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Research Article

Research on Reliability Modelling Method of Machining Center Based on Monte Carlo Simulation

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Abstract: The aim of this study is to get the reliability of series system and analyze the reliability of machining center. So a modified method of reliability modelling based on Monte Carlo simulation for series system is proposed. The reliability function, which is built by the classical statistics method based on the assumption that machine tools were repaired as good as new, may be biased in the real case. The reliability functions of subsystems are established respectively and then the reliability model is built according to the reliability block diagram. Then the fitting reliability function of machine tools is established using the failure data of sample generated by Monte Carlo simulation, whose inverse reliability function is solved by the linearization technique based on radial basis function. Finally, an example of the machining center is presented using the proposed method to show its potential application. The analysis results show that the proposed method can provide an accurate reliability model compared with the conventional method.

Keywords: Machining center, monte carlosimulation, radial basis function, reliability modelling, weibull distribution

INTRODUCTION

With the increasing development of high-speed, high-precision and intensive technologies, machine tools are the main equipment for metal machining in the manufacturing industry. They are not only the basis of the flexible manufacturing system but also play an important role in manufacturing automation. However, frequent failures of machine tools reduce the production volume and economic benefits seriously. Due to the intense competition in the market of machine tools, it is urgently desired to evaluate and improve the reliability of machine tools (Jia *et al*., 1995; Swic and Mazurek, 2011; Wu *et al*., 2009; Yang *et al*., 2011).

Mostly, the reliability models of machine tools were established by the classical statistics method based on fixed number censored samples or fixed time censored samples. A lot of effort has been paid to the improvement and evaluation of the reliability of machine tools.

A reliability method using the classical statistics based on fixed number censored samples was proposed by Jia *et al*. (1995). Through hypothesis testing, the time between failures of the whole machine tools fits the Weibull distribution on the assumption that NC machine tools are repaired as good as new when they fail.

Many researches in the reliability field of machine tools have focused on reliability modelling method on the assumption that machine tools was an integrated unit and the whole machine tools which failed were repaired as good as new (Xu *et al*., 2011; Yang *et al*., 2012; Dai *et al*., 2003).

However, these reliability modelling methods have been criticized for a variety of reasons, some of which are listed as follows:

- Machine tools which consist of electric, mechanical and hydraulic subsystems are complex and there is often more than one failure mode when they fail. So if only one piece of “time between failures” data is used for reliability evaluation and parameter estimation, the reliability model would be inaccuracy
- The assumption machine tools has the Weibull distribution is not always rational, especially for CNC and hydraulic subsystems which always have the exponential distributions
- The assumption components can be repaired as good as new is questionable and debatable. It is almost as bad as old, even though a new component replaces the failure component.

To overcome the drawbacks listed above, several approaches have been developed. For example, a modified reliability modelling approach for machine tools on the assumption that machine tools could be repaired “as bad as old” was presented by Xu *et al*.

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(2011). The study established a model of non-homogeneous Poisson process on the basis that the failure process curve was bathtub curve. The parameters of the distribution were estimated using Maximum Likelihood Estimation (MLE) method and then the related characteristics of reliability were obtained.

A reliability modelling method for the N-unit series repairable system was proposed in the case that the life of the facility and the delay vacation time of the repairman were exponentially distributed (Liu *et al.*, 2008). This method considered the replaceable facility's impact on the whole system reliability. Reliability characteristics were determined by the supplementary variables approach and the method of generalized Markov process.

In spite of the fact that much effort has been paid to the improvement of reliability modelling method for machine tools, the rationality of the conventional reliability modelling method for NC machine tools is still argued among researchers.

The method utilizes Monte Carlo simulation (MC) to solve the reliability function of series systems. Finally, a real-world case of the machining center is presented to demonstrate the potential application of the proposed method.

THEORETICAL KNOWLEDGE OF RELIABILITY

Reliability model of series and parallel system: Components or subsystems within a system may be related to one another in two primary ways: either series or parallel configuration. The series and parallel configuration relationship are represented by the reliability block diagram of Fig. 1 and 2.

