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An Intelligent CAD System for Development of Controllers of Active Magnetic Bearings

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The purpose of this study is to establish a CAD (Computer Aided Design) system for research and development(R&D) of a new product. In the R&D process of a new product, the design objects are frequently redesigned based on the experimental results obtained with prototypes. The CAD/CAE systems (which is based on computer simulation of physical phenomena) are effective in reducing the number of useless prototypes of a new product. These kinds of conventional CAD/CAE systems do not provide a function to reflect the experimental results to the redesign process, however. This paper proposes a methodology to establish the CAD system, which possesses the engineering model of a designed object in the model database, and refines the model on the basis of experimental results of prototype. The blackboard inference model has been applied to infer model refinement and redesign counterplan by using insufficient knowledge of R&D process of new products.

Key Words : Knowledge Base, Artificial Intelligence, R&D, CAD/CAE

1. Introduction

The purpose of this study is to establish a CAD (Computer Aided Design) system for research and development(R&D) of a new product. In the R&D process of a new product, the designed objects are frequently redesigned on the basis of experimental results obtained on prototypes. The CAD/CAE system (which is based on computer simulation of physical phenomena) is effective to reduce the number of useless prototypes of a new product(Brown, 1985, Brown, et al., 1986).

These kinds of conventional CAD/CAE systems do not provide a function to reflect the experimental results to the redesign process rationally, however. That is, the usual CAD/CAE systems are not equipped with the function to infer the reason why the prototype does not satisfy the specifications in the experiments, even though the design result satisfies the specifications in the computer simulation. And these systems do not provide the function to infer the suggestions for redesign counterplans to improve the prototype.

Moreover, in these conventional CAD/CAE systems, the mathematical (engineering) model for simulating the design object has been treated as a perfect model which reflects the physical phenomena exactly, and treated as a fixed one. But it is not always easy to prepare the mathematical model that exactly reflects the physical behavior of the designed object in the R&D process of new products.

Therefore, the mathematical model which simulates the designed object, should be improved

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Table 1 Categorization of R&D process

Process A	Engineering model generation and design evaluation process: This process first suggests a design counterplan based on the design specifications and second, evaluates this counterplan by simulating the model.
Process B	Verification process for designed machine by building prototype and conducting experiments: This is the process to judge if the design counterplan obtained from process A satisfies the specifications.
Process C	Model refinement and redesign process: This is the process that refines the engineering model on the basis of the analysis of experimental results obtained from process B, and redesigns the design object.

gradually according to the experimental results of the failed prototype of new products. This paper proposes a methodology to establish a CAD system, which possesses the engineering model of the designed object in the model database, and refines the model based on the experimental results of prototype.

The blackboard inference model has been applied to infer model refinement and redesign counterplan by using insufficient knowledge of R&D process of new products. The CAD system for R&D process is implemented on personal computer. And the validity of the proposed methodology has been verified by developing a control circuit reduced type active magnetic bearing by using CAD system for R&D process.

2. Categorization of R&D Process and Configuration of the CAD System for Assisting R&D Process

In this study, the R&D process has been categorized and defined as three processes(Table 1). Process A, B, and C in Table 1 are the engineering model generation and design evaluation process, the verification process for designed machine by prototyping and experiments, and the model refinement and redesign process, respectively. Figure 1 is the flow chart of these processes. We propose the CAD system as seen in Fig. 2. And the assisting method of the CAD system to the R&D process is depicted in Fig. 1 by curved lines. In this study, we define trouble as the situation in which the prototype of process B does not satisfy the design specifications.

In general, the design problems in R&D process can be categorized into two parts. One is the part to which we can apply the engineering analysis method. The other is the part to which the engineering analysis method is no longer applicable and, thus, we have to depend on the heuristic knowledge. In this system, the former has been realized as the analysis part(AP), and the latter has been realized as the consulting part (CP) of the CAD system for R&D. The main characteristic of data processing of the CP and AP as the component of CAD system for R&D process are described in Table 2.

