Case-Based Evaluation of Potential Deterioration for Facility Life-Cycle Management

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Received on January 9, 1997

Abstract

Providing appropriate maintenance is essential to achieve effective production. For planning proper maintenance strategy, it is necessary to know potential deterioration of the facility which may lead to various problems. In this paper, we propose a case based approach to the evaluation of potential deterioration modes. Deterioration cases are represented in terms of the deterioration process in which basic deterioration mechanisms are combined. Algorithm for the qualitative evaluation of deterioration of the specified part of the facility is proposed. Propagation of effects of deterioration to other parts of the facility is also discussed. Effectiveness of the method is demonstrated using an experimental system.

Keywords: Maintenance, deterioration, expert system

1. Introduction

Today's manufacturing becomes increasingly dependent upon facilities with the advances in automation and integration of manufacturing systems. Therefore, maintaining the facility at its highest potential throughout its life cycle is one of the most important activities for achieving effective production.

In order to carry out the effective maintenance over the facility life cycle, it is necessary to select a proper maintenance strategy such as time based maintenance, condition based maintenance, or breakdown maintenance. For this purpose, we have to evaluate potential problems which may occur in the facility. Without knowing what to expect, you can hardly devise countermeasures.

Nowadays FMEA (Failure Mode and Effects Analysis) is widely used for evaluating potential deterioration and resultant failures. However, it must be carried out manually by experts. It is a time-consuming task for a complex and large scale facility. Besides, the results of the analysis depends on the expertise of the analyst. Recently, attempts have been made to automate the FMEA process using artificial intelligence techniques [Russomanno, 1994]. Most of them place the emphasis on the analysis of failure effects from the functional point of view. On the other hand, little work has been done on computer support systems for the evaluation of component deterioration, although it is essential for maintenance strategy planning.

We have adopted the case based approach for evaluating potential deterioration modes of the facility components, because we are not knowledgeable enough to evaluate them only from the fundamental failure physics [Riesbeck, 1989]. Our experience taught us that it is effective to rely on the event which have actually occurred [Morrill, 1989].

In our previous work, we have proposed the algorithm for evaluating potential deterioration of the specific part based on deterioration cases experienced in the past [Takata, 1996]. However, there could be a chain of deterioration over multiple parts, because the effects of deterioration propagate to other parts. In this paper, we propose the algorithm for case based deterioration evaluation taking into consideration propagation of deterioration effects in the facility.

In the following, we first discuss the role of the maintenance strategy planning, which the deterioration evaluation system is mainly for, from the aspect of facility life cycle management. Then the algorithm of qualitative evaluation of potential deterioration mode of facility components will be described. As an illustrative example, a chucking mechanism of an automatic lathe is evaluated using an experimental system.

2. Life Cycle Maintenance Management Architecture

For maintaining the facility at its highest functionality, maintenance activities have to be tailored depending on

