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Fault Tree Analysis of Feeding Control System for Computer Numerical Control Heavy-Duty Horizontal Lathes with Multiple Common Cause Failure Groups

MI Jinhua (米金华), *LI Yanfeng* (李彦锋), *PENG Weiwen* (彭卫文)
YANG Yuanjian (杨圆鉴), *HUANG Hongzhong*[*] (黄洪钟)
(Institute of Reliability Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China)

Abstract: The lathes are basic machine tools for manufacturing cylindrical parts. In recent years, the DL-series computer numerical control (CNC) heavy-duty horizontal lathes (HDHLs) have been widely used in the transportation, energy and aviation industries. High availability of the CNC heavy-duty lathes is demanded to guarantee the efficiency and benefit of these manufacturing industries. As one of the key subsystems of the HDHLs, the feeding control system is studied in this paper on reliability modeling and reliability analysis. The fault tree analysis (FTA) method is used for reliability modelling of the feeding control system. Considering the multiple common cause failure groups (CCFGs) existing in the system, a modified beta factor parametric model is introduced to model the common cause failure (CCF) in system. The reliability of feeding control system is then obtained and the effect of CCF on the reliability of the whole system is studied as well.
Key words: fault tree analysis (FTA), feeding control system, heavy-duty horizontal lathes (HDHLs), common cause failure groups (CCFGs), modified beta factor model
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0 Introduction

In recent decades, the research of heavy-duty horizontal lathes (HDHLs) has attracted extensive attentions[1-5]. The DL-series horizontal lathes belong to HDHLs which are used for the turning operation of rotational parts with outside and inside surfaces, such as axles and disc. Such DL-series lathes have optional attachments, including milling tool carriage, end-face tool carriage for boring and turning, grinding head and so on. It can satisfy the rough and finishing machining with high precision for modern large equipment. Therefore, the DL-series lathes have been widely used in energy, transportation, aerospace and other heavy machinery manufacturing industry. The DL-series horizontal lathes are computer numerical control (CNC) types and have the following work axes: X axis of tool head lateral movement, Z axis of tool head longitudinal movement, U_1 axis of left gang tool movement, and U_2 axis of right gang tool movement. The advanced technology of full close-loop control has been implanted on the X and Z axes, and there is linkage with each other. The grating scales are used for position detection. U_1 and U_2 axes use the Siemens's absolute value encoders to detect the position, and it is a half closed-loop control.

The electrical control and drive system for DL-series CNC HDHL is composed of 8 subsystems. Power control system and lubrication system are used to provide lathe with steady power and hydraulic pressure. Tailstock movement control system and control center frame motion system are used to fix the components. The main drive control system and feeding control system are applied for completing the machining process, and other two subsystems are input programmable logic controller (input-PLC) system and out programmable logic controller (output-PLC) system.

The fault tree analysis (FTA) method is used to study the reliability of feeding control system of DL-series CNC HDHLs. For the heavy-duty lathes, the harsh working conditions and the shock caused by environment factor give rise to the common cause failures (CCFs) of components which cannot be ignored[6-8]. A modified beta factor parametric method is used to cope with the multiple CCF groups (CCFGs) within the system. Then the system reliability and failure rate are computed through the quantitative analysis of fault tree.

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∗**E-mail:** hzhuang@uestc.edu.cn

1 Fault Tree Modeling of Feeding Control System

The block diagram of the electrical control and drive system for such DL-series horizontal lathes is shown in Fig. 1. The feeding control system include 3 subsystems: X, Z, as well as U_1 and U_2 axes feeding control systems. A signal generated by 611D-type servo driven module (Mo) is transmitted through electric wire (Ew) to control the motor (Mt) in X axis feeding control system. There exists a speed feedback device (Sf). The grating scales (Gr) feedback the straightness of X axis to Mo to adjust the feed speed and direction. The electrical control of Z, U_1 and U_2 axes is almost the same as that of X axis. Although U_1 and U_2 axes share a 611D-type servo driven module, they yet have different current relays (Re).

Based on the function analysis and failure mechanism analysis of feeding control system, the "functional failure of feeding control system" has been chosen as the top event in FTA. The main functional failure modes of the system include motor that cannot be started, overshooting of axes, short circuit, damage of electronic units, exceeded standards of geometric accuracy, crack of structure, etc. In this section, we have simplified the fault tree to component level without including a deeper failure analysis to the part level. Therefore, the fault tree of feeding control system is constructed and shown in Fig. 2.

