples of the risk arising from the cognitive environment.

3.2 Resources Exposed to Risk

A particular peril or hazard factor can arise in more than one of several considered environments, for example environmental pollution can originate in human error (social environment), or fail in the control system (operational environment). Risk management investigates only these sources of risk that can raise perils for the organization and threaten its resources. That is why the analysis of resources exposed to risk is so important. In fact the organization is what is exposed to risk because the occurrence of an undesirable event can affect the organization as a whole. Nevertheless, bearing in mind the resource exposed to risk can be grouped as follows: physical, financial, human.

1) Physical Resource Exposures

Physical resources may cover machines, buildings, equipment, etc. Clearly they can be damaged or destroyed and therefore they are exposed to risk. A damage or failure leads to losses. An important feature here is that a big production line can stop if even a small part of it is out of order. This can lead to losses higher than the price of this single piece of equipment. The positive aspect here is that the material resources exposed to risk offer the possibility of gain. For example, the ownership of property – buildings, equipment – that can be used is an credit from a bank or similar financial institution are good advantages for starting a business, especially in countries with still changing economies, as in Bulgaria.

2) Human Resource Exposure

Human resources are the wealth of each organization. The success and competitiveness of the organization depend to a large extent on its staff and on the ability of creativity. Risk regarding human resources can be expressed by the injuries leading to partial working inability including physical and psychological health or death of someone in the organization. Even hiring new workers is a risk for the organization. At the same time human resources can be profitable sources as well. The increase of product quality, generation of action can be considered as a negative or positive aspect. For example, at the same time it will provide a possibility of larger gain. In this case the manager's task is to integrate the element that maximizes probability of gain. Employee training is the increasing the workers' skills and decreasing the probability of failures and injuries. The loyalty of workers has to be included in the human resource exposure too.

3) Financial Resources Exposure

Money and other financial assets, such as mortgages, are subject to financial risk. Here the risk is associated with some external effects, but not always with a clear physical change in the assets. In contrast to physical resources, financial resources can increase or decrease their value without direct physical change. Usually losses or gains are associated with the results of changing market conditions. A specific risk related to the financial resources is investment risk. It is connected with investment procedures in new projects possible peril is that invested money will not be returned at the expected rate or will be lost in full.

4. Risk Based Inspection and Maintenance Procedure for European Industry

Risk Based Inspection and Maintenance Procedures for European Industry (RIMAP) is a European project that aims at developing a unified approach to making risk based decisions within inspection and maintenance. Current practice to inspection and maintenance planning is for most industries based tradition and prescriptive rules, rather than being an optimized process where risk measures for safety and economy are integrated. New technology for taking risk based decisions is emerging within a broad range of sectors, and has been proven to be a very efficient tool shown as Fig. 2.2. However, there is a great need to define the technical content, links to local legislation and to integrate this approach with the day-to-day operation [6].

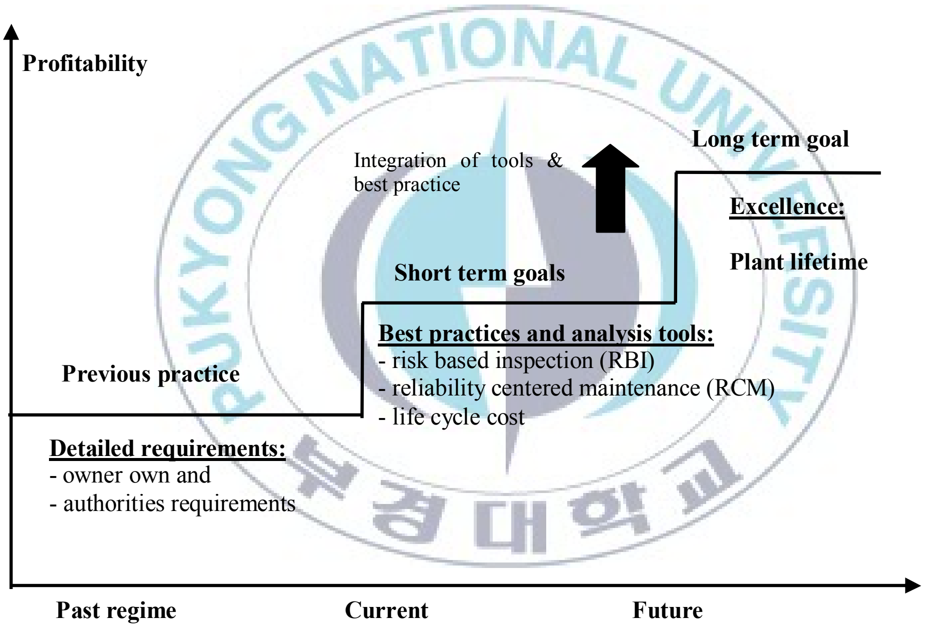

Fig. 2.2 The evolution of decision making in inspection and maintenance.

The objective of the project is to define a unified approach to making risk based decisions, within the field of inspection and maintenance (Fig. 2.3). Risk is here understood as the combined effect of probability of failure and the consequence of a failure (personnel safety, quality of product, environmental damage, and economic loss).

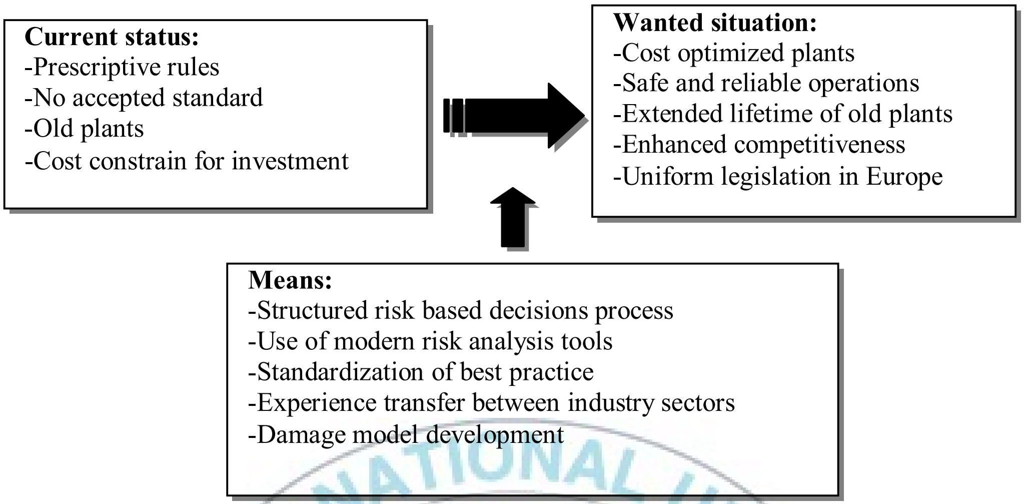

Fig. 2.3 RIMAP objective.

The main benefit of the work will be cost-optimized inspection/maintenance plans that will save operational and risk costs in the order of 10 to 40% for the involved industries, improved safety for plant personnel and the society en-large and a technical framework for a European standard.

4.1 RIMAP Work Process

The RIMAP procedure is shown in Fig. 2.4, which is said to be generic, since it is industry independent and applicable to different equipment types (static, safety systems, etc). The steps in the procedure are the same for different industrial sectors (chemical, petrochemical and power) and for different equipment types even if the techniques (e.g. tools for assessing probability or consequence of failure) may vary from one application to another. So, within the generic RIMAP procedure it is possible to meet the requirements of other already existing risk related programs like EN 1050 for machinery or IEC 61 508 for electrical safety systems. As it can be depicted from the Fig. 2.4 above, the core of the procedure – the multilevel risk analysis includes a seamless transition from screening to detailed analysis. Here, it is obvious that for a certain level of risk a sufficient depth of the analysis is required.

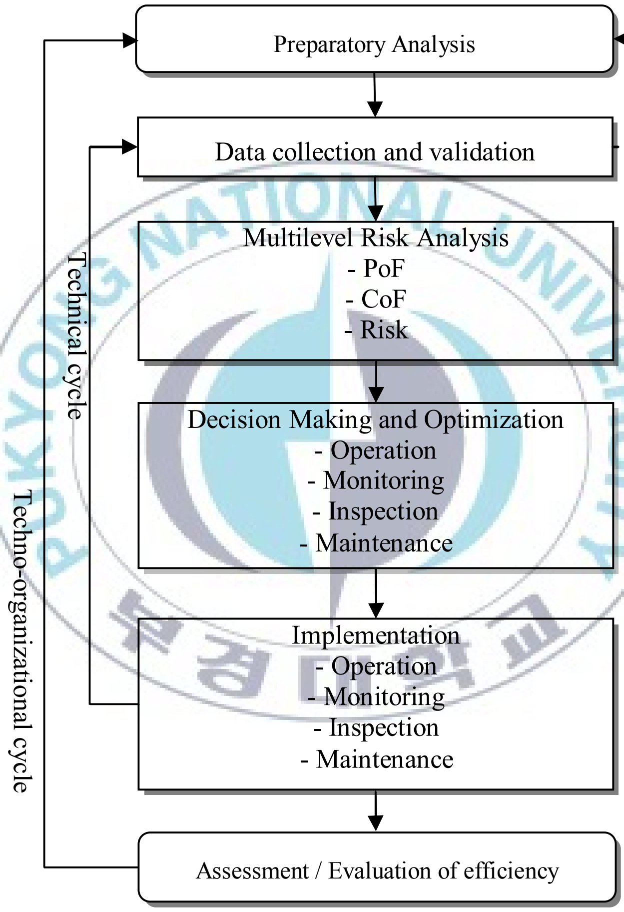

Fig. 2.4 RIMAP procedure.

4.2 The RIMAP description of Risk, PoF, CoF

The RIMAP project provides guidelines on how to perform risk based inspection and maintenance planning for all types of equipment: active components, static components, and safety critical equipment. The steps required to perform maintenance and inspection planning are similar for each type of equipment. The steps in the analysis are similar for all equipment classes:

- Plant hierarchy: The plant hierarchy is a prerequisite for an efficient risk assessment and maintenance and inspection planning, since the plant is divided into manageable sections.
- Failure mode: Assigning functions and sub functions to the physical items at the plant simplifies the identification of failure modes. The failure modes are then used to identify failure cause, root causes, and damage mechanisms.
- Probability of failure (PoF): A number of methods for determining the probability of failure is discussed (expert judgement, rate models, statistical, physical models, etc.)
- Consequence of failure (CoF): Consequence of failure is divides into four categories. Safety – instant consequences on humans within or outside the plant's area. Health consequences – long term effects on humans within or outside the plant's area. Environmental consequences and business consequences of failure. Methods are provided for making this type of assessment.
- Risk assessment: Risk is the combinations of the probability of failure and consequence of failure. The level of risk is compared to the company acceptance criteria regarding safety and environmental risk. For financial and cost consequences, a cost-benefit assessment is proposed. The cost related to the mitigation cost, the benefit is the reduced risk related to the mitigation.
- Mitigating activities and risk reduction: Based on the risk assessment (safety,

health, environment, business) mitigating activities are proposed for the high-risk items as illustrated in the figure below. Mitigation activities can be maintenance/inspection, redesign, operational constrains depending on the actual case [6].

5. Elevator Risk Assessment and Reduction Methodology

Safety is considered as freedom from unacceptable risk. There can be no absolute safety. Some risks may remain as “residual risk”. Therefore a product or process (e.g., operation, use, inspection, testing, or servicing) can only be relatively safe. Safety is achieved by sufficient mitigation or reduction of the risk as shown in Fig. 2.5.

Safety is achieved by the search for an optimal balance between the ideal of absolute safety, the demand to be met by a product or process, and factors such as benefit to the user, suitability for purpose, cost effectiveness, and conventions of the society concerned. Consequently, there is a need to review continually the established safety levels, in particular when experience necessitates review of the pre-set safety levels and when developments, both in technology and knowledge, can lead to feasible improvements to attain sufficient mitigation of the risk compatible with the use of a product, process, or service.

Risk assessment is a series of logical steps that enables, in a systematic way, the examination of hazards associated with lifts. Risk assessment is followed, whenever necessary, by the risk reduction process. When this process is repeated, it gives the iterative process for eliminating hazards as far as possible and for implementing protective measures. Risk assessment includes determination of the subject of analysis, identification of scenarios: hazardous situations cause, and effects, risk estimation and risk evaluation. Risk analysis provides the information required for the risk evaluation, which in turn allows judgments to be made on the level of safety of the lift, lift component, and any relevant process (e.g. operation, use, inspection, testing, or servicing). Risk assessment relies on judgmental decisions. These decisions should be supported by qualitative methods complemented, as far as possible, by quantitative methods. Quantitative methods are particularly appropriate when the foreseeable severity and extent of harm are high. Qualitative methods are useful to assess alternative safety measures and to determine which one gives better protection. The risk assessment shall be conducted so that it is possible to document the procedure, that has been followed and the results that have been achieved [7].

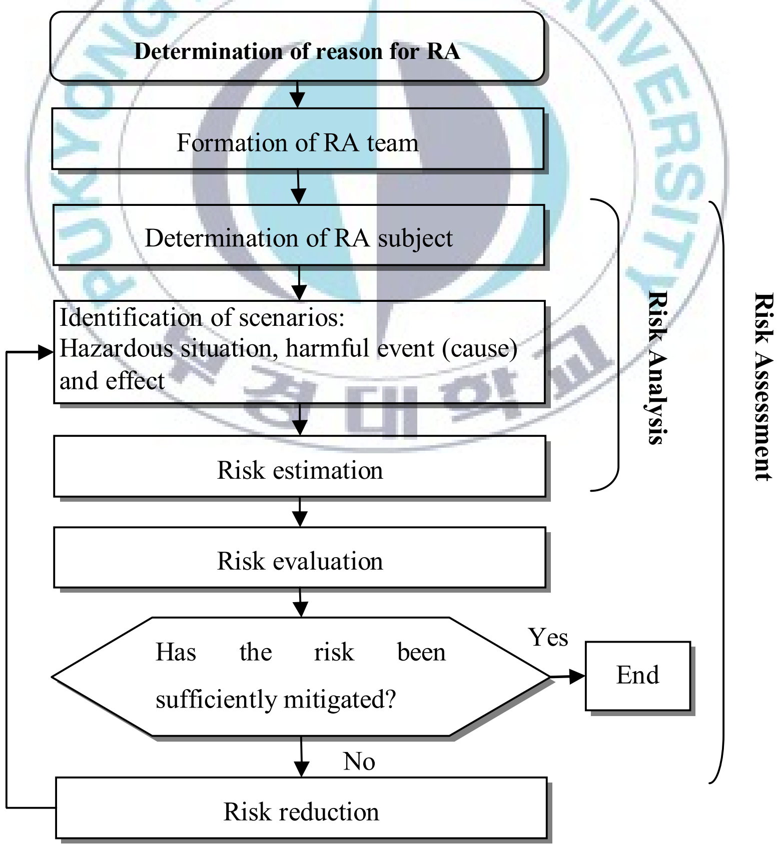

Fig. 2.5 Iterative process of risk assessment and risk reduction

Risk analysis procedure is as the follows:

Step 1: Determination of the reason for conducting a risk assessment

Before a risk assessment process can start, the reason for the assessment should be determined. It can be, but is not limited to, any of the following: verification that the risks are eliminated or sufficiently mitigated in relation to design for, or installation of, a lift, or a component, or a subsystem thereof; the operation and use of a lift; or procedures for testing, inspection, servicing, or performing any other work with intent to maintain the lift or a lift component in its intended operating conditions.

Step 2: Formation of a risk assessment team

Considering the variety in designs, processes, and technologies relevant to lifts and the diversity in the interests and working experience of lift experts, and in order to minimize any bias, a team approach for this risk assessment process is preferable. Selection of the members of the team, including the team moderator, is of paramount importance for the success of this risk assessment process. The team should comprise individuals with varied interests and having experience in all fields that could be affected by the product or process being assessed. Experts with specialized knowledge can be engaged in a consulting role for all or appropriate portions of the risk assessment process. Such participation can significantly enhance the quality of the results. The team moderator should have an overall understanding of the product or process being assessed; understand the risk assessment process; be able to assume an impartial view free of any bias; have “facilitating" abilities; act as a facilitator rather than participant in the debates of the team, and be able to facilitate arbitration when no team consensus agreement can be reached.

Step 3: Determination of the subject of risk assessment and related factors

Once the reason for a risk assessment process is determined in accordance with 5.1, the subject of the assessment shall be determined as precisely as possible. Without limiting generalities, the subject can include one or more of the following: complete lift system, component or subsystem of a lift, persons in relation to a lift, processes related to a lift or its components, such as installation, servicing, repairs, cleaning, testing, modernization and replacement. The intended life cycle is an important factor in determining the probability that a given event can occur. It does not, however, always come into play. If a standard is being written to address intrinsic safety, the life cycle need not apply. Life cycle does have a role when considering the probability that a particular event will occur due to a component failure. In this situation, the life cycle of the system incorporating the component shall be considered. If, for example, the system is to perform its function for 8 years, then the life of components must at least match this to avoid a high probability of failure and, therefore, the occurrence of a given event. If, however, the component, through preventive maintenance, is replaced before failure occurs the probability of the occurrence of a given event is low. Any available information and data that could assist in the qualitative and quantitative analysis should be taken into account, such as accident and incident history, including causes and effects, that is relevant to the subject of the assessment or to similar products or procedures. The absence of an accident history, a small number of accidents, or the low severity of the effects of the accidents should not lead to an automatic presumption of low risk. Quantitative data can be used to supplement the data, based on the consensus of expert opinion derived from experience, as described in this document.

Step4: Identification of scenarios: hazardous situations, causes, and effects

The focal point of a scenario is the identification of hazards that could be associated with the subject being assessed. Table B.1 in Annex B lists typical hazards that could be associated with lifts, including details and examples of the hazards. The list can be used as a starting point when formulating a scenario. The formulation of a scenario includes the identification of a hazard and the formulation of a hazardous situation, cause, and effect. It is important to identify and record the hazards before the formulation of scenario proceeds. It is critical for a scenario to be formulated in the sequence of occurrence of each part of the scenario. All situations or other circumstances in which people (or property or environment) could be exposed to one or more hazards should be identified. This applies to all hazardous situations associated with the subject being assessed. It is not always necessary to list always all hazards before formulating relevant hazardous situations and harmful events, because in most cases the description of the hazardous situation, cause, and effect states the type of hazard being considered. It is, however, important that all members of the risk assessment team agree on the type of hazard, hazardous situation, cause, and effect before the estimation of the risk elements and the risk evaluation proceed.

Step 5: Risk estimation

Through step 4 the scenarios have been formulated, including the hazard, hazardous situation, and cause, as well as the potential effects that can result in harm. The possibility of harm has been identified, but the level of the risk of harm remains to be determined. The risk estimation process is used to establish the level of risk elements and hence the level of risk. When determining elements of risk, and in particular the probability of the occurrence of harm, only one lift shall be considered, rather than multiple installations of the same kind or the whole population of lifts. The risk associated with a particular scenario is derived from a combination of the following elements: the severity of harm; and the probability of the occurrence of that harm, which can be a function of the frequency and duration of the exposure of persons to the hazard, the probability of occurrence of the scenario, and the technical and human possibilities to avoid or limit the harm. The elements are shown in Fig. 2.6.

Risk		**Severity**		**Probability of occurrence of the harms**
Related to the considered hazard	Is a function of the	Possible harm that can result from the considered scenario	and	Which can be a function of - the frequency and duration of the exposure - the probability of harmful events; and - the possibility of avoiding or limiting the harm

Fig.2.6 Elements of risk

For the purpose of this risk assessment process, the level of severity of harm that can occur in a scenario should be estimated by considering possible effects on human life, or property, or the environment, depending on the reason and the subject of the risk assessment.

Level “1”: high

Level “2”: medium

Level “3”: low; and

Level “4”: negligible

When estimating the level of harm, the following should be taken into account: the nature of what is affected: persons, property, environment, and other factors as appropriate.

Probability of occurrence of harm: For the purpose of this risk assessment methodology, the level of probability of occurrence of harm should be estimated as one of the following:

Level “A”: highly probable

Level “B”: probable

Level “C”: occasional

Level “D”: remote

Level “E”: improbable; and

Level “F”: highly improbable.

Probability of occurrence of a scenario: When estimating the probability of occurrence of a harmful event (cause and effect) and of persons being in hazardous situations when the event occurs, the following factors may be useful: statistical data; accident history; history of nature and degree of harm; and comparisons with similar lifting devices, or components, or processes.

Frequency and duration of exposure to hazard: The exposure of all persons working on or using the lift to the hazards relevant to a specific lift situation or event should be considered. The exposure of lift users or mechanics should be estimated in relation to one lift, not to multiple lifts. There are continuously existing hazardous situations, but exposure to a hazard can be very infrequent and of short duration, which implies a lower level of probability.

Step 6: Risk evaluation

Once the level of risk is estimated, evaluation of the risk is to be carried out to determine if any protective measures need be taken to reduce the risk. The risk is evaluated by identifying the corresponding “risk group” based on the estimated risk level. The risk levels are grouped as presented in Table 2.1.

Table 2.1 The risk level

Risk group	Measures to be taken
I	Protective measures are required to reduce risk.
II	Review is required to determine whether any further protective measure is appropriate to reduce risk, taking into account the practicability of the solution and societal values.
III	No action is required.

When selecting the risk to be evaluated, the risk assessment team shall select the highest level of risk, not necessarily the highest severity level.

Step 7: Has the risk been sufficiently reduced?

If the risk evaluation in 6 indicates that the risk belongs to Group I or II, then appropriate protective measures shall be selected. Once the protective measure is implemented, the risk assessment process shall be repeated, starting with Step 4, to verify that risk has been sufficiently reduced.

Step 8: Documentation

The process and results of the risk analysis and assessment shall be documented using the templates.

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III. Elevator Fault Analysis and Life Cycle Assessment

1. The Definition of Elevator

An elevator or lift (in British English) is vertical transport vehicle that efficiently moves people or goods between floors of a building. They are generally powered by electric motors that either drive traction cables and counterweight systems, or pump hydraulic fluid to raise a cylindrical piston.

2. The Structure and Principle of Elevator

An elevator is defined as permanent lifting equipment serving two or more landing levels, including a car for transportation of passengers and other loads, running at least partially between rigid guide rails vertically. Elevator may be classified according to several characteristics. The most important characteristic of an elevator is its drive method, with different design principles and different elevator component construction. Classification is usually divided by electric elevators and hydraulic elevators.

ISO Standard 4190 distinguishes five classes of electric traction elevators and specifies their outline dimensions related to loads, speeds and installation arrangements. The main parts of traction elevators are:

(a) Suspension means for car and counterweight, which are represented by steel wire ropes.

(b) Driving machine, which is the power unit, consisting of:

- Electric motor
- Mechanical gearing
- Brake
- Traction sheave
- Couplings, shafts, journals and bearings
- Machine frame (bedplate).

(c) Car, which carries passengers and other loads. It is composed of the sling, a metal framework connected to the means of suspension, the platform which forms the floor of the car and directly supports the load and the car enclosure attached to the car platform. Its mechanical accessories are:

- Suspension gear
- Guide shoes providing guiding for the car sling along the car trajectory
- Safety gear
- Car door and door operator.

(d) Counterweight for balancing the mass of the complete car and a porting of the rated load.

(e) Elevator well (hoist way), the space completely or partially enclosed, extending from the pit floor to the roof, in which the car and the counterweight, if there is one, travels. It is equipped with guide rails for both the car and counterweight, landing doors and buffers or bumpers in the pit.

(f) Safety gear, a mechanical device for stopping and landing the car or counterweight on guide rails in the event of breakage, slackening of suspension ropes or if the speed of a descending car (cwt) exceeds the rated speed by a predetermined value. The braking action of the safety gear is initiated by the over speed governor, usually located in the machine room.

(g) Buffers representing a resilient stop beyond the normal bottom limit of the car or counterweight travel. They may be of polyurethane, spring or oil type in respect of the rated speed and are designed to store (accumulate) or dissipate the kinetic energy of the car or counterweight.

(h) Electric installations including electric safety devices and lighting.

(i) Control system.

A typically installation of a traction passenger elevator is shown in Fig. 3.1.

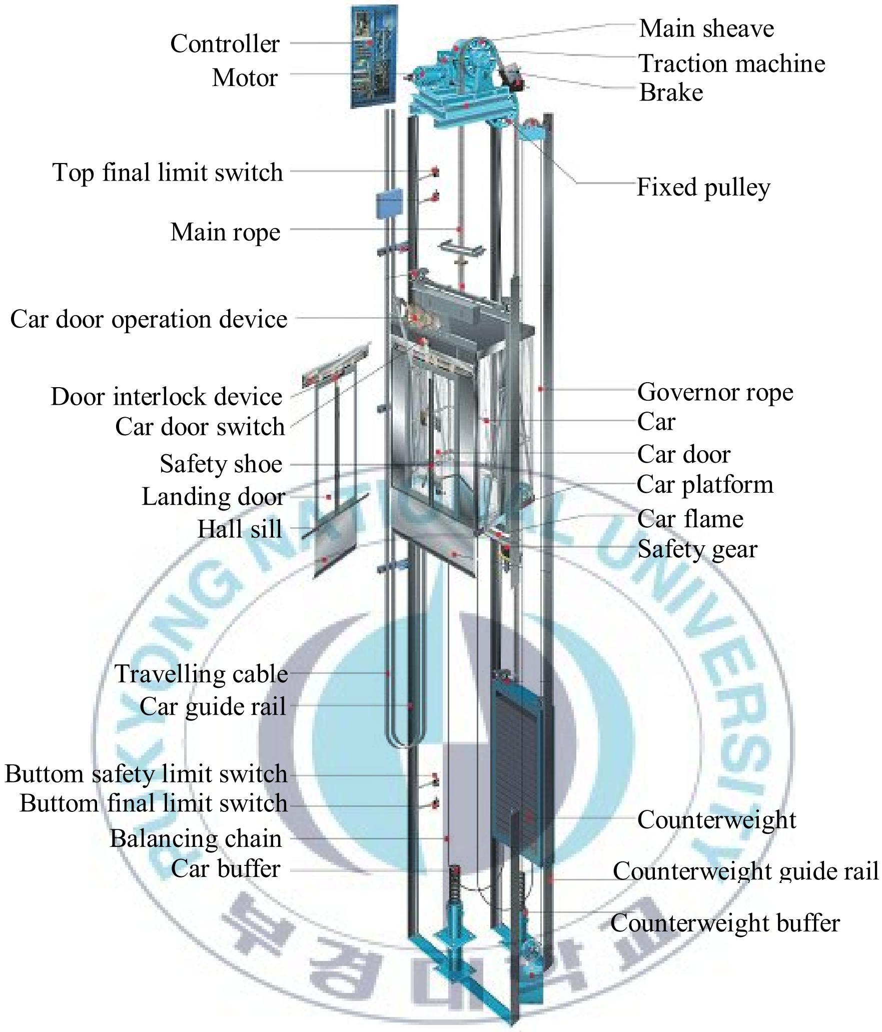


Fig. 3.1 Rope type elevator [1] (adopted from Dong Yang Elevator Co.,Ltd.).

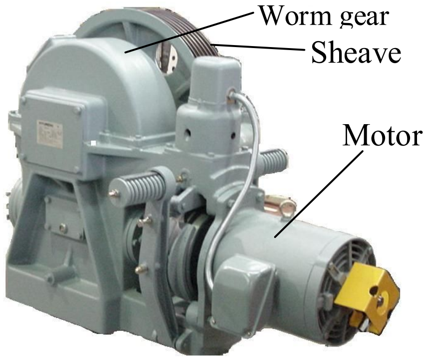
3. Main Component Element of Elevator

3.1. Traction Machine

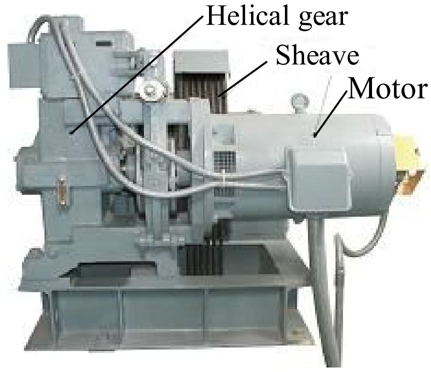
Gearless machine are usually used for rated speeds over 2.5 m/s, while geared machines are applied for lower speeds. Spur gears were used occasionally in the past, but with the advancement of design and production techniques, worm gearing became the accepted standard for conventional geared elevator machines. The application of a worm gear speed reducer brings several advantages:

- it is very compact and of very small dimensions for the given ratio and transmitted power,
- it has a minimum number of moving parts, thus minimizing maintenance and replacement,
- sliding action of worm gearing results in quiet operation,
- it has an inherently high shock load resistance.