3. Required Functions in the CAD System for R&D Process

The CAD system for assisting the R&D process must include the following functions:

a) To be able to infer 1)the cause of trouble and 2)the redesign counterplan using insufficient knowledge obtained from the R&D activities.

b) To be able to modify, easily add and delete knowledge in knowledge database. That is, the modularity of the knowledge database must be high.

c) To possess the engineering model of the designed object in a model database which can evaluate the design counterplan. This evaluation includes dynamic characteristic evaluation and control characteristic evaluation of the design objects.

d) To be able to refine the engineering model based on the experimental result of the prototype of the new product.

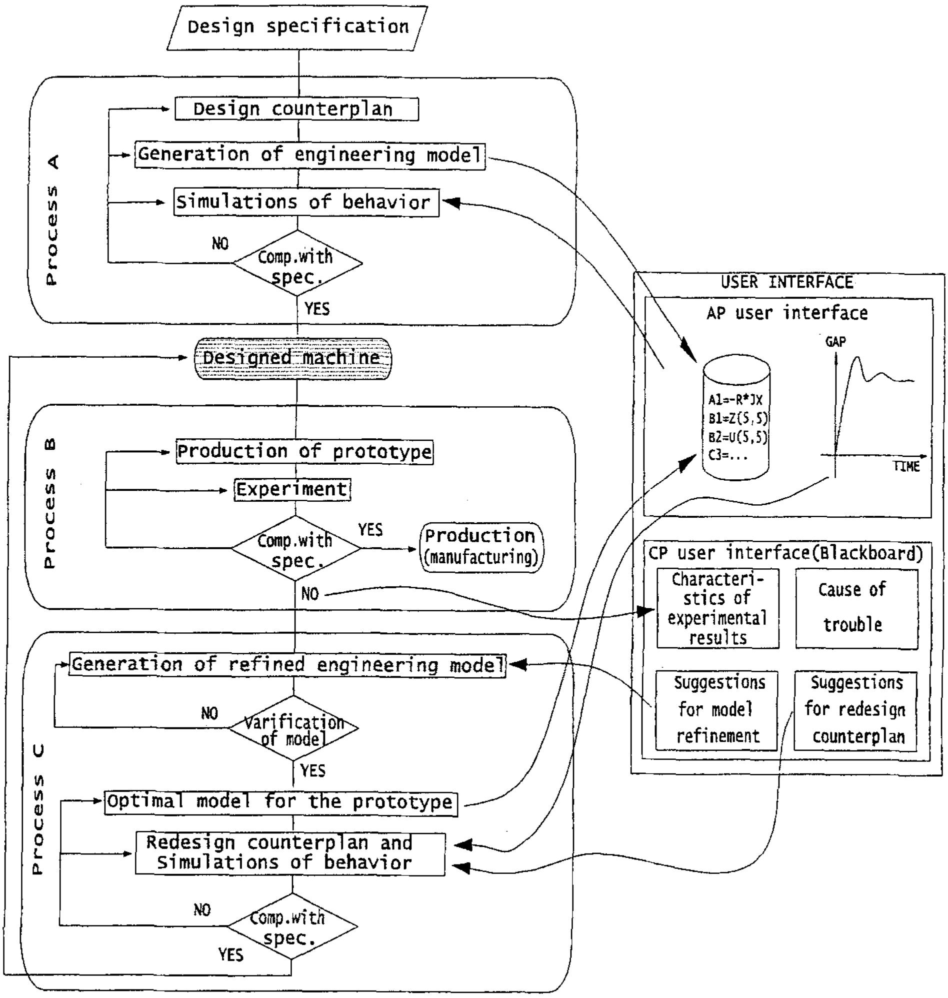


Fig. 1 R&D process and interface of CAD system for assisting R&D process

4. Blackboard Inference Model and Conformity of This Model in the Consulting Part(CP) of CAD System for R&D Process

In this study, the blackboard inference model (Erman, et al., 1980, Silverman, et al., 1989) has been applied to process the heuristic knowledge of R&D process. The blackboard inference model uses a common data domain(this domain is called blackboard) and the multiple knowledge sources in the knowledge database to solve given problems by communicating with each other. The blackboard inference model conforms to the CAD system for R&D process in the following ways.

a) In R&D process, the knowledge available to clarify the cause of trouble and to infer the redesign counterplan is insufficient. However, this problem can be solved using the cooperation and competition among the multiple knowledge sources in this model.