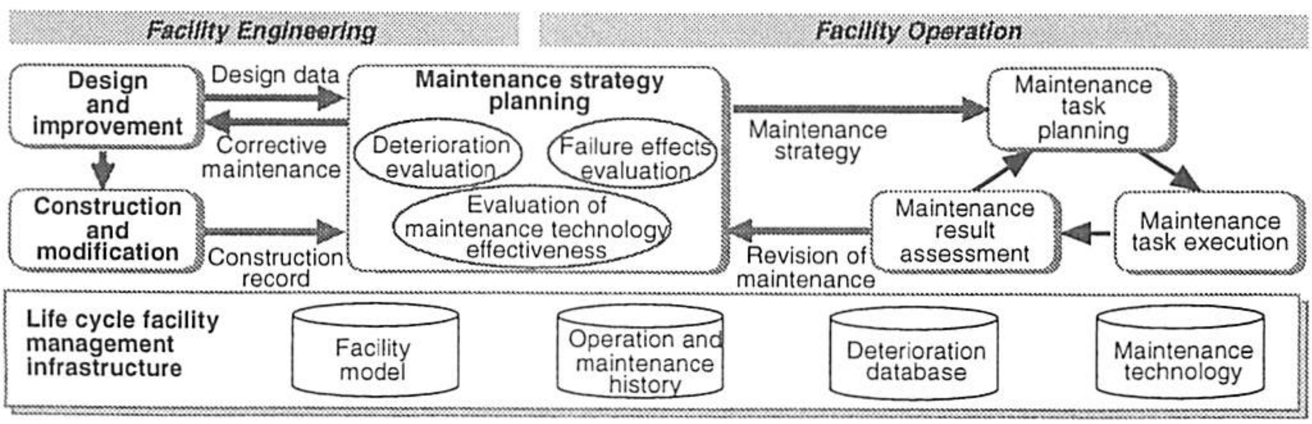

Figure 1 Life cycle maintenance management architecture

characteristics of the facility and its operating and environmental conditions. Since such conditions will change and even the facility itself will be modified during the facility life cycle, we have to provide a proper mechanism to adapt the maintenance strategy to the facility throughout the life cycle. For this purpose, we propose a life cycle maintenance management architecture shown in Figure 1. Maintenance strategies can be categorized from various aspects such as opportunity of inspection or diagnosis (during operation/idling/...), criteria for giving treatment (time/condition/...), and type of treatment (replacement/repair/...). The maintenance strategy planning is to select the method of maintenance among these options. The primal factor to be considered for it is potential deterioration which may occur in the facility. Only by evaluating the characteristics of potential deterioration which could cause various failures, could we select proper actions to cope with them. In addition to the potential deterioration, we should also take two other factors into consideration for the maintenance strategy planning, that is, the effects of functional failure induced by the deterioration, and effectiveness of maintenance technologies such as inspection and diagnostic methods.

There are three feed back loops in this architecture for adapting the maintenance activities to the various changes encountered during the facility life cycle and realizing continuous improvement of the facility. The first one is the loop of the maintenance task management in the facility operation phase which consists of task planning, task execution and assessment of maintenance results. This is the loop for controlling routine maintenance work. The second loop is the one consisting of maintenance strategy planning and maintenance task management. By means of this loop, maintenance strategies can be adapted to various changes such as those in the operation conditions and environment. This is also effective to improve maintenance activities based on the observation of actual phenomena and knowledge accumulated during the facility life cycle. The third loop is the one which includes the facility development. This loop is important for modifying the facility for continuous improvement of the facility during its life cycle.

Information integration is an important issue to actualize such architecture, because various types of data are required for life cycle maintenance management, such as design data, operation and maintenance history, knowledge about deterioration and failure mechanisms, and data associated with maintenance technologies. To provide effective support for managing such data, life cycle management infrastructure has been discussed recently [Krause, 1995].

We have proposed that a core of the databases of the infrastructure should be a facility model which represents the basic information of the facility and can be accessed from any phase of the facility life cycle [Takata, 1995]. We have taken an assembly structure as the basis of the representation of our facility model. It consists of assembly items and assembly relations between the assembly items. An assembly item represents a physical substance in the facility. Assembly items are classified into parts and form features. A part is an individual physical substance. We consider an assembly a kind of part which can be divided into multiple parts. Form feature is a group of geometric elements. An assembly feature is a form feature which mates with another form feature of a different part or sub-assembly to make an assembly, such as holes/pins. Two types of assembly relations, connection and composition are defined to represent assembly structures. Connection is an assembly relation between two items which have no inclusive relation to each other, e.g., a part to a part, an assembly feature to an assembly feature. Composition is an assembly relation between an assembly item and another assembly item which it consists of.

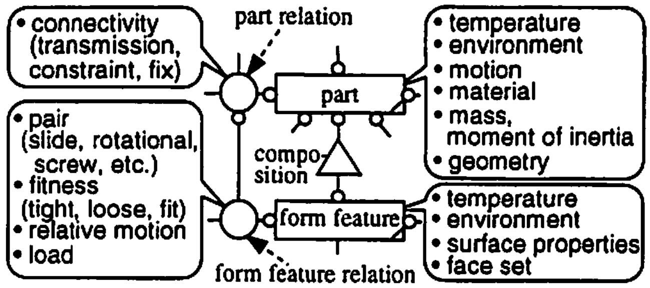

Figure 2 Attributes defined in assembly items and relations

Various information associated with the facility can be accompanied with the facility model. *Figure* 2 shows attributes defined in assembly items and relations for the purpose of deterioration evaluation. Geometric information is maintained in a solid modeler to which the facility model has links.

