Research on Product Failure Prediction Based on TRIZ Theory

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Abstract. Failure prediction at the product design stage can improve product quality and reduce input costs. Many existing failure analysis methods were susceptible to staff brainstorming during failure excavation, resulting in distortion of results. To overcome the shortcomings of the existing failure analysis methods, according to the interaction characteristics of substance attributes from the functional perspective of TRIZ theory, and drawing on the analysis process of anticipatory failure determination (AFD) method, a general model which was suitable for mechanical products and can effectively determine the potential failure modes and causes of components was established. The feasibility of the model was verified by the example of the fixed-bed gas-gas heat exchanger.

1. Introduction

In today's society, enterprises have paid much attention to enhancing the competitiveness of the industry by improving the quality of product design [1]. Therefore, the failure prediction of the product in the design stage and the determination of the potential failure of the system is a crucial step, which can effectively ensure the quality of products put into the market.

Mechanical system failures are characterized by multiple occurrences, randomness, multiple causes and integration [2]. In recent years, many failure analysis methods have been applied to engineering practice. Stravitz et al. [3] introduced failure mode and effect analysis, taking component or system as the research object, discussing through experts and finally presenting potential failures in the form of a table. Mateusz et al. [4] used event tree analysis to express the internal causality through an intuitive tree diagram and reasoned about the potential failure modes of the system based on the graph. Yang et al. [5] used fault tree analysis to express the internal causality through an inverted tree diagram and to infer various causes of faults by failure modes. Liu et al. [6] used analogy design method to analyze the target problem of similar system by using the existing system problems. Su [7] used "5W1H" method to find deep problem areas. Qin [8] used the 5Why analysis method to dig out the reasons of different levels by constantly asking "why". Chen et al. [9] put forward the application of fishbone diagram method to find out the causes of the problem from five aspects: human, machine, material, method and environment. Yan et al. [10] formed the analysis process through the integration of triaxial analysis and functional model.
Czinki et al. [11] used the Cynefin framework to analyze the system problems, divided different problem domains and used TRIZ to solve them. The above methods can effectively identify the potential failure modes and causes, but it is difficult to get rid of the influence of staff inertial thinking, which belongs to the enumeration based on experience. To overcome the shortcomings of the influence of thinking inertia, Boris Zlotin proposed the AFD method, which uses reverse thinking to reverse the ideal state and excavates the potential failure in the technical system. Li et al. [12] applied AFD method to analyze umbrella patent portfolio and determine the failure of the system. He et al. [13] applied the AFD method to analyze the stereo garage and screened out the important failure modes. This method allows the staff's thinking to be unrestricted and excavates deeper failures. However, the method of reversing the ideal state of the technical system lacks a specific process model, the results are incomplete.

According to the interaction characteristics of substance attributes from the functional perspective of TRIZ theory, and drawing on the process of AFD, a general model which is suitable for mechanical products and can effectively determine the potential failure modes and causes of components is established, forms a failure prediction method based on function-attribute analysis, and elaborates the application process of the method.

2. Function analysis based on component units

2.1. Component units

A component is the basic unit of the technical system, the interaction relationship between components is the main constituent element of component functions, and two interacting components constitute a component unit [1]. Zhang et al. [14] proposed that the interaction of two components is the result of their attribute interaction, this interaction changes or maintains the attribute of one of the components, which will produce useful or adverse functions. As shown in figure 1, S1 and S2 constitute a component unit; A1 and A2 are the respective attributes. After A1 and A2 interact, a useful or adverse function is generated.

![Figure 1. The function of a component unit.](image)

Component unit analysis needs to be established on the basis of the function model. Through the function analysis, determine the relationship of each component unit, establish the function model, determine the main function, basic function and auxiliary function of the system, thinking about the structure of mechanical products is transformed into thinking about functions, thus not to be bound by the existing structure and constitute new design ideas, as shown in Figure 2[15-16].

![Figure 2. Classification of functions.](image)

2.2. Substance attributes
Attributes are the inevitable, essential, and inseparable nature of a substance that clearly distinguishes other substances; it is the basic concept defining various kinds of substances and the basic element to realize the function. That is, attributes are directly related to function [17]. There is a mapping relationship between components and attributes, which can be represented by "one-to-many" or "many-to-one".