b) This model can offer knowledge processing ability for R&D process which originally has the cooperative characteristics.

c) Different kinds of knowledge representations and knowledge processing are available in each module.

d) The knowledge in the knowledge source can be easily modified, added, and deleted, since the modularity of this model is very high(In R&D

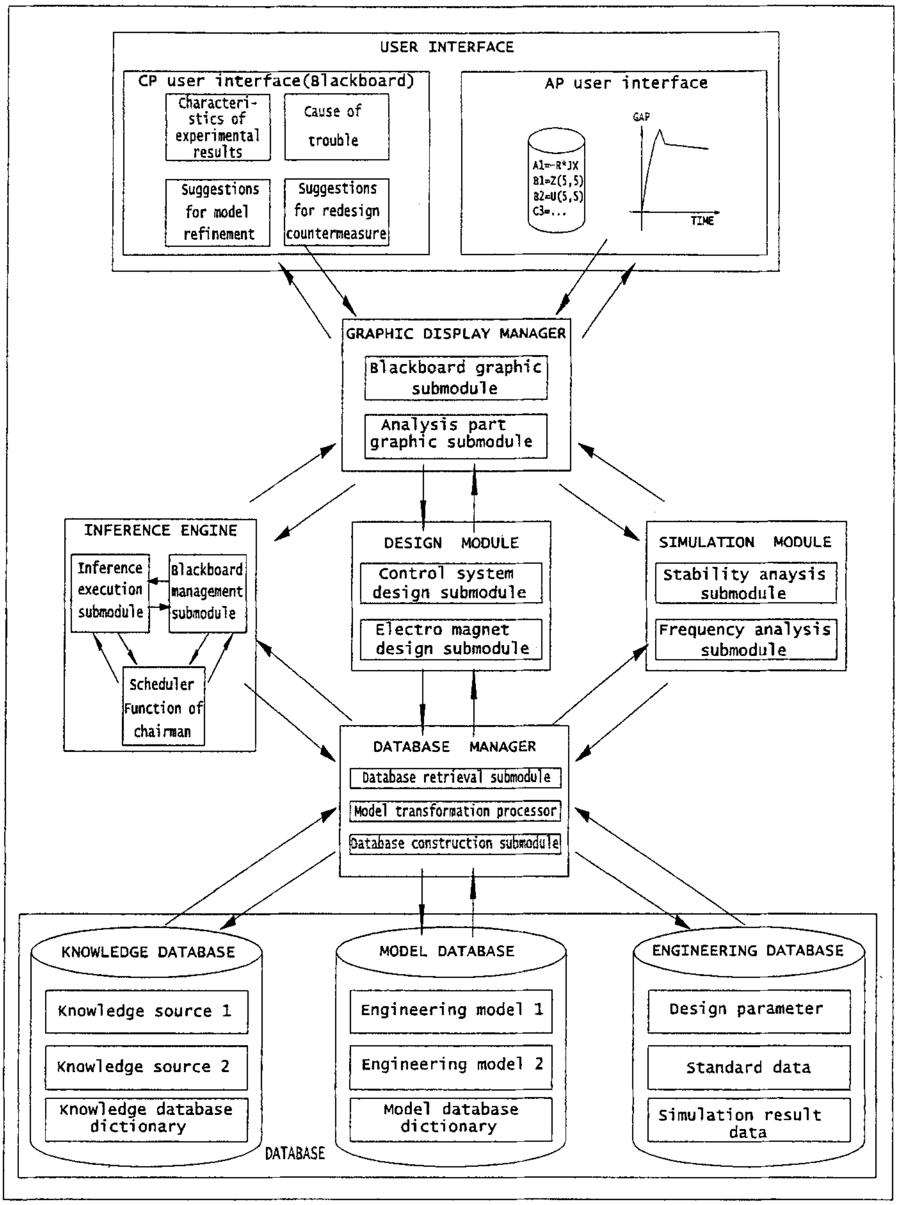


Fig. 2 Architecture of CAD system for assisting R&D process

process, the addition, deletion and modification of knowledge are frequently occurred).

5. Architecture of the CAD System for R&D Process

In this study, the CAD system for R&D process is composed of the following seven modules (see Fig. 2).