The worm is usually cut from forgings of alloy steel which provides a hard working surface. The material is nickel-chromium or nickel-chromium-molybdenum steel. The hardened worms are ground of the surface to minimize friction and wear. The rims of worm wheels are made of centrifugally cast bronze, machined to mate with the worm. The worm shaft is always supported by two radial bearings and one axial bearing for sustaining the axial trust. It can be places either in the upper position (over-driven worm gear) or the lower position (under-driven worm gear) below the worm wheel. The upper position seems to be used frequently with light-duty and medium-duty machines. The advantages are easy sealing of the gearbox, easy control of the gearing and the worm wheel shaft located low above the machine framework. However, the lubrication of the worm is generally worse than with under-driven worm gears, particularly during starting periods when metal-to-metal contact may occur under high loads. A typical under-driven worm gear is shown in Fig. 3.2.



(a) Worm gear type



(b) Helical gear type

Fig. 3.2 Traction machine of geared type [2].

The gearless machine is equipped with a high speed, with speeds in the range of 100-220 rpm. The speed control is accomplished by a frequency converter. There is no gearing between the rotor and the traction sheave. All principal components of the machine, i.e, the rotor, traction sheave and brake drum and mounted on the same shaft, supported by two bearings. The shaft and the bearings must sustain the load imposed on the sheave as well as the weight of components mentioned above and transmit the complete load to the building structure. The traction sheave and brake drum are usually made as one piece. With no gearing employed, the mechanical efficiency is higher compared to geared elevator machines. A typical AC gearless traction machine is shown in Fig. 3.3.

Fig. 3.3 AC Traction machine of gearless type [3].

a) Reducer

The reducer of geared type is generally used worm gear and helical gear type. Worm reducer can do reducer ratio largely, easy to process but it is necessary large motor because the torque transmission efficiency is low. The worm gear usually has an efficiency of 70 to 75% as compared to the helical gear of around 90%. Helical reducer has large torque transmission efficiency, but because it occur high sound more than worm reducer, so worm reducer is used usually.

b) Electric Motor

Electric motor is the device to convert an electric energy by a mechanical energy. A three-phase induction motor, presented in Fig. 3.4 has two main parts: a stationary stator and a revolving rotor. The rotor is separated from the stator by a small air gap that ranges from 0.4 mm to 4 mm, depending on the power of motor.

The stator consists of a steel frame that supports a hollow cylindrical core made up of stacked laminations. A number of evenly spaced slots, punched out of the internal circumference of the laminations, provide the space for the stator winding.

The rotor is also composed of punched laminations. These are carefully stacked to create a series of rotor slots to provide space for the rotor winding. There are two types of rotor windings: conventional 3-phase windings made of insulated wire and squirrel-cage windings. The type of winding give rise two main classes of motors: squirrel-cage induction motors and wound-rotor induction motors.

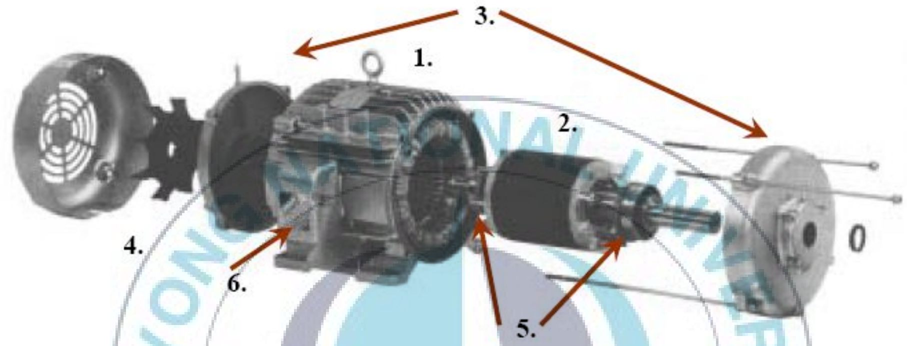


Fig. 3.4 Exploded view of cage motor: Stator (1), Rotor (2) End-caps (3), Cooling fan (4), Ball bearings (5), Terminal box (6) [4].

A squirrel-cage rotor is composed of bare per bars, slightly longer than rotor, which are pushed into the slots. The opposite ends are welded to two copper end-rings, so that all the bars short-circuited together. The entire construction resembles a squirrel-cage, from which the name is derived. In small and medium size of motors, the bars and end-rings are made of die-cast aluminum, molded to form an integral block

Another type is a wound-rotor has a 3-phase winding, similar to the one of the stator. The winding is uniformly distributed in the slot and is usually connected in 3-wire. This motor is, however, less efficient than the squirrel-cage induction motor, and it is used only when a squirrel-cage induction motor cannot deliver the high enough starting torque.

When the stator winding of a three-phase induction motor is connected to a three-phase power source, it produces a magnetic field that is a constant in magnitude and revolves around the rotor at the synchronous speed. If f is the frequency of the current in the stator winding and P is the number of poles, the synchronous speed of the revolving field is

$$n_s = \frac{120f}{P} \tag{3.1}$$

where n_s is synchronous speed (r/min), f is frequency of the source (Hz) and P is number of poles. This equation shows that the synchronous speed increases with frequency and decreases with number of poles.

The revolving field induces electromotive force (EMF) in the rotor winding. Since the rotor winding forms a closed loop, the induced EMF in each coil gives rise to an induced current in that coil. When a current-carrying coil is in a magnetic field, it experiences a force that tends to rotate it. The rotor receives its power by induction only when there is a relative motion between the rotor speed and the revolving field. Since the rotor rotates at a speed lower than the synchronous speed of the revolving field, an induction motor is also called an asynchronous motor.

The slip of induction motor s, is defined as the difference between the synchronous speed and the rotor speed, expressed as a percent (or per unit) of synchronous speed. The per unit slip is given by equation

$$s = \frac{n_s - n}{n_s} \tag{3.2}$$

where n is rotor speed (r/min), The slip s is practically zero at no-load and is equal to 1 (or 100%) when rotor is locked.

c) Brakes

The elevator braking system, which must be set in operation automatically in the event of loss of power supply and loss of supply to the control circuits, must be provided with an electromechanical friction brake. This brake must be capable of stopping the machine when the car with 125% of rated load is traveling at its rated speed and must hold the system at rest afterwards. The retardation must not be in excess of that resulting from the operation of the safety gear or by stopping the car on its buffers. During the stopping action, the kinetic energy of the moving parts of the elevator is converted into thermal energy; the holding function of the brake prevents a change in potential energy.

The brake is usually mounted on the high-speed shaft (motor shaft), because the braking torque is relatively small here, providing that the shaft is coupled on the sheave (drum, sprockets) by direct mechanical means. With indirect-drive machines, utilizing V-belts, toothed drive belts or drive chains, the brake must be located on the traction sheave (drum) assembly side of the machine to be fully effective in the event of a belt set or chain set failure.

The brake must be applied by compression springs or by gravity. It can be released either electromagnetically or electrohydraulically (Fig.3.5). The interruption of the current must be controlled by at least two independent electric devices. Braking should occur when the electric circuit operating the brake is interrupted. When the machine is fitted with a manual emergency operating device, the brake must be so designed to enable releasing by hand and constant effort must be exerted to keep the brake open. Elevator brakes are mostly provided with a drum; however, the application of disc brakes has become more frequent [5].

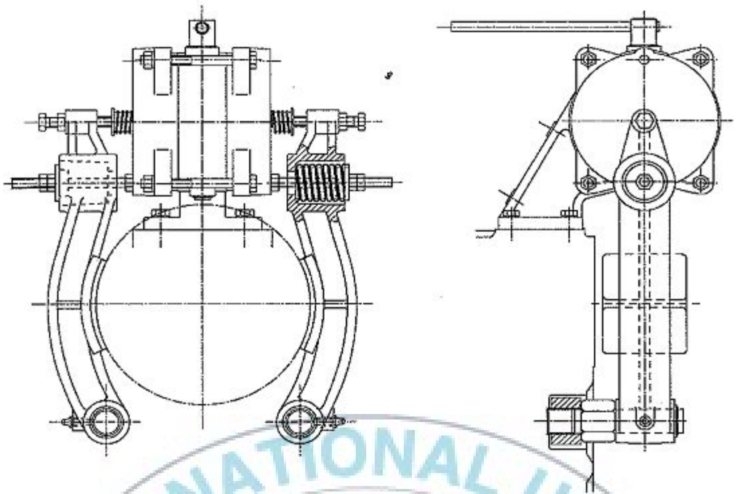


Fig. 3.5 DC brake system.

3.2. Safety Gear

The car of every elevator which is suspended by wire ropes or chains, and which may be entered by persons for the purpose of transportation or mechanical handling of goods at landings, must be provided with a safety gear. The counterweight must be equipped with a safety gear when occupied spaces are located under the hoist way.

The safety gear is a mechanical device for stopping the car (or counterweight) by gripping the guide rails in the event of the car speed attaining a predetermined value in a downward direction of travel, irrespective of what the reason for the increase in speed may be. The safety gear is preferably located below the lower members of the car frame and operates on one pair of guide rails. The operation should be simultaneous on both guide rails; the floor of the car with the load uniformly distributed must not incline more than 5% from its normal position.

The predetermined value of the car (counterweight) speed at which it must be stopped is the tripping speed of the over speed governor. The counterweight safety gear may be either tripped by the failure of the suspension gear, or by a safety rope, if the rated speed does not exceed 1 m/s. A device (overspeed switch) must be mounted on the governor that would initiate cutting off the control circuit before or at the moment of safety gear operation.

Car safety gear is classified on the basis of their performance characteristics. They are as follows:

(1) *Instantaneous type*, which exerts a rapidly increasing pressure on the guide rails during the stopping period. The stopping time and distance are very short; no flexible medium is introduced to limit the retarding force and the stopping distance. This type can be employed for rated speeds not exceeding 0.63 m/s in Europe, but up to 0.76 m/s in the U.S. The behavior of a car or counterweight on the application of this kind of safety gear cannot be exactly predicted nor calculated and must be examined experimentally.

(2) *Progressive type* applies limited pressure on the guide rails during the stopping interval. After the safety gear is fully applied, retarding forces are reasonably uniform. The stopping time and distance are related to the mass of the movable system being stopped and the speed at which the application of the safety gear is initiated. This type must be used for rated speeds in excess of 1 m/s.

3.3. Overspeed Governor

The governor is usually located in the machine room. If governor is located in the hoist way, it must be easily accessible from outside the hoist way. A schematic arrangement of the overspeed governor system is shown in Fig. 3.6. The governor is provided with the governor rope (1), passing round the governor pulley (2), down to a tensioning pulley (3) in the pit and back again to the governor rope is attached at the point (4). When the tripping speed of the governor rope is achieved, the governor stops the rope. Since the car continues in a downward motion, the tension in the governor rope is increased; exceeding the value necessary to engage the safety gear and, consequently, the safety gear is set in operation.

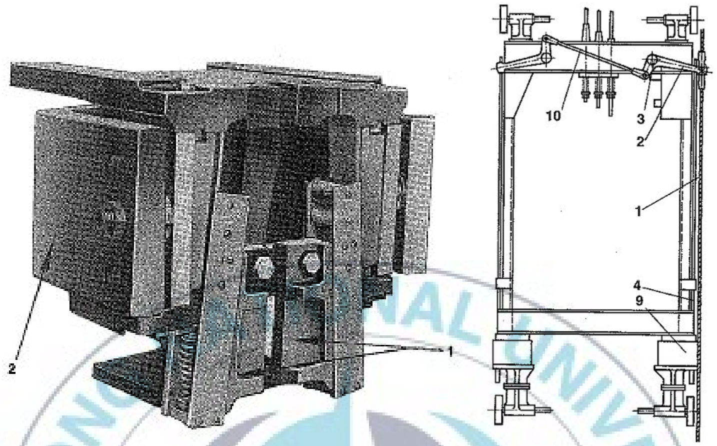


Fig. 3.6 Operating mechanism of flexible guide clamp safety gear:
1. Governor rope 2. & 5. Levers 3. Shaft 4 and 6. Operating rods 7 and 8. Gibs 9. Clamp 10. Connecting rod

In compliance with EN 81-1, the tripping speed of the governor for car safety gear should be at least 115% of the rated speed and less than

(a) 0.8 m/s for instantaneous safety gears except for the captive roller type,

(b) 1,0 m/s for safety gears of the captive roller type,

(c) 1.5 m/s for instantaneous safety gears with buffered effect or progressive safety gear used for rated speeds $\leq$ 1.0 m/s

(d) $1.25\nu + (0.25/\nu)$, where v is rated speed (m/s), for other types of safety gears.

3.4. Buffers

Elevator must be equipped with buffers located in the pit at the bottom limit of travel for both cars and counterweights, to constitute the final emergency device.

If the buffers are attached to the car or counterweight, pedestals at least 0.5m high must be provided at the end of the travel. Pedestals are not required for the counterweight buffers if it is impossible to gain involuntary access under the counterweight.

Positive drive elevators must also be provided with buffers on the car top to function at the upper limit of travel. If a counterweight is provided, the car buffers must not function until the counterweight buffers are fully compressed. There are two principal types of buffers in existence:

(1) *Energy accumulation buffers*, with or without buffered return movement, can be used for rated speeds up to 1.0 m/s or 1.6 m/s, respectively. The total possible stroke must not be less twice the gravity stopping distance corresponding to 115% of the rated speed v, i.e.,

$$2\times\frac{(1.15v^2)}{2g_n}=0.135v^2 \tag{3.3}$$

The stroke must be covered under a static load of between 2.5 and four times the mass of the car plus its rated load in Europe, while the multiples are two and three in the U.S.

(2) *Energy dissipation buffers* may be used irrespective of the rated speed of the elevator. The total possible stroke must be at least equal to the gravity stopping distance corresponding to 115% of the rated speed, i.e., $0.0674v^2$. Reduced stoke buffers may be used when a device is provided that checks the effective slowdown of the machine before arrival at terminal landings. Reduced speed may be used instead of the rated speed when calculating the buffer travel; however, the stroke must be at least

(a) 50% of $0.0674v^2$, if the rated speed v does not exceed 4 m/s

(b) 33% of $0.0674v^2$, if the rated speed v exceeds 4 m/s

4. Survey of Elevator Parts Life Cycle

4.1. Maker Survey of Elevator Parts Life

- Purpose of survey: survey to manufacture about life cycle and replacement cycle of parts of elevator.
- Propose of survey: five elevator manufacturers in position of more than enterprise of middle standing.
- Means of survey: by fixed questionnaire.

1) Maker Survey Related to Life of Main Parts

This survey was conducted for the elevator parts presented in Table 3.1.

Table 3.1 Survey related to life of elevator parts

Name of parts	Maximum life	Life expectancy
Main rope	9.2	4.4
Motor	24	16.4
Sheave	10.4	4.4
Oil Seal	10.0	5.4
Brake	23.0	16.6
Lining	9.6	6.2
Relay	6.8	5.4
Door safety shoe	19.6	13.6
Door guide shoe	5.9	3.7
Hanger roller	12.7	7.6
Interlock switch	11.8	7.4
Door gate switch	11.8	7.4
Door motor and controller	18.0	10.4
Door spring colser	12.8	8.4
Balancing weight	17.2	13.6
Absorbing rubber	14.4	11.4
Leveling sensor	12.0	8.0
Limit switch	14.0	11.0
Button and Ramp	6.7	4.4
Indicator	10.4	6.2
Car or Counter weight guide shoe	8.0	5.2
Traction machine bearing	13.2	8.8
PC Board	12.0	7.8
Main contactor	7.8	6.2
brake contactor	9.0	7.6

2) Maker Survey Related to Elevator Parts Life

For this survey, we asked some questions related to elevator parts life. The questions for the maker are presented as follows:

- How long is the life of mentioned parts in comparison with your expected life?
  ① Usually appeared that the life was same the expected life (1)
  ② Usually appeared that the life was more longer than the expected life Approximately 5~10% in comparison with expected life (1)
  ③ Usually appeared that the life was less longer than the expected life Approximately 80~90% in comparison with expected life (3)
- If the life is less long than the expected life, which is the factors as follows? (Write all of relevant data according to priority order_)
  ① Poor produce (23%)
  ② Poor quality control (14%)
  ③ Poor design (low safety factor and overload etc.) (2%)
  ④ Use environment (34%)
  ⑤ Poor maintenance (insufficient of maintenance and fuel) (27%)
- How do you think that technological level of domestic elevator parts manufacture companies is how?
  ① International level (2)
  ② It is technological level that pass in domestic (2)
  ③ It is middle (1)
- What is the motivation of Modernization by changing of purpose, control type, rated speed, rated load etc. (Write all of relevant data according to priority order : ______)
  ① For the performance improvement of elevator (39%)
  ② Life is expired (28%)
  ③ For safety (31%)
  ④ The others (2%)

- Which of the parts is replaced when life is expired?
  - ☞ Guide shoe (2)
  - ☞ Hanger roller (0)
  - ☞ Relay (3)
  - ☞ Door shoe (2)
  - ☞ Main contactor (2)
  - ☞ Button Switch (3)
  - ☞ Brake lining (1)
  - ☞ Oil sill (0)
  - ☞ Bearing (1)
  - ☞ Interlock (2)
  - ☞ Limit Switch (1)
  - ☞ The others (8)
- What is your thinking that condition of replaced parts of elevator when Modernization be conducted?
  - ① Decelerator [good (1), slight defect (3), critical defect (1)]
  - ② Motor [good (2), slight defect (1), critical defect (2)]
  - ③ Control panel [good (0), slight defect (3), critical defect (2)]
  - ④ Cage [good (0), slight defect (5), critical defect (0)]
  - ⑤ Door system [good (0), slight defect (4), critical defect (1)]
- What is the mainly cause to determine the changing time of parts?
  - ① Condition of parts (2)
  - ② Working condition of parts (4)
  - ③ Code of replacement and maintenance (1)
  - ④ Code from experience (1)
  - ⑤ The others (0)
- If you judge to replace time by experience, how much reliable it has?
  - ① More than 90% (2)
  - ② More than 80% (2)
  - ③ More than 60% (0)
  - ④ More than 40% (1)
  - ⑤ The others (0)

▪ Each what thing do you have by parts changed in dimension of preventive maintenance at replace of parts and changed parts when breakdown or failure happens (Write all of relevant data)

① Which of the parts is(are) replaced in dimension of preventive maintenance?

☞Main shave (5) ☞Door guide shoe (2)
☞Relay (1) ☞Car and counterweight guide shoe (2)
☞Main contactor (0) ☞Door hanger roller (2)
☞Brake lining (3) ☞Interlock switch (0)
☞Button (0) ☞The others (7)

② Which of the parts is(are) replaced when damaging or trouble are occurred

☞Button (4) ☞Relay (3)
☞Motor (0) ☞Bearing (1)
☞Main contactor (1) ☞Indicator (4)
☞Door hanger roller (0) ☞Ramp (1)
☞Switches(4) ☞The others (7)

3) Concluding remarks

It is surveyed by result of survey to manufacture about elevator part life that the difference is very large between expected life time and average life time in most of elevator parts, and it is caused by lack of maintenance standard. It is estimated that simple maintenance without replacement cycle or technical standards is a common form. The rank of the replacement by preventive maintenance viewpoint is sheave, brake lining, guide shoe, door hanger, relay. etc and it's caused by it can be checked by numerical value or eye. The rank of the replacement when causing damage or faults is each switches, button, indicator, relay, bearing etc. and It is caused by lack of maintenance standard. There are such differences among manufactures in replace elevator part because of lack of maintenance standard or technical judgment about replacement, and there are many parts which are replaced after brake he judgment based on these results, most of elevator maintenance are being managed by break down maintenance or preventive maintenance. It is required more organized and scientific maintenance for approving reliability and accident prevention

4.2 Maintenance Company Survey about Component Life

- Purpose of survey: survey to maintenance corporate about life cycle and replacement cycle of parts of elevator
- Subject of survey: five elevator manufacturers in position of more than enterprise of middle standing
- Means of survey: by fixed questionnaire

1) Maker Survey related to life of mainly parts

This survey was conducted for the elevator parts presented in Table 3.2.

Table 3.2 Survey related to life of elevator components

Name of parts	Maximum life	Life expectancy	Replacement cycle
Main rope	7.1	4.6	4.4
Motor	16.2	13.7	13.9
Sheave	7.1	4.7	4.5
Oil seal	6.3	4.8	4.3
Brake ASSY	11.3	9.8	9.4
Lining	7.9	5.8	5.4
Relay	7.4	5	4.6
Door safety shoe	8.3	6.3	6.1
Door guide shoe	5.2	4	3.9
Hanger roller	6.6	4.9	4.6
Interlock switch	7.4	5.6	5.2
Door gate switch	7.2	5.6	5.2
Door motor and controller	10.4	8.2	7.9
Door spring closer	9.2	7.7	7.3
Balancing weight	11.6	9.9	9.7
Absorbing rubber	12.2	10.4	10.2
Leveling sensor	8	6	5.8
Limit switch	8.1	6.1	5.8
Button and Ramp	5.3	3.8	3.7
Indicator	9.5	7.5	7
Car or counterweight guide shoe	7.1	5.5	5.2
Traction machine bearing	8.5	6.6	6.2
PC Board	11.1	8	7.9
Main contactor	5.2	3.7	3.6
brake contactor	5.4	3.9	3.7

2) Maintenance Company Survey Related to Elevator Parts Life

Survey related to elevator is performed by asking some questions listed below:

- How long is the life of mentioned parts in comparison with your expected life?

  ① Usually appeared that the life was same the expected life (25, 34%)

② Usually appeared that the life was more longer than the expected life (16, 22%) approximately 5.8 years

③ Usually appeared that the life was less longer than the expected life (32, 44%) approximately 5.8 years

- If the life is less long than the expected life, which are the factors as follows? (Write all of relevant data according to priority order____)
  - ① Poor produce (10, 16%)
  - ② Poor quality control (8, 13%)
  - ③ Poor design (low safety factor and overload etc.)(10, 16%)
  - ④ Use environment (29, 47%)
  - ⑤ Poor maintenance (insufficient of maintenance and fuel) (5, 8%)
- How do you think that technological level of domestic elevator parts manufacture companies is how?
  - ① International level (14, 19%)
  - ② It is technological level that pass in domestic.(29, 40%)
  - ③ It is middle (30, 41%)
- What is the motivation of Modernization by changing of purpose, control type, rated speed, rated load etc. (Write all of relevant data according to priority order : ______)
  - ① For performance elevation of elevator (32, 44%)
  - ② Life is expired (16, 22%)
  - ③ For safety (23, 31%)
  - ④ The others (2, 3%)
- Which of the parts is replaced when life is expired?

☞Guide shoe (34, 11%) ☞Hanger roller (32, 10%)
☞Relay (32, 10%) ☞Door shoe (28, 9%)
☞Main contactor (27, 9%) ☞Button SW (20, 6%)

☞Brake lining (15, 5%) ☞Oil sill (11, 4%)
☞Bearing (10, 3%) ☞Interlock (10, 3%)
☞Limit SW (7, 2%) ☞The others (82, 28%)

- What is your thinking that condition of replaced parts when Modernization is conducted?
  ① Decelerator [good (34, 50%), slight defect (26, 38%), critical defect (8, 12%)]
  ② Motor [good (32, 47%), slight defect (29, 43%), critical defect (7, 10%)]
  ③ Control panel [good (8, 12%), slight defect (27, 39%), critical defect (34, 49%)]
  ④ Cage [good (16, 23%), slight defect (43, 61%), critical defect (11, 16%)]
  ⑤ Door system [good (6, 9%), slight defect (38, 55%), critical defect (25, 36%)]
- What is the mainly cause to determine the changing time of parts?
  ① Condition of parts (18, 26%)
  ② Working condition of parts (44, 64%)
  ③ Code of replacement and maintenance (3, 4%)
  ④ Code from experience (1, 2%)
  ⑤ The others (3, 4%)
- If you judge to replace time by experience, how much reliable it has?
  ① More than 90 % (31, 44%)
  ② More than 80 % (31, 44%)
  ③ More than 60 % (6, 1%)
  ④ More than 40% (1, 1%)
  ⑤ The others (3, 4%)

▪ Each what thing do you have by parts changed in dimension of preventive maintenance at replace of parts and changed parts when breakdown or failure happens (Write all of relevant data)

① Which of the parts is (are) replaced in dimension of preventive maintenance?

☞Main shave (57, 14%) ☞Door guide shoe (46, 12%)

☞Relay (34, 9%) ☞Car and counterweight guide shoe (33, 8%)

☞Main contactor (29, 7%) ☞Door hanger roller (23, 6%)

☞Brake lining (22, 6%) ☞Interlock switch (12, 3%)

☞Button (11, 3%) ☞The others (127, 32%)

② Which of the parts is(are) replaced when damaging or trouble are occurred?

☞Button (42, 13%) ☞Relay (23, 7%)

☞Motor (19, 6%) ☞Bearing (16, 5%)

☞Main contactor (16, 5%) ☞Indicator (15, 5%)

☞Door hanger roller (13, 4%) ☞Ramp (11, 3%)

☞Switches (10, 3%) ☞The others (157, 49%)

3) Concluding remarks

It is surveyed by result of survey to maintenance company about elevator parts life that the difference is very large between expected life time and average life time in most of elevator parts, and it is caused by lack of maintenance standard. It is estimated that simple maintenance without replacement cycle or technical standards is a common form. The rank of the replacement by preventive maintenance viewpoint is main sheave, door guide shoe, relay, counterweight guide shoe, main contractor, door hanger roller, brake lining, interlock switch, button and it's caused by it can be checked by numerical value or eye. The rank of the replacement when causing damage or faults is button, relay, motor, bearing, main contractor, indicator, door hanger roller, ramp, switches etc. and it is caused by lack of maintenance standard. There are such differences among manufactures in replace elevator part because of lack of maintenance standard or technical judgment about replacement, and there are many parts which are replaced after brake he judgment based on these results, most of elevator maintenance are being managed by break down maintenance or preventive maintenance. It is required more organized and scientific maintenance for approving reliability and accident prevention

5. Life Cycle Analysis of Main Component

Life cycle of elevator component is considerable difference between theoretical and actual due to influence of load capacity, use frequency, use environment, design condition, install status and maintenance etc. and also there is much difference based on the material, process level, assembly status & design life cycle.

Following table shows the explanation of factors impact to elevator component, life cycle which is investigated by manufacturer and maintenance company and by elevator world. There are difficulties on prevention maintenance and foreseen maintenance due to lack of information on life cycle of elevator component.

