

Failure Mode and Observability Analysis (FMOA): An FMEA-based Method to Support Fault Detection and Diagnosis

Renan Favarão da Silva

Department of Mechatronics and Mechanical Systems, University of São Paulo, Avenida Professor Mello de Moraes 2231, São Paulo, SP, 05508-030, Brazil. E-mail: renanfavarao@usp.br

Arthur Henrique de Andrade Melani

Department of Mechatronics and Mechanical Systems, University of São Paulo, Avenida Professor Mello de Moraes 2231, São Paulo, SP, 05508-030, Brazil. E-mail: melani@usp.br

Miguel Angelo de Carvalho Michalski

Department of Mechatronics and Mechanical Systems, University of São Paulo, Avenida Professor Mello de Moraes 2231, São Paulo, SP, 05508-030, Brazil. E-mail: michalski@usp.br

Gilberto Francisco Martha de Souza

Department of Mechatronics and Mechanical Systems, University of São Paulo, Avenida Professor Mello de Moraes 2231, São Paulo, SP, 05508-030, Brazil. E-mail: gfmsouza@usp.br

Condition-Based Maintenance (CBM) is a well-known strategy that organizations implement to prevent failures of their physical assets. For that, Fault Detection and Diagnosis (FDD) processes need to be implemented successfully. Nevertheless, this stage requires the structuring of expert knowledge regarding the potential failure modes and their observability and failure data. Without a supporting tool, this setup can be difficult for many organizations. In this context, this paper proposes the Failure Mode and Observability Analysis (FMOA) to support fault detection and diagnosis implementation in asset management. The proposed method is a variation of the Failure Mode and Effects Analysis (FMEA) that analyses the potential failure modes of selected systems and correlates them with relevant properties for FDD. The proposed FMOA method was demonstrated through a case study based on a Brazilian hydroelectric power plant. The results obtained showed that the method can support organizations in the study of selected systems, equipment, and components for the implementation of fault detection and diagnosis. It contributes to the organizations to implement a CBM strategy as it organizes the knowledge base about the physical assets while correlating the potential failure modes with properties of FDD.

Keywords: Fault Detection and Diagnosis, FDD, Failure management, Failure mode, FMOA, Hydroelectric power plant.

1. Introduction

Ensuring that physical assets are available and in health conditions for operation is essential as well as challenging for organizations. For this to happen, maintenance management not only needs to coordinate the preventive maintenance activities but also monitor and mitigate any degradation in its engineering systems (de Souza et al. 2021).

The recommendation of maintenance actions based on machinery health information collected

through condition monitoring is known as Condition-Based Maintenance (CBM) (Jardine et al. 2006). Thus, it is a decision-making strategy to enable real-time diagnosis of impending failures and prognosis of future equipment health (Peng et al. 2010). In this maintenance strategy, Fault Detection and Diagnosis (FDD) are the main processes.

According to Saufi et al. (2019), FDD is crucial to preventing unexpected breakdowns of machinery and ensuring production efficiency

and operational safety. Basically, fault detection can be defined as the process of recognizing that a fault has occurred, while fault diagnosis is applied to find the cause and location of the fault (Melani et al. 2021).

FDD integrates several activities to effectively support maintenance management in the failure prevention of physical assets. According to de Souza et al. (2021), the organization shall define the relevant engineering systems for condition monitoring first and then shall identify the potential failure modes that may occur and be prevented with this strategy. Finally, it is possible to associate the variables of interest for the failure modes considered to be prevented with the CBM strategy.

Thus, the foremost step in the development of the FDD processes is to obtain prior knowledge of the system (Abid et al. 2020). In other words, to successfully implement them, it is necessary proper preparation and its setup should not be neglected. However, due to a lack of supporting tools, organizations may struggle during this stage.

In this context, this paper proposes the Failure Mode and Observability Analysis (FMOA) method to support fault detection and diagnosis implementation in asset management. The proposed method is a variation of the Failure Mode and Effects Analysis (FMEA) that intends to support the setup of the FDD process in organizations. Then, it is demonstrated through a case study based on the context of a Brazilian hydroelectric power plant.