System reliability denoted by R_s can be determined from the reliability models of the components or subsystems in the following formulas according to Charles (2008):

$$R_s(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{1}$$

$$R_s(t) = R_1(t) \times R_2(t) \times \cdots \times R_n(t) = \prod_{i=1}^{n} R_i(t) \tag{2}$$

Equation (1) is determined in the case that all "*n*" units of system are independent in parallel while Eq. (2) is determined when all "*n*" units are independent in series.

Process of modelling reliability based on MC: Since the complex structure of machine tools, establishment of reliability model is truly difficult so that it is necessary to carry out research for understanding the procedures of reliability evaluation. MC is a very effective method which is widely used in the reliability

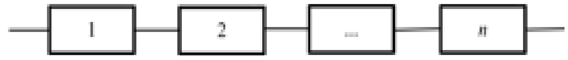

Fig. 1: Reliability block diagram for components in series

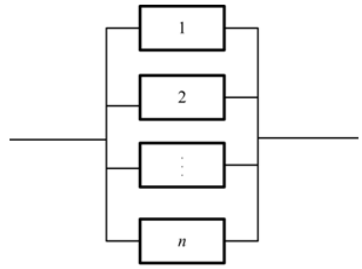

Fig. 2: Reliability block diagram for components in parallel

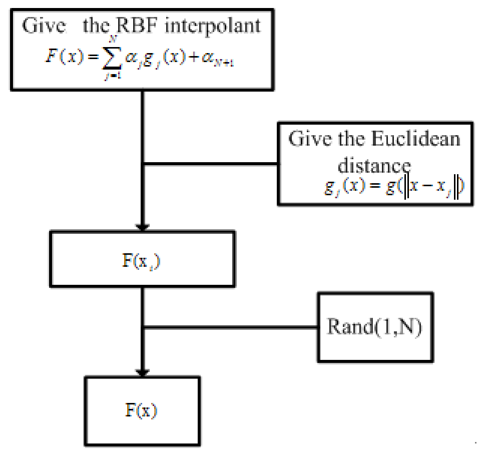

Fig. 3: Interpolation method of complicated continuous functions

evaluation of real engineering application. So it is feasible to establish the reliability model by MC.

- **Sampling of special continuous distribution:** It is easy to take a random sample for items whose failure data follows exponential, normal, uniform, or Weibull distribution and then the statistic characteristics associated with the functions can be got by calculation. But it is impossible to sample from some complicated continuous functions whose inverse functions can't be got because there is no analytic solutions. Radial Basis Functions (RBF) are used for function approximation and interpolation. Then inverse functions can be approximately got by RBF approximation and interpolation method which is useful for complicated continuous functions (Wei *et al.*, 2012; Wu *et al.*, 1998). The process is shown in Fig. 3.
- **Process of establishing reliability model:** Assume that the fitting reliability function of machine tools is $\hat{\boldsymbol{R}}$w (t), the real reliability function of NC machine tools is R_s(t), so the error between $\hat{\boldsymbol{R}}$w (t), and R_s(t) is denoted by:

