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METHODOLOGY FOR EVALUATION OF FAILURE DIAGNOSIS IN DESIGN OF MACHINE TOOLS

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Abstract: *Tool monitoring and machine tool diagnosis in real machining have been crucial to the realisation of fully automated machining. This paper discusses methodology for increasing the diagnosability of the machine tool. The principal concept is that a machine tool can be designed, in conceptual stages, to be easier to diagnose for failures. Four diagnosability metrics are evaluated for diagnosability of machine tool. The application of the diagnosability evaluation methodologies to a kinematic positioning chain with hydraulic action is presented.*

Key words: *Fault diagnosis, machine tool, conceptual design, diagnosability.*

1. INTRODUCTION

Recently the need for unmanned machining and intelligent manufacturing systems has grown vigorously, so tool monitoring and machine diagnosis in real machining has been actively researched and applied into industry. Most machine tools are employed, either simply or in groups, within manufacturing cells which again are either arranged as simple cells or grouped into complex manufacturing systems. The ultimate aim of any monitoring system is to ensure the continuous reliable production of components of acceptable quality, while maintaining the integrity and well-being of the production machinery. The machine tool monitoring system must be equipped with [2, 3, 4]:

a) sensors and detectors;
b) data processing means;
c) access to appropriate actuators;
d) suitable displays, alarms;

so as to ensure as for as possible that the machine tool can be maintained continuously in good working order. Any definite or apparent malfunction will be corrected on-line wherever possible and a record of the symptoms and the corrective action should be displayed and recorded for reference. In theory, a monitoring system has to fully integrate with a CNC controller in order to achieve the automation of the machinery process as illustrated in Fig. 1.

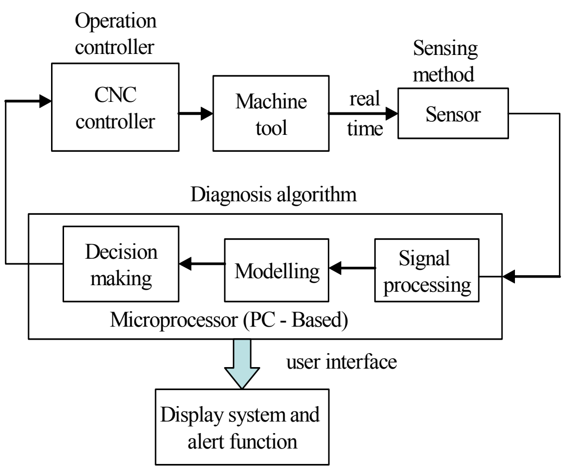

Fig. 1. Monitoring system for a machine tool.

The essential aim of any monitoring system is:

a) to monitor the performance of the activity, operations or process under consideration;
b) to ensure that the performance is satisfactory;
c) to identify immediately when any change in performance occurs, wheter dangerous, potentially dangerous or of no consequence;
d) to process all received signals;
e) to carry out whatever corrective actions may have been programmed, both promptly and effectively.

2. ANALYSIS OF DIAGNOSABILITY

In Fig.2 each of machine tool (MT) are decomposed into kinematic chain (KC). Each KC has a performance measure (PM). These MT are satisfied by design mechanisms containing parameters (P). Each machine tool function maps to a unique set of kinematic set of kinematic chain functions and each kinematic chain function maps to a unique set of parameters. In diagnosing the machine tool of Fig.2, three performance measures would be taken to locate the mechanism outside the design state.

After that, the tree parameters contributing to that performance measure would have to be measured. If multiple kinematic chains were at fault each of their parameters would have to be tested. For a simple fault, in this machine tool a maximum of six measurements would be required for fault isolation (three performance measures and three parameter measures).