The paper is structured as follows: Section 2 presents a brief discussion on the methods that support the analysis of potential failure modes. Section 3 presents the proposed FMOA method to support the FDD process implementation. Section 4 applies the method to a hydroelectric power plant context. Finally, Section 5 presents the authors' conclusions about the proposed method and case study.

2. Existing Methods for Analysing Failure Modes

Preventing failures of physical assets is one of the main challenges maintenance management faces to ensure availability in organizations. Ensuring efficient process monitoring and early detection and diagnosis of abnormal operations is essential to prevent losses (Alauddin et al. 2018). This may

become even harder without the support of methods to identify and analyze the potential failure modes of critical systems, equipment, and components.

To identify the main methods of studying potential failure modes, a literature review was carried out in February 2022 on the Web of Science Core Collection as it is a relevant scientific production database. Documents with the terms "failure mode" in their title, abstract, or keywords and "FM" in their abstract were searched in the database. The document type and search period fields were not restricted to identifying all types of publications throughout the database coverage time.

This search protocol returned a total of 2,936 documents that were assessed to compile the main methods applied to study the potential failure modes in the literature, as presented in Table 1 ordered by occurrence.

Table 1. The main methods to study failure modes.

Method	Description	Qty
FMEA	Failure Mode and Effects Analysis	2180
FMECA	Failure Mode, Effects and Criticality Analysis	497
FMMEA	Failure Mode, Mechanisms and Effects Analysis	31
FMEDA	Failure Mode, Effects and Diagnostic Analysis	30
FMA	Failure Mode Analysis	23
FMVEA	Failure Mode, Vulnerability and Effects Analysis	4
FMMECA	Failure Mode, Mechanisms, Effects, and Criticality Analysis	2
FMSA	Failure Mode and Symptoms Analysis	2
FMESRA	Failure Mode, Effects and System Resilience Analysis	1
FMETA	Failure Mode and Effects Tree Analysis	1
FMCA	Failure Mode and Cause Analysis	1
FMEMA	Failure Mode, Effects and Monitoring Analysis	1

As can be seen in Table 1, Failure Mode and Effects Analysis (FMEA) is the most applied method to identify the potential failure modes by

far in the literature. This can be explained due to the fact that FMEA is a 70 years old method introduced in the US Army to study problems that might happen from malfunctions of military systems (Spreafico et al. 2020). Since then, it has been worldwide improved and applied in different fields as well as has been modified several times which provided other variations such as those shown in Table 1.

The main focus of the FMEA is to identify, prioritize, and act on the potential failure modes of a system before they occur. When this application includes a criticality analysis, the method is called Failure Mode, Effects and Criticality Analysis (FMECA) (Huang et al. 2020). It is noteworthy that is the main variation of traditional FMEA and the second method most applied in the literature.

From the methods listed in Table 1, FMSA and FMEMA are the closest to the needs for setting up an FDD process. The FMSA focuses on assessing the capacity to monitor failure modes but it does not structure information necessary to support the detection and diagnosis (Murad et al. 2020). As for the FMEMA, it aims to define specific indicators based on monitored parameters to establish a method for a health assessment (Xinlei et al., 2017).

Although there are different FMEA variations with their own particularities to study the potential failure modes of physical assets, none specifically prioritizes the structuring of the necessary information to support the setup of the FDD in organizations. Therefore, the proposed FMOA method associates the failure modes with three properties for detection and diagnosis that were not found together in previous methods.

Accordingly, discussing a novel method that correlates the identified potential failure modes with properties for FDD is relevant to the field of condition-based maintenance and the theme of this paper.

3. Proposed Method

This paper proposes a novel method to analyze the potential failure modes to support the fault detection and diagnosis process. It intends to systematically structure the expert knowledge regarding the physical assets' failure modes and properties for FDD.

For that, the Failure Mode and Observability Analysis (FMOA) includes two main sections:

Identification of the potential failure modes (I) and Correlation of the potential failure modes with properties for FDD (II). The proposed method is detailed and represented in Fig. 1.