3. Representation of Deterioration Cases

Deterioration is a physical and/or chemical process occurring at various parts of the facility depending on operational and environmental stresses. Mechanisms which induce deterioration at certain areas of parts or assemblies are called deterioration mechanisms. The resultant deteriorated states are distinguished by deterioration modes. There are a certain set of deterioration mechanisms which are basic and common for many types of facilities, such as fatigue, wear, and corrosion [Dasgupta, 1991]. We call them fundamental deterioration mechanisms.

The deterioration mechanism is caused by a certain set of conditions which we call causal factors. They can be classified into four categories: a) inherent characteristics such as geometry and material, b) exerted stress such as mechanical stress and thermal effects, c) relative motion, and d) operating environment such as in a gas, in a liquid, or in particles.

In many cases, a chain of multiple fundamental deterioration mechanisms are related to deterioration of a certain part of the facility in such a way that one of the causal factors of a deterioration mechanism could be provided by other deterioration mechanisms. For example, fatigue failure could be initiated by a notch created by corrosion. There is also a case where some of the causal factors are provided by mechanisms other than deterioration mechanisms, which we call causal factor formation mechanisms. An example of this type of mechanism can be seen when the rotation of a shaft with a radial load creates cyclic stresses which lead to fatigue at a stepped part of the shaft. The chain of deterioration mechanisms and causal factor formation mechanisms is termed a deterioration process [Takata, 1994].

Deterioration can be represented in terms of deterioration processes. Figure 4 shows an example representation of a deterioration case of a spindle gear box of a machine tool shown in Figure 3. In this case, chips generated by cutting processes (carried out at the right side of the figure) caused abrasive wear of a seal. This led to intrusion of cutting chips to a bearing and caused its wear which consequently led to rotational inaccuracy of the spindle. In the figure, the rectangles represent the

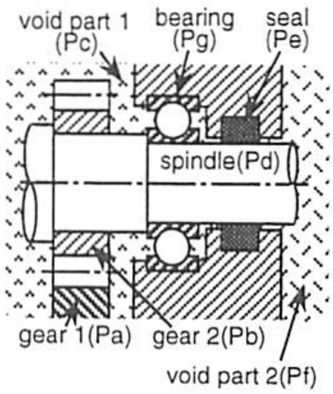

Figure 3 Spindle gear box

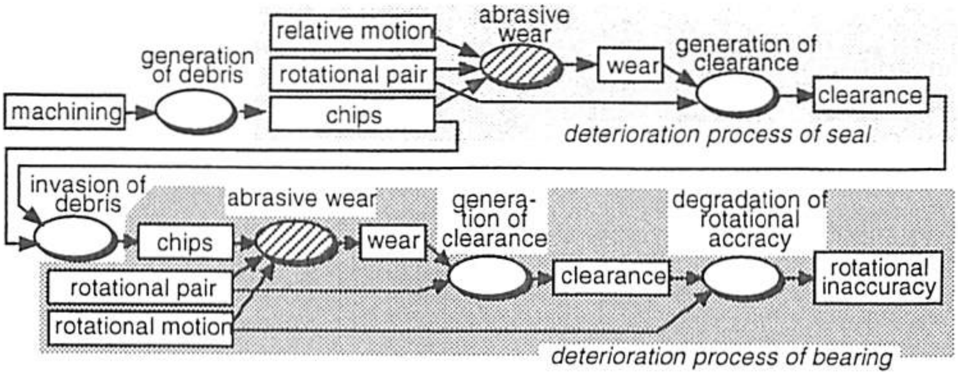

Figure 4 An example representation of a deterioration case

causal factors, whereas the ovals represent the mechanisms. The white ovals indicate the causal factor formation mechanisms and the shaded one indicates the deterioration mechanism.

As indicated in the figure, this case contains deterioration processes of two different parts, the seal and the bearing. In the deterioration process of the bearing, the existence of cutting chips, one of the causal factors of the bearing wear, was brought through the clearance of the seal which was generated by the seal wear. In the deterioration evaluation, we have to take such propagation of the causal factors into account so as to estimate a chain of deterioration at different parts.

