IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 20, 2018, accepted December 12, 2018, date of publication December 20, 2018, date of current version January 11, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2888542

A More Reasonable Definition of Failure Mode for Mechanical Systems Using Meta-Action

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This work was supported in part by the National Natural Science Foundation of China under Grant 51705048 and Grant 51835001, and in part by the National Major Scientific and Technological Special Project for High-grade CNC and Basic Manufacturing Equipment of China under Grant 2016ZX04004-005 and Grant 2018ZX04032-001.

ABSTRACT Identification of failure modes is a vital work in the process of failure mode and effect analysis (FMEA). Since the traditional failure mode is defined as a specific function failure or a part failure, there are uncountable failure modes for mechanical products. Then, it is too hard to list or predict all of the potential failure modes when we do FMEA on a machine. Besides, the same failure can be defined as a failure mode or a failure cause casually, which makes the analysis work stuck. To solve these problems, we propose a meta-action failure mode in this paper. A machine is decomposed into meta-action units based on the meta-action concept, and the abnormal motion performance of the unit is defined as the meta-action failure mode. All the potential failure modes of meta-actions and the expressions are given in theory. To verify the practicality and advantages of the proposed method, an illustrative example is provided. The results show that the meta-action failure mode can overcome these problems in traditional failure modes and simplify the FMEA process.

INDEX TERMS Failure mode and effect analysis (FMEA), reliability analysis, motion failure, meta-action, mechanical product.

I. INTRODUCTION

A failure mode is defined as the phenomenon of function failure of systems or components [1]–[4]. Finding out all possible failure modes of the analysis object is a major task of failure mode and effect analysis (FMEA) in reliability design. Nowadays, there are much more researches of failure modes on electronic systems than those on mechanical systems. Since the electronic component has a single function, its failure mode is limited and fixed, and it has accumulated plenty of basic data already and established many specifications and standards [5]. However, a mechanical part always owns various functions, and the combination of parts is very complicated, which makes the failure modes of the mechanical system unfixed and numerous [6]. For the mechanical system failure mode, there is seldom a specification.

The effect of FMEA has a close link to the integrity of the listed failure modes, and it will reduce deeply if there are some of the failure modes are missed. As a result, there is possibly no emergency plan ready once an unexpected failure happens during the machine operation. Furthermore, it is even fatal for some important equipment, such as a nuclear machine or an aerospace machine. Since the classification of traditional failure modes lacks of hierarchy and systematicness, some potential failure modes of machines are often omitted in FMEA. Stone *et al.* [7], Stone and Wood [8], and Hirtz *et al.* [9] pointed out it should find out all the function failures according to the function levels of machines. McNelles *et al.* [10] classified system failures by following the structure hierarchy of machines, and assigned the failure modes which own the similar effect and detection to the same group. Based on the function levels of equipment, O'Halloran *et al.* [11] classified the failure mechanisms into three levels and described failures by using the original environment, failure mechanism, etc. Saxena *et al.* [12] proposed an encoding method for failure modes by the components and functions of equipment, which saves plenty of effort for the determination of failure modes.

Failure modes of mechanical systems are various, and the different combinations of failure mechanisms and loads form different failure modes. For different products, the failure modes are possibly different even if they bear the similar load under the same failure mechanism [13]. A classification of failure modes can contribute to the unified analysis and control of failures. Besides, it can also reduce the workload and simplify the process of failure analysis. According to the different effects of failures, Ford Motor Company [14] divided failure into degraded function failure, no function failure, partial function failure, intermittent function failure and unintended function failures. Zhu *et al.* [15] sorted failure into soft failure and hard failure, where the latter causes loss of equipment functions while the former only results in a performance decline. Avizienis *et al.* [16] classified failure from eight aspects, such as the phase of occurrence, system boundaries, and so on. Blischke and Murthy [17] divided failure into intermittent failure and persistence failure, and the latter is subdivided into partial failure and complete failure further. Möhrle *et al.* [18] classified failure as input failure and output failure on the basis of the fault tree. Meanwhile, the two types are both divided into provision failure, content failure and timing failure. Powell [19] defined failure from single-user services and multiple-user services and developed the mathematical models for various types of failure. Collins [20] classified mechanical failure by the failure manifestation, failure agents and failure locations. Uder *et al*. [21] extended Collins' method to the electronic field, and described 43 mechanical failure modes and 38 electronic failure modes in total. According to the difference attributes of failure, there are ten kinds of failure sorted by Moohialdin and Hadidi [22], such as mechanical failure, electrical failure and raw material rejection, etc. Guo [23] divided the common failure of Computer Numerical Control (CNC) machine into eight types, such as damage failure, action failure, and technology failure, *et al.* Similarly, Chen [24] divided the failure of CNC machines into seven types, which include damage failure, function failure and loose failure, *et al.* Each type of them can be subdivided into several items further, and there are 107 failure modes in total.