Table 3.3 Life cycle analysis and survey of elevator components (Continued)

Component name		Life cycle factor	Forecast Life cycle				Life cycle Extension plan
			Survey		Theory	Elevator World	
			Maker	Maintenance company			
Reducer	Gear	① Material : Surface stress coefficient & Bending stress coefficient is fixed belongs to the material, heat treatment hardness and process level. ② Speed coefficient : Decision Allowable load for gear wear & strength ⇒ Inverse proportion relation between friction speed & circumference speed ③ Friction coefficient : Relating to material, surface roughness, speed, load & accuracy ⇒ Impact to gear efficiency ④ Life cycle coefficient : Value considering life cycle time required on allowable stress ⇒Impact from lubricant, pitch speed, remained stress & material surface condition ⑤ Lubricant : impact to plasticity of gear & heat damage by lubricant quantity & type	12~ 23	10~ 20	10~ 25	20~ 25	-Proper material selection & assembly according to purposes -Decision center distance & speed rate on purposes -Decrease gear damage considering pitch line speed, torque capacity of gear pair - Manage for accurate geat surface contact -Lubricant to be used mineral oil & high sticky -Periodically change lubricant, height of lubricant should be under worm axis about ⅔
Bearing		① speed : Allowable load is decrease when high speed load : early defect occurred like crack, tumble fatigue & fatigue defect ② lubricant : protect early defect occur by making oil film on loading part	16~44	6-15	6-30	10-15	
Brake		① cleanlyness : Frictional resistance increase due toImpurities inflow of plunger ->insulation decrease	10~16	9~ 14	-	20~ 25	-Consistent maintenance of plunger - maintain insulation

Table 3.3 Life cycle analysis and survey of elevator components (Continued)

Main rope	① pitch diameter ratio of lope & sheave : repeat bending times decrease when diameter ratio of lope & sheave Is small (life cycle shorten) bending occurrence frequency ② : lope life cycle is shorten when bending occurrence frequency is high ③ groove type & size : friction coefficient change & type coefficient change according to groove type ④ Repeat bending times change by size material of rope & sheave : wear ratio difference occur between sheave & rope ⇒life cycle shorten Traction angle ⑤ Traction power, contact pressure, repeat bending times increase according increase of groove angle	4～5	4～5	3～9	7～10	-decision sheave diameter according to rope diameter -> diameter ratio 40 times high -Groove size fixed considering traction capacity & rope twist etc. -Sheave material decision according to the rope type -Selection of proper groove angle
	① Load on rope : decrease repeat bending times unbalanced wear due to tension difference on same acting point					- Decrease of tension safety factor above 12 ·Same tension sustenance
Sheave	① Material : Change of wear rate according to material Material hardness sustenance roughness of contact surface ② Frictional wear ratio change with rope by material wear : One side frictional wear occurred due to difference tension -> occurred rope slip vibration & noise,	4～5	4～5	-	8～12	-Material selection for maintain of constant hardness for all circumference -Constant rope tension -Maintain of groove cleanness
Steel	① used material : stainless steel plate is better than carbon steel plate on anti-corrosion ② painting : Prevention to combine the element of steel and oxygen (rust prevention)	-	-	-	-	- Selection of proper clean cycle per each environmental & partial

Table 3.3 Life cycle analysis and survey of elevator components (Continued)

Steel		① Use environment : crack rusting, stress rust crack etc. occurred by used environment	-	-	-	-	-Selection clean method as per surface status
Magnetic contactor	AC	Select Applicable specification on Magnetic contactor ① Setup break coil voltage : Apply voltage area is different in accordance with load type, environment condition & on_off condition. ② surge protect circuit exist or not : Surge make occur arc on contact point of magnetic contactor and make it to wear ③ Load current volume : Contact load current makes the wear high as per high current ④ Cleanness	-	1~2	-	10～15	- Select Applicable specification on magnetic contactor -Check coil terminal's connection - Strong fixing of magnetic ontactor - Remove impurities on contactor - Proper contactor change -Apply surge reduction circuit
Magnetic contactor	AC	Application specification selection of magnetic contactor control method & motor type ① load current volume on contact point : Contact load current makes the wear high as per high current ② Cleanness	-	1～2	-	10～15	- Select Applicable specification on magnetic switch - Check coil terminal's connection -Strong fixing of magnetic contactor - Remove impurities on contactor - Proper contact point change
Relay		① Laod - Induced load - Iesistant load ② load current volume on contact point ③ load voltage volume on contact point ④ Cleanness	5～7	5～6	-	10～15	- Proper specification select on relay - Proper design for load voltage & current on contact point - Connection status of relay should be maintained good condition - cleanliness of mechanical room
PC Board		① factor on manufacturing process : fixing part, Flux & clean status ② factor on environment condition ③ Tolerance on emission, static electricity, surge, sudden voltage down , sudden power failure & voltage change	5～8	4～10	-	10～15	-EMI,EMC test criterion -Machine room ground coting - Handle with care when maintain - Periodic dust elimination of PCB

Table 3.3 Life cycle analysis and survey of elevator components (Continued)

		④ Cleanness					Board
Door	Guide shoe	① Wear : Do not support door from shock, noise and outside impact because rubber or Urethane is been worn away by alien substance storing accumulation of transfer path ② corrosion : Weakening of strength because of the corrosion of iron plate, bolt joint and nut	3～7	3～4	-	1～2	-Selection of material with good abrasion resistance -cleanness maintenance of sill -maintenance of sill transformation -Sill maintenance not to permeate water and detergent
Hanger roller		① Load : If load distributed is not suitable, Urethane is separated and exploded	7~8	3~6	-	5~10	-Urethane selection of high elasticity -cleanness maintenance
Travelling cable		① maximum operate speed and path: The occurrence of crack, cracking, disconnection, confusion according to path(hanged length), ② Material : Life change because of existence and nonexistence of impurities ③ Filled substance : Flexibility increase Lubrication ⇒ Life increase ④ Clearness : If alien substance is attached, Life is shortened by oxidation and degradation ⑤ Temperature in path : If the temperature over recommended temperature, Life is shortened ⑥ Condition of installation : If degree of bending is small, system is weared by interference in wall of path	7～13	7～17	7～13	10～15	-Decision of inserting reinforcement line according to maximum speed and path -Choice of material that impurities do not exist -maintenance of clearness -In path Recommended temperature (-5℃～40℃) should be maintained - Do maintenance as there is no outside impact and contact

Table 3.3 Life cycle analysis and survey of elevator components

Guide shoe	① material : material which has tensile strength, hardness, oil resistant and wear resistant ② Lubrication : reduce noise and wear	5～7	3～6	-	5～8	- Material selection that have wear resistant, low friction coefficient, non-moisture absorption -preservation of oil film -maintain clearness in oli supply device and guide rail
Guide roller	① material : wear resistant, absorbing impact ② Load : Occurrence of separation and rupture according to increasing load ③ Lubrication - maintenance of busing	1	6～8	-	10～15	- Selection of material that is suitable to working conditions - Enlargement of Roller diameter⇒ Dispersion of Load -check lubrication condition regularly
Interlock switch	① Installation condition) electric corrosion and wear ③ Insulation condition of switch base ④ Cleanness : impurity(oil, dust), moisture inflow ⇒ insulation weak	5～10	5～6	7~14	5～10	-Insulation maintenance -cleanness maintenance

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[4] ANSI/ASME A17.1-1996 Safety Code for Elevator and Escalators.

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[6] Elevator Design, Korea Elevator Association, 1995.

IV. New Concept of Performance Measurement and Evaluation

1. Introduction

Owing to sophisticated electronic tools and technologies, electrical or electronic sectors may be diagnosed or analyzed from remote places without having to visit the sites. But, because special equipments as well as expertise for operating them are required to measure and analyze the mechanical sectors such as ride quality or performance, running condition of rotating machinery parts related with vibration and noises, these diagnostic systems are not widely used in the field and new handy system is demanded which can measure and analyze quantitatively the installation and maintenance quality of elevators in the field. Moreover, existing diagnostic equipments for ride quality have caused significant inconveniences and inefficiencies because the data collected from sites have to be analyzed at other places using separate PCs. Further the frequency range they may measure lies in below 200Hz, which causes the equipments to be unable to diagnose the performance, manufacturing and assembly quality, possibility of defects in rotating machinery parts. Only limited numbers of elevator manufacturers have been utilizing them because the FFT analyzers are very expensive and experts on rotating machinery vibration Analysis are needed. In consideration of such reality and necessity, we has developed a new system – Dr. Elevator – with which field engineers may easily perform the on-site measurement, analysis and diagnosis on ride quality as well as rotating machinery parts plus the implementation of remedies and verification. This system also can be applied on-line.

2. Description of the System

Dr. Elevator is an integrated portable type diagnostic tool to analyze and evaluate the ride quality together with rotating machinery parts which combines personal digital assistants (PDA) and data acquisition device using Window-base program which realizes at the same time the user-friendly optimal user interface structure and web-based system which makes on-line communication as well as processing possible. It consists of 4 categories – setup, measurement, storage and analysis. In each category, main information is displayed in single screen to enhance the efficiency and convenience while sub-information or related one may be cross-referred through the use of linkage or pop-up window. It can expand its storage capacity by adding Compact Flash Memory so that significant amount of information may be collected from the sites. It can perform on-site measurement, comparative analysis and diagnosis on ride quality as well as rotating machinery parts. It also has a built-in program which may not only prescribe the remedial measures but also verify their proper implementation afterwards. The reliability of this system has been proved by Korea Research Institute of Standards and Science.

2.1. The Composition of System

As illustrated in Fig. 4.1, the equipment to measure, analyze comparatively and evaluate the ride quality consists of built-in 3 axis low frequency acceleration sensor, noise measuring microphone, data analysis program, portable PC to control data acquisition device and USB cables to connect data acquisition device.

Fig. 4.2 illustrates the equipment to record the frequencies of rotating machinery parts, analyze and evaluate the probable cause of defects, if any. It consists of 4 external acceleration sensors, data analysis program and USB cables to connect data acquisition device.

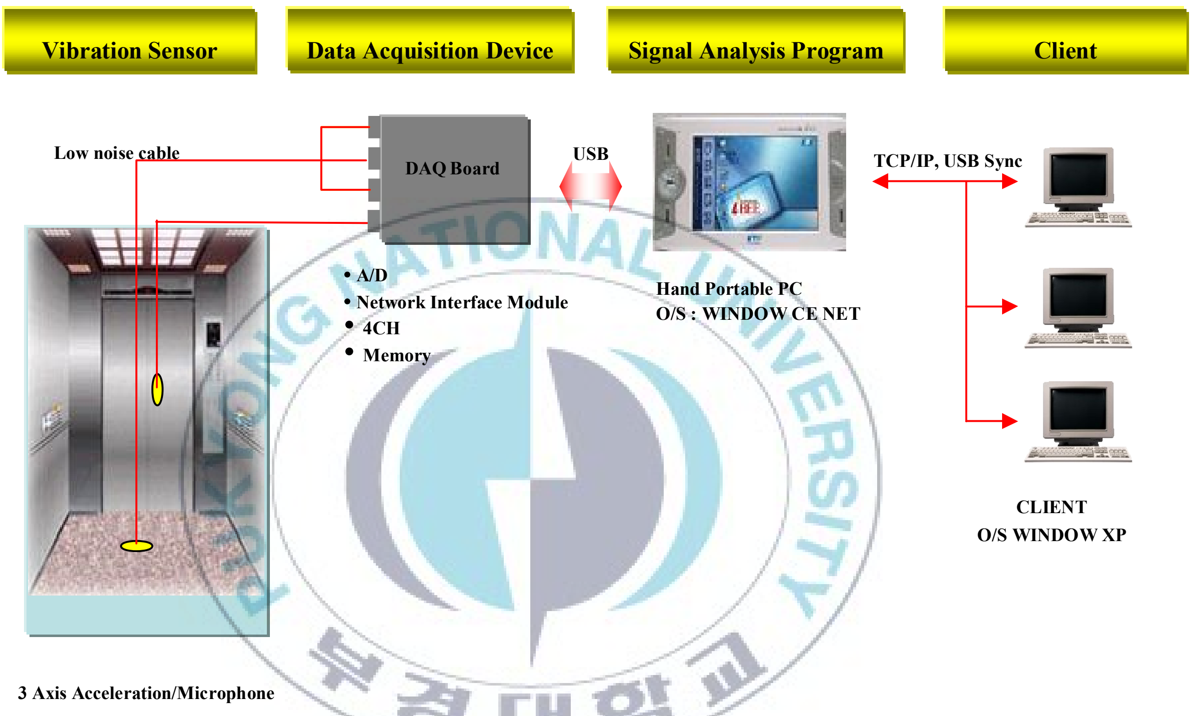


Fig. 4.1 Diagram of ride quality analysis system.

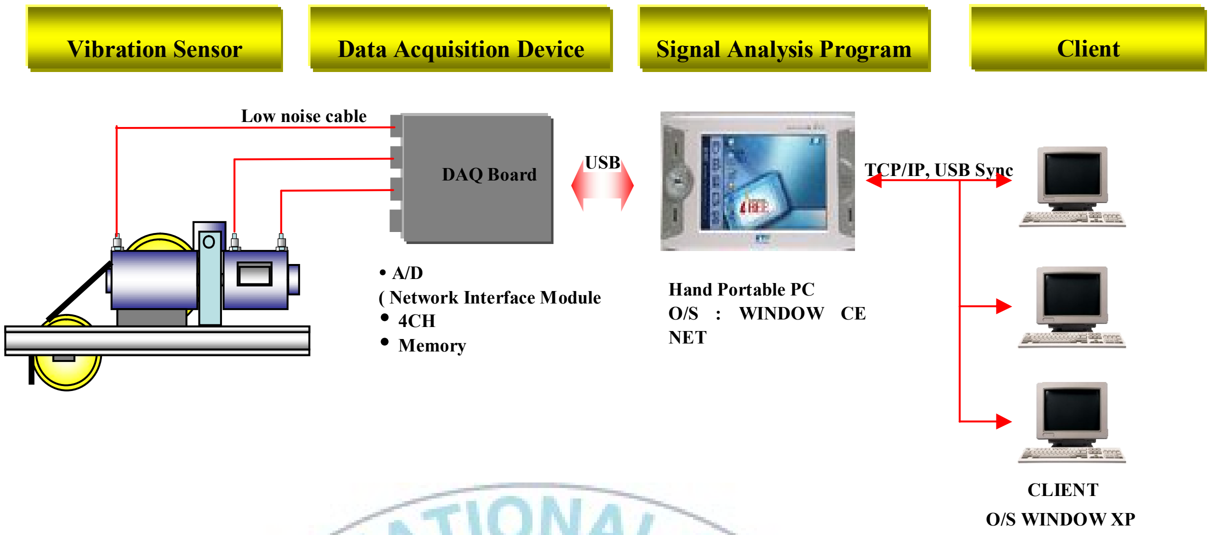


Fig. 4.2 Diagram of FFT analysis system

2.2. Basic Specification

As shown in Table 4.1, three axis low frequency acceleration signals were expressed by the means of human response to vibration in accordance with ISO 8041 and ISO 2631-1 while sound is indicated by SPL value and LAeq value through the application of A-Weighting and Fast Time Weighting in accordance with IEC60651.

Table 4.1 Specification of ride quality analysis system

Classification	Detail Item	Dr. Elevator
Frequency weighting	Vibration	Whole body x, y, z (ISO 8041, ISO2631-1)
	Sound	A Weighting (IEC 60651)
Band limiting	Vibration	ISO 8041
	Acceleration	10Hz low-pass filter (2-Pole Butterworth)
Accuracy	Sound	Type1 (IEC 60651)
Time Weighting	Sound	Fast (IEC 60651)

Rotating machinery parts analysis system consists of 4 channels. Each channel has its own 16 bit A/D converter and maximum frequency range is 12.8 kHz. The gains for amplification of measured signals may be adjusted by 0dB, 10dB, 20dB, 30dB, 40dB so that the accuracy of amplitude may be enhanced. This configuration is presented in Table 4.2.

Table 4.2 Specification of rotating machinery parts analysis system

Classification	Dr. Elevator
Channel	4Ch
Frequency Range	DC ~ 12.8kHz
A/D	16bit
Gain	0dB, 10dB, 20dB, 30dB, 40dB

Portable PDA processes the signals and display necessary information. It measures and analyzes vibration and noise data on real time basis at site. The feature display of PDA is described in Table 4.3.

Table 4.3 Display of PDA

Classification	Dr. Elevator
Processor	Intel PXA255X Scale 400MHz
Memory	Flash ROM 64MB(NAND Type), SDRAM 128MB External Memory 1GB or above
Display	5″ TFT LCD , 64k Color, Touch Screen
Operating System	Windows CE 4.1

2.3 Analysis Function

1) Ride Quality Analysis Function

- *Diagnosis on ride quality*

The basic screen is shown in Fig. 4.3. There are 12 icons on left side and their respective functions are described below. Wave forms are shown on the right side. The wave form corresponding to the icon to be diagnosed is shown on the upper right side. When neither of any icons on the left side is clicked, noise wave form is shown on the upper right side with vibration wave forms in X, Y, Z directions respectively shown below.

- Diverse analyses are available through the application of Sound, Vibration(X, Y, Z axes), Acceleration, Distance, Velocity, Jerk, FFT, RMS, HPF(1Hz), LPF(1Hz~200Hz), ISO filter(2631-1) in accordance with ISO18738.
- Sound Analysis Function
- In accordance with IEC60651, SPL values are indicated. As LAeq values on the basis of boundary are indicated for each section as full-run, pre-run and post-run, sound analysis may be done for each section and frequency analysis on noise source is possible.
- Defective frequency is easily detected because corresponding frequencies are indicated as icons on Spectrum Graph when user inputs concerned information such as motor revolution frequency, diameter of main sheave, diameter of secondary sheave.
- Management of information on elevator installation through DB
- Desired information can be searched by giving diverse search conditions. Information on defective frequency is provided on Spectrum Graph so that it may be easily analyzed.
- Automatic Reporting

- The report on ride quality is prepared and outputted automatically using Excel. The format may be adapted to desired one if necessary

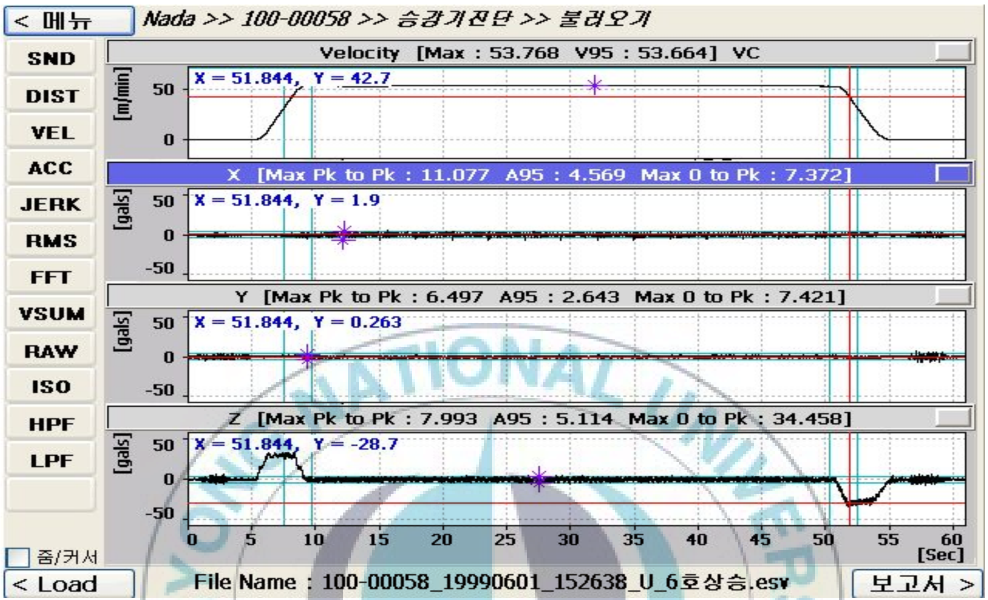


Fig. 4.3 Display of ride quality analysis.

- *Sound*

The noise pattern is shown in Fig. 4.4. The noise is measured in the cabin or residence while car is traveling from the lowest floor to the highest floor. If excessive noise is found, the source of noise may be detected in accordance 3.2.12.

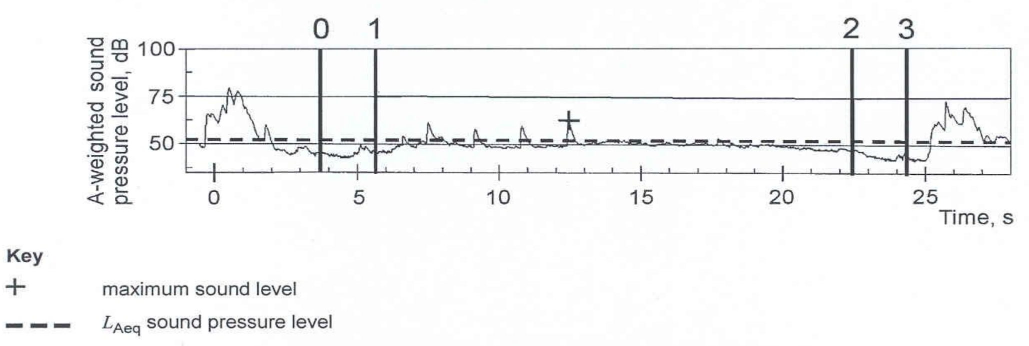


Fig. 4.4 Noise pattern.

- *Distance*

The moving distance pattern is shown in Fig. 4.5. The vertical vibration is measured while car is traveling from the lowest floor to the highest floor and the moving distance of car is graphed against time. The exact location where any abnormal vibration occurs is detected on the graph and appropriate remedy can be applied to alleviate the exposed problem. The graph also may be used to diagnose performance by measuring the brake slip distance and safety gear moving distance.

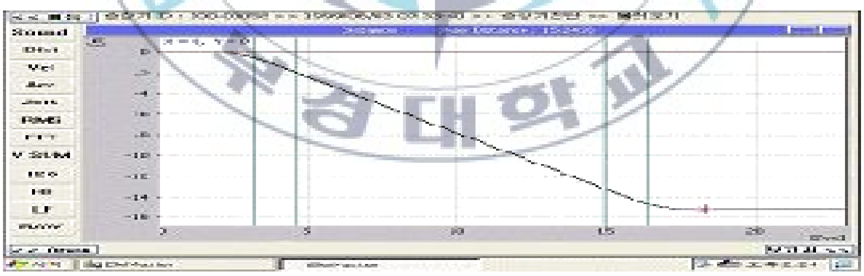


Fig. 4.5 Distance pattern.

- *Velocity*

The velocity pattern is shown in Fig. 4.6. The vertical vibration is measured while car is traveling from the lowest floor to the highest floor and the velocity pattern (showing how fast it is moving from zero to peak) is graphed against time. The resultant graph is compared against rated speed so that any abnormalities exceeding tolerances may be adjusted accordingly.

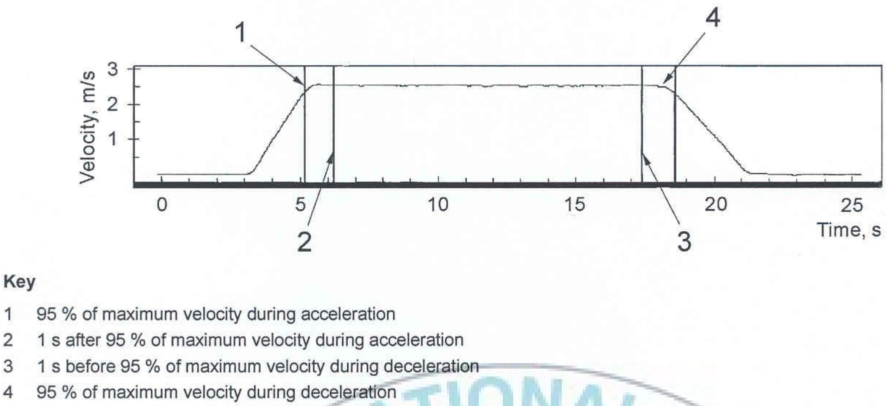


Fig. 4.6 Velocity pattern.

- *Acceleration*

The acceleration pattern is shown in Fig. 4.7. The vertical vibration is measured while car is traveling from the lowest floor to the highest floor and the acceleration (the rate of change in speed from zero to peak) pattern is graphed against time. The resultant graph is compared against rated speed so that any abnormalities exceeding tolerances may be adjusted accordingly.

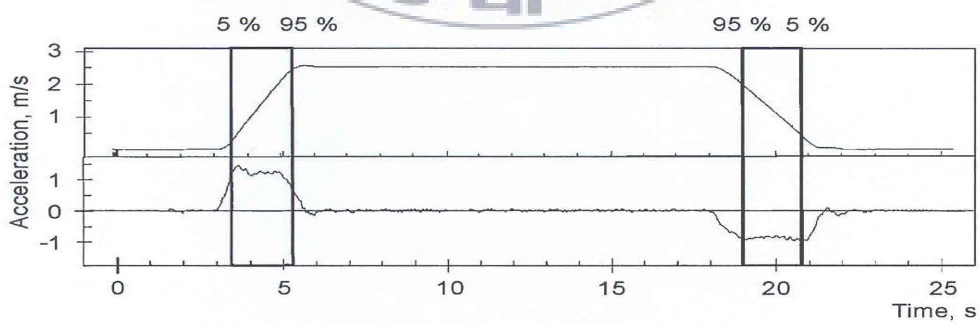


Fig. 4.7 Acceleration pattern.

- *Jerk*

Fig. 4.8 shows the jerk graph which is obtained through differentiation of acceleration by time. It diagnoses the ride quality.

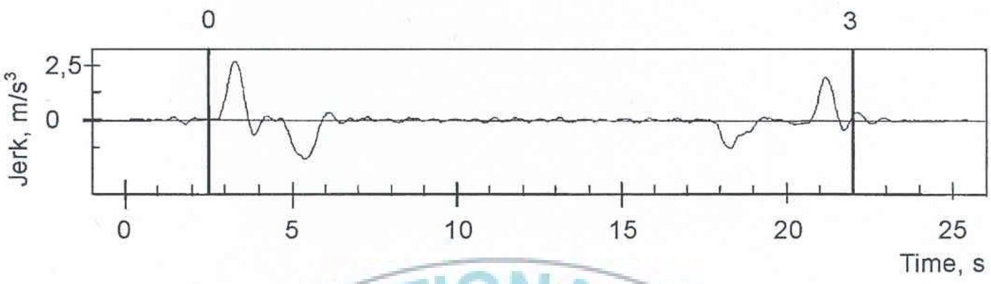


Fig. 4.8 Jerk pattern.

- *FFT*

Fig. 4.9 shows the FFT pattern which may diagnose the cause of vibration. Users may analyze the frequency and amplitude by putting the cursor just before the place to be analyzed and setting FFT time and channel.

Fig. 4.9 FFT pattern.

2) Analysis of Rotating Machinery Parts

While existing ride quality analyzers are able to analyze only partial condition of an elevator by checking the vibration and noise inside car, Dr. Elevator enables overall care of an elevator with greater economy and efficiency by providing analysis function on mechanical defects in rotating machinery parts of an elevator. In addition, it may diagnose easily the causes of defects (bearings, gears, unbalance, misalignment, eccentric rotators, etc) by supporting wide range of solutions and applications for efficient maintenance of installations.

- FFT spectrum analysis
- Fig. 4.10 is showing the vibration wave form against frequency. As frequency wave form presents itself consecutively, the nature of defect may be detected. ISO 10816 (The standard on the magnitude of vibration) is applied as the criteria. It can diagnoses unbalance, wear and tear of bearing, defective axial alignment, defects in bearing, resonance, eccentricity of rotator, loose-fitting, eccentricity of motor rotator, uneven gap and etc.
- Time waveform analysis
- Fig. 4.10 is showing vibration wave form against time. As time signal wave form presents itself consecutively, this enables the analysis on changes in amplitude, changes in cycle and the shape of wave form. Major uses are the analysis on the state of machinery and diagnosis on installation defects.
- Noise frequency analysis
- The causes of noise resulting from mechanical problems can be diagnosed with frequency analysis on sound signal through the application of A, B or C type frequency weighting in accordance with noise level. Octave band analysis is also possible.
- Envelop
- The problem in bearings is one of the most common types of problems and it is also known that all other defects may have significant effects on bearings. So regular inspection on bearings is very essential but it is not so easy to find any symptom of problems until the defect have proceeded considerably. Among various diagnostic methods for bearings, the

frequency analysis is known as the most effective one – especially the function which obtains the natural frequency of each part of bearings by reprocessing the spectrum which is generated from broken down bearings.

- Setting of warning threshold for each frequency range
- The system can help perceive the severity of defects by setting warning threshold for each frequency range.

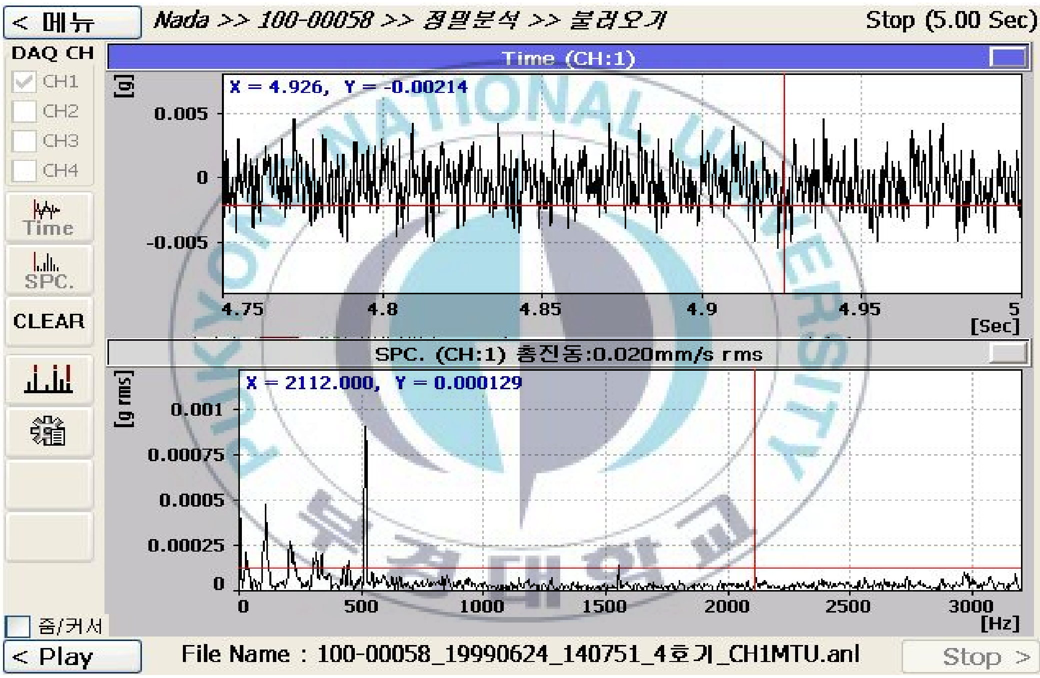


Fig. 4.10 Display of FFT analysis.