4. Case Based Deterioration Evaluation

4.1 Procedure of deterioration evaluation

The procedure of deterioration evaluation is shown in Figure 5. The evaluation is carried out qualitatively using the facility model and a deterioration database containing deterioration cases and fundamental deterioration mechanisms. The procedure is divided into two major steps. First, a form feature to be evaluated is specified and potential deterioration which may occur at this form feature is inferred. Then a check is made to see if estimated deterioration induces propagation of causal factors, and, if any, the results of the propagation are registered in the facility model. For identifying chain of deterioration processes relating to multiple form features, this evaluation procedure is iterated by specifying the form feature which is affected by the propagation of causal factors.

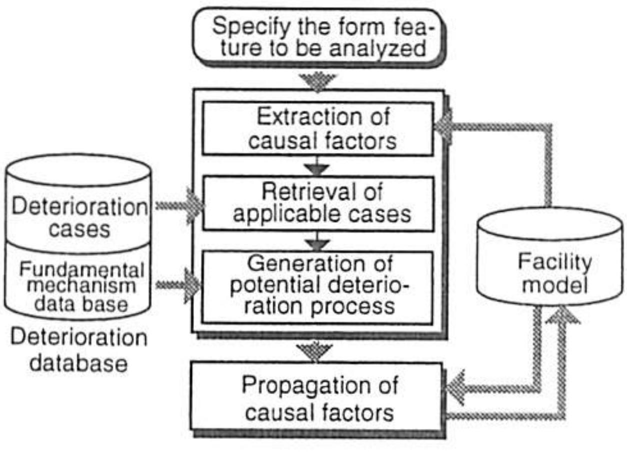

Figure 5 Procedure of deterioration evaluation

4.2 Deterioration evaluation of a specified form feature

The evaluation of a specific form feature of the facility is carried out in three steps as shown in Figure 5 [Takata, 1996]. First, causal factors associated with the specified form feature are extracted from the facility model. Second, deterioration cases which could be induced by the causal factors identified in the first step are retrieved from the case base. In the final step, the potential deterioration process is constructed by assembling partial processes which are identified in the retrieved deterioration cases. In this step, the fundamental mechanisms are used as a binder of the partial processes.

(1) Identification of causal factors: The first step in the evaluation process is to identify the assembly items and assembly relations associated with the specified form feature in the facility model. They are the form feature itself, the part to which it belongs, and the form feature relation and the part relation connected with them. The attributes which are defined in these assembly items and relations are extracted as causal factors and registered in a causal factor list (CFL).

(2) Retrieval of applicable cases: Second, the deterioration cases which are likely to happen at the specified form feature are selected from the case base by referring to the extracted causal factors. For this purpose, an adaptability index is defined. Let's assume that the case base contains a deterioration case C_p ($p=1,...,m$), C_p has n_p mechanisms, each of which is denoted by M_{pi} ($i=1,...,n$), and M_{pi} has k_{pi} causal factors which condition its occurrence. If the number of the causal factors which coincide with those in CFL is e_{pi} out of k_{pi}, we define an index of possibility of occurrence of each mechanism M_{pi} as,

$$\alpha_{pi}= e_{pi}/k_{pi} \quad (i=1,...,n). \tag{1}$$

The adaptability index α_p is defined as the sum of α_{pi} ($i=1,...,n$).

$$\alpha_p=\sum_{i=1}^{n} \alpha_{pi} . \tag{2}$$

The basic notion of this index is to indicate the number of the mechanisms in the deterioration cases which are activated by the causal factors in CFL. By definition, the mechanism does not occur, if even one of the causal factors of the mechanism is not satisfied. However, there could be other mechanisms which induce the causal factors which are necessary to activate the mechanism, but not in the current CFL. The adaptability index is defined in consideration of this possibility. The

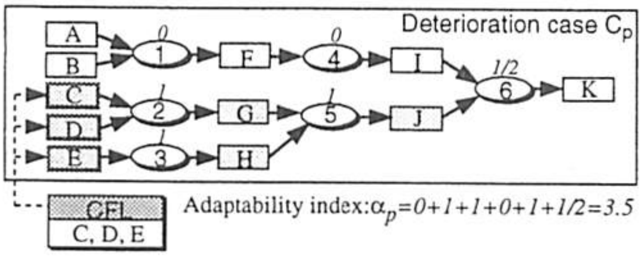

Figure 6 Calculation of adaptability index of the case

deterioration cases are selected when their adaptability indices are more than a specified threshold value, α_p^{th}.