The classification of failure modes were studied by the methods mentioned above. However, these methods do not distinguish the failure modes and the failure causes strictly. For the FMEA work of mechanical systems, it is needed to find out all the potential failure modes, causes and effects of all levels top-down according to the construction of machines [25]–[27]. Since a current failure mode can be not only the failure cause of the upper level but also the failure effect of the lower level, there is much repetitive work in the reliability analysis [11]. Because there is no strict demarcation between failure modes and failure causes, they can always convert to each other. As a result, it is hard to know how to do the FMEA due to the confusion between failure modes and failure causes when a failure occurs.

To solve these problems, we propose meta-action failure modes in this paper. The parts which achieve a single minimal action are defined as a meta-action unit in the mechanical system. Each unit is treated as a black box, and then a machine can be regarded as the composition of numbers of black boxes. When there is an abnormality in the black box output, a meta-action fails. The specific motion abnormal form is the meta-action failure mode, and the factors which lead to the abnormality are the meta-action failure causes. To verify the advantages of the meta-action failure modes, an example of CNC machine common failures is adopted, and the proposed failure modes are compared with traditional failure modes.

II. META-ACTION CONCEPTS

The concept of meta-action is proposed by Zhang *et al.* [28], Li *et al.* [29], and Yan *et al.* [30]. For the characteristic that movements and functions are performed by actions in the mechanical product, he defined the minimal action as a meta-action and the total of all the related parts of the action as a meta-action unit. In each meta-action units, there is an input part and an output part. An input part is what receives the power from the former meta-action or power source in a meta-action unit. An output part is the part which supplies the power to the latter meta-action or the actuating component. According to the different kinds of motions, there are two basic types of meta-actions in the mechanical product, rotation-meta-action and translation-meta-action. Fig. 1 shows the two typical meta-action units, a gear rotation-meta-action unit and a rack translation-meta-action unit.

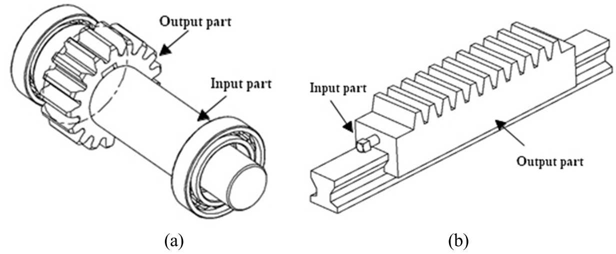

FIGURE 1. Two typical meta-action units. (a) Gear rotation-meta-action unit. (b) Rack translation-meta-action unit.

As the functions are performed by the way of "Actions-Movements-Functions", a machine can be decomposed into numbers of meta-actions and units. The whole meta-actions which perform a certain movement constitute a meta-action chain and several meta-action chains achieve the functions together, as shown in Fig. 2.

III. ANALYSIS OF META-ACTION OUTPUT PROPERTIES

Since a series of meta-actions perform a machine, that the machine is reliable means none of the meta-actions fail. Once the meta-action output cannot meet its requirement, the meta-action fails. Thus, it is necessary to analyze the output of meta-actions.