- The function in which the user can create at his option overall sections with respect to each band for Spectrum Graph and set alarm for each band respectively.
- The system is designed so that user can establish frequency band for the patterns of defects occurring in each rotating component and take care of

the trend. So if total vibration value increases, the defect may be inferred without precise analysis by checking which band has the increased vibration value through the comparison of vibration value of each band. This can become more accurate and reliable base for judgment as measured data accumulate.

- Waterfall
- This indicates the change infrequency against time and is very useful data.
- Zoom
- A specific frequency section is put into re-sampling so that it may be analyzed more closely.

3) The reliability of Dr. Elevator System

The reliability of the system has been proved by Korea Research Institute of Standards and Science. The measured frequency is 2.5, 5, 10, 20, 40, 63, 80Hz (Octave band). The relative standard uncertainty is max 0.054%, and tolerance range is under 5%.

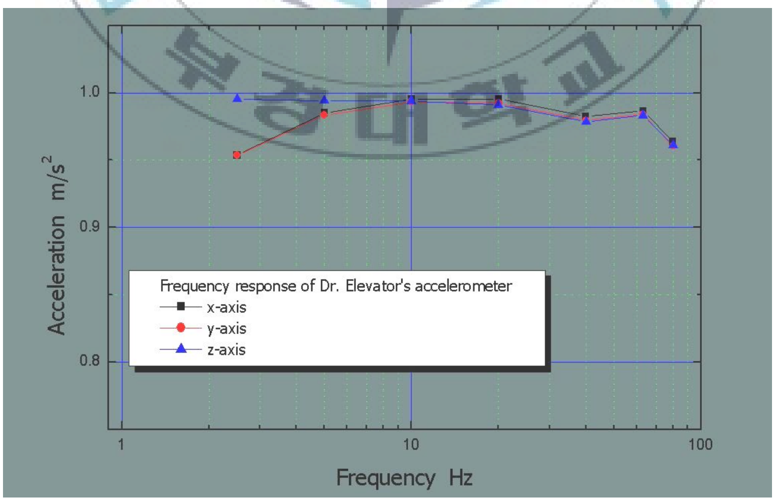


Fig. 4.11 Frequency response of Dr. Elevator accelerometer.

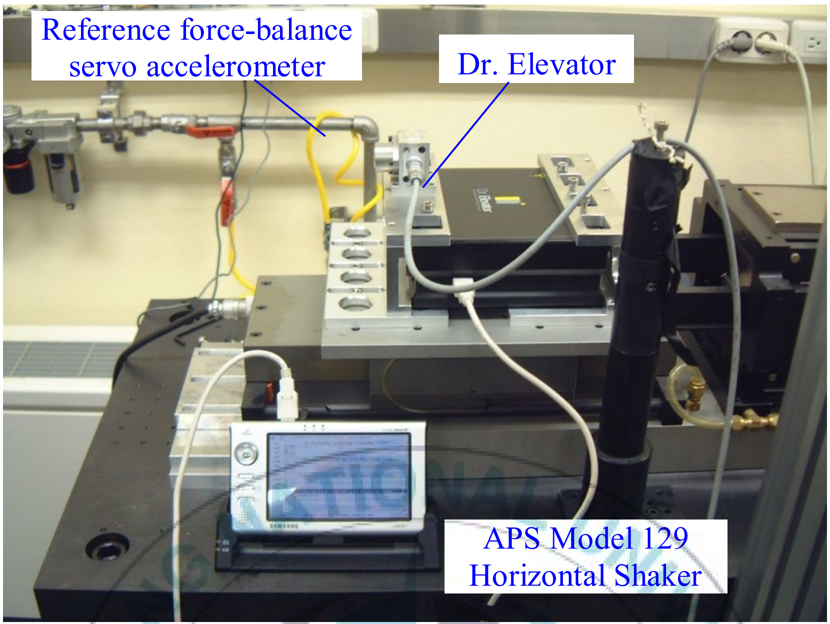


Fig. 4.12 Reliability test of Dr. Elevator.

4) Evaluation

There is no international criterion for evaluation on ride quality and rotating machinery parts of elevator. Therefore, major elevator models installed the local area were selected and data were gathered from them by sampling. The optimal criterion was established by processing the collected data with statistical technique. The data acquired from site are compared against the criterion. The deviate data are analyzed for remedial measure and later verification

- *Evaluation on ride quality*

Data on ride quality are collected in accordance with ISO18738. The data are compared with the criterion data. For deviate data, analysis may be performed for each type of defect (badly installed rails, poor electrical adjustment, defect in cage design, resonance, etc).

- *Evaluation on rotating machinery parts*

Data on rotating machinery parts are gathered via sensors attached on the predetermined places of housing in the side of motor output and machine input. The data are compared with the criterion data. For deviate data, analysis may be performed for each type of defect (defective gears, defect in bearing cases and balls, misalignment, mass unbalance, etc).

- *Analysis On The Changes In Performance*

Major performance items for an elevator are quantified and established into a check list. The check list is compared and reviewed on yearly basis. If there are any considerable variations which may shorten the life cycle or cause hazards, they are to be investigated to detect the cause and establish remedial measures.

5) Proposed Standards by Performance Assessments

Ride quality is one of the key indexes to evaluate an elevator's system performance, and elevator vibration will have a direct influence on passenger's feeling. The quantity of car vibration is related to external exciting energy, its frequency distribution and the robustness of system design.

The proposed value of Table 4.4 is conducted the statistical analysis on the measured value of ride quality and vibration of traction machine. Thus, it is necessary to use the analysis as performance assessment standards. If such standards are exceeded, the causes need to be analyzed through FFT analysis. It is deemed that the measurement and analysis on elevator ride quality and vibration of traction machine in combination with prevention maintenance and prediction maintenance would guarantee the higher stability and reliability [1-3].

Table 4.4 Proposed performance assessment criteria

Item		NEII (1.75m/s)	Hong Kong (acceptance criteria) less than 6 m/min	Proposed criteria (1.75 m/s)
Car inside vibration	Horizontal vibration X axis Horizontal vibration Y axis Vertical vibration Z axis	25 25 25	25 25 25	15 gal 15 gal 25 gal
Traction machine vibration	Motor load(vertical/horizontal) Gearbox(vertical/horizontal)	-	-	2.8 mm/s rms
Car inside sound	Sound in car at rated speed	60	60	55 dB(A)

3. The Rotating Machinery Fault Feature

3.1 Introduction

Three phase induction motors are the motors most frequently used in industry. They are simple, rugged, relatively low-price, and easy to maintain. In this chapter, the basic principle of three phase induction motors is reviewed including its general structure and construction. Moreover, fault in induction motors that are frequently occurred and measurement for fault diagnosis will be reviewed.

Condition monitoring and fault diagnosis of induction motors are also presented which are the main part of this chapter. First, the existed method for fault diagnosis of induction motor is reviewed and then followed by introducing the proposed method. Finally, case study of fault diagnosis of induction motor is presented based on vibration and current signals.

3.2 Fault Occurrence for Diagnostics

The faults frequently occurred in induction motors components are rotor, stator and bearing defects. Based on EPRI which has conducted large survey on motors fault of 5000 sample motors, 97% among them are three-phase squirrel-cage induction motors. The fault occurrence based on the survey is presented in Fig. 4.13. Most common fault is worn bearing that generate excessive vibration, noise and possible misalignment of the rotor shaft. Most of the stator related faults are due to degraded insulation in stator windings causing an inter-turn, phase-to-phase or phase-to-ground short circuits. Other case is rotor fault which can be divided into faults related to motor eccentricity and physical damage of the rotor and they are usually slowly although in the end the broken bars may damage the stator windings.

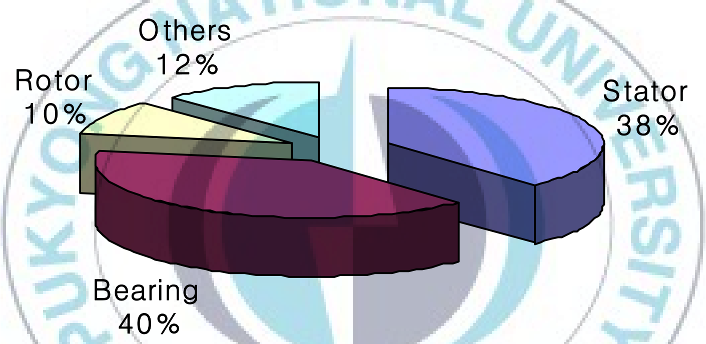


Fig. 4.13 EPRI survey on occurrence of motor faults [2].

It is found out that a variety of measurements can be applied to collect information that is useful in the detection of induction motor faults. In this thesis, two of them are elaborated using stator current of the motor and vibrations of the motor. Vibration analysis has been used in motor fault detection for decades. Each fault in a rotating machine produces vibrations with distinctive characteristics that can be measured and compared with reference ones in order to perform the fault detection and diagnosis. Motor current monitoring is also called motor current signature analysis (MCSA) and it is widely studied, because no extra instrumentation is needed, if the faults can be detected based on the current. It is also claimed that MCSA give the same information on motor condition as vibration measurements [3].

In this thesis, the faults frequently occurred in induction motors are reviewed as follows:

- *Bearing Fault*

A bearing consists of two rings inner and outer, between which a set of balls or rollers rotate in raceways. Fig. 4.14 shows the part of a deep groove ball bearing. Under normal operating conditions of balanced load and good alignment, fatigue failure begins with a small fissure, located between the surface of the raceway and rolling elements, which gradually propagate to the surface generating detectable vibrations and increasing noise levels [4]. Continued stressing causes fragments of the material to break loose producing a localized fatigue phenomenon known as flaking or spalling [5]. Once started, the affected area expands rapidly contaminating the lubrication and causing localized overloading over the entire circumference of the raceway.

Eventually, the failure results in rough running of the bearing. While this is the normal mode of failure in rolling element bearings, there are many other conditions which reduce time of bearing failure. These external sources include contamination, corrosion, improper lubrication, improper installation or brinelling.

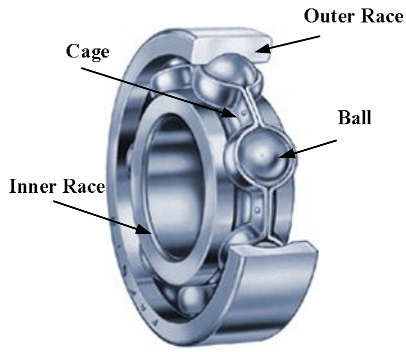


Fig. 4.14 The structure of a deep groove ball bearing.

Contamination and corrosion frequently accelerate bearing failure because of the harsh environments present in most industrial settings. Dirt and other foreign matter that is commonly present often contaminate the bearing lubrication. The abrasive nature of this minute particle, whose hardness can vary from relatively soft the diamond like, causes pitting and sanding actions that give way to measurable wear of the balls and raceways [5]. Bearing corrosion is produced by the presence of water, acids, deteriorated lubrication and even perspiration from careless handling during installations [4,5]. Once the chemical reaction has advanced sufficiently, particles are worn off resulting in the same abrasive action produced by bearing contamination. Improper lubrication includes both under and over lubrication. In either case, the rolling elements are not allowed to rotate on the designed oil film causing increased levels of heating. The excessive heating causes the grease to break down which reduces its ability to lubricate the bearing elements and accelerates the failure process. When the lubrication conditions become inadequate, the increased friction results in metal – metal contact.

Installation problems are often caused by improperly forcing the bearing onto the shaft or in the housing. This produces physical damage in the form of brinelling or false brinelling of the raceways which leads to premature failure.

Misalignment of the bearing, which occurs in the four ways depicted in Fig. 4.15, is also a common result of defective bearing installation. The most common of these is caused by tilted races [5].

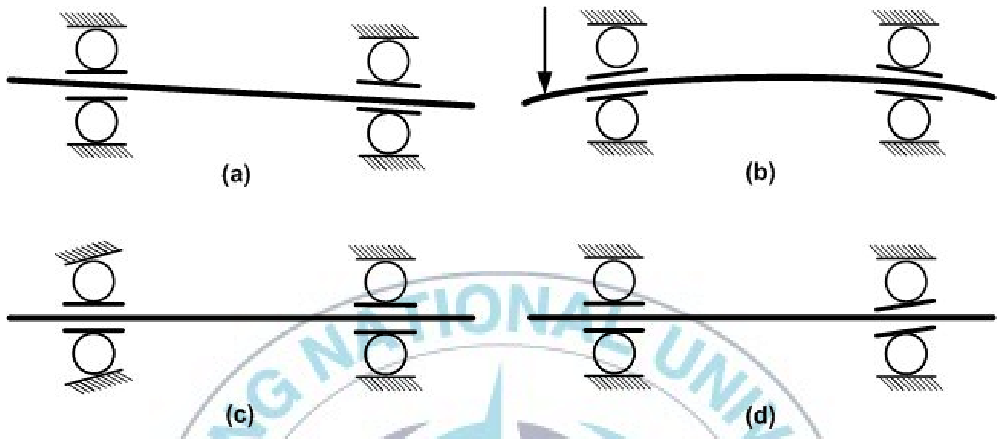


Fig. 4.15 (a) Misalignment (Out-of-Line), (b) Shaft deflection, (c) Crooked or tilted outer race (d) crooked or tilted inner race

Brinelling is the formation of indentations in the raceways as a result of deformation caused by static overloading. While this form of damage is rare, a form of "false brinelling" occurs more often. In this case, the bearing is exposed to vibrations while even though lightly loaded bearings are less susceptible, false brinelling still happens and has even occurred during the transportation of uninstalled bearings [4].

Regardless of the failure mechanism, defective rolling element bearings generate mechanical vibrations at the rotational speeds of each component. These characteristic frequencies, which are related to the raceways and the balls or rollers, can be calculated from the bearing dimensions and the rotational speed of the machine. Mechanical vibration analysis techniques are commonly used to monitor these frequencies in order to determine the condition of the bearing.

The characteristic frequencies of bearing are as follow

$$BPFO = (N/2) f_r \{1 - (B/P) \cos\phi\} \tag{4.1}$$

$$BPFI = (N/2) f_r \{1 + (B/P) \cos\phi\} \tag{4.2}$$

$$BSF = (P/2B) f_r \{1 - (B/P)^2 \cos^2\phi\} \tag{4.3}$$

$$FTF = (f_r /2) \{1 - (B/P) \cos\phi\} \tag{4.4}$$

BPFO is ball pass frequency of the outer race; generated by rollers passing over defective outer race. *BPFI* is ball pass frequency of the inner race; generated by rollers passing over defective inner race. *BSF* is ball spin frequency; generated by ball defects. *FTF* is fundamental train frequency; generated by cage defects or improper movements. Then, N is number of rolling elements, P is pitch diameter (mm), B is ball or roller diameter (mm) and f_r is rotating speed in revolution per second.

The frequencies in Eqs. (4.1)-(4.4) are valid for ideal bearings; in practice, the rolling element slides in addition to its rotation. Using a sliding factor that ranges from 0.8-1.0, this phenomena can be taken account. In both literature and practice the equations are often replaced by approximate equation [6] which can be used when the exact bearing geometry is not known. A characteristic frequency using approximate formula for outer race and inner race defects are

$$f_o = 0.4Nf_r \tag{4.5}$$

$$f_i = 0.6Nf_r \tag{4.6}$$

Schoen [7] implemented motor current in technique to detect rolling-element bearing fault in induction motors. Line current spectral components are predicted at frequencies of

$$f_{bng} = | f_e \pm m f_v | \tag{4.7}$$

where f_v is one of the characteristic vibration frequencies, f_e is the supply frequency, and m = 1, 2, 3, … . Although the magnitudes of this harmonic component are small compared to other spectral constituents, they fall at different location from those of the supply and machine inherent slot harmonics. This phenomenon makes it feasible to distinguish between healthy and faulty operations.

- *Stator Fault*

Stator winding faults constitute almost 30-40% on induction motor faults according the survey. These faults are usually short circuit between a phase wining and the ground or between two phases. It is strongly believed that such fault initiate as undetected turn-to-turn faults that develop to a major short circuit. Stator winding fault might have a destructive effect of the stator coils.

Armature of stator insulation can fail due to several reasons as follows

1. Short circuit or starting stress.
2. Stack core lamination, slot wedges and joints.
3. Electrical discharge.
4. High stator core or winding temperature.
5. Loose bracing for end winding.
6. Contamination due to oil, moisture and dirt.
7. Leakage in cooling system.

There are several methods proposed to detect the mentioned faults. Cash [8] summed up the machine line-to-neutral voltages instantaneously and filtered out the undesired saturation, slots and other sound operation harmonic. The RMS value of the remaining voltage component was utilized to detect the existence and severity of stator inter-turn faults, the standard deviation of the RMS line current of an induction motor was used to detect stator inter-turns [9].

Penman [10] monitored the axial leakage flux resulting from the stator winding to detect and locate stator inter-turns. The voltage induced in a search coil wound concentrically around the machine shaft was proportional to this flux component. Some spectral constituents of this voltage were observed to detect a turn-to-turn fault. These frequencies are given by

$$f_t = \left[k \pm \left(\frac{n}{p} \right) (1 - s) \right] f_e \tag{4.8}$$

where k = 1, 3 and n = 1, 2, 3, …, (2p-1), p is the number of pole pairs, s is the slip and f_e is the supply frequency. The location of the inter-turn fault could be specified using four auxiliary winding mounted symmetrically in the four quadrants of the motor near the end winding. The flux RMS magnitudes at the various locations were measured. The change in readings from the four coils could be used to triangulate the area of the unbalanced flux, and hence, locate the shorted turn.

According to the modes of stator winding failure, there are five types of modes, which are illustrated in Fig. 4.16.

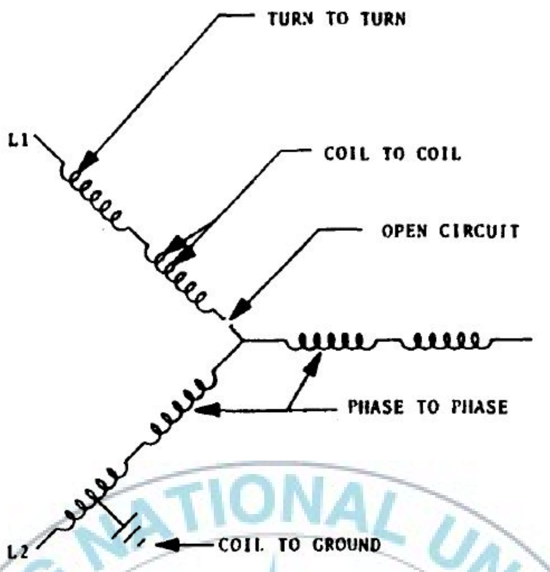


Fig. 4.16 A possible failure modes in wye-connected stator winding [11].

Bonnet [11] reported in detail cause and analysis of stator faults those are influenced by various of stresses such as the following:

a. Thermal Stress

The stress in induction motor that caused by temperature effects such as thermal aging and thermal overloading. The AIEE 510 and IEEE 275 test procedures can be used to determine the effect of temperature on the winding insulation system. Thermal overloading is influenced by various factors i.e. voltage variations, unbalanced phase voltage, cycling, overloading, obstructed ventilation and ambient temperature. The relationship between the various classes of insulation and operating temperature is presented in Fig. 4.17.

Unless the operating temperature is extremely high, the normal effect of the thermal aging is to render the insulation system vulnerable to other influencing factor or stresses that actually produce the failure. The detail of this information is reported in aforementioned reference.

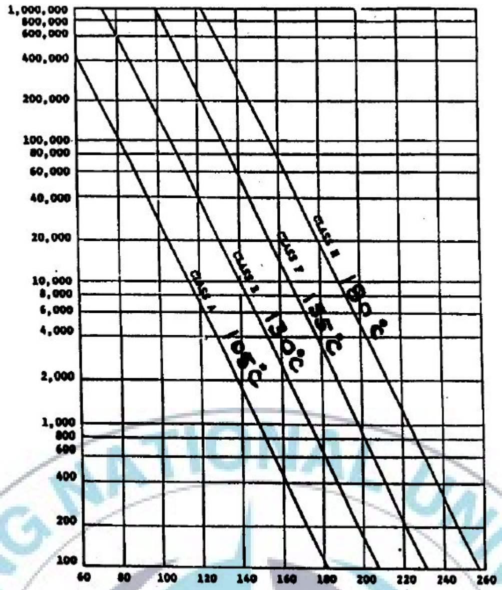


Fig. 4.17 Total winding temperature (°C) versus life [11].

b. Electrical Stress

Electrical stress are generally discussed as failures in the windings such as phase-to-phase, turn-to-turn, or phase-to-ground shorts. Testing to determine the integrity of the insulation is paramount to long motor life. Checking the integrity of the insulation can be accomplished by the MCE standard test. Insulation can also have tracking occur in which the insulation develops a small hole which leakage to ground. If the motor is contaminated with conductive foreign materials, this will create a path to ground causing the insulation to burn, which causes further deterioration of the insulation. Keeping the insulation dry and contaminant free will help to minimize or prevent tracking from occurring. Another method employed to prevent tracking is to use insulation capable of being completely immersed in accordance with NEMA MG 1-20.49 and IEEE 429.

c. Mechanical Stress

The stator coils can and do move during operation of the motor, especially when the motor is started. When the motor is started, the current in the coils is at highest which result in a high magnetic force that causes the coils to vibrate at two times line frequency. This vibration causes the coils to move, which can result in damage to stator, rotor and other motor components. Bearing failures and misalignment can cause the rotor to strike the stator, which can result in grounded coils, excessive heat generation, or severe damage to both the rotor and stator.

Some of the common causes of the winding failures, which can fit into the miscellaneous mechanical type of failure, are as follows:

- Rotor balancing weights coming loose and striking the stator.
- Rotor fan blades coming loose and striking the stator.
- Loose nuts and bolts striking the stator.
- Foreign particles entering the motor through the ventilation system and striking the stator.
- A defective rotor (usually open rotor bars), causing the stator to overheat and fails.
- Poor lead lugging of connections from the motor leads to the incoming line leads, causing overheating and failures.
- Broken lamination teeth striking the stator due to fatigue.

d. Environmental Stress

The quickest way to discuss environmental stress is to call it what it is: contamination. Contamination is anything in the motor that is not supposed to be there. Any foreign material that enters the motor can cause environmental stress. Some examples are moisture, oil, dirt, coal, dust, etc. All of these contaminants can have the following effects on the motor:

- Reduction in heat dissipation, which will increase operating temperature, thereby reducing insulation life.
- Premature bearing failure due to high localized stresses.
- Breakdown of the insulation system, causing shorts and grounds.

- *Rotor Fault*

The reasons for rotor bars and end-ring breakage are several. They can be caused by

- Thermal stress due to overload and hotspot or excessive looses and sparking.
- Magnetic stresses caused by electromagnetic forces, unbalanced magnetic pull, electromagnetic noise and vibration.
- Residual stresses due to manufacturing imperfections.
- Dynamic stresses arising from shaft torque, centrifugal forces and cyclic stresses.
- Environmental stresses caused by for example contamination and abrasion of rotor material due to chemical or moisture.
- Mechanical stresses due to loose laminations, fatigued parts, bearing failures, etc.

Motor current signature analysis was extensively used to detect broken rotor bar and end ring faults in induction motors [12,13]. The sideband components used to detect broken rotor bars is given by

$$f_b = (1 \pm 2s) f_e \tag{4.9}$$

while the lower sideband was fault related and the upper sideband was due to consequent speed oscillation. Bellini [14] stated the summation of magnitudes of these two sideband components was a good diagnostics index. It was concluded that MCSA was superior to signature analysis of current space vector modulus and instantaneous power and torque. The actual sequence of sidebands was given by [15]

$$f_b = (1 \pm 2ks) f_e \tag{4.10}$$

where k = 1, 2, 3, … .

Considering the speed ripple effects, it was reported that other frequency components, which could be observed in the stator current spectrum, are given by

$$f_b = \left[\left(\frac{k}{p} \right) (1 - s) \pm s \right] f_e \tag{4.11}$$

where p is the number of pole pairs, and k = 1, 2, 3, … .

The other method for rotor fault detection is reported using current Park's vector approach to diagnose rotor cage faults of three-phase induction motors [16]. This technique can be used to distinguish between the effect of this fault and that associated with driving time-varying loads. Rotor cage faults can be detected by the identification of an elliptic figure in Park's vector representation. When the load has low-frequency oscillating component, the current Park's vector pattern is an ellipse oriented along the first quadrant of the coordinate axes. In the presence of rotor cage fault, the pattern of ellipse becomes oriented in the second quadrant of the coordinate axes.

- *Eccentricity*

Rotor eccentricity, which results in uniform airgap, is divided into two catagpries, static and dynamic. In static eccentricity case, the airgap has a fixed minimal position, whereas this position rotates with the rotor in case of dynamic eccentricity. In practice, both of types occur simultaneously. Due to some designs and manufacturing imperfections, up to 10% eccentricity is allowed. Higher order of eccentricity can cause rotor-to-stator rub, resulting in damage of rotor and/or stator winding or core.

Eccentricity faults could be diagnosed by monitoring the airgap flux in induction motors. Internal and external search coils were placed in the stator and the spectral constituents of their induced voltage were observed for diagnosing component at

$$f_{ec} = f_e \pm f_r \tag{4.12}$$

where f_1 is supply frequency and f_r is the rotational frequency.

Dorrel [17] monitored casing vibration components at a frequency $2f_e \pm f_r$ to diagnose eccentricity faults in induction motors. Motor current signature analysis (MCSA) was used extensively to diagnose eccentricity faults in three-phase induction motors. Specific frequencies related to fault are given by

$$f_{ec} = \left[(kR \pm n_d)\frac{(1-s)}{p} \pm v \right] f_e \tag{4.13}$$

Where k is any positive integer, R is the number of rotor bars, p is the number of pole pairs, n_d is the eccentricity order (n_d = 0 for static eccentricity, n_d = 1 for dynamic eccentricity), s is the motor slip, v is the order of some harmonics present in the power supply driving the motor (v = 1, 3, 5, …).

In the case of static eccentricity, principal slot harmonic and supply time harmonics contribute to these components. If the order of one of this harmonics is a ultiple of three, it may not theoretically appear in the spectrum of a balanced machine. However, it was shown that for a specific combination of the number of fundamental pole pairs and number of rotor slots, the machine would give rise to only static or only dynamic eccentricity related components [18].

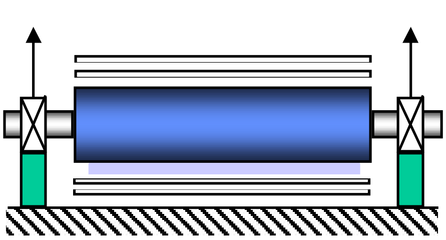
Obaid [19] used MCSA to diagnose eccentricity faults in three-phase induction motors by observing the components

$$f_{ec} = \left[\left(\frac{m}{p} \right)(1-s) \pm 1 \right] f_1 \tag{4.14}$$

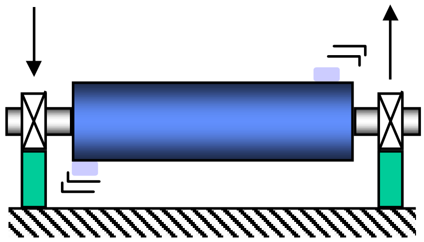
where m is a positive integer. The RMS value of each component was calculated after filtering out the fundamental. The RMS values were compared to a preset threshold that was determined the observation of sound operation. Under load imbalance, and horizontal and vertical misalignment conditions, the machine gave rise to such harmonic components with magnitudes dependent on the condition.

- Unbalance mass

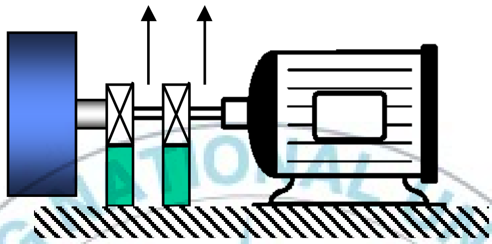
Mass unbalance is the most common fault associated with rotating shaft. It occurs when the geometric center (shaft centerline) and the mass center of a rotor do not coincide. There are three types of unbalance (Fig. 4.18): Static unbalance coupled unbalance and overhung rotor unbalance. Static unbalance has equal phase on each bearing, so vibration along with radial direction in phase. While in coupled unbalance, phase changes 180° across bearing, so vibration along with radial direction out phase. Overhung rotor unbalance contains both radial and horizontal vibration, so both static and dynamic unbalance can be seen together.