5.1 User interface(Blackboard and AP user interface)

This module is the interface of communication between the product developer and the CAD system. The product developer communicates with consulting part(CP) of the CAD system by using the blackboard(see Fig. 1). The blackboard (CP user interface) is the common data domain which remembers the hypotheses and the

Table 2 Configuration of CAD system for R&D process

Consulting Part(CP)	1. Ill-structured problem 2. Symbolic processing 3. Heuristic 4. Knowledge base(without model) 5. Knowledge engineering approach
Analysis Part(AP)	1. Well-structured problem 2. Numerical processing 3. Theoretical(Mathematical) 4. Model base(with model) 5. Engineering analysis approach

solutions. In this system, the blackboard is composed of the following four domains(see Fig. 2).

1) Characteristics of experimental results: The characteristics of experimental results are input to this domain by the product developer(see Fig. 6 as an example).

2) Cause of trouble

3) Suggestions for model refinement

4) Suggestions for redesign counterplan 2), 3) and 4) is the common data domain in which the results of inference by the knowledge sources are written(see Fig. 6 as an example).

And the product developer communicates with analysis part(AP) of the CAD system by using the AP user interface(see Fig. 2).

5.2 Inference engine

The inference engine is composed of the following three submodules.

1) Blackboard management submodule
   a) Initializing blackboard
   b) Monitoring blackboard
2) Inference execution submodule
   a) Executing the inference according to each knowledge source.
3) Scheduler
   a) Function of chairman
   b) Function to fire the knowledge sources under the condition of blackboard

5.3 Database manager

The database manager is composed of the following three submodules.

1) Database retrieval submodule
   a) Retrieval of engineering model in model database
   b) Retrieval of engineering data in engineering database
   c) Retrieval of knowledge in knowledge database
   d) Retrieval of dictionary of knowledge, model, and engineering database
2) Database construction submodule
   a) Assist for addition, deletion, and modification of knowledge, engineering data, and engineering model
   b) Generation of knowledge database dictionary
3) Model transformation processor

5.4 Design module

This module designs the control system and the electro magnet based on the modern control theory using the model database and the engineering database.

5.5 Simulation module

This module evaluates the design counterplans. The frequency response and the time response of control system are simulated by using numeric analysis packages. The results are stored in the engineering database.

5.6 Graphic display manager

This module has the following two functions.

1) Blackboard graphic submodule

Graphic display of the inference results(that is, the cause of trouble, the suggestions for model refinement and the suggestions for redesign counterplan)

2) Analysis part graphic submodule

Graphic display of the design objects

Graphic display of the simulation results

5.7 Database

5.7.1 Engineering database

The engineering database contains the following three types of the data.

a) Simulation result data: time response data, frequency response data, stability analysis data of control system.

b) Design parameters: mass of rotor, rotary inertia, feedback coefficients, steady state current of the electro magnet, and so forth.

c) Standard data: standard data of enameled coil which is used in electro magnet design(these samples are from the example of R&D process in section 6).

5.7.2 Knowledge database

The knowledge database is composed of the following six knowledge sources and the knowledge database dictionary.

a) Knowledge sources(KS)

KS1: Knowledge source for trouble cause of mechanical engineers

KS2: Knowledge source for trouble cause of electrical engineers

KS3: Knowledge source for model refinement of mechanical engineers

KS4: Knowledge source for model refinement of electrical engineers

KS5: Knowledge source for redesign counterplan of mechanical engineers

KS6: Knowledge source for redesign counterplan of electrical engineers

b) Knowledge database dictionary Reserving the management information of knowledge database

5.7.3 Model database

The model database contains the following two types of engineering model and the model database dictionary.

a) Engineering model

- Initial engineering model, which is generated by the initial design counterplan.
- Refined engineering model, which is refined by the experimental result of the prototype of a new product.

b) Model database dictionary

Reserving the management information of knowledge database

In this study, the CAD system for R&D process(R&DCAD ver. 1) has been implemented on computer system. PC(PIII, 800MHz) is used, and FORTRAN and Common Lisp are used for AP and CP, respectively.