A. WORK PROCESS OF META-ACTIONS

Each type of meta-action is made up of several moveable parts and unmovable parts. Fig. 3 shows an example of the structures of two basic types of meta-action units, but there

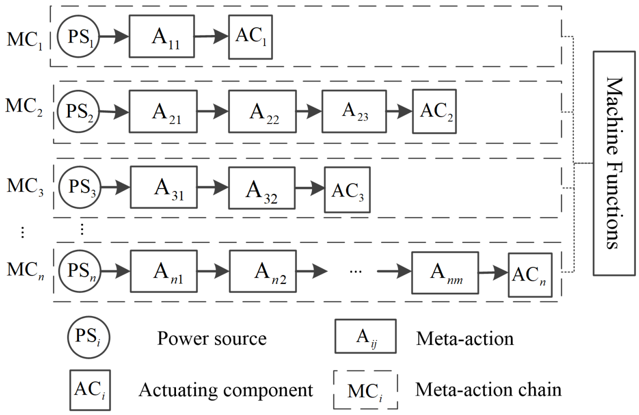

FIGURE 2. The meta-action composition of mechanical systems.

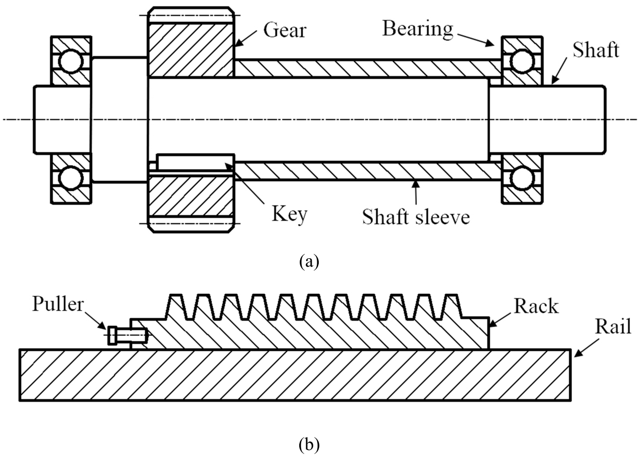

FIGURE 3. Example of the structures of two basic types of meta-action unit. (a) Gear rotation-meta-action unit. (b) Rack translation-meta-action unit.

still some parts which are supporting and unmovable are not showed in the figure, such as end covers, racks *et al.* As shown in Fig. 3(a), the gear rotation-meta-action unit is made up of one gear, one key, one shaft, one shaft sleeve and two bearings. For Fig. 3(a), when the gear rotation-meta-action works, the gear rotates around the axis which is driven by the rotational shaft via the key. Meanwhile, the gear drives its next meta-action to work. Since it provides the power for the next meta-action, the gear is the output part. For the rack translation-meta-action in Fig. 3(b), the puller drives the rack to reciprocate on the rail, and the rack is the output part of this meta-action.

For the reason that an output part provides power for a meta-action or an actuating component, the states of kinematic parameters of the output part show whether the meta-action is in good condition or not. However, the state of the output part depends on both of movable parts and unmovable parts in the meta-action. The moving parts affect the output directly as they transmit the power to the output part. For example, if the key or the shaft breaks in Fig. 3(a), the power transmission path is cut off and the gear is not able to work. For unmovable parts, their position or surface roughness changes will vary the stress of the output part, which causes the abnormal output of the meta-action. Thus, all these parts in a meta-action have influences on the output properties of output part, and then affect the performance of the next meta-action.

B. DYNAMIC MODELING OF META-ACTION

Let a mechanical system be made up of K movable rigid parts, and S_i be the mass center of part i, and m_i be the mass of part i, and J_{si} be the moment of inertia of part i about the mass center S_i, and ω_i and v_{si} be the angular velocity of part i and the velocity of the mass center S_i respectively. Assume that there is a non-conservative force F_i and a moment of force M_i acting on part i.

According to the principle of work and energy, the kinetic energy increment of system dE in time dt is equal to the resultant work dW of all the external forces in the same time interval. That is

$$\mathrm{d}E = \mathrm{d}W = N\mathrm{d}t, \tag{1}$$

where N is the instantaneous power of all the external forces.