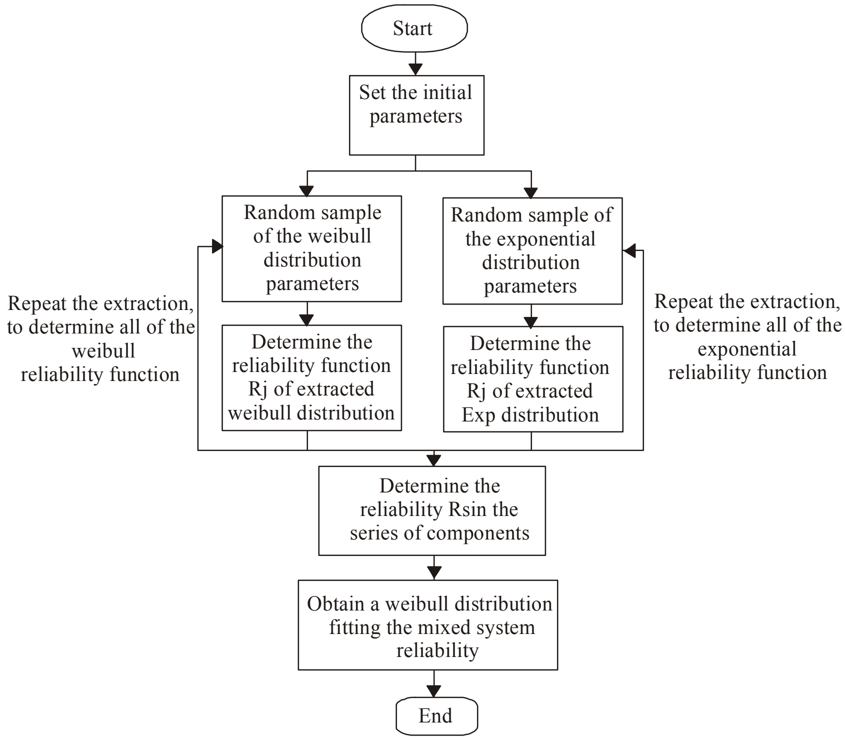

Fig. 4: Monte Carlo simulation of reliability modeling for NC machine tools

$$\mathrm{IB} = E\int_0^{t_R}\left|\hat{R}_w(t) - R_s(t)\right|dt \tag{3}$$

The estimated IB is solved by MC and it is approximately equal to the following formula:

$$\hat{\mathrm{IB}} = \sum_{m=1}^{N}\int_0^{t_R}\left|\hat{R}m(t) - R_s(t)\right|dt \tag{4}$$

where N is the number of simulation cycles
$\hat{R}$m (t), is the m^{th} fitting estimate.

So the procedure of reliability modelling method for NC machine tools is proposed in Fig. 4:

Illustration: The developed reliability model using MC is validated by the following instance of the machining center of one type.

System division of machining center: The structure of machining center is complicated so it is divided into n subsystems which are mutually independent in series. Based on the system assignment principles of function sharing, function independence and convention, the machining center could be divided into the following subsystems:

Hydraulic system, Spindle system, Electrical systems, CNC system, Protection system, Cooling system, Lubrication system , Pneumatic system, Tool magazine, Chip system, Rotary table system, Screw guide system, Servo system , Fixture system.

Reliability models of subsystems: The rules of failure distribution of each subsystem for machining center can be analyzed based on the database whose data mainly come from field experiments and experiments in the laboratory. In order to overcome the drawbacks of the conventional reliability modelling method, the best fitting distribution F (t) versus time between failures for each subsystem was optimized using the proposed method of Zhang *et al*. (2009). The parameters of Weibull, Normal and logarithmic distributions can be determined by least-square fitting method and the parameter of exponential distribution can be determined by MLE method. The reliability models of each subsystem of machining center are shown in Table 1.

The number of failures of Pneumatic subsystem and Lubrication subsystem are few so the failure data of Pneumatic subsystem is combined with that of Lubrication subsystem, then the reliability model is in the 12$^{\text{th}}$ row of Table 1.

Figure 5 shows failure distribution functions of subsystems of machining center and it is easy to see that the Hydraulic subsystem, Rotary table system, Chip system and Tool magazine are the weak subsystems in sequence according to the curves.