6. R&D Process of Control Circuit Reduced Type Active Magnetic Bearing Using R&DCAD Ver. 1

The R&D process of an active magnetic bearing of which the number of control circuits is reduced compared with conventional active magnetic bearing(AMB), and bears 80000 rpm with stable rotation, will be explained in this section. This AMB will be used as the bearing of the turbo-molecular vacuum pump(TVP).

6.1 Process A

6.1.1 Design counterplan

(a) The control method of the AMB(5 axes control) is changed from the voltage control type to the current control type(in this case, the number of circuits can be reduced to 1/4)(Matsumura, et al., 1983).

(b) Cross circuits needed in the conventional AMB are removed. The cross circuit is the control circuit in which the signal of GAP-1 in Fig. 3 provides feedback to GAP-2 and GAP-3.

(c) An integral type optimal regulator is adopted in the control system to bear 80000rpm.

With design counterplan a), b) and c), the 68-control circuit of the conventional AMB is be reduced to 15 circuits.

6.1.2 Generation of initial engineering model

The engineering model describing the rotor motion represented in matrix form, has been stored in the model database(see Fig. 3 and Table 3). The engineering model which represents the behavior of the electromagnet and state equation of the current control type AMB, have also been stored in the model database.

6.1.3 Determination and evaluation of the design parameters

The feedback coefficients of the controller of AMB are determined and stored in engineering

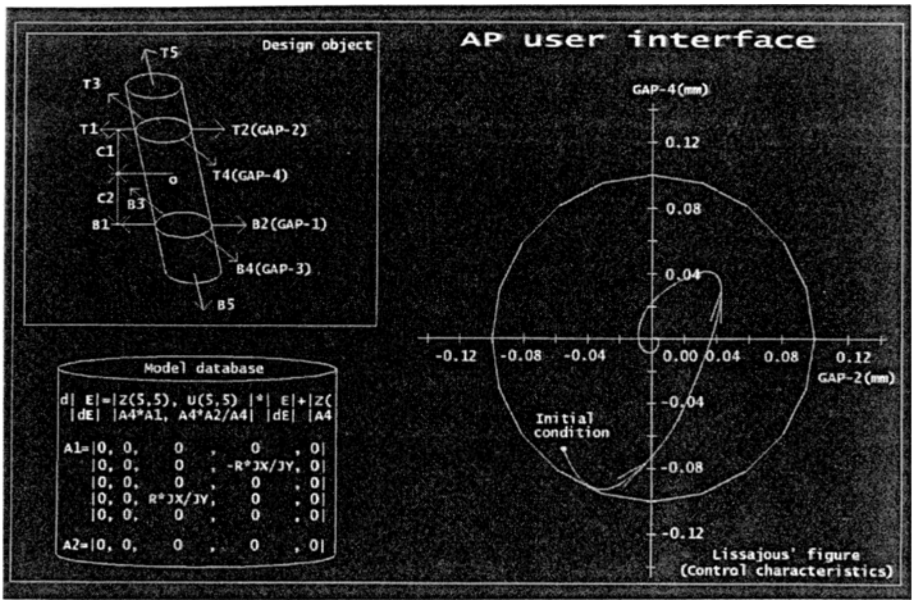


Fig. 3 Result of design of AMB in process A

Table 3 Nomenclature for engineering database

B1,···,B5,T1,···,T5	Electro magnetic forces(N)
C1, C2	Lengths from center to electro magnets(m)
d	Time derivative (d/dt)
JX, JY	Moment of inertia about X and Y axis (kg/m2)
R	Rotational speed of rotor(rad/sec)
U(m, m)	Unit matrix of m by m
X, Y, Z	Cartesian coordinates
Z(m, m)	Zero matrix of m by m
|	Matrix expression

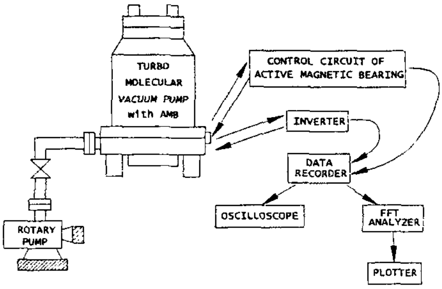


Fig. 4 Experimental apparatus of AMB

database. Figure 3 shows the control characteristics of the initially designed AMB (simulation result by AP). This simulation result shows the control characteristics(Lissajous' figure) when the center of rotor is moved from the center of stator by a disturbance force. The rotational speed of rotor in this simulation is 80000rpm and the control characteristics is very good.