(a) Static unbalance



(b) Coupled unbalance



(c). Overhung rotor unbalance

Fig. 4.18 Mass unbalance.

- *Bowed rotor*

A bowed rotor or bent shaft usually causes a preload on the bearings. The center of the mass of a bent shaft can be moved far enough away from the geometric center to cause some mass unbalance (Fig. 4.19). A bent shaft is looking like a misalignment in the spectrum. A phase measurement for axial vibration across the shaft will distinguish between misalignment and bent shaft, as the bent shaft will produce a 180 degrees phase shift. Also the vibration style of a bent shaft contains Axial and radial direction. Among them, 180°phase shift in axial vibration, while 0° phase shift in radial vibration.

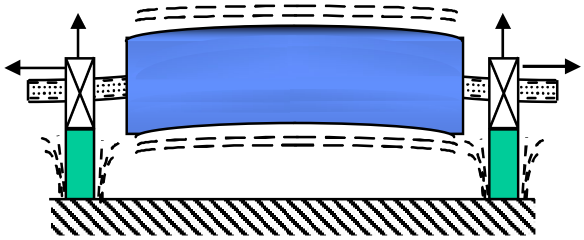


Fig. 4.19 Bowed rotor.

3.3 Condition Monitoring and Fault Diagnosis of Induction Motors

Induction motor is an essential component in many industrial processes which deals with moving and lifting products. Special attention is urgently required in condition monitoring of induction motors in order to guarantee its stable and high performance. By applying early fault diagnosis of operating induction motors which give incipient fault condition, little effort to overcome such fault can avoid more serious conditions.

Condition monitoring and fault diagnosis methods to identify the faults may involve different types of techniques. These techniques can be described as follows

- Electromagnetic field monitoring, search coils, coils wound around motor shafts (axial flux related detection)
- Temperature measurements
- Infrared recognition
- Radio frequency (RF) emissions monitoring
- Noise and vibration monitoring
- Chemical analysis
- Acoustic noise measurements
- Motor current signature analysis
- Model, artificial intelligence based techniques

Several methods of condition monitoring and fault diagnosis that related to fault can be detected are presented and compared in Table. 4.5.

Table 4.5 Comparison of detection techniques

Methods	Fault detected				
	Insulating	Stator winding	Air-gap Eccentricity	Broken Rotor bars	Bearing damage
Vibration	No	No	Yes	Yes	Yes
MCSA	No	Yes	Yes	Yes	Yas
Axial flux	No	Yes	Yes	Yes	
Lubricating oils debris	No	No	No	No	Yes
Cooling gaps	Yes	Yes	Yes	No	No
Partial discharge	Yes	No	No	No	No

4. Vibration Features Study of Induction Motor

The experiment is performed in elevator test center in Fig. 4.20. Vibration analysis was conducted of induction motor. The specification of induction motor is shown Table 4.6. Seven types of fault frequency information are explained Table 4.7, and the fault conditions are shown in Fig. 4.20. However, the bearing fault frequency can calculate by Eqs. (4.1) - (4.4). The variables of equation are composed of number of balls, pitch diameter, ball diameter, and contact angle in Fig. 4.21. From the #6310 bearing information the result of bearing fault frequency is shown Table 4.8.

Fig. 4.20 Apparatus of test center.

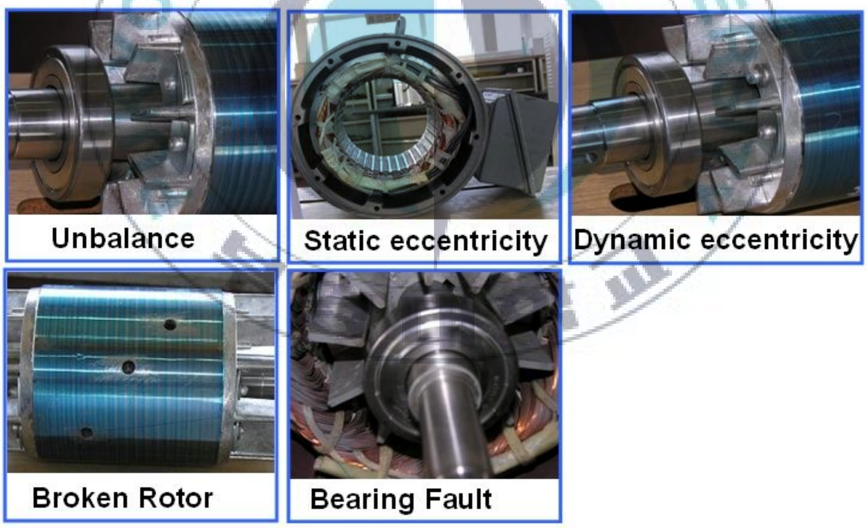


Fig. 4.21 Fault condition of induction motor.

Table 4.6 Specification of induction motor

Power	15 kW	
Poles	4 poles	
Rotating speed	1450 rpm	
Line frequency	50 Hz	
Bearing type	Drive	6310
	Non-drive	6308

Table 4.7 Dominant frequencies of faults

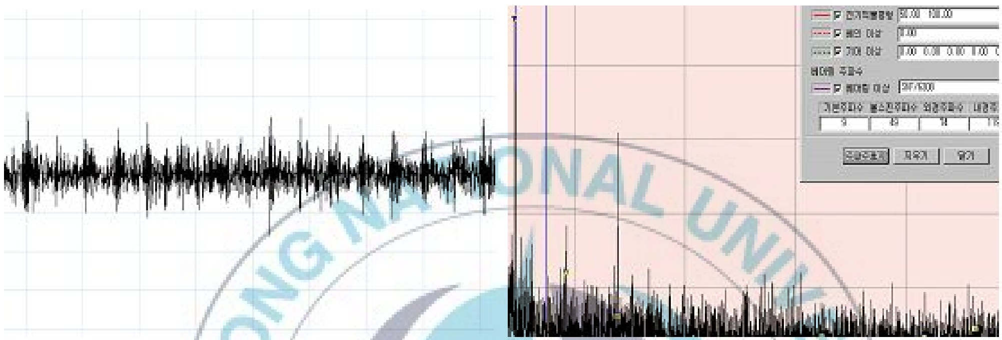
Item		Frequency	Remarks
Unbalance		1X	1X : rotation frequency f_t : rated frequency f_p : pole passing frequency
Motor	Static eccentricity	2X, $f_t \pm f_p$	
	Dynamic eccentricity	1X, $f_t \pm f_p$	
	Broken rotor bar	kX, kX $\pm f_p$ (k = 1, 2, 3, ...)	
Bearing defect	Ball	BSF	
	Outer race	BPFO	
	inner race	BPFI	

Table 4.8 Calculation result of 6310 bearing fault frequency

Bearing fault type	Harmonics of fault frequency (Hz)	
	f	$2f$
BPFI (4.9525)	119.69	239.37
BPFO (3.0475)	73.65	147.30
BSF (1.98067)	47.87	95.73
FTF (0.380938)	9.21	18.41

4.1. Bearing Outer Race Fault

The periodic impact signal of bearing outer race fault is shown in Fig. 4.22(a). The envelop spectrum is conducted to identify the fault frequency and the frequency is detected 74 Hz in Fig. 4.22(b). The frequency result is match with BPFO of Table 4.8.

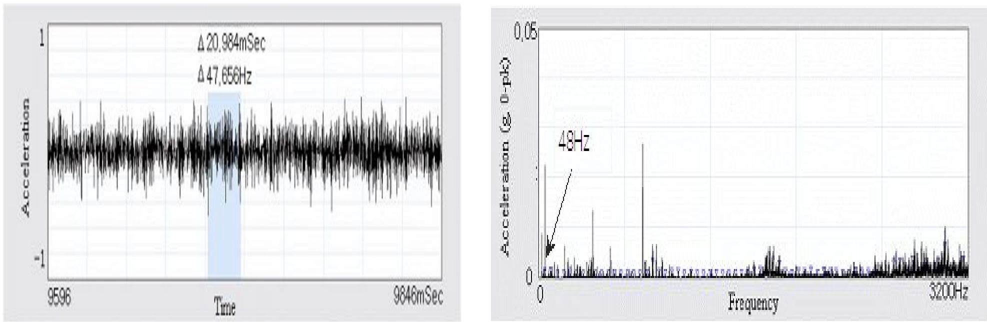


(a) Time waveform (b) Enveloping spectrum

Fig. 4.22 Bearing outer race fault signals.

4.2. Bearing Ball Fault

The ball fault signal of time domain is different with outer race fault. The ball of bearing is defected and the period of time is 0.020984 second in Fig. 4.23(a). The fault frequency is occurred 48 Hz in Fig. 4.23(b). The frequency is similar with BSF of Table 4.8.

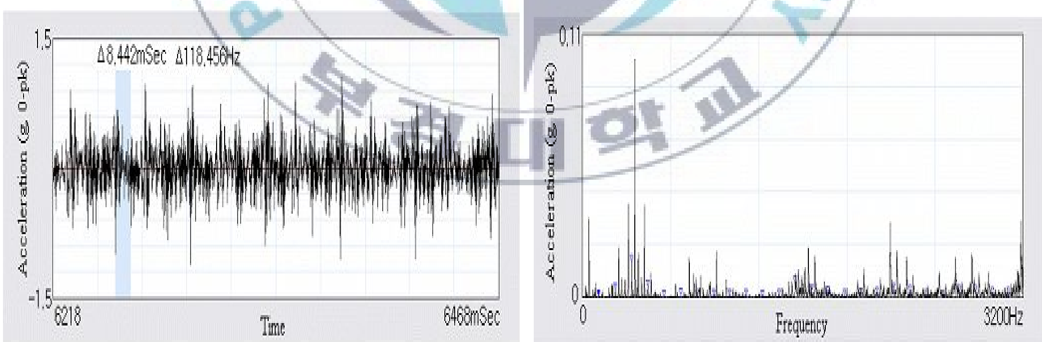


(a) Time waveform (b) Frequency spectrum

Fig. 4.23 Bearing ball fault signals.

4.3. Bearing Inner Race Fault

The inner race fault signal of vibration is shown in Fig. 4.24(a) and the period of impact signal is 0.008443 second. The fault frequency is detected 119 Hz in Fig. 4.24(b). The frequency is represented well bearing inner race comparing with Table 4.8.

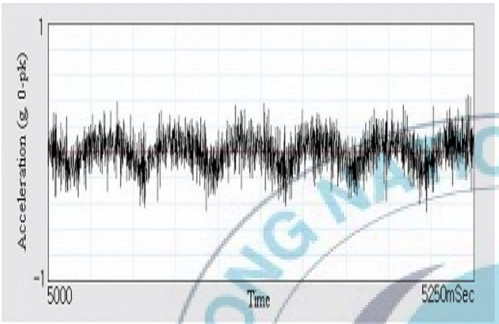


(a) Time waveform (b) Frequency spectrum

Fig. 4.24 Bearing inner race fault signals.

4.4. The Unbalance of Induction Motor

The unbalance fault is related to whirling motion of induction motor. Unbalance mass occur the whirling motion and the result is represented by rotating frequency. The rotating speed is 1450 rpm and the frequency is 24 Hz shown in Fig. 25.

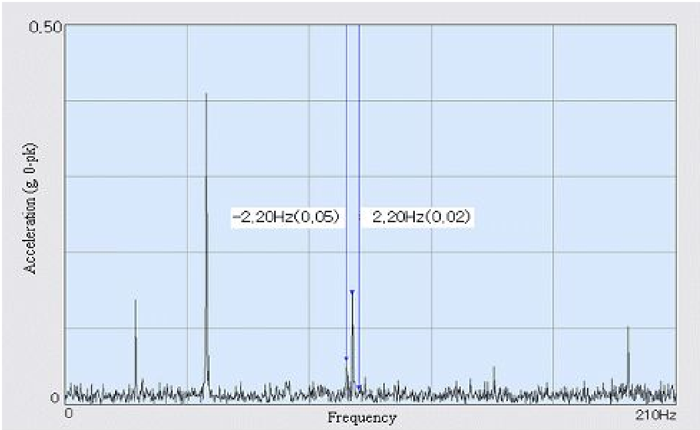


(a) Time waveform (b) Frequency spectrum

Fig. 4.25 Unbalance signals.

4.5. Static Eccentricity of Induction Motor

The static eccentricity fault comes from discarding between rotor and stator. In this case, first and second harmonics of rotating frequency and twice of line frequency are dominant components in spectrum domain. The second harmonic is 48 Hz and the line frequency is 98 Hz and pole pass frequency is 2.2 Hz as shown in Fig. 4.26.

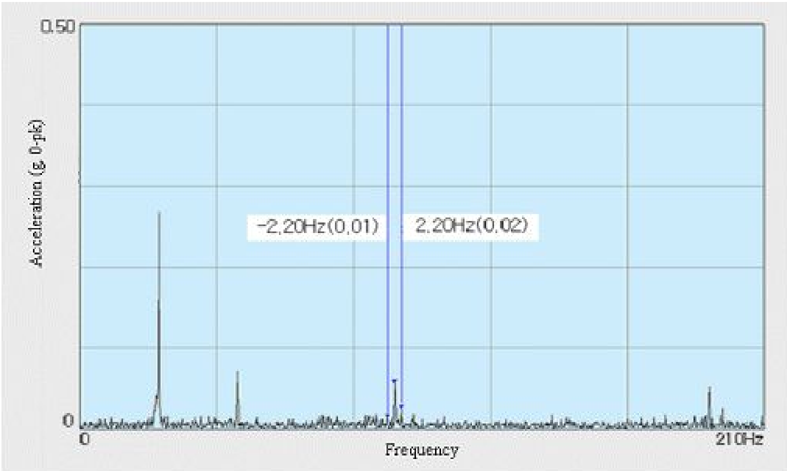


Static eccentricity

Fig. 4.26 Static eccentricity fault signal.

4.6. Dynamic Eccentricity of Induction Motor

The dynamic eccentricity has similar frequency with static eccentricity fault, but the first and second harmonics of rotating frequency trend are different with that. In this case, the first harmonic is bigger than second harmonic. The frequency is 24 Hz and pole pass frequency is 2.2 Hz in Fig. 4.27.



Dynamic eccentricity

Fig. 4.27 Dynamic eccentricity fault signal.

4.7 Broken Rotor Bar of Induction Motor

The broken rotor bar fault frequency is shown in Fig. 4.28. The fault frequency occurred 24 Hz and 48 Hz, it is twice of rotating frequency. Also pole pass frequency is shown 2.2 Hz.

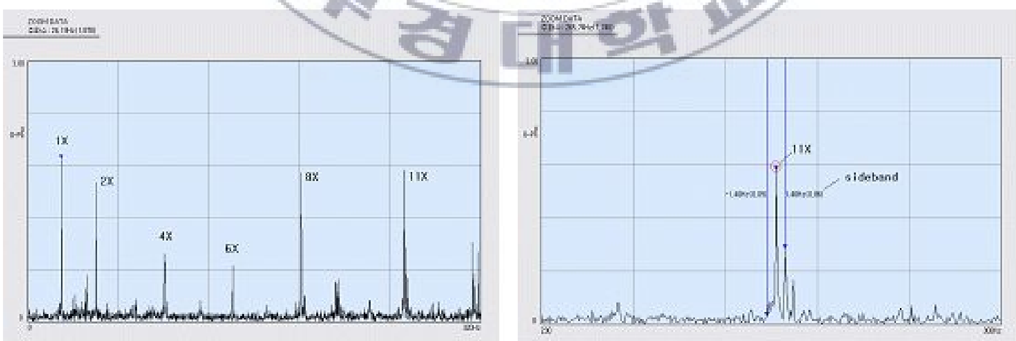


Fig. 4.28 Broken rotor bars signal.

5. Case Studies: Performance Assessment

Ride quality is one of the key indexes to evaluate an elevator's system performance and elevator vibration will have a direct influence on passenger's feeling [13-16]. The quality of car vibration is related to external exiting energy, its frequency distribution and the robustness of system design. Based on the practical work in elevator vibration, common vibration-exiting sources of elevator systems are summed here, so as to refer for engineers in this field.

5.1 Car Resonance

For a driven machine with a rotating speed of 1460 rpm, which has a reduction gearbox of worm-wheel, the rotating frequency is 1460 / 60 = 24.33 Hz and the gear mesh frequency is 48.6 Hz because the worms have two threads. This elevator resonance is occurred by resonance phenomenon shown in Fig. 4.29, in the conjugation zone of cage frequency and the 48 Hz element as gear mesh frequency (GMF) combined with excited frequency of motor. For reducing the vibration, the dynamic absorber was employed as shown in Fig. 4.30.

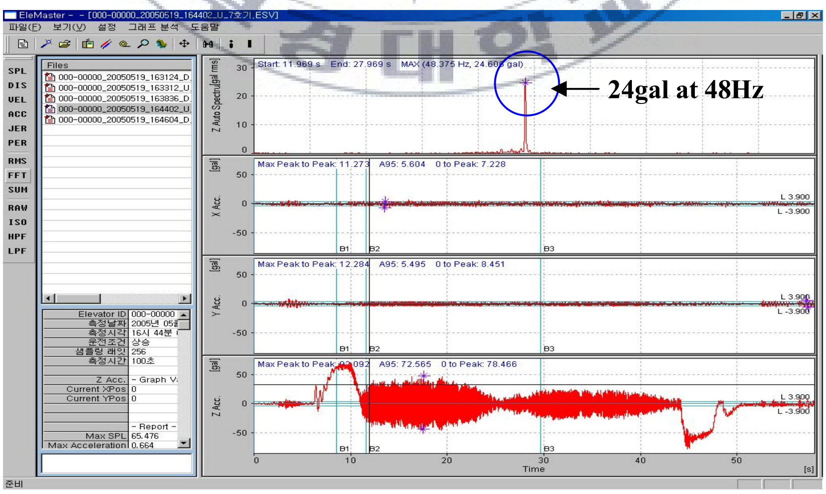


Fig. 4.29 Excessive vibration due to resonance (Z axis: 94 gal).

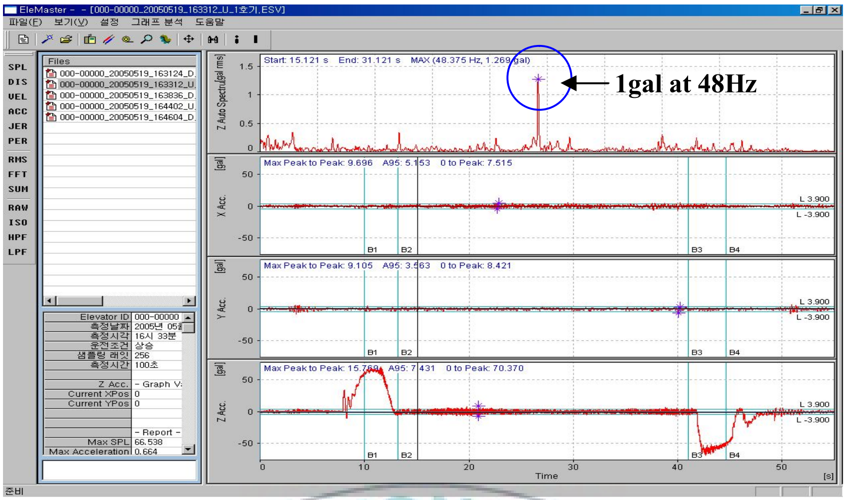


Fig. 4.30 Vibration reduction by dynamic absorber (*Z* axis: 7 gal).

5.2 Rail Installation Check by Car Vibration Measurement

Fig. 4.31 shows the time waveform of the vibration in the elevator car. In the time domain, apparent impact appears every 5 meters periodically as shown in Fig. 4.31 for each guide rail, length is 5 m. It can be improved by readjusting the rail installment as shown in Fig. 4.32. Influencing factors is that dynamic friction comes from contacting surface between guide shoe and guide rail, especially on the side surface.

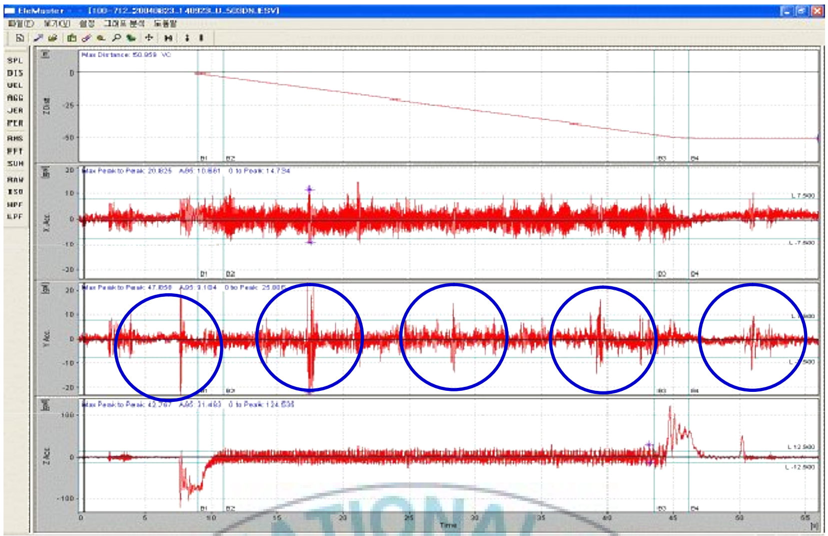


Fig. 4.31 Periodical vibration occurrence because of bad installation (*Y* axis: 25 gal).

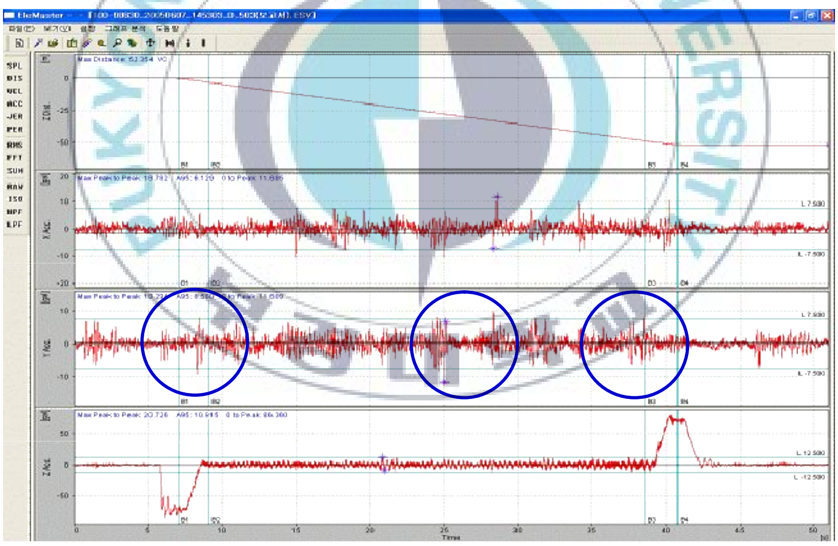


Fig. 4.32 Data of installation state of the rail after adjust (Y axis: 11 gal).

5.3 Mechanical Faults

Table 4.9 indicates frequency features of various faults that obtained through the site inspection.

Table 4.9 Vibration frequency due to mechanical faults

Fault	Frequency
Misalignment	Dominant 2X component
Unbalance	Dominant 1X component
Guide roller vibration	π × guide roller diameter × RPM
Bearing fault	Bearing fault frequency
Resonance	Coincidence of GMF element and cage frequency
Rail vibration	Periodic peak vibration waveform

Fig. 4.33 shows the time waveform and frequency spectrum of unbalance vibration. For a driven machine with a rotating speed of 1460 rpm, which has a reduction gearbox with a worm and worm-wheel, the frequency feature appears by 1X component (1460/60 = 24 Hz) dominantly because of elevator motor unbalance. Fig. 4.33 shows a measuring result at a site.

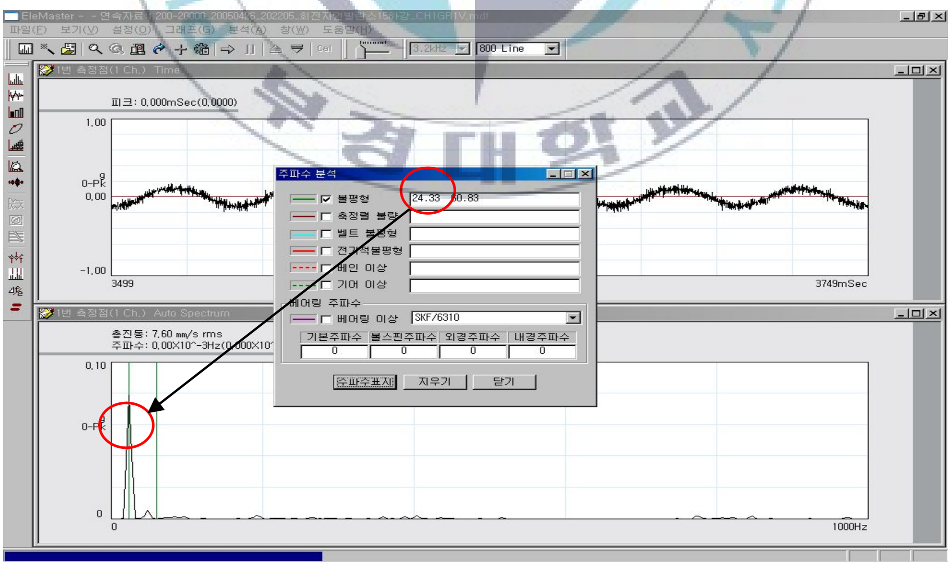


Fig. 4.33 Unbalance fault.

Fig. 4.34 shows time waveform and frequency spectrum of misalignment vibration. For a driven machine with a rotating speed of 1460 rpm, which has a reduction gearbox with a worm and worm-wheel, the frequency appear to be double frequency(2 × 1460/60 = 48 Hz) of rotating speed as shown in Fig. 4.34. In the time domain, the waveform feature appears by a period of 13.39 ms as shown in the time domain of Fig. 4.34. When the frequency component is prominent at 2X, it is mainly misalignment (the rotating frequency of rotor: 1460/60=24.3 Hz, 2X = 28.6 Hz). The frequency and time waveform of Fig. 4.34 which is occurred by misalignment.

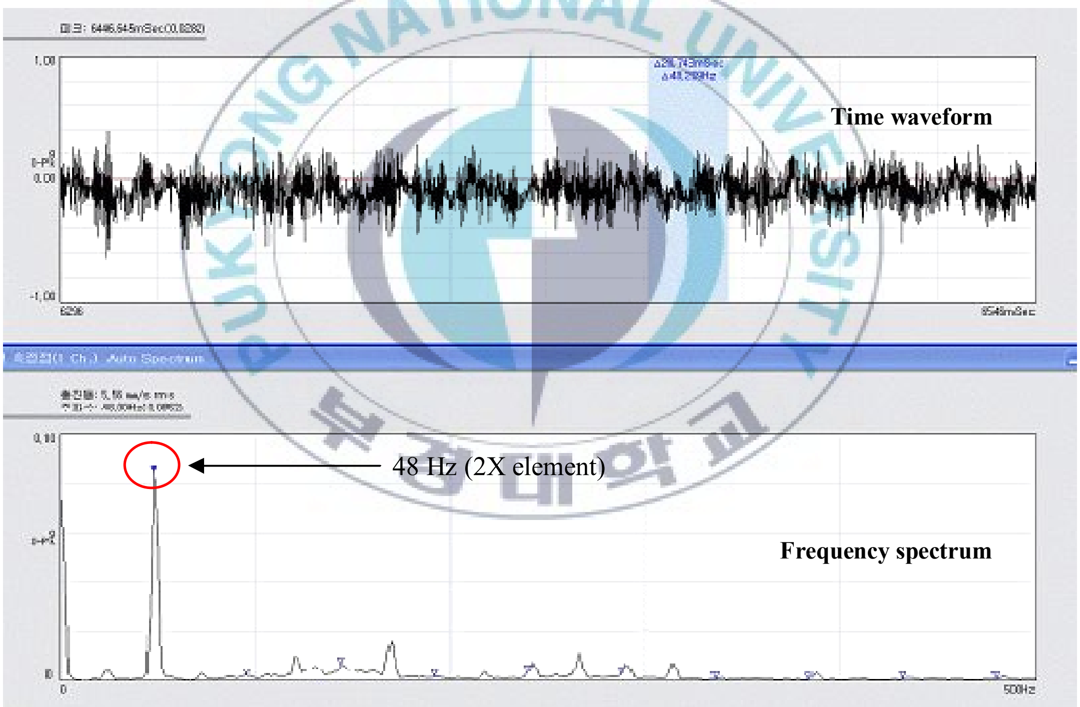


Fig. 4.34 Misalignment fault (48 Hz).