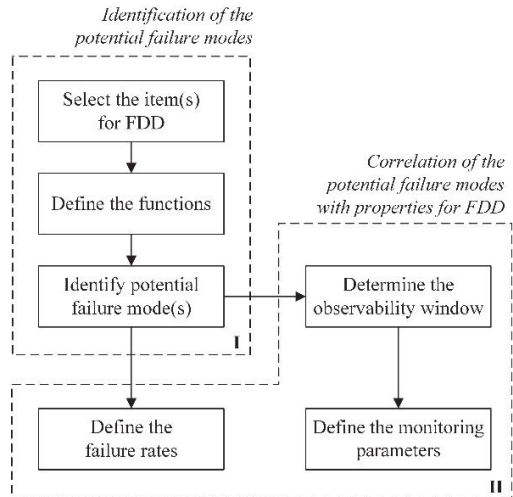


Fig. 1. The proposed FMOA method designed to support the fault detection and diagnosis process.

3.1. Identification of the potential failure modes

The proposed method starts by identifying the potential failure modes of the physical assets of interest for fault detection and diagnosis in the organization. For that, as shown in Fig 1, this section comprises a sequence of three activities.

First, the user needs to select the item(s) for FDD and, consequently, for the scope of the application of the FMOA method. It should be noted that the term “item” was used in its broadest sense to include different hierarchical levels such as systems, equipment, and component that this method may be applied to.

For the selected scope, the user needs to define the function(s) for each item. Then, from this set of functions, it is possible to identify and associate potential failure mode(s) for each one of them. It is worth mentioning that these three activities are similar to the traditional FMEA method for the analysis of failure modes.

3.2. Correlation of the potential failure modes with properties for FDD

Once the identification of potential failure modes is complete, the next section of the FMOA begins. For that, the user correlates each failure mode with properties of relevance for the FDD process, as presented in Fig. 1.

- (i) Failure rate: it represents the frequency at which failure modes are observed.
- (ii) Monitoring parameter: they represent the variables measured through sensors or inspection routes in which symptoms associated with failure modes are observed.
- (iii) Observability window: it represents an appropriate time frame for failure mode symptoms to be observed.

First, each failure mode shall be associated with its failure rate. Component failure data, such as failure rate, can be identified by analyzing historical data for each Failure Mode (FM)

(Melani et al. 2021). The failure rate information is of importance for calculating the reliability of each item as well as for some diagnosis approaches such as Bayesian Networks.

Next, the identified failure modes shall be correlated with their observability window and monitored parameters. In other words, both tasks intend to establish the observability of the failure modes based on the correlation of their symptoms with the respective monitoring parameters and the time window required to observe the symptoms' progression.

It is worth mentioning that the window size is directly related to the observability of the FM symptoms and the way they are reflected in the monitored parameters. Accordingly, the window size will be directly proportional to the time it takes for the FM symptoms to be observable since the fault is present in the system (Melani et al. 2021).

Finally, the information compiled throughout the tasks of the FMOA application can be organized as proposed in Table 2.

Table 2. Example of the FMOA layout

Item	Function	Potential Failure Modes	Failure rate (h^{-1})	Observability Window	Monitoring parameters
Component 1	Function of component 1	Failure Mode A	λ_A	180 h	Flow
		Failure Mode B	λ_B	480 h	Pressure
Component 2	Function of component 2	Failure Mode C	λ_C	24 h	Flow Temperature

4. Case Study

In this paper, the proposed method is demonstrated through a case study based on a Brazilian Hydroelectric Power Plant (HPP) composed of four Kaplan turbine generating units with a total installed capacity of around 200 MW. This plant has been undergoing several studies for asset management improvements.

The scope of the FMOA application was limited to some of the critical physical assets of major interest in the organization's fault detection and diagnosis process. The criticality analysis of the physical asset portfolio was previously developed for this HPP and supported this task (da Silva et al. 2019).

Thus, the case study started with the "Identification of the potential failure modes"

section of the FMOA. Six equipment of one generating unit were selected in the first task of the method: the turbine shaft, the heat exchanger of the Turbine Guide Bearing (TGB), the stator, the generator shaft, the heat exchanger of the Generator Combined Bearing (GCB), and the generator's radiators.