The attributes of a component are diversified, which can be roughly divided into self-attributes and functional attributes. Among them, functional attributes are very important for functional analysis and are expressed by "verb + attribute word ".

For a technical system, accurately determining the attributes of a component is an important step. The attribute search algorithm is shown in figure 3.

Figure 3. Attribute search algorithm.

The attribute search algorithm steps are as follows:
1. Determine each component unit of the technical system based on functional analysis.
2. Determine the attribute type of each component unit.
3. Initially determine the component's self-attributes through working principles, process requirements, etc.
4. When the component is the action object, analyze which parameter of the action object is changed or maintained when each component unit implements the function, so as to determine the corresponding attribute.
5. When the component is the function carrier, the functional attributes of the function carrier are determined by the functions implemented of the component unit and the attributes of the action object in step 4 and supplement the attributes of the action object.
6. At the end of attribute acquisition, the attributes of each component are integrated.

3. Anticipatory failure determination (AFD)
Algorithm for inventive problem solving (ARIZ) [18] is a tool in TRIZ theory, which mainly emphasizes the ideal final result and conflicts, and solving invention problems, the AFD method is developed on the basis of ARIZ. This article mainly studies the analysis method to determine the failure mode, so the specific steps of the first stage of AFD are shown in Figure 4 [19].
Determine the ideal state of the system and reverse it

Finding ways to make the system to reverse the ideal stage

Application system available resources analysis to determine whether each hypothetical method is possible

According to the possible hypothetical method, get the potential failure modes and causes of the system

Figure 4. Flow chart of the first phase of the AFD.

Using the AFD method to determine the ideal state of the system is to determine the main function of the system, the realization of the main function of the system is the ideal state achieved by the system. Using the reverse thinking method to reverse the ideal state can make the designer become a destroyer, and solving the problem becomes an invention problem, which effectively overcomes the designer's thinking inertia, the designer found the method to produce the failure, and then understood the mechanism and reason of the failure.

AFD method overcomes the shortcomings of traditional failure analysis methods and digs out deeper failures. However, the method of reversing the ideal state lacks a specific process model, which results in the lack of accuracy and convergence of the results. This paper makes further research in this aspect.

4. Research on failure modes prediction based on the interaction of substance attributes

4.1. Construction of failure prediction model based on the interaction of substance attributes from the functional perspective

The function of the technical system is the result of attribute interaction between components. When there are inadequate, excessive or harmful functions, the enterprise will take effective measures to eliminate the adverse functions. In the process of improvement, it is actually to change the original attributes of components or introduce new substances to eliminate it. Reverse thinking is to turn the useful functions among components into adverse functions. Therefore, the essence of predicting the potential failure based on the interaction of substance attributes from the functional perspective is to find a scheme to destroy the useful functions, the result of the scheme is the failure mode, and the two interaction components are the failure reason.

As shown in figure 5, when the attributes of the component S1 and S2 interact to generate the adverse function, changing the attribute of the S1 or the attribute of the S2 or both attributes can eliminate the adverse function. The reverse analysis is to reverse the model of figure 5; the useful function generates adverse function by changing the attributes of components, as shown in figure 6.

Figure 5. Functional transformation model.  Figure 6. Functional reverse transformation model.
Based on the above principle analysis, get the five general models for predicting product failure, as shown in Table 1.

**Table 1.** The general model of product failure prediction.

| General model | Word description |
|---------------|-----------------|
| **Model 1**   | Find the component S<sub>1</sub> in the system or super system, so that the interaction between S<sub>1</sub> and S<sub>2</sub> will produce adverse function F<sub>h</sub> |
| **Model 2**   | Change the attribute of S<sub>1</sub> or the attribute of S<sub>2</sub> or both attributes to produce adverse function F<sub>h</sub> |
| **Model 3**   | Find the component S<sub>3</sub> in the system or super system, the attribute A<sub>3</sub> of S<sub>3</sub> affect S<sub>1</sub>, which causes S<sub>1</sub> to generate new attribute B<sub>1</sub>, and the interaction between S<sub>1</sub> and S<sub>2</sub> produces adverse function F<sub>h</sub> |
| **Model 4**   | Find the component S<sub>4</sub> in the system or super system, the attribute A<sub>4</sub> of S<sub>4</sub> affect S<sub>2</sub>, which causes S<sub>2</sub> to generate new attribute B<sub>2</sub>, and the interaction between S<sub>1</sub> and S<sub>2</sub> produces adverse function F<sub>h</sub> |
| **Model 5**   | Find the component S<sub>3</sub> in the system or super system. When S<sub>1</sub> and S<sub>3</sub> interact or S<sub>2</sub> and S<sub>3</sub> interact, the third substance S<sub>4</sub> and the attribute A<sub>4</sub> are excited. And then S<sub>4</sub> and S<sub>2</sub> interact or S<sub>4</sub> and S<sub>1</sub> interact produces adverse function F<sub>h</sub> |