Reliability model of machining center established by MC: The reliability model of machining center can be achieved according to the method presented in previous section. The reliability model is shown in the following formulas:

$$\begin{aligned} R_s = & [e^{(-t/957.967)^{0.925}}]\cdot[e^{(-t/1338.676)^{0.905}}]\cdot\{1-[\Phi((\ln t-6.967)/1.347)]\} \\ & \cdot[e^{(-t/1414.951)^{1.286}}]\cdot[e^{(-t/1278.532)^{0.899}}]\cdot\{1-[\Phi((\ln t-6.879)/1.2015)]\} \\ & \cdot\{1-[\Phi((\ln t-7.095)/1.273)]\}\cdot[e^{(-0.0003\times(t-48))}]\cdot[e^{(-t/7200.527)^{2.388}}] \\ & \cdot\{1-[\Phi((\ln t-7.061)/1.360)]\}\cdot[e^{(-t/3400.687)^{0.899}}]\cdot[e^{(-t/3961.895)^{0.602}}] \end{aligned} \tag{5}$$

The best fitting $\hat{R}$ (t), shown in the formula (6) can be obtained according to the presented simulation process:

$$\hat{R}(t) = e^{(-t/168.56)^{1.15}} \tag{6}$$

So, the failure distribution function is:

$$F(t)=1-e^{(-t/168.56)^{1.15}} \tag{7}$$

And the value of MTBF can be determined as follows from Eq. (6):

$$\text{MTBF} = \int_0^{\infty} e^{(-t/168.56)^{1.15}} dt = 160.42h$$

Verification of the proposed reliability modelling method: In this section, the reliability model built by the proposed method is demonstrated through Blocksim. Fault tree is a symbolic analytical logic technique that can be applied to analyze system reliability and related characteristics. The fault tree of machining center is established by Blocksim as shown in Fig. 6. So the reliability analysis of machining center can be performed through fault tree. The reliability models of subsystems are achieved by the Blocksim according to Table 1 and the result of reliability simulation using Blocksim is shown in Fig. 7.

Table 1: Reliability models of subsystems

i	Subsystem	Reliability model	MTBF
1	Hydraulic system	F(t) = 1-exp(-t/957.97)^0.93	990.73
2	Tool magazine	F(t) = 1-exp(-t/1338.68)^0.91	1400.16
3	Electrical systems	F(t) = Φ((lnt-6.97)/1.35)	6584.67
4	Rotary table system	F(t) = 1-exp(-t/1414.95)^1.29	1308.88
5	Chip system	F(t) = 1-exp(-t/1278.53)^0. 90	1345.25
6	Fixture system	F(t) = Φ((lnt-6.88)/1.20)	4105.16
7	Protection system	F(t) = Φ((lnt-7.10)/1.27)	6080.85
8	Spindle system	F(t) = 1-exp(-0.0003*(t-48)	3333.33
9	Cooling system	F(t) = Φ((lnt-7.06)/1.36)	7402.70
10	CNC subsystem	F(t) = 1-exp(-t/3400.69)^0.90	3578.15
11	Screw guide system Servo system	F(t) = 1-exp(-t/3961.90)^0.60	5960.98
12	Pneumatic system Lubrication system	F(t) = 1-exp(-t/7200.53)^2.39	6382.66