Once the items of the application were selected, the functions and potential failure modes for each of these items were defined. Then, each identified failure mode was correlated with its failure rate, observability window, and monitoring parameters. The FMOA application is represented as follows in Table 3.

Table 3. FMOA for the main items of the HPP

Item	Function	Potential Failure Modes	Failure rate (h ⁻¹)	Observability Window	Monitoring parameters
Turbine shaft	Provide rotation for electricity generation	Excessive vibration	8.69E-06	360 h	Vibration RMS 1
					Vibration RMS 2
					Temperature bearing 1
					Temperature oil 1
Heat exchanger (TGB)	Cooldown the lubricating oil	Low water flow (internal clogging)	3.38E-06	240 h	Temperature oil 2
					Temperature water 1
		Water leak (external)	7.97E-06	240 h	Temperature oil 2
					Temperature water 1
		Low oil flow (internal clogging)	3.38E-06	240 h	Vibration RMS 1
					Vibration RMS 2
		Oil leak (external)	7.97E-06	240 h	Temperature water 1
					Vibration RMS 1
Stator	Conduct magnetic flux for power generation	Premature degradation of copper insulation	3.92E-06	360 h	Vibration RMS 2
					Temperature copper 1
					Temperature copper 2
					Temperature copper 3
					Temperature copper 4
					Temperature iron 1
					Temperature iron 2
					Temperature iron 3
					Temperature iron 4
					Vibration RMS 3
Generator shaft	Provide rotation for electricity generation	Excessive vibration	3.92E-06	360 h	Vibration RMS 4
					Temperature bearing 2
					Temperature oil 3
					Temperature oil 4
Heat exchanger (GCB)	Cooldown the lubricating oil	Low water flow (internal clogging)	3.38E-06	240 h	Temperature water 2
					Temperature oil 4
		Water leak (external)	7.97E-06	240 h	Temperature water 2
					Vibration RMS 3
		Low oil flow (internal clogging)	3.38E-06	240 h	Vibration RMS 4
					Temperature water 2
		Oil leak (external)	7.97E-06	240 h	Vibration RMS 3
					Vibration RMS 4
Radiators	Cooldown the generator air	Low water flow (internal clogging)	3.38E-06	360 h	Temperature air 1
					Temperature air 2
					Temperature water 3
		Water leak (external)	7.97E-06	360 h	Temperature air 1
					Temperature air 2
					Temperature water 3

As can be seen in Table 3, one item is expected to have more than one potential failure mode. Consequently, each failure mode may have its properties for FDD, represented in the last three columns “Failure rate (h^{-1})”, “Observability window”, and “Monitoring parameters”. For instance, in the heat exchangers case, four failure modes were identified that had different failure rates and different monitoring parameters.

Regarding the observability windows, it is worth mentioning that they are related to the degradation of the associated failure mode. Then, the slower the degradation trend, i.e., the lower the system degradation rate, the wider the window must be. In contrast, for FMs with a high degradation rate, i.e., when the FM symptoms are promptly observed, the narrower the window (Melani et al. 2021).

The higher the need of monitoring the condition of physical assets in the organization the higher the support provided for the FMOA. As the proposed method identifies and correlates the potential failure modes with their failure rates, monitoring parameters, and observability windows, this analysis is fundamental to setting up the FDD process.

Finally, these relationships between FM and properties for FDD as a result of the FMOA application contribute to the structure of the knowledge base regarding the selected physical assets. From the FMOA, the user can choose the appropriate detection and diagnosis method that will use this organized information as input. Besides, the failure rates and observability windows can also be used as criteria for FM prioritization.

5. Conclusions

In face of the increased pressure for better performance of the physical assets, maintenance management is more dependent on appropriate failure prevention. Despite the relevance of the FDD process within the condition-based maintenance, organizations still may struggle to implement them due to the lack of supporting tools.

Therefore, the present work presented the FMOA method for fault detection and diagnosis implementation in organizations. It intended to examine the potential failure modes of selected systems and correlate them with properties for

FDD. For that, a two-section method was developed and demonstrated based on the context of a hydropower plant through a case study.