The meanings of the notations in Fig. 2 are as follows:

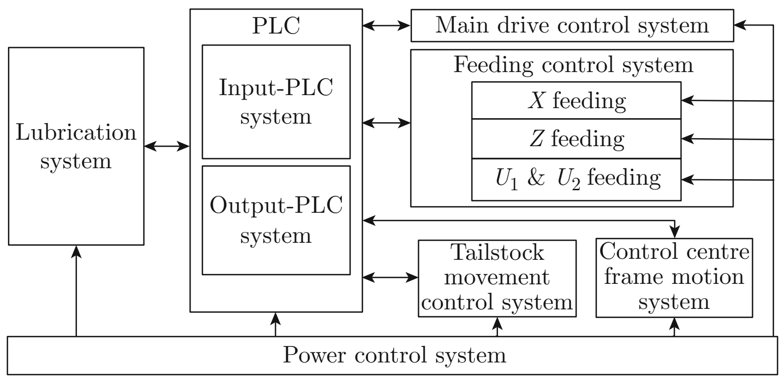

Fig. 1 The structure of electrical control and drive system for the DL-series CNC HDHL

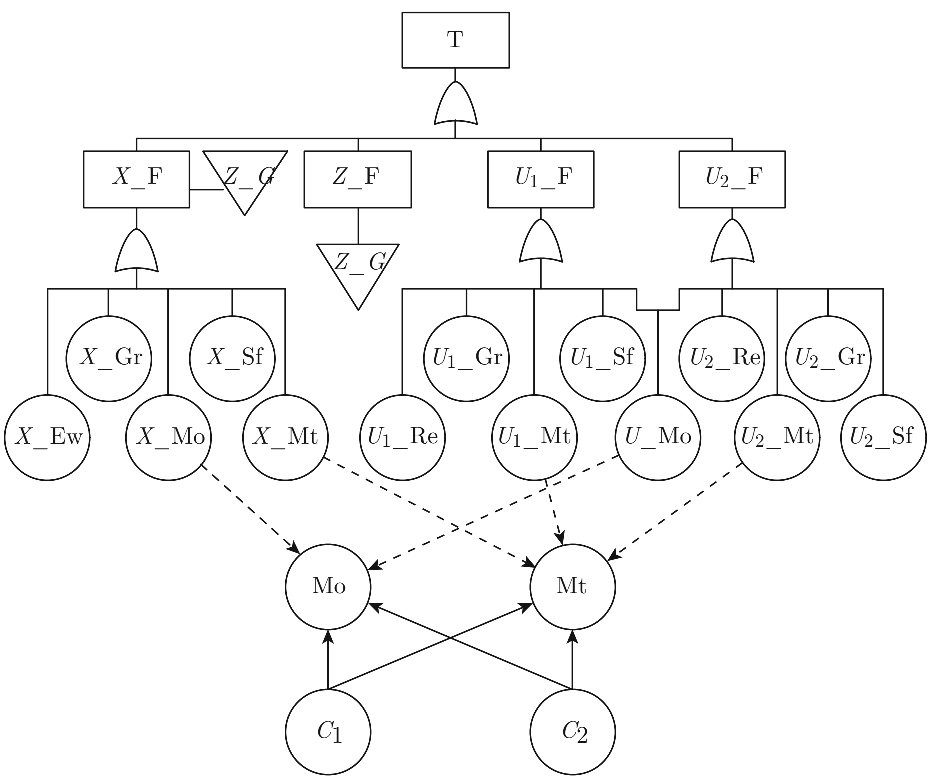

Fig. 2 Fault tree model of the feeding control system

T denotes the functional failure of feeding control system; X_F, Z_F, U_1_F and U_2_F are the functional failures of X, Z, U_1 and U_2 axes feeding control systems. The basic components of each axis feeding control system include Gr, Sf, Ew, Mo, Mt and Re. Therefore, in the fault tree model, the failure events of basic components are noted by two parts: the code of axes and the code of each component. For example, X_Ew represents the Ew failure of X axis feeding control system, and the other notations follow the similar interpretations.

Considering the CCF caused by interior component physical interactions C_1 and human interactions C_2 in system,

CCFG$_1$={X_Mo, Z_Mo, U_Mo},

CCFG$_2$ ={X_Mt, Z_Mt, U_1_Mt, U_2_Mt}

are used to represent the CCFGs caused by these two factors. They exist between Mo and Mt, as shown in Fig. 2.