Fig. 4.35 shows time waveform and frequency spectrum of bearing fault vibration. It shows the bearing frequency feature occurring because of bearing outer race abrasion. In the frequency domain, the frequency feature is shown by ball pass frequency of outer race (74 Hz) as shown in Fig. 4.35.

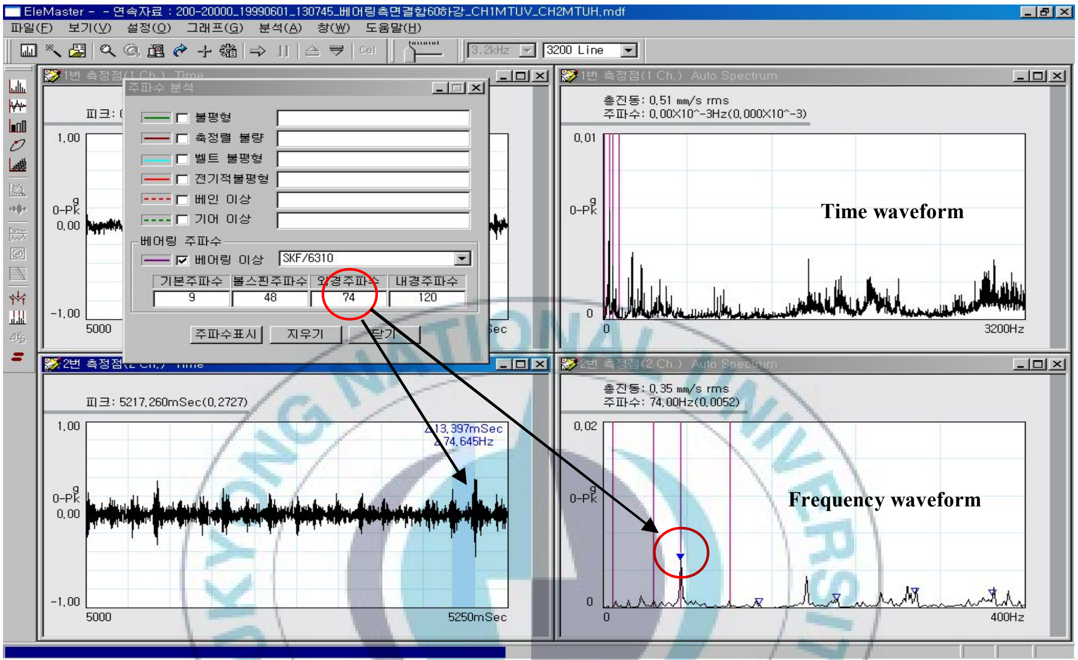


Fig. 4.35 Bearing outer race fault (74 Hz).

Fig. 4.36 shows time waveform and frequency spectrum of worm gear vibration. The gear mesh frequency is occurred at 924 Hz and its sidebands. (Meshing frequency between gears or worm wheel and worm = number of gears or worms * rotating spend of gear or worm wheel/60). Influencing factors of GMF is meshing accuracy between gears or worm wheel and worm.

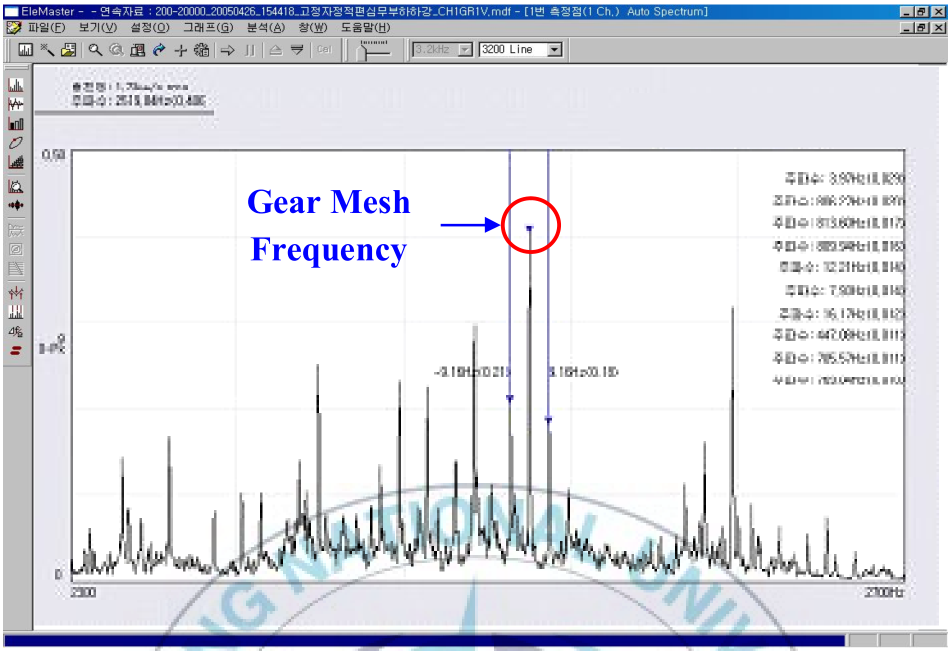


Fig. 4.36 Worm gear vibration signal.

5.4. Conclusion

Dr. Elevator is an integrated portable type diagnostic tool to analyze and evaluate the ride quality together with rotating machinery parts which combines PDA (Personal Digital Assistants) and data acquisition device.

First, it can measure the ride quality in accordance with ISO 18738 and furthermore diagnose the sources of vibrations and noises, which helps improve the ride quality conveniently.

Second, it may perform the precise analysis on probable causes of vibrations and noises in rotating machinery parts by using the built-in 0~12,800 Hz FFT analyzer as well as various software which help evaluate the performance, manufacturing and assembly quality, possibility of defects in rotating machinery parts.

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V. Risk Based Inspection of Elevator

1. Introduction

Maintenance management is about making decisions; about determining the optimal maintenance policy to adopt, whether a piece of equipment needs to be replaced now or can be left in service until the next inspection, how many spares should be held, and so on. While we can try to base these decisions on good data and a rational understanding of the issues and tradeoffs involved, some uncertainly is always involved. It is nature of our job, therefore, to manage risk. Risk is, in effect, the product of probability and consequence. So, two apparently different situations-one with a high probability and low consequence, such as tripping on an uneven floor and hurting your foot, and one with a low probability and high consequence, such as the aircraft you are traveling in crashing and killing everyone on board-can actually have similar risk values. In any operation, there is always some degree of risk. All activities expose people or organizations to a potential loss of something they value. In maintenance, the impact is typically on equipment failure, people's health and safety, or the environment. Risk involves three issues:

- The frequency of loss
- The consequences and extent of the loss
- The perception of the loss to the ultimate interested party

A major equipment failure represents an extreme need to manage maintenance risk. The production downtime could delay product delivery to the customer and cost the business a great deal of money. There could be further losses if the equipment failure threatened the safety of users or adversely affected the environment. A critical, high-profile failure could also create the impression that the business is out of control and tarnish its reputation in the marketplace. Risk can also occur when the wrong maintenance decision is made about an asset. The consequences can be many: lessened plant reliability and availability, reduced product availability, and increased total operating costs.

The best practices for maintaining equipment are based on the premise that more maintenance and prevention result in less downtime, and greater revenues. The information that risk decisions are based on will never be totally complete or enable us to foretell the future. Uncertainty is inevitable, so setting the maintenance policy is question of managing risk. The objective of risk management is to ensure that significant risks are identified and appropriate action taken to minimize them as much as is reasonably possible. To get to this point, we must balance risk-control strategies, their effectiveness and cost, and the needs, issues, and concerns of stakeholders.

Numerous tools and processes can be used to make such decisions. But there is also a tradeoff between the amount of effort put into the analysis and its possible benefit. The investigations demanded additional interlocks, regular condition monitoring. To make effective decisions about the risk-management process, the risk team and the stakeholders need to communicate frequently. There must be open dialog so that the team's hypothesis is validated at each step, and to ensure that all stakeholders are involved. Also, risk assessment is best applied when risks can be readily identified for the critical equipment in a process. [1]

Building owners and managers have their work cut out when it comes to ensuring that those rides are uneventful. Proper installation and ongoing maintenance and inspection are a must. Long-time continuous usage increases fault-occurrence probability, which requires troubleshooting quickly [2]. To assess the reliability and efficiency of the elevators a maintenance program is a significant part of overall elevator system. The safe and reliable operation of the elevator is of paramount importance to the owners, the management company and, ultimately, to the tenants and visitors who travel throughout these buildings daily. The target of elevator maintenance is as follows:

- Prolong equipment life
- Improve equipment safety and reliability
- Reduce the cost of major repairs
- Minimize the inconvenience of equipment downtime

Since the early 1910s when the elevator was introduced, the Korean elevator industry has its remarkable growth with 2,000,000 housing constructions in 1990 as well as in 1986 Seoul Asian games and 1988 Seoul Olympics. Currently, about 360,000 elevators are working in Korea which is ranking 9th in the world.

Meanwhile, the number of people who have been rescued by 911 rescue team, owing to elevator accidents, reaches the second-highest level following traffic accidents. The data by the National Statistics Office on elevator accidents shows that there were 90 and 97 accidents in the year of 2006 and 2007, respectively. These accidents are increasing annually as indicated in Table 1.

There is a need for new technical solutions to lessen the safety accidents and break-down. It has to be provided as a technical guide to promote the progressive and selective maintenance and improvement of the safety of existing elevator. So, the ageing elevators should be made more effective, safer, more reliable and more comfortable through effective maintenance and improvement .

In this study, to reduce the probability of elevator breakdowns and be safer to elevator users, a risk-based inspection (RBI) for elevator maintenance is proposed and seeks for the most appropriate ways to solve the fundamental problems in managing and maintaining elevator.

2. Conventional Risk Analysis Methods

2.1. Qualitative Risk Analysis Methods

1) Dow and Mond Index

This technique considers the hazards of the material involved the inventory, operating conditions, and the type of operation. While the values of the indices cannot be used in an absolute sense as a measure of risk, they can be used for prioritization, selection, and ranking. The value of the index may be helpful in deciding whether a QRA should be applied, and the appropriate depth of study [2].

2) Checklist

A checklist is a list of questions about plant organization, operation, maintenance and other areas of concern [3]. The main purpose for creating checklist is to improve human reliability and performance during various stages of a project, and to ensure compliance with various regulations and engineering standards. Each item is physically examined and verified while the appropriate status noted on the checklist. The results of checklist show insights into the degree of compliance with prescribed procedures and identify potential hazards.

3) What-If Analysis

The What-if method is one of the simplest forms of conducting a hazard analysis. This method does not require special quantitative methods or extensive preplanning. The method does utilize input information specific to a process to generate a set of checklist type questions. It prepares this comprehensive list of questions which are then collectively answered by being summarized in tabular form [4].

4) Preliminary Hazards Analysis

PHA (Preliminary Hazards Analysis) is a hazard identification method that focuses on the conceptual deign phase of a project. This method considers pre-identified hazards such as potential undesired events, worst-case potential consequences, safeguards and mitigation measures, etc [5].

The results of PHA include precautions or operator safeguards to incorporate into the final administrative controls, recommended modifications to the process, enhancements to the design of associated facilities and desirable alternatives that are significantly reduce and limit inherent hazards.

5) Hazard and Operability Study

The HAZOP (Hazard and Operability) study is a program that allows its user to employ imaginative thinking in the identification of hazards and operational problems. The objectives of the HAZOP study are to identify undesirable consequences of deviations form normal process and operating hardware related events, to evaluate adequacy of proposed safety design and instrumentation to prevent consequences and to identify further controls to minimize consequences. The HAZOP study can be applied to all new designs, unless it it an exact copy of an existing plant. It is recommended satisfactory for identifying the hazards and the problems which prevent efficient operation [6]. The HAZOP study step evaluates the adequacy of the mechanism in order to control hazards in plants. These mechanisms include administrative procedures as well as hardware controls. This study identified the way of improving the operating efficiency by the assessment of P&ID (Piping and Instrument Diagram) sheets.

2.2 Quantitative Risk Analysis Methods

1) Failure Mode Effect Analysis

FMEA is the technique to allow the evaluation of multiple failure events. By the use of a regimented booking procedure, it is possible to list for evaluation all potentially relevant combinations of any selected maximum number of coexisting, equipment failures and/or human errors that may cause or contribute to release of process materials [7]

2) Frequency Analysis

Results of FA (Frequency Analysis) classify and analyze failure cases that are developed for the hazard identification. Failure cases are the means by which the risk analysis models all possible discrete failures that result from the operation of process systems [8]. These are determined by breaking the terms of material, temperature pressure, and discharge rate and dispersion characteristics. The overall failure frequency for each failure case is calculated by counting the type and number of equipment items contributing to each failure case. Inspection of the tables reveals the technique applied in the estimation of the leak frequencies for a failure case. By combining the process equipment count with the failure rate per equipment item, the overall failure case frequency is estimated.

3) Fault Tress Analysis

FTA is a deductive technique that focuses on one particular accident or main system failure, and provides a method for determining causes of that event [Power and Lapp, 1989]. The purpose of FTA identifies combinations of equipment failures and human errors that can result in an accident. The fault tree is a graphical model that displays the various combinations of equipment failures and human errors that result in the main system failure of interest as a top event.

The FTA produces system failure logic models that use Boolean logic gates such as AND and OR to describe how equipment failures and human errors combine to cause a main system failure. The FTA solves each logic model to generate a list of failures by minimal cut sets that result in the top event. The number and type of failures in each cut set qualitatively rank lists of minimal cut sets. These lists of minimal cut sets reveal system design or operation weaknesses for which possible safety improvement alternatives are suggested [9].

4) Event Tree Analysis

ETA shows the possible outcomes of an accident that result from an initiating event. The ETA considers the responses of safety systems and operators to the initiating event when determining the potential outcomes of accident. Event trees are used to identify the various accidents that occur in a complex process [10]

The results of the ETA are the event tree models and the safety system successes or failures that lead to defined outcome. Accident sequences depicted in an event tree represent logical AND combinations of events, so these sequences put into the form of a fault tree model for further qualitative analysis. This method uses these results to identify design and procedural weaknesses and normally provides recommendations for reducing the likelihood and consequences of the analyzed potential accidents. The ETA is suited for analyzing complex processes that have several layers of safety systems or emergency procedure in place to respond to specific initiating events.

5) Consequence Analysis

An analysis of the consequences of releases forms the precursor to the risk analysis. Such an analysis does consider the frequency of events: it merely determines the scale of flammable, explosive or toxic releases [11]. Before flammable and toxic effects are modeled, it is necessary to establish how a material would behave and dispersion characteristics are dependent on physical properties of the material involved, hole size or release rate, release pressure and temperature, release phase, ambient conditions, nature of the surrounding, etc.

Ambient conditions are considered as humidity, weather class, and wing speed, ground and air temperature. The nature of the surrounding land is regarded as tall buildings, trees, increase air turbulence, thus encouraging more rapid air entrainment and dilution of dispersing vapor cloud, etc. The likelihood and consequences of release igniting are central to the evaluation process undergone in this study [12].

6) Cause Consequence Analysis

CCA diagram is used to display graphically the relationships between incident consequences and their basic causes. It contains elements of both Fault Tree and Event Tree Analysis. It can be developed in either direction: forward toward the consequences or backward toward the basic causes. The forward direction is similar to Event Tree Analysis and the backward direction is similar to Fault Tree Analysis. The solution consists of a list of incident sequence minimal cut sets, which are analogous to fault tree minimal cut sets.

3. Statistic Analysis of Elevator Accident and Breakdown

3.1. Elevator Accidents

The total number of elevators is installed up to 359,098 in the late of 2007 in Table 5.1, and the rate of elevator accidents per ten thousand elevators accounted for 1.54. For the damaged accidents, the deceased accounted for 148 people or 21.8%, the severely injured accounted for 263 people or 39.8%, and less-severely injured reached 266 people or 38.4%. For each cause of elevator accidents, users' errors accounted for 15.3%, poor maintenance accounted for 20.2%, while poor management and maintenance reached 11.9%, workers' errors and substandard manufacturing reached 6.1% and 3.9%, respectively. The rest took up with 6.7%.

Table 5.1 Accident number and installation number

Year	Total number of installation	Accident number	The incidence of accident (%)	Accident number per 10,000
1998	159,230	28	0.0176	1.76
1999	174,261	12	0.0069	0.69
2000	190,187	22	0.0116	1.16
2001	208,497	28	0.0134	1.34
2002	231,562	16	0.0069	0.69
2003	259,850	40	0.0154	1.54
2004	289,808	25	0.0086	0.86
2005	314,495	42	0.0134	1.34
2006	336,311	90	0.0268	2.68
2007	359,098	97	0.0270	2.70

1) Accident Type and Cause

Elevator accidents are increasing with year as shown in Table 5.2. Even though same kinds of accidents have steadily occurred, the causes have not been eliminated yet. Accidents in relation to escalators or moving walkers among total safety accidents account for the highest rate of 20.3% as shown in Table 5.2. The rapid increase of the installed escalator triggers accidents to surge among most children and the aged.

Table 5.2 Appearance of accident type

Appearance of accident type	Rate (%)
Crushing riding after opening the landing door with emergency key	12.4
Occurrence from escaping and rescuing process	4.4
Occurrence by trying failure repair by elevator laymen directly	3.2
Worker accident occurred by disobeying safety rules during working	8.0
User accident occurred by disobeying safety rules during working	1.6
Accident occurred by thoughtlessness when the car enters in the car lift	4.0
Accident occurred by jamming and crushing in the gap between the car bottom and hoist way walls at the car lift	9.2
Accident occurred by poor component.	15.9
Accident occurred by user carelessness or disorder conduct.	8.0
Accident occurred by maintenance carelessness	3.2
Accident on dumb waiter	8.0
Accident on escalator and moving walk	20.3
Accident on a wheel chair lift for disabled persons	1.2
Others	0.8

While most citizens have very high expectations and awareness of safety, however, accidents still rise, owing to the absence of the double-function units of safety devices or the age of the elevators. Accordingly, efforts are made to improve the safety laws which are necessary for reinforcing public safety, across the world. The longer the life span of elevator is the higher accident probability is. Also, the same sorts of accidents are frequently occurred. At this point, when the lift laws are only applied to elevators to be newly-built, it is necessary to improve the safety level of aged elevators.

2) Risk Assessment of Accident by FMEA Method

A risk analysis is a series of logical steps that enable a systematic identification and study of hazards and their corresponding causes and effects. The identification of hazards, when followed by an assessment of their severity and probability of occurrence shown in Table 5.3, yields a measure of risk associated with the individual hazards. Through the use of an interactive process, each hazard and effect is evaluated and either eliminated or, if necessary, controlled by means of appropriate safety measures that reduce the corresponding risk to an acceptable level of safety shown in Fig. 5.1. For this purpose the best approach is to form a risk analysis team by selecting the members and by choosing a team leader/moderator. The cause and effect of each hazard in terms of probability of occurrence and the severity of its effects is assessed. The combination of severity and frequency of occurrence quantifies the risk associated with the hazard. The assessment results are evaluated in terms of residual risk and the acceptable level of safety. If the level of safety is unacceptable, further risk reduction measures are required and the following procedure should be used:

- Eliminate the hazard.
- If the identified hazard can be eliminated, take the necessary measures to reduce the risk to an acceptable level of safety as determined by the lift technician.
- Inform the user of the residual risks.

If the risk evaluation still indicates that the remaining risk is not within an acceptable level of safety, the whole process has to be repeated as shown in Fig. 5.1 [13].

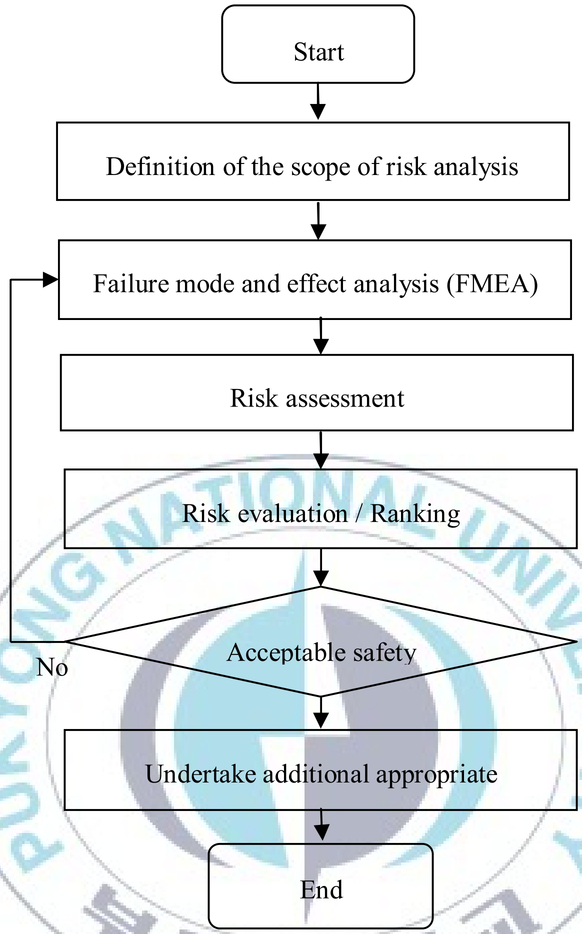

Fig. 5.1 Risk analysis procedure.

Table 5.3 indicates relation between severity/frequency and corresponding risk level. The level of risk can be divided with four grades shown in Table 5.3:

- Unacceptable (IA, IB, IC, IIA, IIB, IIIA): corrective action required to eliminate the risk
- Undesirable (ID, IIB, IIC, IIIC): corrective action required to mitigate the risk
- Acceptable with review (IE, IID, IIE, IIID, IVA, IVB): review required to determine whether any action is necessary

• Acceptable without review (IF, IIF, IIIE, IIIF, IVC~F): no action required

Table 5.3 Relation between severity/frequency and corresponding risk level

Frequency		Severity			
		I (High)	II (Medium)	III (Low)	IV (Negligible)
A	Highly probable	I A	II A	III A	IV A
B	Probable	I B	II B	III B	IV B
C	Occasional	I C	II C	III C	IV C
D	Remote	I D	II D	III D	IV D
E	Improbable	I E	II E	III E	IV E
F	Highly improbable	I F	II F	III F	IV F

This study has investigated elevator accidents resulting from poor safety parts, safety circuit, design and systems. And, this study has conducted the analysis on failure modes, estimated causes and effects of each category, and then made evaluations on risks and decided maintenance ranking. By establishing safety strategies, it can assure the safety of elevators.

The failure mode and effects analysis (FMEA) technique determines how individual elements of a system can malfunction and what combinations of failure can result in an unsafe condition. Redundancy is a property of a system that is provided by using two or more elements to influence the final action of that system. Table 5.4 shows the result of risk assessment on accident by using Korea disaster statistics that is evaluated risk analysis by FMEA method. It is an aim to assure the safety of existing elevator by using the maintenance.

Table 5.4 Risk assessment examples of accident by FMEA method(continued)

Item	Function	Failure mode	Assumed Cause	Effect	Estimation of risk elements		Grade	Protective measures (risk reduction measure)	After protective measures		Type
					S	F			S	F	
Slip distance	Braking distance when car stop during the running in no load	Over stopping distance	Lack of braking capability	Injury, or death because of starting with doors open or slip occurrence	2	C	2	(1) periodical maintenance	2	E	Elevator Dumbwaiter
Counterweight	Weight change of car and counterweight	Control incapacity	The change of overbalance rate	Injury, a serious wound or death because of starting with doors open or slip occurrence	2	C	2	(1) weight conpensation of counterweight when the interior of a car is done (2) periodical check	2	E	Elevator Dumbwaiter
Door control circuit	Function for door opening and closing by the control signal	Starting with car door open	Door monitor circuit is designed in single circuit	Injury, a serious wound or death because of jamming or crushing of passengers	1	D	2	(1) Circuit supplementation by dual system of door circuit	1	E	Elevator
Earth of safety circuit	Function to stabilize power supply and protect men when leakage currents or electric shocks occur	No cut off Fuse	If safety circuit is not earthed, incase of leakage currents, fuse is not cut off and take fire or starting with doors open	Injury, a serious wound or death because of fire or doors open or slip occurrence	1	D	2	(1) Earth of safety circuit (2) Periodical check	1	E	Elevator

Table 5.4 Risk assessment examples of accident by FMEA method(continued)

reverse phase prevention devices	function to stop elevator operation when one of the three phases power disconnected by mistake.	Reverse run	Reverse phase detect function was not operated or not installed	Shock of occurrence because of malfunction	3	C	2	(1) Circuit supplementation of reverse phase detect function (2) Periodical check	3	E	Ropes elevator Hydraulic elevator
Over load detection devices	The function to stop a start of car with door opening if people ride with overload	Slip of car	Riding more than the capacity of the car	Injury by crushing of car	2	D	3	(1) Circuit design of over load switch by Normal Close (B contact) (2) Periodical check of over load switch	2	E	Elevator
Slip distance	Braking distance when car stop during the running in no load	Over stopping distance	Lack of braking capability	Injury, or death because of starting with doors open or slip occurrence	2	C	2	(1) periodical maintenance	2	E	Elevator Dumbwaiter
Counterweight	Weight change of car and counterweight	Control incapacity	The change of overbalance rate	Injury, a serious wound or death because of starting with doors open or slip occurrence	2	C	2	(1) weight conpensation of counterweight when the interior of a car is done (2) periodical check	2	E	Elevator Dumbwaiter
Door control circuit	Function for door opening and closing by the control signal	Starting with car door open	Door monitor circuit is designed in single circuit	Injury, a serious wound or death because of jamming or crushing of passengers	1	D	2	(1) Circuit supplementation by dual system of door circuit	1	E	Elevator

Table 5.4 Risk assessment examples of accident by FMEA method(continued)

Earth of safety circuit	Function to stabilize power supply and protect men when leakage currents or electric shocks occur	No cut off Fuse	If safety circuit is not earthed, incase of leakage currents, fuse is not cut off and take fire or starting with doors open	Injury, a serious wound or death because of fire or doors open or slip occurrence	1	D	2	(1) Earth of safety circuit (2) Periodical check	1	E	Elevator
reverse phase prevention devices	function to stop elevator operation when one of the three phases power disconnected by mistake.	Reverse run	Reverse phase detect function was not operated or not installed	Shock of occurrence because of malfunction	3	C	2	(1) Circuit supplementation of reverse phase detect function (2) Periodical check	3	E	Ropes elevator Hydraulic elevator
Over load detection devices	The function to stop a start of car with door opening if people ride with overload	Slip of car	Riding more than the capacity of the car	Injury by crushing of car	2	D	3	(1) Circuit design of over load switch by Normal Close (B contact) (2) Periodical check of over load switch	2	E	Elevator
The distance between car and walls	Vertical distance between the car bottom and hoistway walls for crushing prevention on car lift	Judgement power decrease	Distance between car and walls is large	A serious wound or death because of crushing into car bottom and hoistway walls	1	C	1	(1) The protection panel is installed in the hoistway walls where vertical distance between car bottom and hoistway walls is below 125mm (2) Warning sign "Use prohibition except for the service (person riding prohibition)" shall be fixed at visible location for user	1	E	Car lift

Table 5.4 Risk assessment examples of accident by FMEA method(continued)

Gap between landing and jamb or between car door and car door frame	Aim to prevent jamming incident between landing and jamb gap or between car door and car door frame gap	Contact with panel when opening the door	Gap between landing door and jam or between car door and car door frame gap exceed 6mm	Injury, a serious wound because of occurrence of jamming incident	3	C	2	(1) Gap between landing door and jamb or between car door and car door frame must be adjusted below 6mm	3	E	Elevator
Door guide shoe	The function to prevent separation of door when operating the door by guidance along the sill groove	The landing door is impacted from the outside	Obsolete or shortage strength of door guide shoe	A serious wound or death by crushing because door guide shoe is separated to sill groove	1	D	2	(1) Changing Design to hold enough intensity to prevent doors from being separated (2) The buried extent of door guide shoe must be adjusted above 6mm (3) periodical check	1	E	
Door close safety device	The reopening function to protect the person when he p is contacted by door safety devices	Badness of adjustment or badness of design	Door closing safety device is not operated the last part of Door closing	A serious wound or death because of starting the car with jammed door gap	1	D	2	(1) Design change and circuit supplementation of door close safety device	1	E	Elevator
Tension Relaxation perceive device	The devices automatically cut off power when main rope or chain is relaxed during the running	No installation or operation badness	Tension relaxation perceive device is not installed	A serious wound or death because rope was desertted at the pulley by crushing	1	D	2	(1) Additional installation of relaxation of tension perceive device (2) Periodical check or maintenance	1	E	Hydraulic elevator

Table 5.4 Risk assessment examples of accident by FMEA method

Temperature of hydraulic oil perceive device	Device to stop running to detect the temperature of hydraulic oil when Hydraulic elevator oil temperature exceeds a	Stoppage between floor and floor	Lock fault in the car because hydraulic oil exceeds a set point during the running	Impact, fear and famine occurrence because they are locked in due to floor stop fault	3	C	2	(1) Circuit design is changed by the function that car can arrive at the landing when temperature to get out passengers detection device operated (2) Automatic return was operated after enough cooling	3	E	Hydraulic elevator
The step separation sensing device	The function to stop the running when step is separated while escalator is running	In the condition which step is separated, escalator is running normally	The step separation sensor device is not installed.	Minor injury or severe injury by fall of passengers who is caused by with separation of t step	2	D	3	(1) The circuit design is changed by the function to perceive the separation of the step (2) Inspection or repair of operational status	2	E	Escalator
Comb switch	The function to stop running to protect person when getting jammed between comb and step	Operation stop	Comb switch is installed	Minor injury or severe injury by getting jammed between comb and step	2	D	3	(1) The circuit design is changed by the function to perceive when getting jammed in between comb and step (2) Inspection or repair of operational status	2	E	Escalator
Gap between balustrade of escalator inlet and exit	To Prevent a fall in the gap balustrade of escalator inlet and exit	The infants pass in the clearance	Gap between balustrade of escalator inlet and exit is large	Death or severe injury by a fall	1	C	1	(1) Gap between balustrade of escalator inlet and exit is below 100mm	1	E	Escalator

3) Elevator Breakdown

The statistical analysis on elevator breakdown is implemented by using the data for three years in two domestic manufacturers. The number of elevators installed in public housing and multi-use facilities is total 1,174 units (682 for manufacturer A and 492 for manufacturer B). The total number of breakdowns is 10,506 (3,235 in manufacturer A and 7,271 in manufacturer B).