The principal parameters which may be monitored on the machine tool itself are:

a) forces and stresses caused by the cutting or other process;
b) vibrations of the machine elements;
c) generation of heat by the process itself or in the machine actuators;

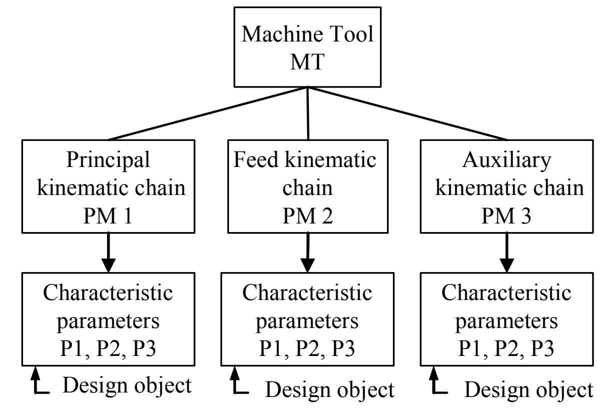

Fig. 2. Machine tool diagnosis.

d) prime power supplied to the machine which will be influenced by the process.

The analysis of the machine tools can begin in one of the two ways.

First a fault tree analysis (FTA) could be performed to identify the parameters (P) causing the performance measure (PM) to be outside the design value. Then the effects of the failed parameter could be incorporated, such as done in failure modes and effects analysis (FMEA) to determine the interaction effects from the performance measure-parameter relationships. The second way would be simply to begin with the FMEA step.

The first measure of diagnosability is the Maximum Number of Parameter Measures (MNPM). This metric is the maximum of the number of parameter measures required to verify which parameter is at fault in a failed system after performance measure have been taken. For any machine tool, the fewer parameter measures required, the more diagnosable the systems. For example, the machine tool by Fig.3 would have the highest diagnosability by this metric. The system of Fig.3 would require a maximum of eight parameter measures.

The second measure of diagnosability is the Machine Tool Interaction Complexity (MTIC). This metric is used to determine how much rule information about the machine tool the diagnostician, whether human or computer, must have beforehand to be able to immediately isolate the cause of the system fault.

The third measure of diagnosability is the Average Number of Parameter Measures (ANPM). This metric gives an indication of the average amount of ambiguity the diagnostician may face in diagnosting the machine tool.

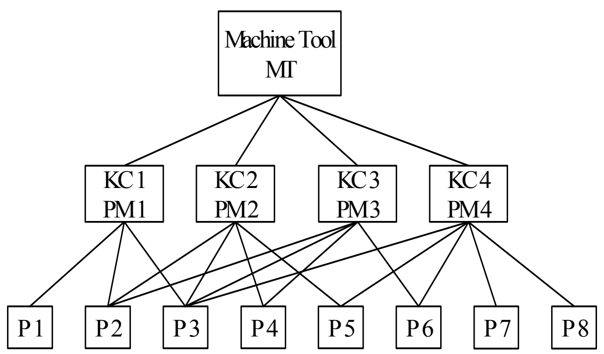

Fig. 3. Machine tool diagnosability.

The fourth measure of diagnosability is Parameter Measure Cost (PMC). This metric takes account the total number of parameters to be measured in the system and the measurement difficulty of each one.

To rate a number of competing machine tools on a diagnosability only stand point, one would rank the machine tools by considering the following: first a machine tool with the lowest MNPM; second a machine tool with the lowest ANPM; third the lowest PMC and fourth the lowest MTIC.

The successful implementation of an on-line machine tool monitoring system depends on two factors, that is, the quality of the information collected by the monitoring sensors and the diagnosis algorithm used to analyse the sensory data in order to make proper decision. The diagnosability of the machine tool is increased by adding sensors to the system, or extracting more information out of the existing sensors. The second part concerns the learning and decision-making procedures used to associate the current sensory information with the process state. The strategy for a proper integration of these two parts is a major issue for a machine tool monitoring system.

3. EVALUATION OF CONCEPTS FOR KINEMATIC POSITIONING CHAIN

As an example of the use of the diagnosability evolution methodology, this section describes the evolution and comparison of three design concepts that accomplish the overall system function of kinematic positioning chain. This kinematic chain function has three major subfunctions:

1) Rapid Advance (RA): rapid movement of the slide to a set position;