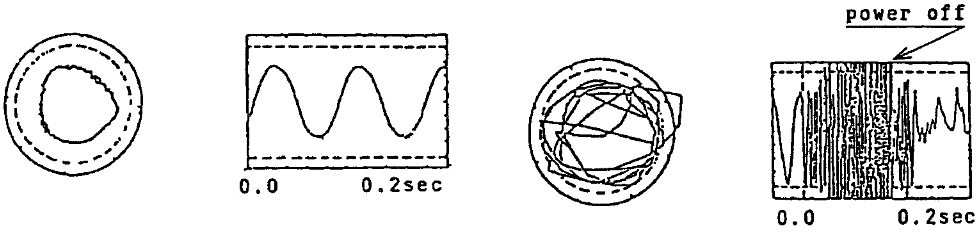
6.2 Process B

Figure 4 shows the block diagram of experimental apparatus of AMB assembled in TVP. Figure 5 shows the experimental results. Up to 60 000rpm, the rotation of rotor supported by the AMB is very stable. However, the amplitude of vibration increased suddenly at 65200 rpm, and the rotor touched the dry bearing. The vibrational frequency is 11 Hz at this time.

6.3 Process C

The experimental results obtained in process B, have been transferred to the domain of characteristics of experimental results in the CP user interface(blackboard). Figure 6 shows the inference results of the CP (see the domain of cause of trouble, suggestions for model refinement, and suggestions for redesign counterplan).

Figure 6 shows that the chairman(the scheduler in inference engine(Fig. 2) has the chairman's functions) has summarized the cause of trouble as



(a) Immediately before touch-down (b) Immediately after touch-down

Fig. 5 Experimental result of AMB designed in process A(rotational speed=65200rpm)