Let's consider a deterioration case shown in Figure 6, as an example. Supposing there are causal factors C, D, E in CFL, the indices of possibility of occurrence of each mechanism are calculated as $\alpha_{p1}=0$, $\alpha_{p2}=1$, ... , $\alpha_{p6}=0.5$ as indicated by the figures right above the mechanisms depicted by ovals in Figure 6. Therefore, the adaptability index of this case is calculated as,

$$\alpha_p=0+1+1+0+1+0.5=3.5 \qquad (3)$$

(3) Generation of potential deterioration process: The potential deterioration process which may occur at the specified form feature is generated by use of the retrieved applicable deterioration cases and the fundamental deterioration mechanisms stored in the database. The method is explained by using the example shown in Figure 7. In this example, two deterioration cases, Case 1 and Case 2, are selected from the case base as applicable cases. Causal factors registered in CFL regarding the specified form feature are A, B, C, D and E.

a) Partial processes are searched in the applicable cases based on the current CFL. The partial process is a subset of the deterioration case which is activated by the causal factors in CFL. If any partial process is identified, it is appended to the potential deterioration process. If none of the partial process is identified, go to c). In Case 1, the partial process α caused by the causal factors A, B and C is identified. It involves the mechanisms 3 and 4. In the same way, the partial process β is identified in Case 2, which is induced by the causal factors C, D and E, and involves the mechanisms 6, 7 and 9. Both partial processes α and β are appended to the potential deterioration process indicated at the bottom of the figure.

b) The causal factors included in the partial processes which are newly appended to the potential deterioration process are identified and appended to CFL. Then go to a). In the example, causal factors of F, I, M, N and P are appended to CFL.

c) If partial processes are not identified anymore, fundamental mechanisms which could be activated by the causal factors in CFL are searched in the fundamental deterioration mechanism database. If any mechanism is identified, it is appended to the potential deterioration process. If not, go to e). In the example, the fundamental mechanism λ is identified and appended to the potential deterioration process.

d) The causal factors included in the fundamental mechanisms which are newly appended to the potential deterioration process are identified and appended to CFL. Then go to a). In the example, a causal factor O is appended to CFL.

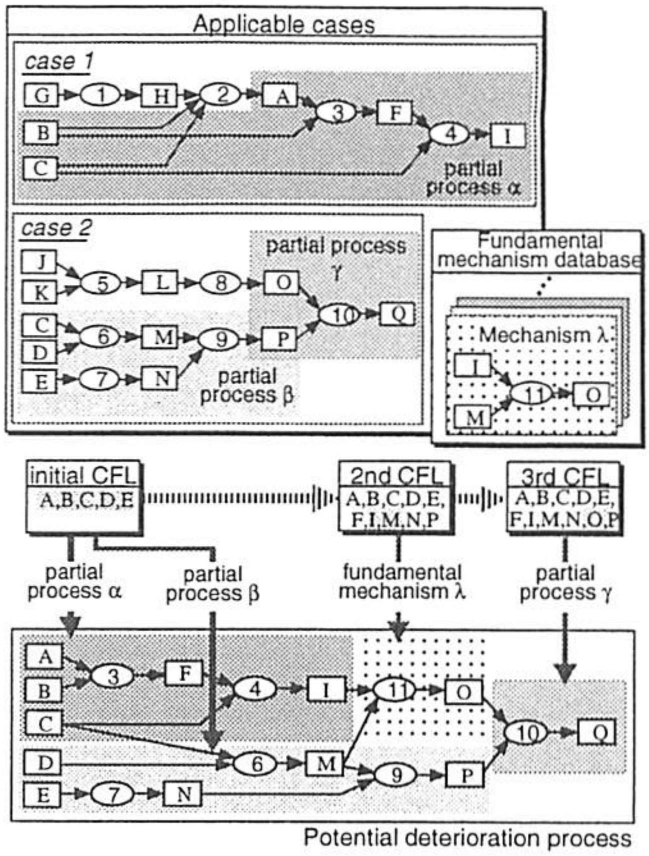

Figure 7 Procedure for generation of the potential deterioration process

e) Terminate the algorithm and output the potential deterioration process as the result of the evaluation.