4) Breakdown Parts

A comparative analysis on the breakdown parts such as button and floor indicator, hall door, car door, controller, and hoist way are usually broken are indicated in Table 5.5 in order of descending rate. Among these, faults of floor indicator, hall door, and car door account for about 58%.

Table 5.5 The order of fault components

Fault components	Number of	Rate (%)
Button and position indicator	2,448	23.3
Hall door	1,900	18.1
Car door	1,801	17.1
Controller	958	9.1
Car	820	7.8
Hoist way	484	4.6
Governor	386	3.7
Counterweight	179	1.7
Traction machine	77	0.7
Others	1,453	13.8
Sum	10,506	100.0

5) Breakdown Causes

Table 5.6 indicates that the causes of breakdowns owing to the changed adjustment parts, loosened/ destructed/ and destroyed breakdowns account for 66.64%. Other breakdowns result from sound or vibration, are high ratio.

Table 5.6 Breakdown rate according to causes

Breakdown causes	Rate (%)
Changed adjustment parts, looseness, transformation	46.2
Destruction, damage	20.2
Abnormal sound, vibration	4.6
Life excess, component aging, abrasion	4.0
Contact badness	2.8
Contamination	1.8
User carelessness	1.4
Malfunction	1.1
Jamming	0.9
Trip	0.8
Snapping of a wire	0.8
Others	15.5
Sum	100

6) Analytic Results of Breakdowns

The breakdown parts are button and position indicator, hall door, car door, controller, and hoist way in order. The breakdown parts often derive from incapability in operating. The noises and vibration including sub standardized door and button cause much breakdown. The elevator malfunction is mainly because of the changed and loosed adjusted parts. The old worn-out, damage, destruction of component, poor conjugation, and alien substance-caused contamination breed such breakdowns.

- This result evidently shows that elevator button, floor indicator, old worn-out, and ill treatment trigger are the most enormous elevator damages and breakdowns.
- The alien substances-caused contamination and mal-adjusted parts in hall door and car door trigger are the second-most enormous breakdowns.
- Factors such as tensile blocks, balance chains in regulator, because noises, interphone and regulator switch are often out of order. Noises out of balance weight result from the relatively frequent breakdowns.
- All of hall buttons and indicators are often switched and repaired. The damages owing to common quality maintenance difference from each manufacturer and users' carelessness in maintaining parts are analyzed as the major cause of elevator breakdowns.
- Among break-downs related to part durability, the short-durable switch contactor and magnetic contactor have to be substituted in advance, but, they tend to be replaced after the breakdowns happen.
- The contamination-causing breakdowns can be prevented in advance about 9% by making regular maintenance and cleanliness. parts that require special attention are hall door sill, car door sill, push button, hall door switch contact, and gate switch contact in that order.

7) Risk Assessment of Breakdown by FMEA Method

The cause and effect of each hazard in terms of probability of occurrence and the severity of its effects is assessed. The combination of severity and frequency of occurrence quantifies the risk associated with the hazard. The assessment results are evaluated in terms of residual risk and the acceptable level of safety. If the level of safety is unacceptable, further risk reduction measures are required.

Table 5.7 shows the result of risk assessment used as the elevator break-down data of domestic manufactures that is evaluated risk analysis by FMEA method. It is an aim to assure the safety of existing elevator by using the maintenance.

Table 5.7 Risk assessment examples of accident by FMEA method (Continued)

Item	Function	Failure mode	Presumption Cause	Effect	Estimation of risk elements S	Estimation of risk elements F	Grade	Protective measures (risk reduction measure)
Button	Car calling registration, registration function of the desired floor	The button malfunction caused by super-annuation	Life superannuation, damage, the operational inability which is caused by variation of the regulation region	Use inconvenience of passenger	4	B	3	• Periodical inspection • The periodic part replacement which considers a useful life
Hall door device	The device to protect a passenger from being intercepted by door between the platform and hoistway when car departs	Operation standstill, noise and vibration	Interlock switch, the operational inability which is caused by foreign substance etc. of the sill groove	The shock caused with noise and vibration, or breakdown confining	3	B	2	
Car door device	The device to protect a passenger from being fallen to the entrance and exit during the running	Operation standstill, noise and vibration	Adjustment badness of the switch type, variation and contact badness		3	B	2	
Control panel	The function to control the operation of the elevator	Operation standstill	Change of the adjustment part, superannuation and attrition, the operation inability which is caused by malfunction etc.		3	B	2	

Table 5.7 Risk assessment examples of accident by FMEA method

Cage	Movement means of the passenger who is direct in the space where boards the passenger	Operation standstill, noise and vibration	Parts superannuation, variation and coming loose, adjustment badness		3	B	2	
Traction machine Etc.	Power unit to lifting up and down the car by using the wire rope	Operation standstill and function loss	Parts superannuation, the damage of bearing, gear, unbalance, misalignment, looseness,		3	B	2	• The tendency management which leads the periodic measurement of the noise and the vibration • The periodic parts replacement which considers a useful life

4. Risk evaluation

Each country keenly recognized those risks involved in existing elevators. Europe established the standardization through EN81-80. France and Belgium made safety diagnosis and progressive improvement compulsory through legislature. But aside from those legal issues, safety diagnosis is necessary as a tool of risk evaluation. So this system formulates those essential safety conditions and parameters for each respective category of elevator into checklist with reference to GESR(General Essential Safety Requirement) and European standards so that even general technicians may easily diagnose the risk using following method.

4.1. Essential Safety Conditions

When the diagnosis is implemented in accordance with Table 5.9 and Table 5.10 which are prepared as per GESR and safety parameters verified by each country, the program outputs Table 5.8 which displays the items to be improved as well as the methods of improvement.

Table 5.8 Risk assessment Check List

Place	Item	Risk Item	Result
Machine Room	Control(design)	Excessive wear and tear of brake contact	Yes, No
	Control(design)	Brake contact in single unit	Yes, No
	Control(design)	Door control relay in single unit	Yes, No
	Control(design)	Safety circuit not earthed	Yes, No
	Control(design)	No time limit device on motor	Yes, No
Cabin	Car door(design)	To be opened easily by external force during running	Yes, No
Pit	Overload sensor	Overload sensor inoperative	Yes, No

* If the risk is applicable, Yes (correction recommended). If not applicable, No (no correction required)

4.2. Comparison with Previous Year's Inspection Report

Table 5.9 is the screen of risk value items. The data obtained this year are compared with those of previous year and the differences are analyzed so that those changes which could shorten the life span of machine or cause risk may be predicted.

Table 5.9 Comparison Check List

Item		2008(A)	2009(B)	Result
Quantity of Counterweight				Yes, No
Rope Diameter[mm]				Yes, No
Undercut[mm]				Yes, No
Lining Thickness[mm]				Yes, No
Brake Spring Length[mm]				Yes, No
Brake Plunger Travel[mm]				Yes, No
Max. Stopping Dis.[mm]				Yes, No
Speed[m/min]				Yes, No
Current	Up[A]			Yes, No
	Down[A]			Yes, No
Insulation Resistance[MΩ]				Yes, No
Noise in Cabin[dB]				Yes, No
Vibration in Cabin				Yes, No
Rotator Vibration				Yes, No

* If the standard values are exceeded when the measurements made previous year are compared with those of this year, then Yes (correction recommended) is automatically displayed while No (no correction required) is displayed in opposite case.

4.3 Maintenance Decision Method of Main Components

Elevator users and maintenance companies are required to be interested in the time and the standard to replace the parts of an elevator, and such a standard has enormous influence on the business of elevator users and maintenance companies.

In this chapter, we are going to collect reference materials to decide the time of the disuse of an elevator which is the standard to replace main parts of it.

As investigated in this research, it is considered impossible to indicate and control the time of the disuse an elevator since an error or deviation ranging from several tens percent to several hundred percent may occur according to design, materials, production, installation, environment and frequency.

Therefore, it is considered that the best replacement plan is to decide the replacement cycle in overall consideration of the condition and the service life of parts. The reference materials to judge the condition in which the parts of an elevator should be replaced or disused are as follows.

Table 5.10 Maintenance Decision Criterion of Component (Continued)

Parts		Maintenance Decision Criterion
Reducer	Gear	① In case that irregular vibration (enough to give a passenger in an elevator an unpleasant feeling) caused by pitting or gear mesh frequency(GMF) in the worm wheel occurs ② In case that the pitting in the worm wheel ranges in the overall tooth surface and that PCD of the worm wheel has pitting, the depth of which is more than 20% of thickness of the tooth surface and more than 70% of which is distributed toward the length of tooth width ③ In case that, in PCD, there is a pitting or more, the depth of which is more than 40% of the thickness of tooth ④ In case that the wear of stepped pulley, the length of which is more than 0.5 mm, occurs ⑤ In case that it is impossible to adjust the backlash size recommended by the manufacturer
	Bearing	In case that strange sound occurs and there is no relaxation of the nut and washer receiving the axis or that bearing defect frequency is created

Table 5.10 Maintenance Decision Criterion of Component (Continued)

Parts	Maintenance Decision Criterion
Main rope	① In case of not meeting the inspection standard No. 4.1.3 (8)④ ② In case that the main rope gets bent or loose
Sheave	In case that a crack occurs in sheave
	① In case that the remainder of undercut fails to meet the inspection standard ② In case that there is excessive amount of creep ③ In case that there is severe rope mark in the groove of sheave
	In case slip occur because of the wear of sheave groove
	In case that the difference of height between pieces of the main rope is more than 2mm
Brake ASS'Y	① In case that there is a crack or damage in break pin ② In case that noise occurs because the plunger gets bent ③ In case that there is not enough area for lining because of significant wear in the drum
	In case that it is impossible to slow down or stop an elevator safely in the range of the adjustable tension of the spring
	In case of less than 5MΩ (of less than 2 ㏁ when the use of rated voltage is permitted)

Table 5.10 Maintenance Decision Criterion of Component (Continued)

Parts	Maintenance Decision Criterion
Lining	① In case that there is severe side wear ② In case that the amount of wear is less than the size recommended by manufacturer
	① In case that the lining get worn and thin or that the rivet almost reaches the break drum. ② In case that there is a crack in the lining
Traction Machine Oil	In case that the color of the oil is discolored into a not-recommended color
	In case that there is severe bubbles, emulsion or pollution
Oil Seal	① In case that there is full of oil in the oil receiver during the period of 3 weeks ② In case that oil gets scattered in the break drum after 3 weeks of the worm axis cleaned
Guide Shoe	In case that a crack or transform occurs
	In case that there is more than 1mm of excessive distance allowance between the rail and gib
Guide Roller	① In case that the spring of the guide roller is transformed ② In case that exfoliation or explosion occurs in the roller ③ In case that side wear occurs in the roller
	in case that there in noise in the bearing

Table 5.10 Maintenance Decision Criterion of Component (Continued)

Parts	Maintenance Decision Criterion
Hanger Roller	In case that a crack between the upper and the lower parts of the platform door gets big enough to be seen with a person's eye because of the hanger roller
	In case that there is noise caused by the hanger roller with an abnormal condition
	In case that exfoliation or a crack occurs in urethane
	In case that the hanger roller can stand no longer
Door Guide Shoe	The door guide shoe should be replaced when there is severe noise because of the wear of it.
	In case that the guide shoe is transformed or corroded, or the rubber of it is severely worn
	In case that the guide shoe can stand no longer
Landing Sensor	① In case that lead switch (with magneto system) is corroded ② In case that there is an error such as malfunction because of the damage of the landing device
Limit Switch	① In case that the switch box gets rusted, worn or transformed ② In case that the switch roller gets worn severely ③ In case that the switch lever has severe damage
Spring Closer	In case that the spring causes abnormal noise or the door is not closed because of relaxation of the spring
	In case that spring has a crack

Table 5.10 Maintenance Decision Criterion of Component (Continued)

Parts	Maintenance Decision Criterion
Rubber	In case that damage or oxidization occurs
	In case that the equipment prop is inclined because of deterioration of the vibration-proof rubber
	In case that there is no change in the amount of rubber when an elevator starts or stops
Relay	① In case that the surface of the point of contact is oxidized ② In case that the point of contact is worn, changed or deteriorated ③ In case that there is abnormal noise ④ In case that the coil is deteriorated or discolored ⑤ In case that chattering occurs
Main Contactor	① In case that the amount of the wipe of contact point (the amount of movement of the holder) is decreased to a certain value ② In case that chattering occurs ③ In case that the condition of contact point is bad because of wear
	① In case that the operation pipe is halved because of wear or that there is abnormal wear in diagonal direction ② In case that the contact or the returning spring is damaged or transformed ③ In case that there is abnormal wear in the contact point of the sub-contractor or that there is damage or transformation in the returning spring

Table 5.10 Maintenance Decision Criterion of Component (Continued)

Parts	Maintenance Decision Criterion
Brake Contactor	① In case that the amount of the wipe of contact point (the amount of movement of the holder) is decreased to a certain value ② In case that chattering occurs ③ In case that the condition of contact point is bad because of wear ① In case that the operation pipe is halved because of wear or that there is abnormal wear in diagonal direction ② In case that the contact or the returning spring is damaged or transformed ③ In case that there is abnormal wear in the contact point of the sub-contractor or that there is damage or transformation in the returning spring ④ In case that there is wear in the contact lever of the sub-contactor
Gate Switch	In case that there is severe wear, transformation or crack in the returning or finger spring
Button & Lamp	① In case that the protection ring of the push button is damaged ② In case that the illumination intensity is extremely low

Table 5.10 Maintenance Decision Criterion of Component

Parts	Maintenance Decision Criterion
Indicator	① In case that the floor-indicating acrylic is broken off or damaged ② In case that the position-indicating lamp is broken off or severely relaxed ③ In case that there is significant deviation of illumination intensity of the lamp ④ In case that the indicator does not work or blinks
Travelling Cable	① In case that the transferring cable is torn ② In case that the disconnected wire of the inside cordial is projected to the outside of the transferring cable or causes interference to the wire ③ In case that the inside electric wire of the cable is damaged
Overload Switch	① In case that there is abnormal drooping, crack or corrosion ② In case that the lead line gets deteriorated
Interlock Switch	In case that the hanging wheels are engaged less than 7mm or less than the size recommended by manufacturer because of wear
	In case that the locking does not work in the force less than 300N which opens the door or the force less than as recommended by manufacture because of wear of the switch
	① In case that there is severe rust and corrosion in the sticking part ② In case that there is severe wear and transformation in a point of contact

4.4 The Flow Chart of Risk based Inspection according to each units

Elevator vibration is very important role to decide the elevator quality and safety. So, the proposed step1 is the procedure of elevator performance measurement as shown in Fig 5.2. The developed device is used to measure the elevator performance measurement on rotating machinery and ride quality. The measured value is evaluated comparing by criterion. If the measured value is exceeded, it is analyzed by the fault feature classifier. After the fault feature is shown by them, the risk assessment is performed. According to the risk frequency and severity, the grade is classified by grade 1, 2, 3, 4. Finally, protective measures and maintenance schedule is decided about maintenance time, period and cost. After the protective measures are implemented, if the measured result is satisfied, it is finished, if not, it is performed again by the process of step 1.

Step 2 presented in Fig. 5.2, is the procedure of comparison with previous year's inspection report of elevator. The previous year's inspection report is compared whether the inspection result of this year is exceeded or not. If they exceed allowance value, they were analyzed by the fault feature classifier. After the fault feature is shown by them, the risk assessment is performed. According to the risk frequency and severity, the grade is classified by grade 1, 2, 3, 4. Finally, protective measures and maintenance schedule is decided about maintenance time, period and cost. After the protective measures are implemented, if the measured result is satisfied, it is finished, if not, it is performed again by the process of step2.

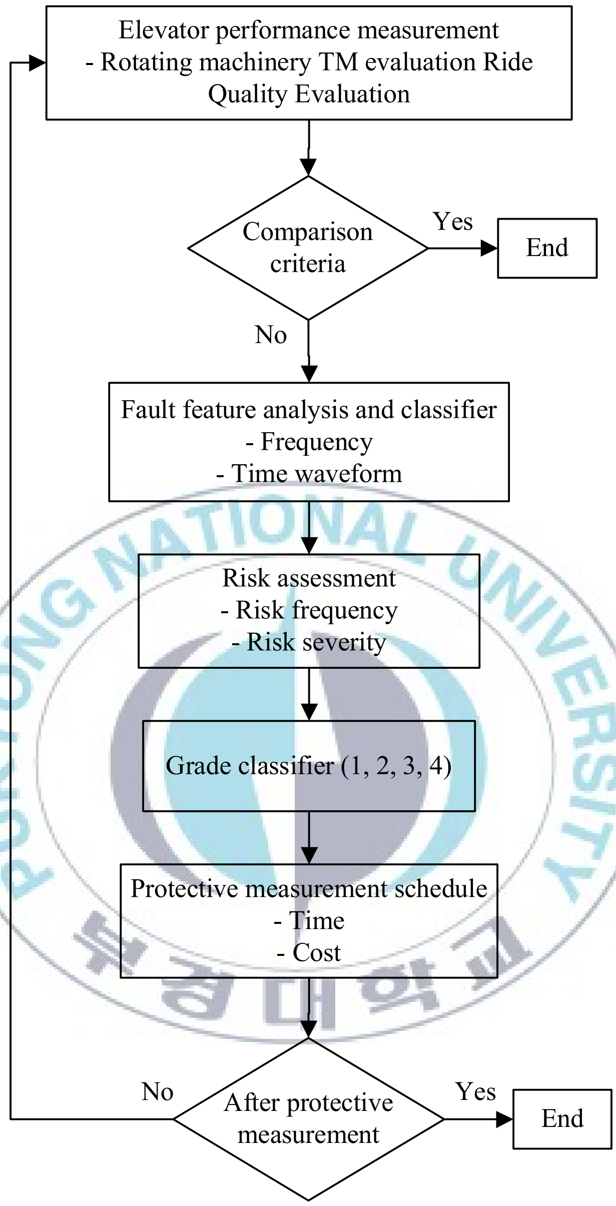

Fig. 5.2 Elevator performance measurement procedure.

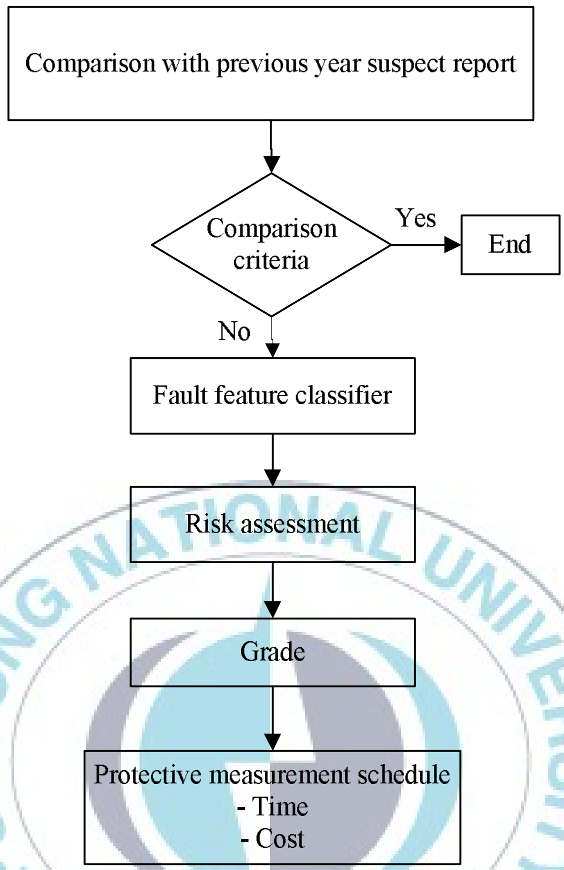

Fig. 5.3 Comparison procedure with previous year criterion.

Step 3 described in Fig. 5.3 is the procedure inspecting on the risk items of elevator system and parts analyzed through the risk assessment of elevator accidents and breakdown data in Republic of Korea. Through the elevator design drawing and site visual inspection, they are evaluated whether there are risks, or not. If there are risks, they are analyzed by the fault feature classifier. After the fault feature is shown by them, the risk assessment is performed. According to the risk frequency and severity, the grade is classified by grade 1, 2, 3, 4. Finally, protective measures and maintenance schedule is decided about maintenance time, period and cost. After the protective measures are implemented, if the measured result is satisfied, it is finished, if not, it is performed again by the process of step3.

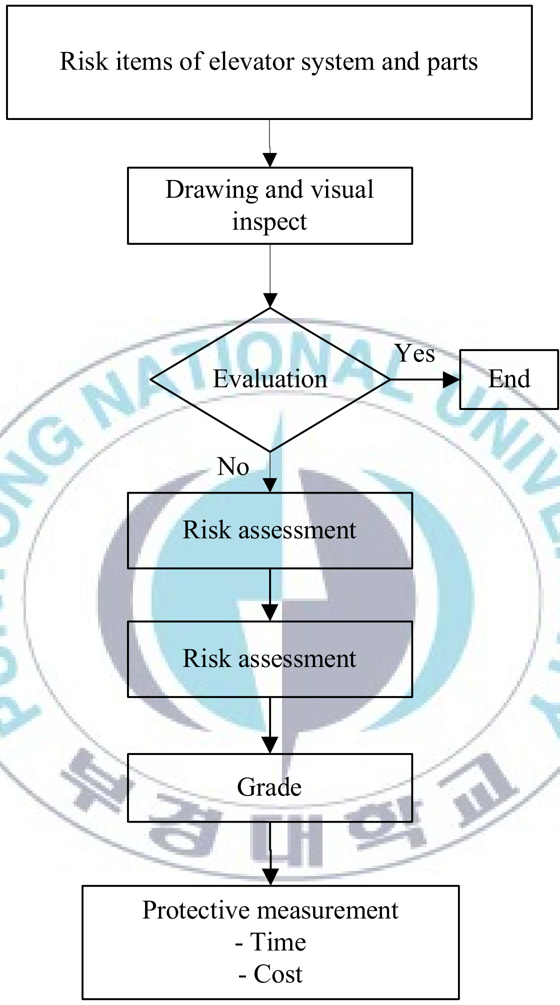

Fig. 5.4 Risk items of elevator system and parts.

Step 4 is the procedure to maintain the life cycle of elevator main parts (Fig. 5.4). They are performed to replace the elevator parts comparing the life cycle criterion obtained by the survey and study of elevator parts. If they are exceeded at criterion, the maintenance schedule should be established on maintenance period, time and cost per year.

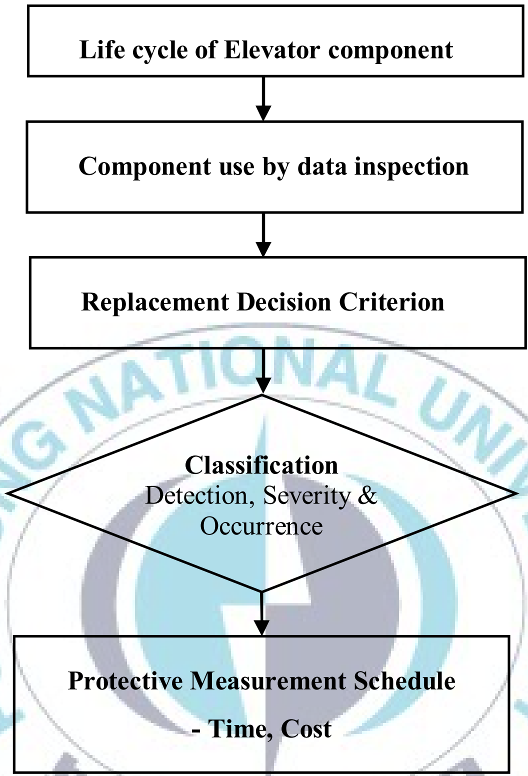

Fig. 5.5 Life Cycle of Main Components.

Step 5 is the procedure of periodic inspection as shown Fig. 5.4~5 If the inspection results exceed, or are not satisfied comparing by criterion, it is analyzed by the fault feature classifier. After the fault feature is shown by them, the risk assessment is performed. According to the risk frequency and severity, the grade is classified by grade 1, 2, 3, 4. Finally, protective measures and maintenance schedule is decided about maintenance time, period and cost. After the protective measures are implemented, if the measured result is satisfied, it is finished, if not, it is performed again by the process of step5.

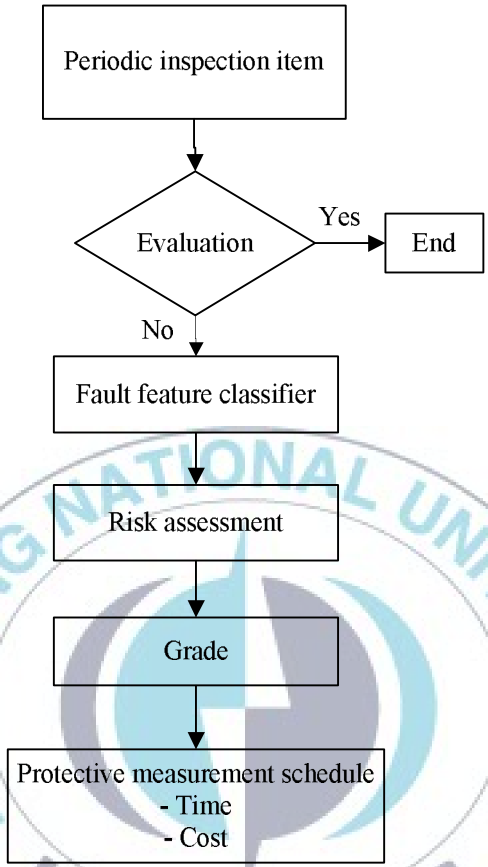

Fig. 5.6 Periodic inspection procedure

Step 6 is the procedure of total maintenance from step1 to step 5 as shown Fig. 5. 6. Through the comparison of criterion value, they are evaluated. If they exceed allowance value or criterion value, they were analyzed by the fault feature classifier. After the fault feature is shown by them, the risk assessment is performed. According to the risk frequency and severity, the grade is classified by grade 1, 2, 3, 4. Finally, protective measures and maintenance schedule is decided about maintenance time, period and cost. After the protective measures are implemented, if the measured result is satisfied, it is finished, if not, it is performed again by the process of step 6. The proposed procedures are very important to implement the optimum maintenance of elevator by risk-based inspection. They could provide us the safety and cost reduction to implement the risk-based inspection for elevator optimum maintenance. The developed framework is presented in Fig. 5.7. The Integrated RBI maintenance procedure represent RBI for elevator optimum maintenance to ensure a safety scientifically by new method and to lessen maintenance cost by adopting the risk based inspection. It consist of the following concepts or themes; performance measurement about machinery rotating and car vibration, comparison with previous inspection data, risk assessment of elevator, replacement life cycle of elevator, elevator monitoring about travelling frequency, door operation, safety function. And each concepts were classified according to different damage mechanism and failure probability of each item with a view to not only reducing unnecessary inspection items, but also reducing failure probability of elevator system effectively, also reducing the maintenance cost longer term.