Plugging all the parameters of the mechanical system into (1), the correlations between them can be expressed as

$$\frac{1}{2}\mathrm{d}\left(\sum_{i=1}^{K} J_{Si}\omega_i^2 + \sum_{i=1}^{K} m_i v_{Si}^2\right) = \left(\sum_{i=1}^{K} \boldsymbol{M}_i \cdot \boldsymbol{\omega}_i + \sum_{i=1}^{K} \boldsymbol{F}_i \cdot \boldsymbol{v}_{Si}\right)\mathrm{d}t, \tag{2}$$

where $\boldsymbol{M}_i$, $\boldsymbol{\omega}_i$, $\boldsymbol{F}_i$ and $\boldsymbol{v}_{Si}$ are the vectors.

For planar motion mechanisms, $\boldsymbol{M}_i \cdot \boldsymbol{\omega}_i = \pm M_i \cdot \omega_i$, the sign here is plus when the directions of $\boldsymbol{M}_i$ and $\boldsymbol{\omega}_i$ are the same, otherwise, it is minus. $\boldsymbol{F}_i \cdot \boldsymbol{v}_{Si} = F_i v_{Si} \cos\alpha_i$, where α_i is the angle between $\boldsymbol{F}_i$ and $\boldsymbol{v}_{Si}$. Therefore, (2) can be written as

$$\frac{1}{2}\mathrm{d}\left(\sum_{i=1}^{K} J_{Si}\omega_i^2 + \sum_{i=1}^{K} m_i v_{Si}^2\right) = \left(\pm\sum_{i=1}^{K} M_i\omega_i + \sum_{i=1}^{K} F_i v_{Si}\cos\alpha_i\right)\mathrm{d}t \tag{3}$$

Now, we treat a meta-action unit as a miniature mechanical system. Assume that all the parts of meta-actions are rigid. As a meta-action is the minimal motion in the mechanical system, it can be regarded as a single freedom mechanism, where the rotation meta-action is the fixed-axis rotation mechanism and the translation meta-action is the rectilinear motion mechanism. Therefore, the two basic types of meta-actions can be simplified to the two equivalent dynamic models, as Fig. 4 shows.

Let ω be the angular velocity of the equivalent part of rotation-meta-action and φ be the rotation angle, and J_e be the equivalent moment of inertia, and M_e be the equivalent moment. For translation-meta-action, let v be the velocity of the equivalent part and s be the displacement, m_e and F_e be the equivalent mass and the equivalent force respectively.

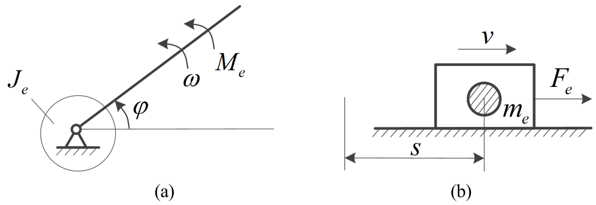

FIGURE 4. Equivalent dynamic models of two basic types of meta-actions. (a) Rotation-meta-action. (b) Translation-meta-action.

Considering that an equivalent part used to be the part which does a fixed-axis rotation or a rectilinear motion [31], the output part is selected as the equivalent part in a meta-action. Therefore, for rotation-meta-action as Fig. 4(a), ω is the angular velocity of the output part, and (3) can be rewritten as

$$\frac{1}{2}\mathrm{d}\left\{\left[\sum_{i=1}^{K} J_{Si}(\frac{\omega_i}{\omega})^2+\sum_{i=1}^{K} m_i(\frac{v_{Si}}{\omega})^2\right]\omega^2\right\} = \left[\pm\sum_{i=1}^{K} M_i(\frac{\omega_i}{\omega})+\sum_{i=1}^{K} F_i(\frac{v_{Si}}{\omega})\cos\alpha_i\right]\omega\mathrm{d}t. \quad (4)$$