4.3 Propagation of causal factors

As mentioned in section 3, we have to consider the propagation of causal factors in the deterioration evaluation. How the causal factors are propagated is classified into the following three categories depending on their characteristics. a) A causal factor related to a pair such as excess clearance have also an effect on the mate of the pair. b) Causal factors such as vibration and heat conduction spread through a part and are transmitted to other parts which are connected to the part. c) Environmental causal factors such as cutting fluid and chips spread in space and are directly transmitted to the part which faces the space.

Propagation paths of the causal factors categorized in a) and b) can be identified by tracing assembly relations in the facility model. However, those of category c) could not be directly identified from the assembly relations in the facility model, because the facility model does not explicitly represent spatial configuration of parts. To enable the inference of this type of propagation, we introduce a void part. The void part is a closed space or a half space which is not occupied by parts of the facility. Let's take the spindle gear box shown in Figure 3 as an example. In this example, we can define two void parts 1 and 2 which are separated by the seal. The void parts are represented in the facility model in the same way as usual parts. Figure 8 shows the facility model of the spindle gear box. Here, Pa, for example, represents 'part a', and Fab represents a assembly feature of the 'part a' which mates the assembly feature Fba of 'part b.' Using void parts, propagation of causal factors of category c) can be reasoned in the same way as that of category b). In the

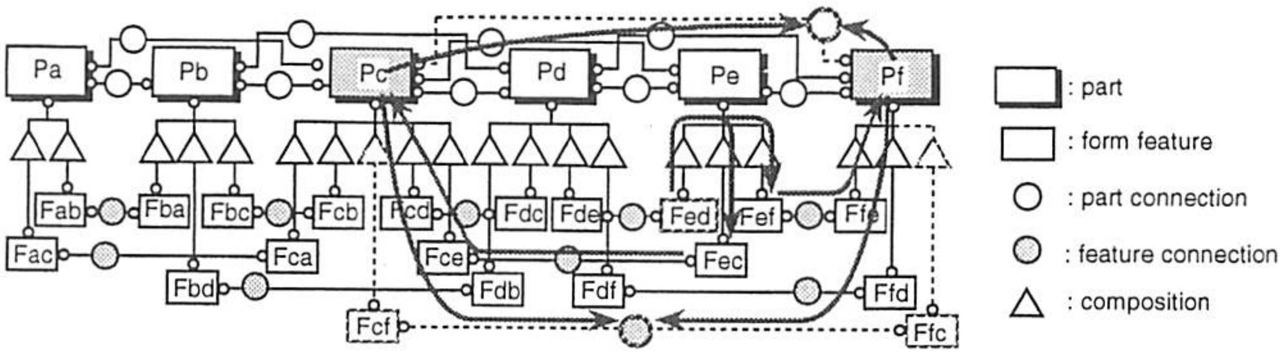

Figure 8 Model representation of the spindle gear box

case of the spindle gear box, wear of the seal results in a gap at the assembly connection between Fed and Fde. This induces the connection between 'void part 1' and 'void part 2.' Then, the causal factor of 'void part 1,' that is, 'cutting chips' is propagated to 'void part 2' and further to the parts which have connections to 'void part 2,' such as the bearing and the gears.

In the above example, the connection between 'void part 1' and 'void part 2' is established by the following algorithm. a) Search adjacent features of the deteriorated feature in the facility model. Here, adjacent features are defined as form features which have faces adjacent to each other. Adjoining information among faces can be identified from the geometric model. In the example of the gear box, Fec and Fef are the adjacent features of the deteriorated feature Fed. b) Find parts which have connections to the adjacent features. In the example, Pc (void part 1) and Pf (void part 2) are the connected parts to the adjacent features Fec and Fef respectively. c) If there is a void part in the connected parts, create the connection between the void part and other connected parts. Since both Pc and Pf are void parts in the example, the connection is established between them.