As a result, the proposed method can systematically structure the expert knowledge of selected systems, equipment, and components for the implementation of fault detection and diagnosis in organizations. It is recommended to use the proposed FMOA method during the setup of the FDD process in a condition-based maintenance strategy. Its results contribute to the organizations as it organizes the knowledge base about the items while correlating the potential failure modes with properties of FDD.

Although the case study considered the main critical equipment of one generating unit of the hydroelectric power plant, the proposed method is generic and can be replicated in other industries. Since the FMOA is an FMEA-based method, it has similar broad applicability to the FMEA.

It is noteworthy that some circumstances can lead to barriers to the success of the FMOA application. For instance, the user needs to access historical failure data to correlate the failure rates of the selected items. However, depending on the organization, this data by failure mode may not be available or incomplete. In this case, it is recommended the user consult data handbooks to support this task.

Regarding the observability windows and the monitoring parameters, the FMOA depends on the expert knowledge of the professionals. The correlation of the identified potential failure modes with their failure development periods and their observability windows is not a trivial task. The lack of knowledge about the physical assets and their failure modes also can be limited the benefits of the proposed FMOA.

Finally, the proposed method and results of this paper are expected to contribute to the physical asset management research and maintenance professionals as the proposed method can support the implementation of a condition-based maintenance strategy.

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References

- Abi, A., M. T. Khan, and J. Iqbal (2021). A review on fault detection and diagnosis techniques: basis and beyond. *Artificial Intelligence Review* 54, 3639-3664.
- Alauddin, M., F. Khan, S. Imtiaz, and S. Ahmed (2018). A bibliometric review and analysis of data-driven fault detection and diagnosis methods for process systems. *Industrial & Engineering Chemistry Research* 57 (32), 10719-10735.
- da Silva, R. F., A. H. A. Melani, M. A. C. Michalski, G. F. M. de Souza, and S. I. Nabeta (2019). Defining maintenance significant items based on ISO 55000 and AHP: A hydropower plant case study. *Proceedings of 29th European Safety and Reliability Conference*, 3437-3445.
- de Souza, G. F. M., A. C. Netto, A. H. A. Melani, M. A. C. Michalski, and da Silva, R. F. (2021). *Reliability Analysis and Asset Management of Engineering Systems*, Elsevier.
- Huang, J., J. X. You, H. C. Liu, and M. S. Song (2020). Failure mode and effects analysis improvement: A systematic literature review and future research agenda. *Reliability Engineering and System Safety* 199, 106885.
- Jardine, A. K. S., D. Lin, D. Banjevic (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing* 20 (7), p. 1483-1510.
- Melani, A. H. A., M. A. C. Michalski, R. F. da Silva, and G. F. M. de Souza (2021). A framework to automate fault detection and diagnosis based on Moving Window Principal Component Analysis and Bayesian network. *Reliability Engineering and System Safety* 215, 107837.
- Murad, C. A., A. H. A. Melani, M. A. C. Michalski, A. C. Neto, G. F. M. de Souza, and S. I. Nabeta (2020). Fuzzy-FMSA: evaluating fault monitoring and detection strategies based on Failure Mode and Symptom Analysis and Fuzzy Logic. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering* 6, 031001-1.
- Peng, Y., M. Dong, and M. J. Zuo (2010). Current status of machine prognostics in condition-based maintenance: a review. *International Journal of Advanced Manufacturing Technology* 50 (1-4), 297-313.
- Saufi, S. R., Z. A. B. Ahmad, M. S. Leong, and M. H. Lim (2019). Challenges and opportunities of deep learning models for machinery fault detection and diagnosis: a review. *IEEE Access* 7, 2169-3536.
- Spreafico, C., D. Russo and C. Rizzi (2017). A state-of-the-art review of FMEA/FMECA including patents. *Computer Science Review* 25, p. 19-28.
- Xinlei, G., Z. Hongfu, S. Jianzhong, X. Juan, and W. Hong (2017). Civil aircraft engine start system health monitoring method based on QAR Data. *International Conference on Sensing, Diagnostic, Prognostic, and Control*, p.168-173.