2 Modified Beta Factor Parametric Model for Multiple CCFGs

Considering the dependent failure caused by interior component physical interactions and human interactions in system, the beta factor parametric model[9] has been widely used for such cases. Assuming $P_{\rm t}$ is the total failure probability of a component, it can be expanded into an independent contribution $P_{\rm ind}$ and a dependent contribution $P_{\rm ccf}$ ($P_{\rm ind}$ and $P_{\rm ccf}$ are functions of time t). When the component is assumed to follow the exponential distribution, $\lambda_{\rm t}$, $\lambda_{\rm ind}$ and $\lambda_{\rm ccf}$ are failure rates of the entire system, independent part and dependent part, respectively. Then the parameter β can be defined as the fraction of the total failure probability attributable to dependent failures[10], and it can be mathematically described as

$$\beta = \frac{P_{\rm ccf}}{P_{\rm t}} = \frac{P_{\rm ccf}}{P_{\rm ind}+P_{\rm ccf}} = \frac{1-\exp(-\lambda_{\rm ccf}t)}{1-\exp(-\lambda_{\rm t}t)} = \frac{1-\exp(-\lambda_{\rm ccf}t)}{1-\exp(-\lambda_{\rm ind}t)+1-\exp(-\lambda_{\rm ccf}t)}. \quad (1)$$

The value of β-factor can be obtained by the direct use of field data and experts' experience. The range of β is from 0 to 0.25, in general, for hardware failure; it will be in the range of 0.001 to 0.10 for human failure. The value of β-factor reflects the sensitive of the associated components to environmental stressors, including physical and human interactions.

A simple deduction is performed for signal component within the FTA model in order to present how the beta factor model works. For a basic component A, the failure probability of A can be divided into two proportions: independent part and CCF parts, and it can be expressed as

$$P_A = P_{A\_{\rm ind}} + P_{A\_{\rm ccf}}. \quad (2)$$

For the CCF parts, the failure probability is

$$P_{A\_{\rm ccf}} = \beta P_A. \quad (3)$$

When a single component fails simultaneously within multiple CCFGs[7], a modified beta factor parametric model is used to express the coupling mechanism. The explicit modelling of component A with multiple CCFGs is shown in Fig. 3.

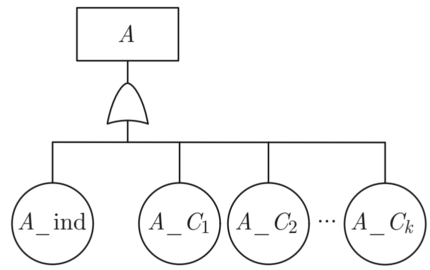

Fig. 3 Explicit modelling of multiple CCFGs within fault tree

The failure probability of component A is given as follows

$$P_A = P_{A\_{\rm ind}} + P_{A\_{\rm ccf}} = P_{A\_{\rm ind}} + P_{A\_C_1\cup\cdots\cup A\_C_k} = P_{A\_{\rm ind}} + P_{A\_C_1} + \cdots + P_{A\_C_k}. \quad (4)$$

In this way, the failure probability of component A is divided into CCF parts and independent part as follows

$$P_{A\_{\rm ccf}} = P_{A\_C_1} + P_{A\_C_2} + \cdots + P_{A\_C_k} = \beta_1 P_A + \beta_2 P_A + \cdots + \beta_k P_A = P_A \sum_{i=1}^{k} \beta_k, \quad (5)$$

$$P_{A\_{\rm ind}} = \Big(1 - \sum_{i=1}^{k} \beta_k\Big) P_A. \quad (6)$$

Because the beta factors are obtained by expert judgments, there exists the limitation of this modified beta factor parametric model for $\beta_1 + \beta_2 + \cdots + \beta_k > 1$. In this case, the failure probability of CCF parts is bigger than the probability of total components. A proportional reduction factor (PRF) method[7] is applied in this paper to cope with this limitation in the model. The PRF factor is defined as follows

$$\text{PRF} = \Big(\sum_{j=1}^{k} \beta_j\Big)^{-1}. \quad (7)$$

Then a set of new reduced beta factor can be generated as follows

$$\boldsymbol{\beta} = [\beta_1' \quad \cdots \quad \beta_k'] = \mathrm{PRF}[\beta_1 \quad \cdots \quad \beta_k]. \tag{8}$$

In this way, the failure probabilities of CCF parts and independent part are rewritten as

$$P_{A\_\mathrm{ccf}} = P_A \sum_{i=1}^{k} \beta_k', \tag{9}$$

$$P_{A\_\mathrm{ind}} = \Big(1 - \sum_{i=1}^{k} \beta_k'\Big) P_A = 0. \tag{10}$$

3 Reliability Analysis of Feeding Control System

According to the logical relation of fault tree and the rule of Boolean calculation, the Semanderes method[11] which means the bottom-up method is used to identify the minimal cut sets (MCSs) of the fault tree for the feeding control system.