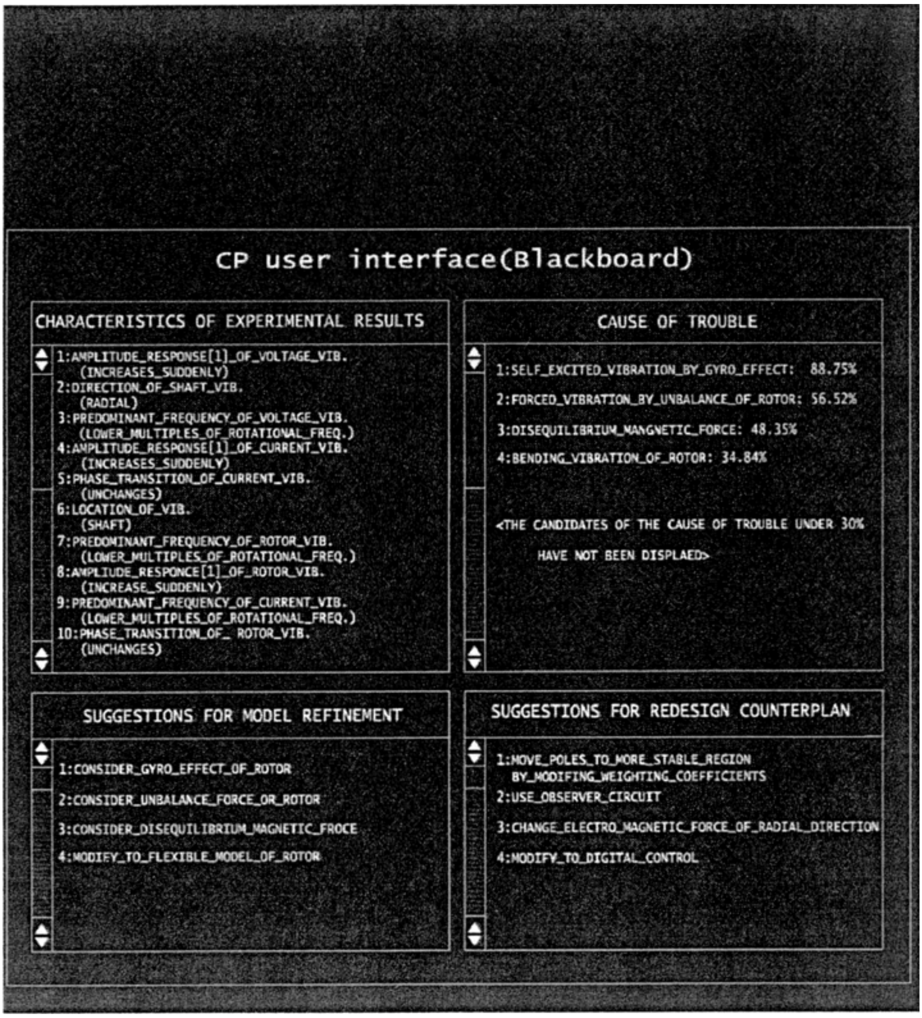


Fig. 6 Inference result of CP

self-excited vibration caused by the gyroeffect with the possibility of 88.75% $[=75+(100-75)*(55/100)]$,

a) for the opinion of mechanical engineer by whom the cause of trouble is assumed to be self-excited vibration with the possibility of 75%(This knowledge is fired from the knowledge source for trouble cause of mechanical engineers(KS1)), and

b) for the opinion of the electrical engineer by whom the cause of trouble is assumed to be self-

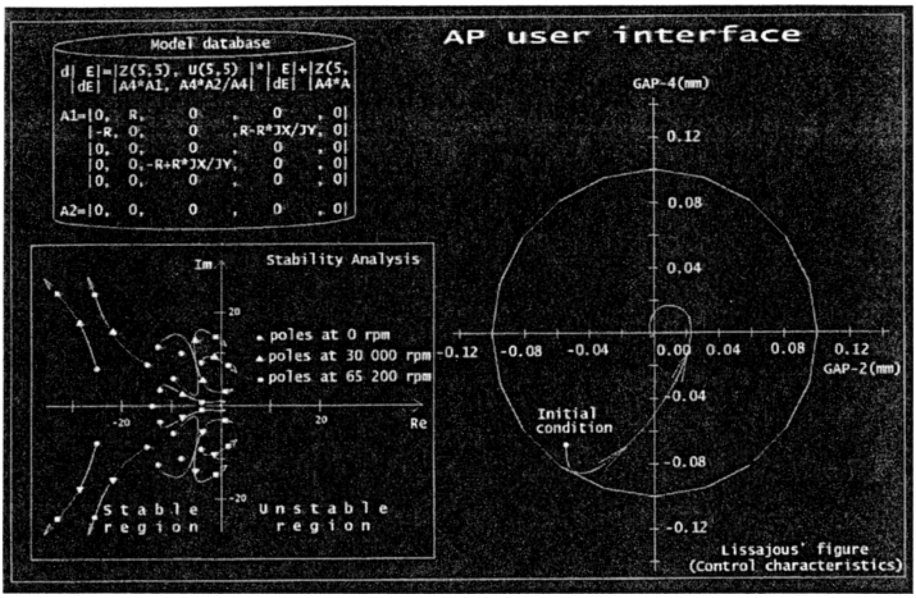


Fig. 7 Stability analysis and result of redesign of AMB according to the suggestion by CP

excited vibration with the possibility of 55%(This knowledge is fired from the knowledge source for trouble cause of electrical engineers(KS2)).

This means that the unknown part 25(=100−75)% from the mechanical engineer's viewpoint has been supported by electrical engineer's viewpoint [13.75%(=25*(55/100)]

Further, the opinion a) is inferred by firing the following knowledge in the knowledge source for trouble cause of mechanical engineers(KS1).

IF Predominant_Frequency_of_Rotor_Vib.
(Lower_Multiples_of_Rotational_Freq.)
& Phase_Transition_of_Rotor_Vib.
(Unchanges)
& Location_of_Vib.
(Shaft)
& Amplitude_Response[1]_of_Rotor_Vib.
(Increase_Suddenly)
& Direction_of_Shaft_Vib.
(Radial)
THEN Self_Excited_Vibration_by_Gyroeffect (75%)

And the opinion b) is inferred by firing the following knowledge in the knowledge source for trouble cause of electrical engineers(KS2).