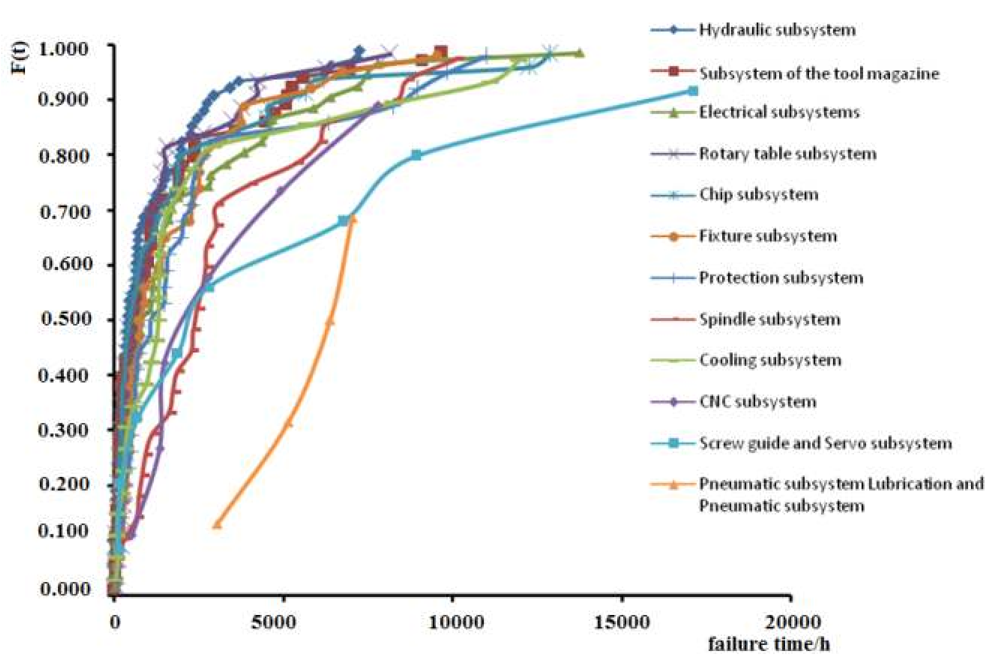

Fig. 5: The curves of failure distribution functions of subsystems

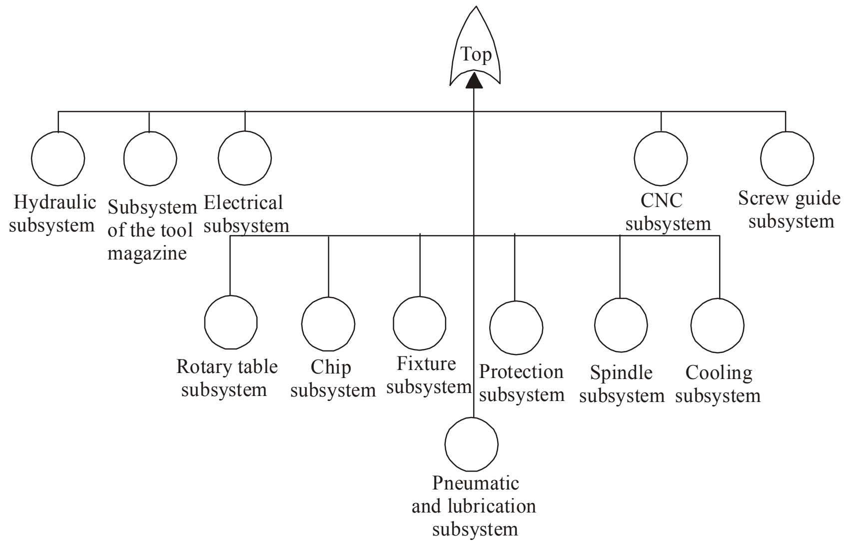

Fig. 6: Fault tree of machining center

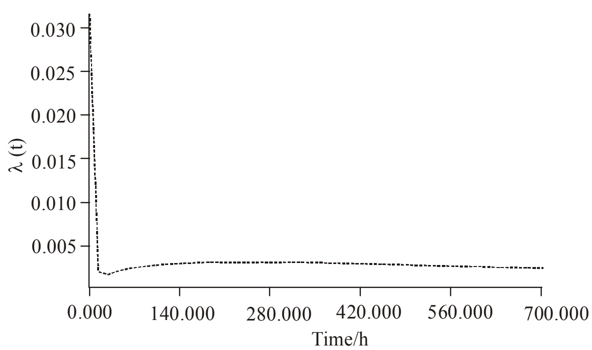

Fig. 7: Failure rate of machining center (Rs) obtained by Blocksim

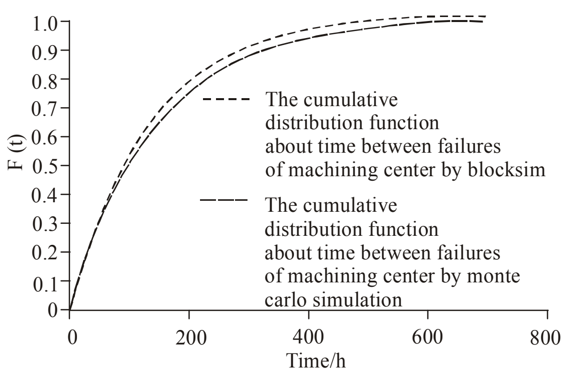

Fig. 8: The cumulative distribution functions obtained by Blocksim and Monte Carlo simulation