This general model is a transformation of a basic function, the system generally has multiple basic functions, and each basic function needs to be analyzed using this general model to determine potential...
failures. When using the general model, first determine the attributes of each component through the attribute search algorithm, and then find the other components $S_i (i = 1, 2 \ldots n-1)$ that directly interact with $S_1$ and $S_2$ respectively according to the functional model, and finally, the component $S_i$ and corresponding attributes are brought in for solution.

4.2. The application process of product failure prediction based on the interaction of substance attributes from the functional perspective

Through the above analysis, the application process of product failure prediction is established. The application process is divided into two stages: determining the potential failure modes and causes stage and design improvement stage. This paper mainly introduces the first stage of the application process, as shown in figure 7.

![Figure 7. Flow chart of the first stage of product failure prediction.](image)

The first stage of the application process of product failure prediction is as follows:
(1) Determine the ideal state of the system and reverse it.
(2) Perform the functional analysis of the system, establish the functional model, and determine the component units that the system uses to implement basic functions.
(3) Establish the component attribute list according to the attribute search algorithm.
(4) Apply the general model of product failure prediction and attribute list to get the scheme of system failure.
(5) Determine potential failure modes and causes of the system.

Five kinds of general models guide how to destroy from five different perspectives, making the prediction process simpler, the prediction results more comprehensive and accurate, providing the right direction for the follow-up research.

5. Case study—fixed bed gas-gas heat exchanger
5.1. Design background of fixed bed gas-gas heat exchanger

A fixed bed gas-gas heat exchanger is a kind of equipment used for heat exchange of high and low-temperature gas in a chemical enterprise, referred to as heat exchanger. The structure diagram of the heat exchanger is shown in figure 8. 1 and 5 are the inlet and outlet of high-temperature gases (chlorosilane, hydrogen, a small amount of silicon powder), 2 and 6 are the inlet and outlet of low-temperature gases (silicon tetrachloride, hydrogen), 3 is the shell, 4 is the baffle, 7 is the heat exchange tube, 8 is the expansion joint, 9 is the tube sheet. Using the first stage application process of product failure prediction to analyze the potential failure modes and causes of the heat exchanger, the feasibility of the application process is demonstrated.

![Figure 8](image)

**Figure 8.** Structure diagram of the heat exchanger.

5.2. Failure analysis

(1) Determine the ideal state of the system. The ideal state of the heat exchanger is that the high and low-temperature gases exchange heat for a long time. Reverse the ideal state, that is, the heat exchanger often fails, and high and low-temperature gases cannot exchange heat efficiently.

(2) The functional model of the heat exchanger is established through functional analysis, as shown in figure 9. According to the function model, the core basic function of the heat exchanger is to heat the low-temperature gases by the heat exchange tubes.

![Figure 9](image)

**Figure 9.** Functional model of the heat exchange.

(3) Solve the component attributes according to the attribute search algorithm, and establish the attribute list of related components, as shown in table 2.
Table 2. Component attribute list.

| Component          | Attribute 1 | Attribute 2     | Attribute 3 | Attribute 4    | Attribute 5                  | Attribute 6 |
|--------------------|-------------|-----------------|-------------|----------------|------------------------------|-------------|
| Heat exchange tubes| Metallicity | Localizability  | Weldability | Heat transfer attributes | Thermal resistance attributes | Imbalance   |
| Baffles            | Metallicity | Destruction-resistant attributes | Weldability | Controllability | Porosity | Localizability |
| Tube sheets        | Metallicity | Destruction-resistant attributes | Weldability | Localizability | Imbalance |
| Low-temperature gases | Fluidity | Corrosion attributes | Impact properties | Permeability | Pausibility | Internal energy |
| High-temperature gases | Fluidity | Impact properties | Directionality | Internal energy |

It can be seen from the attribute list that the interaction between the thermal conductivity of the heat exchange tubes and the fluidity of the low-temperature gases produces the heating function, and the functions of the two are shown in figure 10.