Assume that

$$\left.\begin{aligned} J_e &= \sum_{i=1}^{K} J_{Si}(\frac{\omega_i}{\omega})^2+\sum_{i=1}^{K} m_i(\frac{v_{Si}}{\omega})^2 \\ M_e &= \pm\sum_{i=1}^{K} M_i(\frac{\omega_i}{\omega})+\sum_{i=1}^{K} F_i(\frac{v_{Si}}{\omega})\cos\alpha_i \end{aligned}\right\}, \quad (5)$$

the kinetics equation of rotation-meta-action, (4), can be expressed by

$$\mathrm{d}(\frac{1}{2}J_e\omega^2) = M_e\omega\mathrm{d}t, \quad (6)$$

and it can be rewritten as (7) when use the differential operation in the both sides,

$$M_e = \frac{\mathrm{d}(\frac{1}{2}J_e\omega^2)}{\omega\mathrm{d}t} = J_e\frac{\mathrm{d}\omega}{\mathrm{d}t}+\frac{\omega}{2}\frac{\mathrm{d}J_e}{\mathrm{d}t}. \quad (7)$$

Similarly, for translation-meta-action as Fig. 4(b), v is the velocity of the output part, the kinetics equation of it can be expressed by

$$F_e = \frac{\mathrm{d}(\frac{1}{2}m_e v^2)}{v\mathrm{d}t} = m_e\frac{\mathrm{d}v}{\mathrm{d}t}+\frac{v}{2}\frac{\mathrm{d}m_e}{\mathrm{d}t}, \quad (8)$$

where

$$\left.\begin{aligned} m_e &= \sum_{i=1}^{K} J_{Si}(\frac{\omega_i}{v})^2+\sum_{i=1}^{K} m_i(\frac{v_{Si}}{v})^2 \\ F_e &= \pm\sum_{i=1}^{K} M_i(\frac{\omega_i}{v})+\sum_{i=1}^{K} F_i(\frac{v_{Si}}{v})\cos\alpha_i \end{aligned}\right\}. \quad (9)$$

Since the equivalent moment of inertia J_e and the equivalent mass m_e are constant in a meta-action, $\mathrm{d}J_e/\mathrm{d}t$ and $\mathrm{d}m_e/\mathrm{d}t$ are equal to zero. Besides, the transmission ratios in (5) and (9) are also unchangeable. Integrating time in (7) and (8), the kinematics parameters of meta-actions are expressed by

$$\left.\begin{aligned} \omega &= \omega_0+\int_{t_0}^{t_1}\frac{J_e}{M_e}\mathrm{d}t \\ \varphi &= \varphi_0+\int_{t_0}^{t_1}\omega\mathrm{d}t \end{aligned}\right\} \text{ or } \left.\begin{aligned} v &= v_0+\int_{t_0}^{t_1}\frac{F_e}{m_e}\mathrm{d}t \\ s &= s_0+\int_{t_0}^{t_1}v\mathrm{d}t \end{aligned}\right\}, \quad (10)$$

where ω_0 is the initial angle velocity of the output part in the rotation-meta-action, and φ_0 is the initial angle position; v_0 is the initial velocity of the output part in the translation-meta-action, and s_0 is the initial position.

IV. FAILURE MODES OF META-ACTION

A failure mode is the identity of a failure to be distinguished from others. It should be defined clear and easy to be diagnosed. However, the traditional failure mode is currently described as a superficial phenomenon of the function failure or an indiscoverable part failure, which causes inconvenience in the process of FMEA. For the functions of a machine are performed by actions, an action failure is obviously to be observed. Thus, we propose the meta-action failure mode.

Unlike traditional definitions, a meta-action failure is defined as the meta-action output cannot meet its requirements in this paper, and a meta-action failure mode is the specific failure performance of the meta-action in machines. As an output part is the only part which can affect the behavior of other meta-actions or actuating components directly, the performance of the output part shows the state of the meta-action. Therefore, if there is a meta-action failure, it means there is an abnormal on its output part, and the specific abnormal content of output is the meta-action failure mode.