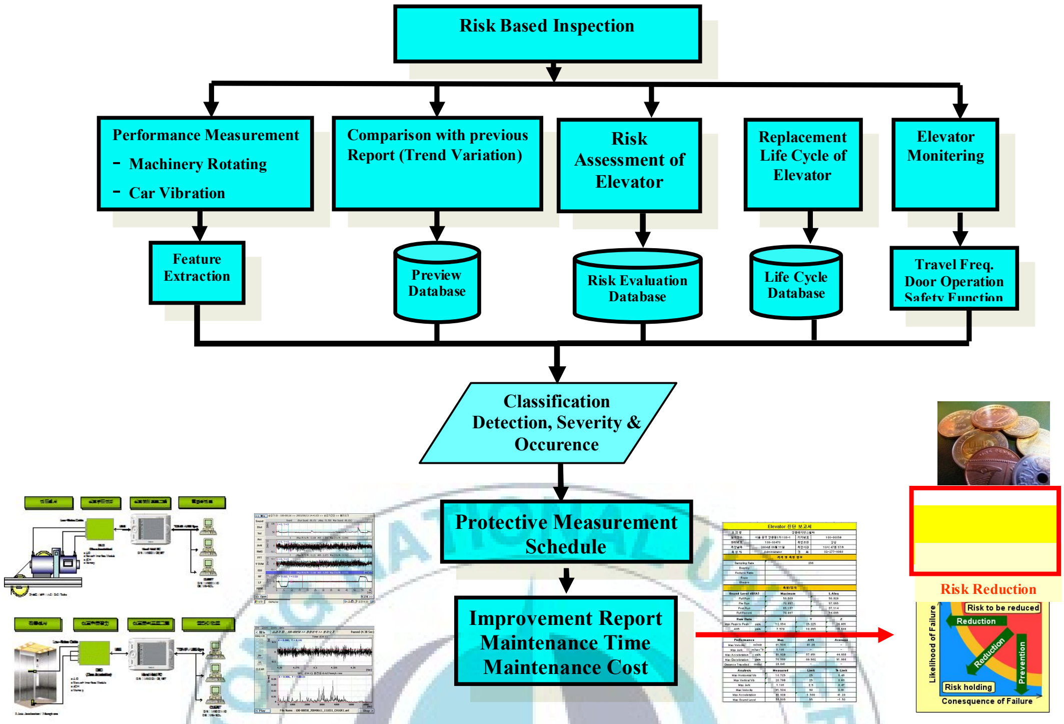

Fig. 5.7 Integrated RBI maintenance procedure.

5. Guidance for Optimal Risk-Based Maintenance

Elevators are the precise machine of which parts are assembled and run in the installment spot. Although the elevator machines are designed, produced or/and installed through accurate quality maintenance, they could only lose their original functions but also cause low performance and safety accidents, without scientific management and maintenance. Thus, this research studies on the possible deficiency arising from each part test, individual parts or systems. And, this study has conducted the examination about the effects on each part break-downs and steps against it along with their regular check-up period.

The management and maintenance strategies right for elevator is expected to exert the very important effects on preventive check-ups in accordance with the regular substitution period. Safety, reliability and comfort would contribute to managing and maintaining elevators. It is also indispensable to make the regular performance test. Table 5.11 shows elevator maintenance guide that can inspect effectively according to fault feature and decide the appropriate inspection period [14].

Table 5.11 Maintenance guidance for elevators

Name of parts		Inspection method	Fault feature	Effect of breakdown	Counter-measure	Inspection Cycle
Cage	Vibration Sound	Vibration & noise	• Increase of the vibration & noise - Resonance - Gear mesh frequency - Misalignment frequency - Unbalance frequency - Rail shock vibration - Guide roller vibration - Fan noise	Vibration Noise Operation shutdown	Repair Adjust-ment	6
	Button Lamp Indicator	Visual	• Button getting stuck • Aging, wear	User inconvenience Unnecessary operation	Repair Change	1
Guide rail		Visual Laser equipment	• Corrosion • Bending • Periodic vibration	Vibration Sound	Adjust-ment Repair	24
Rail guide Shoe		Visual	• Wear, aging • Vibration	Vibration Sound	Change Design change	3
Rail guide Roller		Visual	• Wear, aging • Vibration	Vibration Sound	Change Design change	3
Overload Device		Visual Counterpoise inspection	• Aging, performance degradation • Normal A contact • Overbalance ratio change	Slip Fall of car	Repair Design change	1
Protection against dust rubber		Visual	• Deterioration • Function loss	Vibration	Change	12
Safety gear		Operation inspection	• Wear, corrosion • Malfunction	Fall	Change	3
Landing switch		Visual	• Aging, performance degradation • Malfunction	Operation shutdown	Change	3
Main rope		NDT Visual Size	• Wear, element wire rupture • Excessive slip • Wire rupture	Fall Sliding	Change	6
Limit switch, deceleration and terminal switch		Operation Visual	• Aging, damage • Return spring separation • Roller crack or damage	Operation shutdown	Change	3
Various fuse		Visual	• Fuse cutting	Operation shutdown	Change	1
Spring buffer		Visual	• Damage of spring • Spring rust	Malfunction	Repair Change	3
Oil buffer		Operation Visual	• Operation badness • Insufficient oil	Shock unabsorbed	Oil supply Repair	3

An example of maintenance result report is given Table 5.13 and Table 5.14. Table 5.12 shows the maintenance result report obtained by implementing the risk based inspection, and shown the remaining life and fault feature. Table 5.14 is maintenance improvement measures report obtained by combining the fault feature and remaining life by utilizing the developed system. It provides the contents of improvement measures, inspection plan and maintenance cost.

Table 5.12 Maintenance Result Report

Item	Design Life (Remaining Life)	Fault Feature	Purchase Cost (₩)
Motor	15 (2)	• Aging • Contamination • Insulation degradation	2,000,000
Bearing	16 (0)	• Wear -Inner race,out race,ball • Plastic deformation	24,000
PC Board	8 (1)	• Corrosion • Bending • Periodic vibration	2,500,000
Hanger Roller	5 (0)	• Wear • Aging, damage	20,000
Main Rope	4 (0)	• Wear • Exceesive slip • Wire Rupture	350,000
Spring Buffer	25 (15)	• Damage of spring • Spring rust	300000
Safety Gear	25 (15)	• Wear, Corrosion • Malfunction	250,000
Landing Switch	8 (7)	• Aging • Performance degradation	30,000
Limit Switch	11 (8)	• Aging, damage • Return spring separation • Roller crack or damage	10,000
Guide rail	50 (40)	• Corrosion • Bending	3,000,000

Table 5.13 Maintenance Improvement Measures Report

item	Fault Feature	Improvement Measures	Inspection Plan	Cost (₩)
Motor	• Aging, Contamination • Insulation degradation	• Repair	Less than 1 month	500,000
Bearing	• Wear -Inner race,out race,ball • Plastic deformation	• Replacement	Less than 1 month	24,000
PC Board	• Corrosion • Bending • Periodic vibration	• Repair	Less than 1 month	300,000
Hanger Roller	• Wear • Aging, damage	• Replcaement	Less than 1 month	20,000
Main Rope	• Wear • Exceesive slip • Wire Rupture	• Replacement	Less than 1 month	350,000

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VI. Conclusions

This dissertation presents an investigation of risk management, elevator risk assessment and reduction methodology, elevator fault analysis and life cycle assessment based on studying and surveying about the elevator component replacement life cycle. It also provides the elevator performance management development as well as elevator evaluation criteria to apply the condition prognosis and the inspection/maintenance. The risk management by RBI method gives the proposed guidance for optimal risk-based inspection/maintenance.

Elevator maintenance is very important to decide the best solution of the management about the inspection periodic, replacement time and evaluation method. The fault feature of elevator is obtained from studying, diagnosing and surveying the elevator component cycle assessment in the site.

The replacement life cycle of elevator component surveyed through the elevator maker and the maintenance company, also the design cycle life was studied through the literature and maker design documents. The replacement life cycle of the elevator component proposed the effective data by comparing and analyzing the domestic maker, Elevator World data and survey data through the makers and the maintenance company.

The evaluation of ride quality and rotating machinery is the important techniques when maintaining elevator. Through the development of Dr.Elevator, it is possible to prognosis the condition to the characteristic features which indicate the fault event, and feature representation is a process where the features are calculated on time domain, frequency domain and waterfall function. The proposed evaluation criteria is conducted the statistical analysis on the measured value of ride quality and vibration of traction machine. Thus it is necessary to use the analysis as performance assessment standards. If such standards are exceeded, the causes need to be analyzed through FFT analysis. It is deemed that the measurement and analysis on elevator ride quality and vibration of traction machine in combination with prevention maintenance and prediction maintenance would guarantee the higher stability and reliability. The reliability of Dr.Elevator system has been proved by Korea Research Institute of Standards and Science, the measured frequency is 2.5, 5, 10, 20, 40, 63, 80 Hz, and the relative standard uncertainty is max 0.054%, and tolerance range is 5% below. By applying Dr.Elevator is validated by applying it to diagnosis and predict the elevator fault cases about car resonance, rail installment, reducer fault, bearing fault, unbalance, misalignment and guide roller vibration etc.

This paper studied the risk assessment by using the elevator accident and breakdown statistics data based on FMEA techniques and we tried implementation of risk based inspection for the elevator maintenance in the site. This paper has made the risk based inspection predicting their remaining usage life, optimizing the maintenance decision making for elevator and then it has made the propositions on how to prevent elevator safety accident and make the premium management and maintenance.

VII. Future Works

Engineering Asset Management and more specifically Integrated Asset Management based RBI technology, involves the integration of process of managing physical assets during their useful lives, and requires a certain level of management insight and expertise from diverse organizational disciplines. It is a systematic, structured process covering the whole life of physical assets whereby the underlying assumption is that an organization’s assets exist to support the organization’s delivery strategies. These strategies thus combine with information systems, personnel, and financial resources. Asset management is the process of organizing, planning and controlling the acquisition, use, care, refurbishment, and disposal of physical assets to optimize their service delivery potential and to minimize the related risks and costs over their entire life through the use of intangible assets such as knowledge based decision-making application and business. The RBI framework of future works is presents in Fig. 7.1

The basic principles of them represent the following concepts or themes ; asset service delivery, strategic planning, decision making and risk assessment, asset full life cycle costing and budgeting, asset usage modeling, condition monitoring, maintenance, and replacement, asset data acquisition, information systems, and performance. Consequently, The RBI framework shown in Fig. 7.1 should be developed for elevator maintenance company, manufacture company and inspection agency to use easily by the web-based program of Risk based Integrated Engineering Asset Management. To achieve this goal, it should be consisted of by the following major contents:

- Inspection and Maintenance data collection
- Failure mode and effect analysis data
- Failure and repair cost distributions
- RBI data base of elevator design and site installed elevator

- Performance Measurement data

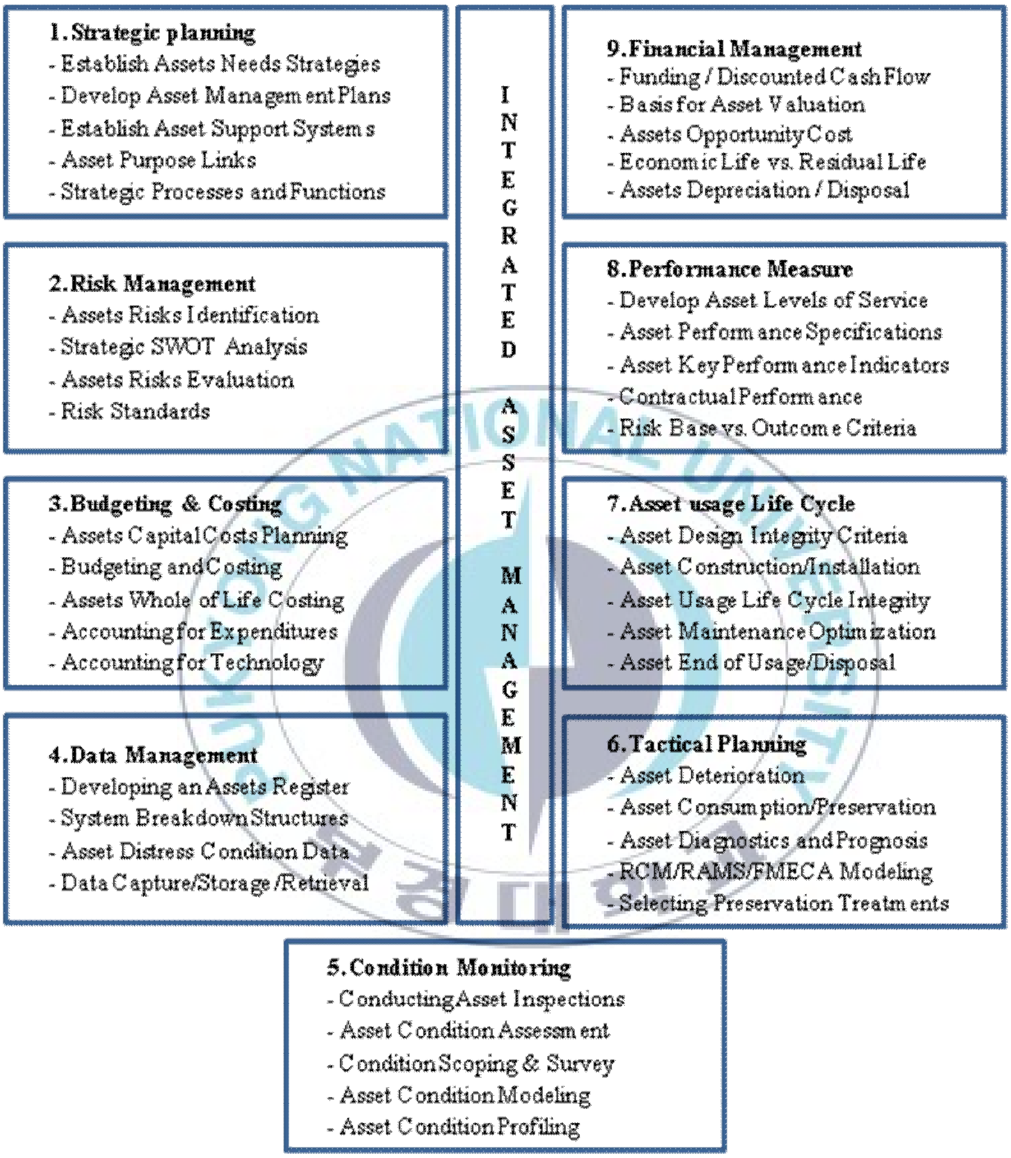

Fig. 7.1 RBI Framework for Integrated Engineering Asset Management

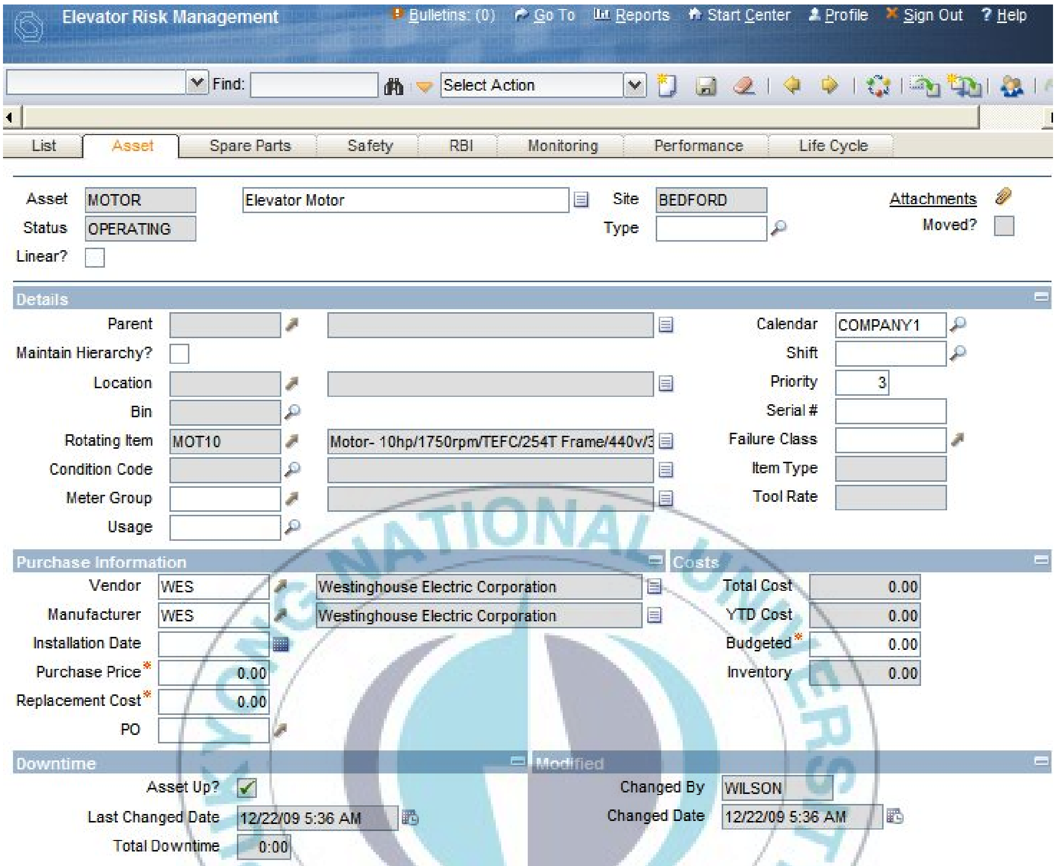

Fig. 7.2 Elevator Risk Management Display

최적의 유지보수를 위한
엘리베이터 위험기반 검사의 실행

박 승 태

부경대학교 대학원 기계협동과정

국 문 요 약

석유화학, 정유, 가스, 전력과 같은 에너지 산업분야의 기술이 급속하게 발전함에 따라 각종 시설들은 복잡, 다양화되고 있으며, 더욱이 생산효율을 증가시키기 위해 압력설비와 같은 고온, 고압의 조건 하에서 운전하는 시설과 설비들의 사용이 급증하고 있다. 이와 같이 장치시설들은 설치 후 시간이 지남에 따라 노후화 되기 때문에 보수, 대체 또는 폐기하고 있으나 경제적 또는 환경적 문제로 보수나 대체가 더욱 높아지고 있다. 따라서 노후화된 장치들은 유지, 보존 상태와 경제성 및 안전성에 따라 가장 효과적이고 적절한 시기에 검사하고 보수해야 될 필요성이 있다. 1980 년 이전에는 문제발생시에 검사(break down inspection)를 실시하였기 때문에 설비에 대한 사고발생 가능성이 높았으며, 검사결과의 기록과 단순한 대책수립만 할 수 있었다. 그 후 80 년대에 들어와서는 문제발생이 많은 설비에 대하여 운전 중에 주기적인 검사를 실시함으로써 검사능력의 한계와 설비에 대한 관리비용이 과다하여 검사와 결과관리의 체계적인 관리의 필요성이 대두되었다. 그리고 90 년대에는 문제발생이 예상되는 부분에 대하여 집중검사를 실시함으로써 사고발생 가능성은 낮아졌으나, 설비의 검사와 관리에 대한 비용이 매우 많

았고, 검사자료의 정확성 향상을 위한 검사표준화의 작업이 필요하였다. 그러나 90 년대 말부터는 공정이나 설비의 위험도에 근거한 검사, 즉 위험기반검사 (risk-based inspection, RBI)에 의해 공정이나 설비에 대한 문제발생 가능성과 대책이 수립되고, 공정의 검사 우선순위 결정이나 설비별 검사방법과 검사주기를 설정하여 설비의 신뢰도를 극대화함으로 설비의 관리비용을 최적화할 수 있게 되었다.

RBI 는 사고발생 가능성과 사고결과 크기의 곱에 의해 위험도를 산출하고, 위험도에 의해 검사체계의 운영과 공정 또는 설비의 검사 우선순위를 결정하여 정량화된 위험도를 제공하여 주요설비를 최적으로 검사할 수 있는 검사방법을 제시하고, 안전, 환경 및 사업 수행에 장애를 주는 위험요소를 검토하여 비용, 효과적인 방법으로 설비를 관리할 수 있도록 하는 새로운 검사방법이다. 또한 RBI 는 검사를 보다 효율적으로 운영하여 사고발생 가능성을 구조적으로 줄일 수 있도록 하며, 시간이 지남에 따라 설비의 위험도가 증가하기 때문에 가정 적절한 시기에 검사를 수행함으로써 검사비용을 최소화하고, 설비에 대한 신뢰도를 증가시킬 수 있도록 할 뿐만 아니라 위험도를 통해 설비의 검사방법과 검사 유효성을 제시하여 설비를 유지 관리하여 위험도에 근거한 관리시스템을 구축할 수 있다.

따라서, 본 연구에서는 국내의 사고 및 고장 통계자료를 최대한 활용하여 유지관리상의 근본적인 문제점을 파악하여 사고저감방안을 마련하였고, 승강기부품수명에 대해 설문조사 및 분석을 통해 주요부품에 대한 사용수명을 제안하였고, 또한 엘리베이터의 승차감과 회전기계의 성능을 진 동 및 소음 파형 및 주파수특성을 통해 설비의 건강을 평가할 수 있는 승강기 성능평가 장비를 개발하고 한국과학표준연구원에서 장비에 대한 신뢰성 검정을 수행하였다. 개발된 성능평가장비로 승강기 결함특성분석 및 상태감시시스템을 실현하기 위해 엘리베이터의 진동 특성주파수 분석과 진동의 크기에 대한 기준을 마련하였으며, 최적의 엘리베이터 유지관리를 실현하기 위해 위험기반에 근거한 검사 시스템을 방안을 제시함으로 승강기의 고장률을 저감시키고 이용자의 안전을 확보함과 엘리베이터 자산관리의 최적화 기법을 찾고자 한다.

제 1 장에서는 연구의 배경과 동기를 소개하였고, 또한 연구의 주요한 목적과 기여도를 설명하고 본 논문의 개요를 약설하였다.

제 2 장에서는 유지관리지식, 위성관리, 위험성평가와 감축방법 등 유지관리 전반에 대한 내용을 다루었다.

제 3 장에서는 승강기 주요안전부품의 특성에 대해 개략적으로 설명하였고, 승강기 제조업체 및 유지보수업체를 대상으로 주요부품의 수명주기에 대한 설문조사를 실시하였으며, 또한 이론수명과 설문조사 및 미국의 엘리베이터 월드사에서 조사한 수명과의 상호 비교를 하였다. 또한 주요부품의 결함원인분석과 연장방안을 제시하였다.

제 4 장에서 엘리베이터의 성능을 평가할 수 있는 장비를 개발하였다. 개발된 장비는 엘리베이터에서 가장 중요한 것 중 하나인 엘리베이터 카 내에서 사람이 느끼는 진동의 크기를 나타내는 승차감 측정과 엘리베이터를 구동시키는 권상기 (traction machine)의 진동측정 및 분석이 가능한 장비이다. 개발된 장비에 대한 신뢰성을 한국표준과학연구원에서 검정하였다. 개발된 장비를 이용하여 엘리베이터 시험타워에서 권상기의 결함종류별 시편을 제작하여 결함특성에 따른 진동특성을 분석하여 분류하였으며, 또한 개발된 장비를 사용하여 엘리베이터가 설치된 현장에서 엘리베이터 정밀진단을 실시하여 사례별로 엘리베이터의 진동특성을 분석하여 결함종류별로 진동특성 및 주파수 결함성분을 찾아낼 수 있었다. 카 내의 전후, 좌우 및 상하 진동의 크기에 대한 기준값을 제시하였고, 기계실의 회전기계인 전동기의 기준값을 제시하였다.

제 5 장에서는 최적의 유지관리를 위한 위험기반검사를 실행하기 위해국내 승강기 사고자료 및 보수업체의 고장자료를 활용하여 원인별 실패모드, 추정원인, 발생빈도, 사고의 심각도 등 위험성 분석을 통해 예방대책을 마련하였다. 이러한 것을 실행하기 엘리베이터성능평가의 수행, 경향분석을 위해 전년도와의 기준값 비교, 사고사례 및 고장사례 분석을 통해 정립된 엘리베이터의 위험성평가수행, 주요부품의 수명비교 등을 조합하여 최적의 검사를 수행할 수 있도록 최적의 유지관리를 위한 위험기반에 근거한 검사시스템 방안을 제시하였다

제 6 장에서는 본 연구에서 얻어진 결과에 근거하여 결론으로 요약하였다

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감사의 글

직장생활을 하면서 지능역학연구실에서 파트타임으로 학업을 시작을 시작한 것이 만 4 년, 새벽 첫차로 KTX 고속열차를 이용하여 광명역과 부산역을 오가면서 대학원과정을 부족하지만 이렇게 마무리 할 수 있도록 인도해 주신 하나님께 영광 돌려드립니다. 먼저, 지금까지 항상 긍정적이고 열정적인 모습으로 연구자로서의 바른 자세를 깨닫게 해주신 양보석 지도교수님께 진심으로 감사의 마음을 전합니다. 교수님을 통해서 배운 가르침을 늘 마음에 기억하면서 창조적인 연구자로서의 자세로 겸손하게 살아가고자 다짐해 봅니다.

바쁘신 중에도 논문지도에 큰 도움을 주신 남기우 교수님, 안병현 교수님, 김선진 교수님, 이선순 박사님께 감사를 드립니다.

특별히 학업을 할 수 있도록 배려와 격려를 해주신 한국승강기안전기술원 임직원님들, 이건철 이사장님, 신서철 기술안전이사님, 박용천 기획관리이사님, 장선식 전임이사장님, 송지태 전임이사장님, 전해진 전임기획기술이사님, 한승호 전임관리이사님, 전복진 기술위원님, 김영학 본부장님, 한익권 본부장님, 송성철 본부장님, 이종철 본부장님, 주혁 팀장님, 윤우진 팀장님, 이승우 차장님, 박찬용 과장님, 이진호 과장님, 김재우 과장님, 성종환 과장님, 최성욱 과장님, 남송희 과장님, 이강일 대리님, 이창우 대리님, 김제헌, 심규봉, 우방희, 김경호, 이안수, 임상현, 김현주, 김현숙 사우님들 및 모든 직원 분들에게 감사의 마음을 전합니다.

지금이 있기 까지 연구실 선배님의 가르침과 후배들의 도움이 제게 큰 힘과 격려가 되었습니다. 김원철 교수님, 김인수 부장님, 이수목 부장님, 길병래 교수님, 최원호 박사님, 김진욱 박사님, 안영공 박사님, 공영모 박사님, 이장우 박사님, 최성필 박사님, 정태영 선배님, 그리고 항상 친절하게 도움을 주었던 후배님들, 손종덕 박사, 이재갑, 김선화, 송

애희, 양승욱 및 모든 후배님들 그리고 외국인 뉴강(Gang Niu) 박사, 퉁(Van Tung Tran) 박사에게 고마움을 전합니다. 논문의 편집과정에서 많은 도움을 준 심민찬 후배님, 위도도(Achmad Widodo) 박사님께 감사의 마음을 전합니다.

대학원 과정을 파트 타임으로 서로 위로하고 격려하면서 힘이 되어주신 김곤 부장님, 임감민 책임연구원님, 김동연 실장님, 김현철 차장님, 권남구 팀장님, 송병곤 사장님, 이소환 사장님, 서상윤 대리님에게 감사드립니다.

항상 기도로 후원과 격려해 주신 영광교회 이상돈 목사님과 사모님 그리고 모든 성도님들에게 고마움과 감사의 마음을 전해 드립니다.

자식의 잘되기만을 위해 지금까지 헌신적으로 이끌어 주신 아버지와 어머니의 은혜와 사랑에 다시 한번 머리 숙여 감사를 드립니다. 항상 기도로 후원해 주신 장인어른과 장모님의 은혜에 가슴 깊이 감사의 마음을 전해 드립니다. 또한 사랑과 격려로 도움을 주신 큰형님과 형수님, 작은형님과 형수님께 감사의 마음을 드립니다. 사랑하는 이기영, 이지연, 이권석, 이혜연, 이광희에게 감사의 마음을 전합니다.

마지막으로 지금까지 묵묵하게 모든 것을 믿고 순종하는 자세로 내조해 준 아내와 아들 현서에게 사랑과 감사의 마음을 선사합니다.