5. Experimental System

The experimental system has been developed based on the above-explained algorithm using the expert shell G2®. The facility model is described by means of the object oriented modeling capability provided by G2. Interface to a solid modeler has been established for manipulating geometric data of parts. The deterioration database is also prepared on G2. Thirty-nine deterioration cases were collected from maintenance records from a mechanical parts production factory. In the fundamental mechanism database, 79 deterioration mechanisms and 32 causal factor formation mechanisms are registered. The inference algorithm is implemented by means of production rules.

A chucking mechanism of an automatic lathe shown in Figure 9 is taken as an illustrative example of deterioration evaluation. To chuck a workpiece, the center is thrust out to hold it with a tail-stock (not indicated in the figure). Then, the workpiece is brought into the collet chuck by retracting the center. Finally, the collet sleeve is pulled rightward to clamp the workpiece. As a form feature to be evaluated, the interface between the collet chuck and the collet sleeve was specified. Figure 10 shows a hard copy of the CRT output of the system. The system reasoned the deterioration process as shown at the upper part of Figure 10. It suggests occurrence of fretting corrosion because vibration induced by rotational motion and cutting process may cause microscopic relative motion between the collet chuck and the collet sleeve. Fretting corrosion generates rusted metallic powder which could be a causal factor of deterioration at other parts. After making the system propagate this causal factor, the interface between the chuck holder and the center was specified as a form feature to be evaluated. The result of the evaluation is shown at the bottom of Figure 10. It suggests positioning inaccuracy of the center due to the wear between the center and the hole of the chuck holder which was caused by the rusted powder which came from the collet.

As shown in the above example, the proposed method is effective in evaluating potential deterioration which can be analogized from past experiences regarding facility deterioration. However, there are still several issues which should be investigated. The most critical issue is that the current system can only perform qualitative reasoning. The system suggests every possible deterioration regardless of the degree of possibility. To avoid combinatorial explosion when the case base becomes large, we need to extend the reasoning mechanism to take the intensity of causal factors into consideration.

Another issue is how to determine the threshold value of the adaptability index in retrieving applicable cases. We think this issue is a trade-off between the amount of computation and the exhaustiveness of the search. We need to make a number of case studies to find the appropriate threshold value which is effective for the actual applications. Since the number of cases is quite limited in the current case base, we set the threshold values of the adaptability index as $\alpha_p^{th}=1$ to make an extensive search.

6. Conclusion

In this paper, we have proposed a method of deterioration evaluation of facility components based on actual cases.