Speed and displacement are the most basic parameters which can reflect the motion state of a moving part. From the relationship of work and energy in Section 3, we can know that ω or v indicates whether the output part or meta-action has adequate energy to perform this action and to provide the power for the next meta-action. Since φ or s shows the position of the output part, it has a direct effect on the precision of the machine. Once any of them exceeds they own limitation ranges, the meta-action fails.

Taking the example of the gear rotation-meta-action, assume that $[\omega]$ and $[\varphi]$ are the normal value ranges of the output, which indicates the meta-action is reliable when the output parameters belong to them. According to the different states of the two parameters, there are following situations:

$$\left.\begin{aligned} &\omega = 0 \\ &0 < \omega < [\omega]_{\min} \\ &\omega \in [\omega] \\ &\omega > [\omega]_{\max} \end{aligned}\right\} \text{ and } \left.\begin{aligned} &\varphi < [\varphi]_{\min} \\ &\varphi \in [\varphi] \\ &\varphi > [\varphi]_{\max} \end{aligned}\right\}, \quad (11)$$

where $[\omega]_{\min}$, $[\varphi]_{\min}$ are the lower limits of their value ranges, $[\omega]_{\max}$ and $[\varphi]_{\max}$ are the upper limits.

That the meta-action is reliable means that both of ω and φ are in their value ranges, which is expressed as

$$\{\omega \in [\omega]\} \cap \{\varphi \in [\varphi]\}. \tag{12}$$

Some singular-service work, like boring *et al.*, only require the output to satisfy the value requirement at once, so that it can obtain the adequate power and precision to achieve the mission. Therefore, for singular-service work, the two parameters can represent their states enough. However, for continuous or repetitive work, such as cutting, milling, *et al.*, their output of each missions need to be kept consistent as possible as they can, or there may be a consistency error. Thus, the fluctuation of the motion should be limited.

A speed fluctuation coefficient is used to describe the operation stability of a machine in mechanical engineering [31] which is expressed as

$$\delta = \frac{\omega_{\max} - \omega_{\min}}{\omega_{\mathrm{m}}}, \tag{13}$$

where $\omega_{\max}$ is the maximal angular speed, $\omega_{\min}$ is the minimal angular speed, ω_{m} is the average speed.

As ω_{m} is not easy to obtain, it is used to be calculated by (14) in engineering,

$$\omega_{\mathrm{m}} = \frac{\omega_{\max} + \omega_{\min}}{2}. \tag{14}$$

Therefore, for continuous or repetitive work machines, there are two more situations as follows,

$$\left.\begin{array}{l}\delta \le [\delta] \\ \delta > [\delta]\end{array}\right\}. \tag{15}$$

The meta-action is reliable only while

$$\{\omega \in [\omega]\} \cap \{\varphi \in [\varphi]\} \cap \{\delta \le [\delta]\}. \tag{16}$$

As for the translation-meta-action, the corresponding parameters of velocity and displacement are v and s respectively. Above all, all the meta-action failure modes are shown in Table 1.

If there is a further need, these factors can be combined with each other, which will easily to trace the failure causes, and there are 24 combinations totally. The meta-action failure causes are the events which contribute to these immediate causes.

V. AN ILLUSTRATIVE EXAMPLE

As the typical transmission parts, gears and racks are wildly used in equipment, CNC machines especially. Gear rotation-meta-actions and rack translation-meta-actions are the widespread meta-actions in CNC machines of which Guo *et al.* [23], [24], [32]–[34] summarized the common failure modes. Table 2 shows the comparisons between the failure modes of CNC machines [23], [24] and the proposed.

As shown in Table 2, there are only six failure modes proposed, however, there are 107 failure modes are given by Guo [23]. The proposed method reduces the number of failure modes deeply. Owing to the ambiguous definitions of traditional failure modes, some single meta-action failure

TABLE 1. Proposed meta-action failure modes.