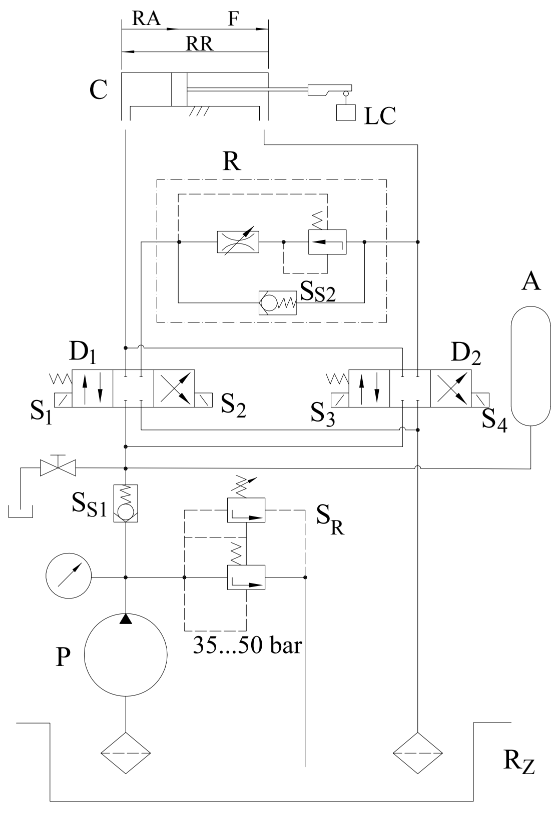

Fig. 4. A system incorporating a pilot operated check valve.

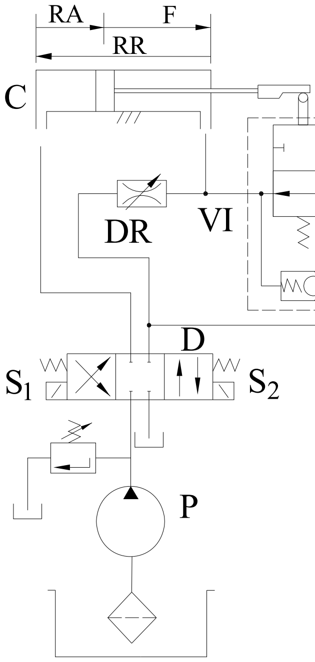

Fig. 5. A system incorporating a deceleration valve.

2) Feed (F): controlled movement of the slide to the end of travel;

3) Rapid Return (RR): rapid motion of the slide to the starting position.

For the purposes of this evaluation, only solutions involving hydraulic power transmission will be considered.

The diagnosability evaluation will use general functional failure modes for each component.

Three concepts have been developed to provide the necessary movement of the slide. These are shown in Fig. 4, Fig. 5 and Fig. 6. Figure 4 shows a system (S1) incorporating a pilot operated check valve.

Nomenclature of Fig. 4 represents: Rz-tank; P-pump; C-cylinder; D1, D2-directional valve; R-pilot operated check valve; LC-switch; S_R-relief valve; A-accumulator; S_S-unidirectional valve.

In operation, the directional control valve D1 and D2 is shifted to route flow from the pump to the head end of the cylinder C. This provides for rapid advance of the slide attached to the end of the rod. At the end of the rapid advance phase, a cam on the rod of the cylinder contains the normally closed limit switch, stopping electrical power to D2. Flow from the rod end of the cylinder is forced to flow through the pilot operated check valve R back to tank. The relief valve also provides protection against excessive system pressure. For rapid return, the directional valve D1 and D2 is shifted to direct flow freely through the check valve to the rod end of the cylinder.

The accumulator discharge in this phase greating the flow in the cylinder. Flow from the head end of the cylinder return freely to the tank.

Figure 5 shows a system (S2) incorporating a deceleration valve. Shifting directional valve (D) initiates rapid advance of cylinder (C) with the rod end flow returning freely to tank through the deceleration valve (VI).

A cam on the rod again initiates the controlled position, forcing the rod end flow through the flow control valve (DR). For rapid returns, the directional valve (D) is