By carrying out the bottom-up method, the bottom level of the fault tree is given by

$$X\_\mathrm{F} = X\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Ew} \cup \mathrm{Mo} \cup \mathrm{Mt}),$$
$$Z\_\mathrm{F} = Z\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Ew} \cup \mathrm{Mo} \cup \mathrm{Mt}),$$
$$U_1\_\mathrm{F} = U_1\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Re} \cup \mathrm{Mt}) \cup U\_\mathrm{Mo},$$
$$U_2\_\mathrm{F} = U_2\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Re} \cup \mathrm{Mt}) \cup U\_\mathrm{Mo}.$$

The top level can be expressed as

$$\begin{aligned} T = {} & X\_\mathrm{F} \cup Z\_\mathrm{F} \cup U_1\_\mathrm{F} \cup U_2\_\mathrm{F} = \\ & X\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Ew} \cup \mathrm{Mo} \cup \mathrm{Mt}) \cup \\ & Z\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Ew} \cup \mathrm{Mo} \cup \mathrm{Mt}) \cup \\ & U_1\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Re} \cup \mathrm{Mt} \cup \mathrm{Mo}) \cup \\ & U_2\_(\mathrm{Gr} \cup \mathrm{Sf} \cup \mathrm{Re} \cup \mathrm{Mt} \cup \mathrm{Mo}). \end{aligned} \tag{11}$$

From the Boolean calculation of Eq. (11), there are 19 MCSs of the feeding control system: $\{X\_\mathrm{Gr}\}$, $\{X\_\mathrm{Sf}\}$, $\{X\_\mathrm{Ew}\}$, $\{X\_\mathrm{Mo}\}$, $\{X\_\mathrm{Mt}\}$, $\{Z\_\mathrm{Gr}\}$, $\{Z\_\mathrm{Sf}\}$, $\{Z\_\mathrm{Ew}\}$, $\{Z\_\mathrm{Mo}\}$, $\{Z\_\mathrm{Mt}\}$, $\{U_1\_\mathrm{Gr}\}$, $\{U_1\_\mathrm{Sf}\}$, $\{U_1\_\mathrm{Re}\}$, $\{U_1\_\mathrm{Mt}\}$, $\{U_2\_\mathrm{Gr}\}$, $\{U_2\_\mathrm{Sf}\}$, $\{U_2\_\mathrm{Re}\}$, $\{U_2\_\mathrm{Mt}\}$ and $\{U\_\mathrm{Mo}\}$.

Assume that the lifetime of all components follows the exponential distribution. By referring the literature and relevant studies, as well as integrating the knowledge of various relevant experts, the failure rate λ and failure probability P ($t = 3\,000$ h) of basic components of feeding control system are given in Table 1.

The failure probability of top event T at $t = 3\,000$ h

Table 1 The failure rate of components

Code	$\lambda \times 10^{-6}/\mathrm{h}^{-1}$	P
Mo	0.2	0.000 6
Ew	0.6	0.001 8
Gr	2	0.006 0
Mt	7	0.020 8
Sf	0.5	0.001 5
Re	2	0.006 0

can be calculated as follows

$$\begin{aligned} P_T = {} & 1 - (1 - P_{X\_\mathrm{F}})(1 - P_{Z\_\mathrm{F}})(1 - P_{U_1\_\mathrm{F}})(1 - P_{U_2\_\mathrm{F}}) = \\ & 1 - \prod_{i=1}^{19} (1 - P_{\mathrm{MCS}}) = \\ & 1 - \prod_{i=1}^{19} (1 - (1 - \mathrm{e}^{-\lambda_i t})) = 0.123\,1. \end{aligned} \tag{12}$$