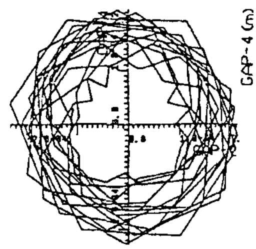
IF Amplitude_Response[1]_of_Current_Vib.
(Increases_Suddenly)
& Predominant_Frequency_of_Current_Vib.
(Lower_Multiples_of_Rotational_Freq.)
& Phase_Transition_of_Current_Vib.
(Unchanges)
& Amplitude_Response[1]_of_Voltage_Vib.
(Increase_Suddenly)
& Predominant_Frequency_of_Voltage_Vib.
(Lower_Multiples_of_Rotational_freq.)
THEN Self_Excited_Vibration_by_Gyroeffect (55%)

The ability to clarify the cause of trouble is improved by the cooperation and competition among the knowledge sources, even though each knowledge source has only it own viewpoint and thus has insufficient knowledge about the physical phenomena of the gyroeffect of the AMB.

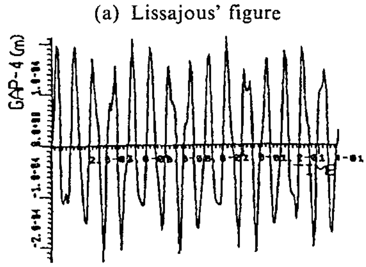
The redesign counterplans in Fig. 6 have been obtained by cooperative work among the knowledge sources to infer the cause of trouble(e. g., KS1, KS2) and knowledge sources to infer the redesign counterplan(e. g., KS5, KS6).

6.3.1 Generation of refined engineering model

The initial engineering model should be modified based on the inference result of the CP. That is, the engineering model in which the



(a) Lissajous' figure



(b) Time response

Fig. 8 Simulation result by refined engineering model(rotational speed=65200rpm)

gyroeffect is considered has been generated by the developer, and the results have been stored in the model database. Model database in Fig. 7 shows the refined part of the engineering model(compare with the model database in Fig. 3)

6.3.2 Verification of model

a) Result of time response analysis

Figure 8 shows the simulation result of time response analysis by refined engineering model. The vibrational frequency of Fig. 8 is 11 Hz and this frequency is the same as the experimental result(see Fig. 5(b)).

b) Result of stability analysis of control system

Some of the poles of the control system of AMB designed in process A(initial design) move to the unstable region at 65200 rpm(see the stability analysis in Fig. 7). In this study, the rotational speed at which poles move to the unstable region is called the limit speed of the AMB. We found that the limit speed of the AMB is reduced by the gyroeffect.

6.3.3 Redesign counterplan

The initial positions of poles of the AMB are designed to be in the more stable region by changing the weighting coefficients based on the

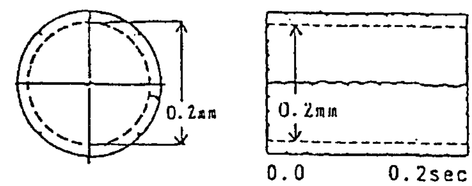


Fig. 9 Experimental result of AMB redesigned in process C (rotational speed=80000rpm)

inference result of the CP. Figure 7(Lissajous' figure) shows the simulation result of the redesigned AMB at 80000 rpm. Figure 9 shows the experimental result for the redesigned prototype. There is no whirling motion even at 80000 rpm.

Consequently, by using the R&DCAD system, we succeeded in developing an AMB for TVP which satisfies the initial design specifications.

7. Results

The CAD system for assisting R&D process of new products, has been proposed. And the following results are obtained in this research.

(1) As the constituents of the CAD system for R &D process(R &DCAD ver. 1), a)the consulting part(CP) to adrise the cause of trouble and redesign counterplan and b)the analysis part (AP) to analyze the design object, have been proposed.

(2) The blackboard inference model has been utilized in the CP system to obtain a)the cause of trouble, b)suggestions for redesign counterplan and model refinement by processing the insufficient knowledge of R&D process.

(3) The model database has been proposed to the AP system to save the engineering model and to make this model gradually more precise based on the experimental results obtained on prototypes.

(4) The R &DCAD ver. 1 have been implemented on computer system. And the validity of the proposed R&DCAD system has been verified by developing a control circuit reduced type active magnetic bearing.

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