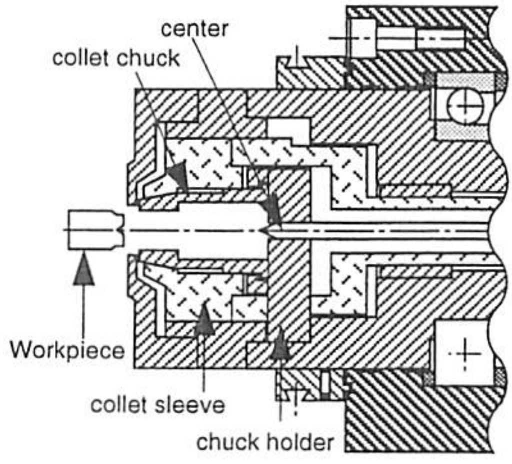

Figure 9 Chucking mechanism of an automatic lathe

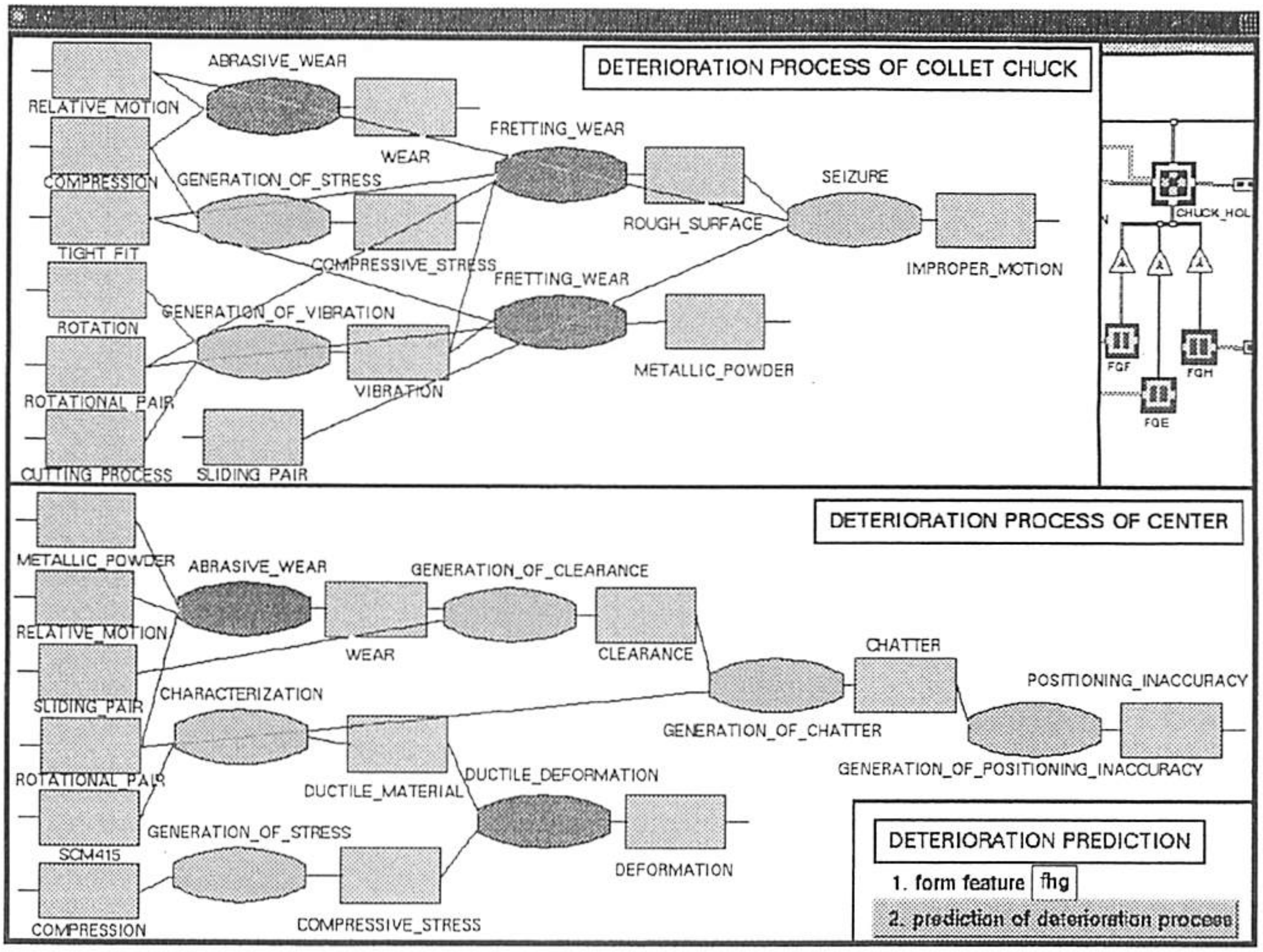

Figure 10 The system output of deterioration evaluation of the collet chuck and the center

a) The deterioration evaluation is an essential step in maintenance strategy planning which serves a key role for facility life cycle management.
b) The deterioration cases can be represented in the form of the deterioration process in which a case is decomposed into a combination of the mechanisms and the causal factors which induce the mechanisms. This makes it easy to apply the cases to other situations.
c) The adaptability index is proposed to extract the applicable cases from the case base, which are useful for the evaluation of the specified part of the facility.
d) The proposed algorithm can generate the potential deterioration process by extracting the partial processes from the applicable cases and combining them by use of the fundamental deterioration mechanisms, if necessary.
e) To evaluate a chain of deterioration over multiple parts, the algorithm for propagation of causal factors is proposed. Introduction of void parts enables the inference of propagation of the causal factors such as cutting chips and fluid.
f) The experimental system has been developed by use of the object oriented expert shell. The system contains the cases collected in a factory for mechanical parts production. The deterioration evaluation of the chucking mechanism of the lath is demonstrated to show the effectiveness of the system.

Acknowledgments

This research is partially supported by the research program conducted in RIKEN (The Institute of Physical and Chemical Research) which is a part of the Cross-over Research Program for Nuclear Base Technology promoted by the Science and Technology Agency, Japan.

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