The common cause factor C_1 and C_2 can affect the reliability of Mo and Mt simultaneously, as shown in Fig. 2. Accordingly, the failure probabilities of Mo and Mt can be divided into two parts: independent and dependent parts. The modified beta factor parametric model in Section 2 is used to cope with the multiple CCFGs in system. From Eqs. (2) to (6), the failure probabilities of basic components Mo and Mt can be obtained as follows

$$\begin{aligned} P_{\mathrm{Mo}} = {} & P_{\mathrm{Mo\_ind}} + P_{\mathrm{Mo\_ccf}} = \\ & P_{\mathrm{Mo\_ind}} + P_{\mathrm{Mo\_}C_1 \cup \mathrm{Mo\_}C_2} = \\ & P_{\mathrm{Mo\_ind}} + \frac{\beta_{\mathrm{Mo\_1}} + \beta_{\mathrm{Mo\_2}}}{1 - (\beta_{\mathrm{Mo\_1}} + \beta_{\mathrm{Mo\_2}})} P_{\mathrm{Mo\_ind}} = \\ & \frac{1}{1 - (\beta_{\mathrm{Mo\_1}} + \beta_{\mathrm{Mo\_2}})} P_{\mathrm{Mo\_ind}}. \end{aligned} \tag{13}$$

$$\begin{aligned} P_{\mathrm{Mt}} = {} & P_{\mathrm{Mt\_ind}} + P_{\mathrm{Mt\_ccf}} = \\ & \frac{1}{1 - (\beta_{\mathrm{Mt\_1}} + \beta_{\mathrm{Mt\_2}})} P_{\mathrm{Mt\_ind}}. \end{aligned} \tag{14}$$

where $\beta_{\mathrm{Mo\_1}}$, $\beta_{\mathrm{Mo\_2}}$, $\beta_{\mathrm{Mt\_1}}$ and $\beta_{\mathrm{Mt\_2}}$ are the beta factors of CCFG_1 and CCFG_2 caused by C_1 and C_2, respectively, and reflect the sensitivities of Mo and Mt to C_1 and C_2. In this paper, according to the experts' judgment, these beta factors are set as $\beta_{\mathrm{Mo\_1}} = 0.1$, $\beta_{\mathrm{Mo\_2}} = 0.15$, $\beta_{\mathrm{Mt\_1}} = 0.1$ and $\beta_{\mathrm{Mt\_2}} = 0.05$.

By using Eqs. (13) and (14) to update the failure probability of corresponding components (Mo and Mt) in Eq. (12), the failure probability of system with multiple CCFGs at $t = 3\,000$ h is computed and equals to 0.136 7. Meanwhile, the curve of reliability R of the entire feeding control system is obtained and shown in Fig. 4.

From Fig. 4 we can see that the reliability of the system is 0.876 9 at $t = 3\,000$ h. Comparing this result with

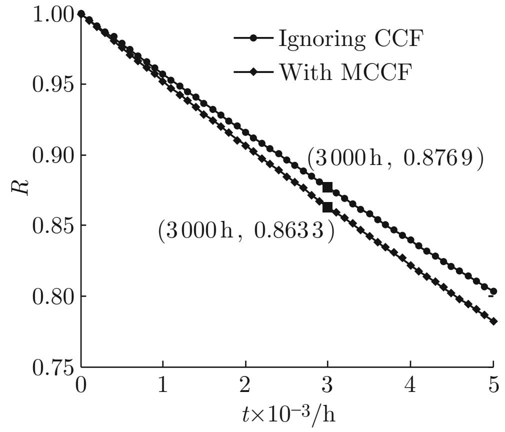

Fig. 4 The system reliability curves

the case that multiple CCFGs in system are considered, we can conclude that the CCF has a remarkable effect on the reliability of feeding control system. When the lifetime of system is assumed to obey exponential distribution, the system failure rate can be calculated and it is approximated to $6.633\,2 \times 10^{-4}\,\mathrm{h}^{-1}$.

4 Conclusion

In this paper, the reliability analysis of the feeding control system of DL-series HDHL has been investigated. Firstly, the fault tree model is constructed based on the functional analysis and failure mechanism analysis. Then, considering the multiple CCFGs in the system, the modified beta factor parametric model is used to model the effect of CCFGs. Finally, the reliability of the system is calculated. It equals to 0.876 9 at $t = 3\,000\,\mathrm{h}$ without considering CCF, and is 0.863 3 under the effect of CCF. The failure rate of the feeding control system is approximated to $6.633\,2 \times 10^{-4}\,\mathrm{h}^{-1}$ under the assumption of exponential distribution components. This paper quantifies the effect of CCF on the entire system and also provides a practical way for the reliability analysis of system with multiple CCFGs.

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