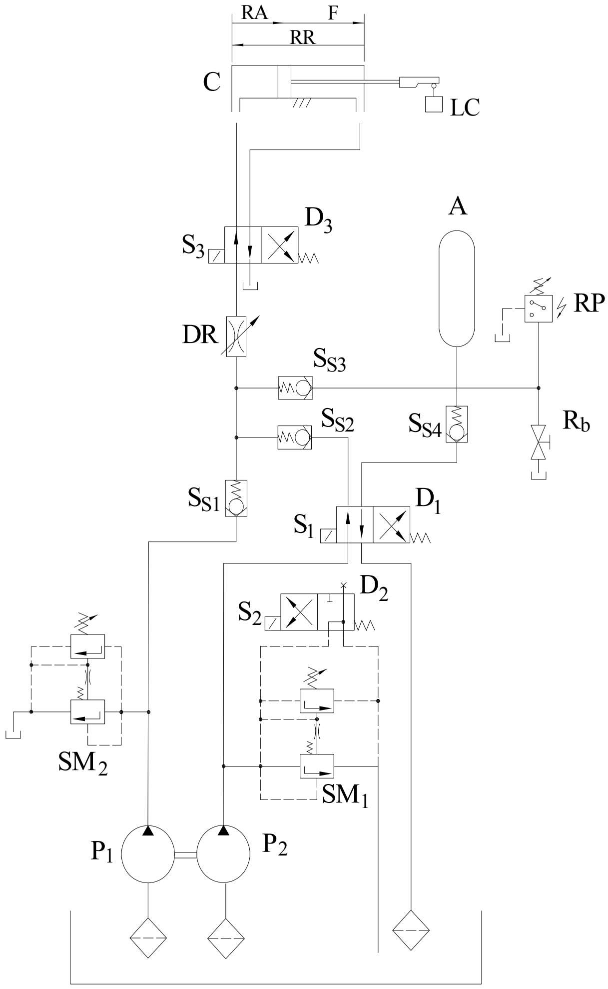

Fig. 6. A system using two separate pumps (powered by the same motor) and an unloading valve.

shifted to direct flow freely through the check valve of (VI) to the rod end of the cylinder.

Figure 6 shows a system using two separate pumps (powered by the same motor) and an unloading valve (S3). Daring rapid advance, the flow of both pumps is routed to the head end of the cylinder (C) through the directional control valve (D3).

A cam on the rod initiates controlled feed by shifting the unloading valve (D1) to position for charging the hydro-pneumatic accumulator (A).

Flow from pump P2 is routed directly to the accumulator, while flow from pump P1 is routed through a flow control (DR). Relief valves SM1, SM2 provide system pressure protection.

By hypotension, generalised failure modes for each of the components in the three slide positioning systems, a functional Failure Modes and Effects Analysis (FMEA) can be developed and a more meaningful comparison can be made among the systems [1, 6, 7].

The diagnosability evaluation using FMEA provides an early indication of the relative and absolute competing of the three systems.

Because of a greater number of components coupled with a relatively small set of observation, the S3 system ranks lower than the other two systems with respect to both MNPM and ANPM.

Table 1

FMEA for the system S1

Failure	Description	Observation set
(1) D1, (1) D2	Fail in extend	RA, F
(2) D1, (2) D2	Fail in retract	RR
(3) D1, (3) D2	Fail in both	RA, F, RR
R	Improper metering	F
C	Internal leakage	RA, F, RR
(1) S_{S2}	Fail open	F
(2) S_{S2}	Fail closed	RA, RR
(1) LC	Fail open	RA
(2) LC	Fail closed	F
P	Fail to deliver flow	RA, F, RR
(1) S_R	Fail open	RA, F, RR
(2) S_R	Fail closed	F

Table 2

FMEA based diagnosability evolution for the slide positioning system

System	Measure of diagnosaility			
	MNPM	MTIC	ANPM	PMC
S 1	6	4	2.6	14
S 2	6	5	2.3	10
S 3	7	6	3.2	18

These failure modes and their effect on the system S1 are detailed in Table 1. for the failure column, the letter represents the component and the subscript the failure nod. Evaluating as in the previous sections results in a FMEA based diagnosability evaluation for the system (Cals Technical Report, 1989) as shown in Table 2.

4. CONCLUSIONS

The design for diagnosability procedures for conceptual phase of the design process are being extended and modified for the embodiment phase of the design process.

Because the cost of diagnosis is proportional to the effort required, either, in time or expertise, increased difficulty in diagnosing failure, results in higher repair costs.

As machine tools become more and more complex, they become increasingly difficult to diagnose thus, the time to diagnose the machine tool and the possibility of an incorrect diagnosis both increase. A machine tool that was designed with increased diagnosability would be easier to be diagnosed.

We believe the concept of design for diagnosability cannot stand alone but must be integrated as part of the concurrent engineering design process.

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