From the above analysis, it can be seen that the asymptotic MTBF determined by Blocksim is:

$$\text{MTBF} = 1/\lambda = 1/0.0054 = 185.19h$$

The two failure distribution functions about t got by Blocksim and MC are shown in Fig. 8. From Fig. 8, it is easy to see that the function curve obtained by Monte Carlo methods is close to that obtained by Blocksim.

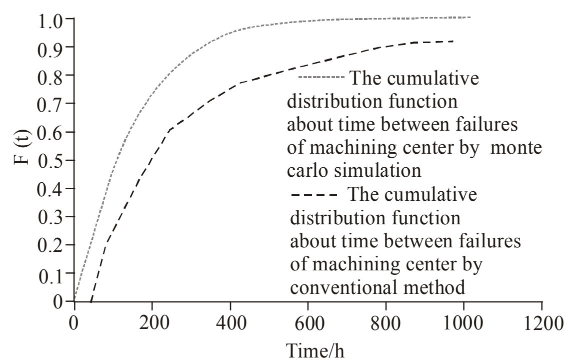

Fig. 9: The cumulative distribution functions obtained by Monte Carlo simulation and the conventional method

As shown in previous section, MTBF determined by MC is equal to 160.42h. Comparing two values of MTBF determined by MC and Blocksim, respectively, the relative error is equal to Δ 1:

$$\Delta 1 = (185.19 - 160.42)/185.19 = 13.38\% \quad (8)$$

Reliability model built by the conventional method: If the failure data are ranked in ascending order, $t_1 \le t_2 \le \ldots \le t_n$ where t_i is the time of i^{th} failure, the reliability model can be obtained by the conventional methods. Therefore, the machining center reliability and failure distribution functions are expressed as:

$$R(t) = e^{(-t/313.16)^{1.38}} \quad (9)$$

$$F(t) = 1 - e^{(-t/313.16)^{1.38}} \quad (10)$$

Then,

$$\text{MTBF} = \int_0^{\infty} e^{(-t/313.1589)^{1.3842}} dt = 286.08h$$

The relative error is equal to Δ2:

$$\Delta 2 = \left|286.08 - 185.19\right| / 185.19 = 35.27\% \quad (11)$$

And two failure distribution functions obtained by the conventional method and MC are plotted in Fig. 9. From Fig. 9 it can be seen that the cumulative distribution function got by the proposed method at any point of t is always higher than that of the other method.

The results show that, the accuracy of reliability model using MC method is higher than that of the conventional modelling method.

CONCLUSION

As an improvement to the conventional reliability modelling method, a modified reliability modelling method by MC is proposed in this study. Using reliability models of subsystems of machine tools, we built reliability model of machine tools according to the reliability block diagram. Considering the fact that the time between failures of machine tools follows Weibull distribution, we fitted the failure data generated by MC to Weibull distribution.

In comparison with the conventional reliability modelling method, the proposed method has the following advantages:

- The reliability models of subsystems can make full use of the failure data of NC machine tools to improve the utilization rate of failure data
- The proposed reliability modelling method can be used on the assumption that machine tools are repaired as old as before. The assumption makes the reliability model more in line with the actual situation and the model built by the proposed method is more accuracy than that built by the conventional method for complicated systems such as NC machine tools
- The reliability model established by the proposed method is applied in the case that one is cautious about reliability. And the reliability model established by the conventional method is preferred when one keep radical attitude

Finally, we point out that the proposed method does not take into account the maintainability and mutual influences of failues. It is expected that the proposed reliabiltiy modelling method can find more applications in reliability engineering of NC machine tools in the future.

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