	Proposed failure modes	Corresponding expressions		Immediate causes
		Rotation	Translation	
MA-FM 1	No action	ω=0	v=0	J_e/F_e is equal to zero
MA-FM 2	Speed insufficient	$\omega<[\omega]_{\min}$	$v<[v]_{\min}$	ω_0/v_0, or J_e/F_e, or action time t is not enough
MA-FM 3	Speed excessive	$\omega>[\omega]_{\max}$	$v>[v]_{\max}$	ω_0/v_0, or J_e/F_e, or action time t is exceeded
MA-FM 4	Position insufficient	$\varphi<[\varphi]_{\min}$	$s<[s]_{\min}$	φ_0/s_0 is in a wrong place, or ω/v is not enough
MA-FM 5	Position excessive	$\varphi>[\varphi]_{\max}$	$s>[s]_{\max}$	φ_0/s_0 is in a wrong place; or ω/v is exceeded
MA-FM 6	Fluctuation excessive	$\delta_\omega>[\delta_\omega]$	$\delta_v>[\delta_v]$	J_e/F_e is instable

TABLE 2. Comparisons between traditional failure modes and the proposed.

	Proposed failure modes	Corresponding expressions		Related failure modes summarized by Guo et al. [23, 24]
		Rotation	Translation	
FM 1	No action	ω=0	v=0	No action; stuck
FM 2	Speed insufficient	$\omega<[\omega]_{\min}$	$v<[v]_{\min}$	Speed disorder
FM 3	Speed excessive	$\omega>[\omega]_{\max}$	$v>[v]_{\max}$	Speed disorder
FM 4	Position insufficient	$\varphi<[\varphi]_{\min}$	$s<[s]_{\min}$	Under displacement
FM 5	Position excessive	$\varphi>[\varphi]_{\max}$	$s>[s]_{\max}$	Over displacement
FM 6	Fluctuation excessive	$\delta_\omega>[\delta_\omega]$	$\delta_v>[\delta_v]$	Creeping

modes are equivalent to several traditional failure modes. For instance, "no action" and "stuck" are defined as two different traditional failure modes, while they are the same one in Table 2. Actually, the parts which have no action or be stuck always act no speed in reality. Additionally, there are "vibration" and "abnormal sound" in traditional failure modes, but a machine vibration is always accompanied by abnormal sounds.

For a meta-action is a motion unit, failure modes shown in Table 2 are only the motion failure modes [23] or a part of function failure modes [24] of CNC machines. The rest of them are defined as the causes of meta-action failure in this paper. This method is practical to avoid the confusion between failure modes and failure causes in traditional definitions. Taking an example, when a gear of rotary table fails in CNC machine, what the repairman firstly notices is that the rotary table doesn't work, which is the most superficial phenomenon. After disassembling and checking the rotary table, the initial cause is the transmission shaft broken. However, both of the failure mode and the failure cause are also the failure modes in traditional definitions [23], [24], which makes it confusing about which one should be recorded. Since any kind of failure events are evolved from abnormal actions into properties degradation or a function failure, an action failure is the most basic and obvious failure phenomenon which can be observed easily. It is more advisable to define an abnormal action as a failure than those part failures and function failures. Additionally, if we do FMEA on the machine, the failure mode and failure cause are ''rotary table no action'' and ''shaft broken'' respectively when we appoint the system as the indenture level. However, when we appoint the parts as the indenture level, the failure mode is ''shaft broken'', and the effect is ''rotary table no action''. The repetitive work has no material help for analysis, but increases the unnecessary workload.

VI. CONCLUSION

Traditional failure modes have no clear definitions, and failure modes and failure causes can always convert to each other. As a result, there is much meaningless repetitive work in the FMEA process. Besides, the traditional failure target can be a system or a part casually, it is too difficult to find out all the potential failure modes, so that the effect of FMEA work is reduced. To overcome these problems, this paper defined an action abnormality as the meta-action failure mode, which solves the confusion between traditional failure modes and failure causes. Moreover, it can avoid plenty of repetitive tasks and simplify the work when we do FMEA based on the meta-action failure modes. The meta-action failure mode can be well applied to reliability analysis of mechanical products and electromechanical products. For future work, the reliable ranges of the motion output parameters need to be investigated. Additionally, the failure mechanisms of all types of the meta-action failures are also worth studying.

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