Figure 10. The function of heat exchange tube and low-temperature gas.

Table 3. Solution model and failure description.

| Model | Solution model                          | Failure description                                                                                                                                 |
|-------|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1     | Corrosion of heat exchange tubes        | The diameter of the baffles is slightly larger than the diameter of the heat exchange tubes, and there is a small gap between them. The low-temperature gases impact the gaps, causing erosion wear and corrosion on the surface of the heat exchange tubes and the baffles |
|       | Porosity                                |                                                                                                                                                    |
|       | Impact properties                       |                                                                                                                                                    |
|       | Baffles                                 |                                                                                                                                                    |
|       | Low-temperature gases                   |                                                                                                                                                    |
| 2     | Vibration of heat exchange tubes        | To enhance heat transfer and prevent scaling, the flow velocity of the low-temperature gases is increased. The impact of the low-temperature gases induces mutual vibration between the heat exchange tubes, eventually causes the heat exchange tubes to be damaged |
|       | Localizability                          |                                                                                                                                                    |
|       | Impact properties                       |                                                                                                                                                    |
During the flow of low-temperature gases, hydrogen atoms penetrate the interior of the heat exchange tubes, react with the carbons in the metal to generate methane, decarburize the steel, crack the heat transfer tubes, causing hydrogen corrosion.

There is a large temperature difference locally in the heat exchange tubes, which generates large thermal stress, and stress corrosion with the chloride ions of low-temperature gases, which causes the heat exchange tube to crack.

When high-temperature gases flow in the heat exchange tubes for a long time, certain impurities adhere to the inner wall of the heat exchange tubes, which reduces the heat transfer capacity of the heat exchange tubes, and contact with low-temperature gases reduces the heat exchange capacity.

When the low-temperature gases flow in a detour through the baffles, there is a flow dead zone and the heat exchange capacity is reduced.

The gaps between the heat exchange tubes and the tube sheets are generated due to insufficient expanded and welded tube joint, and the chlorine ions in the low-temperature gases enter into the tube sheets to produce crevice corrosion, and even the tube sheets crack under the action of thermal stress and residual stress.
The thickness of the baffles is relatively thin, and the low-temperature gases will have a large impact on the baffles, causing the baffles to vibrate, and the contact with the heat exchange tubes will cause large contact stress, which will eventually cause the heat exchange tubes to crack radially.

(5) Determine the potential failure modes and causes of the heat exchanger, as shown in table 4.

**Table 4. Failure modes and causes.**

| Failure modes                      | Failure causes                                                                 |
|-----------------------------------|--------------------------------------------------------------------------------|
| Corrosion damage                  | The low-temperature gases impact the gaps between the baffles and the heat exchange tubes  
|                                   | Chlorine ions in low-temperature gases interact with heat exchange tubes in the thermal stress zone  
|                                   | Heat exchange tubes and tube sheets have gaps due to insufficient expanded and welded tube joint, and chlorine ions enter the gap  |
| Vibration damage                  | Vibration between heat exchange tubes induced by the impact of low-temperature gases  
|                                   | The impact of low-temperature gases causes large contact stress at the contact between the heat exchange tubes and the baffles  |
| The decline of heat exchange capacity | Impurities of high-temperature gases adhere to the inner wall of the heat exchange tubes  
|                                   | Baffles hinder low-temperature gases, and there are the flow dead zones  |

6. Conclusions
Aiming at the shortcomings of the AFD, a general failure prediction model based on function-attribute analysis was established. Used this model to destroy the useful functions of the two core components in the system, got the possible adverse functions according to the interaction of component attributes, and determined the potential failure modes and causes of the system. Finally, the feasibility of this method was verified by the case of the heat exchanger. This method makes the failure mode prediction have better accuracy and convergence, provides the correct direction for the follow-up research.

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