

Analysis on dynamic precision reliability of high-speed precision press based on Monte Carlo method

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Received: 14 April 2017 / Accepted: 7 October 2017 / Published online: 14 October 2017
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Abstract The high-speed precision press is used widely in modern industrial production, particularly in the production of precision parts. The dynamic repeated precision of bottom dead center (BDC) measurement not only affects the quality of stamped parts, but also determines the service life of the pattern. In this paper, the influence of machining error, elastic deformation and joint clearance on the reliable precision reliability of a slider was analyzed. A method of analyzing instantaneous dynamic BDC press precision is presented. Finally, the reliability of the press is evaluated using time-varying reliability in the nominal force travel range. Taking the JF75G-300 high-speed press as an example, the motion precision reliability model of the crank slider mechanism is developed; the BDC position of the press under different speeds is simulated using the Monte Carlo simulation method, and experiments are conducted on the BDC position of the punch with no load. Experimental results and simulated results are similar, demonstrating feasibility of the proposed method.

Keywords High-speed precision press · Dynamic accuracy · Reliability · Monte Carlo simulation

1 Introduction

With high precision, high efficiency and automation capabilities, the high-speed precision press is widely used in the production of automotive parts, precision transmission parts, mobile computer parts, electronic components and products. With the recent development of domestic appliances and advances in the IT industry, demand for small precision stamping parts grows rapidly. The high-precision requirements for these parts translate to a need for precision of the stamping press [1]. Research on the dynamic precision of a press can significantly improve the quality of stamped parts. Currently, most research has been conducted regarding the dynamic precision of the bottom dead center (BDC) measurement of the high-speed precision press [2–5]. The dynamic precision of the BDC is mostly determined by machining error, elastic deformation and joint clearance [6, 7].

Components of the high-speed press inevitably generate errors in the manufacturing process. The accumulation of these errors directly affects the BDC dynamic precision. Li et al. [8] defined the minimum crack length and the maximum punching angle as an evaluation index established a comprehensive optimized model of the press using MATLAB. Yang et al. [9] determined the optimized structural design based on the parameters of an actual press.

At higher speeds, the force of inertia in the slider in the high-speed precision press is significant. During the process of stamping, the bar experiences vary-

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ing degrees of elastic deformation; thus, each component cannot be regarded as a rigid body. Hu et al. established an multi-linkage dynamic model for the high-speed precision press and analyzed the influence of elastic deformation and elastic waves on accuracy of the BDC measurement. The dynamic equation was solved through the method of mode superposition [10]. The dynamic response of the crank link mechanism was analyzed by considering the harmonic drive and link flexibility found in the literature [11]. Guan P P established the overall rigid flexible high-speed coupling dynamic model of the press [12]. In this work, the effects of an unbalanced inertia force and punching force on the overall characteristics of the high-speed press was analyzed in the context of BDC accuracy and vibration.

Joint clearance is a key factor affecting dynamic accuracy of BDC measurements of a high-speed precision press; the impact of joint clearance on the system is currently an area of significant interest in the field of high-speed precision press analysis. Much research has been conducted on the motion of the joints with clearance [13–15]. Khemili et al. examined dynamic behavior of a planar flexible slider–crank mechanism with clearance. They found that in the presence of clearance, the coupler flexibility acts as suspension for the mechanism [13]. The influence of various parameters on the dynamic characteristics of the slider mechanism with clearance was studied using the three state model of Flores [15]. Hu et al. established a dynamic model of the high-speed precision press and analyzed the influence of joint motion on the model clearance under varying loads. This work established the heat balance equation of joint clearance and analyzed the temperature of the high-speed precision press crankshaft [16]. Guan analyzed the influence of speed, static equilibrium pressure, joint clearance and other factors on the BDC precision. In this experiment, they determined the optimal combination of different factors for the JF75G-200 high-speed precision press [17].

The overarching goal of the above work is to establish a suitable model to analyze the BDC position error and to determine the influence of each parameter on the bottom dead center accuracy. Much research has been conducted on the dynamic characteristics of the high-speed precision press; however, there has been less emphasis on the reliability of the bottom dead center accuracy. This paper introduces an analysis of BDC accuracy along with analysis of the instantaneous reli-

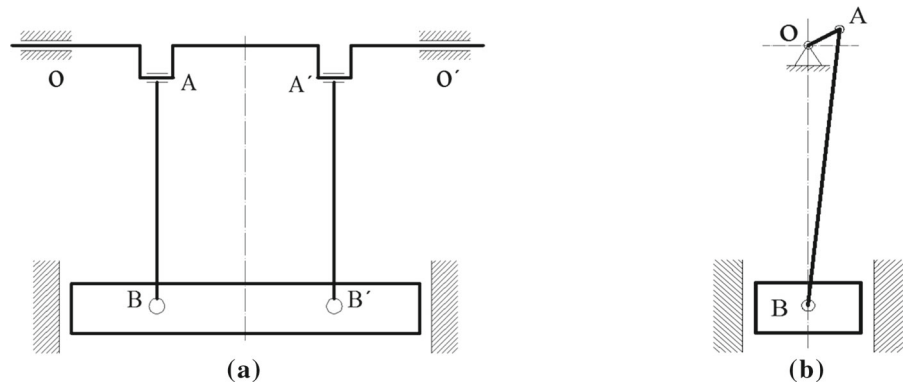
ability of BDC accuracy and evaluates the reliability of the press according to the time-varying reliability of the nominal force travel range.

Yang et al. has also conducted research on this subject [18–22]. By establishing the reliability model of each subsystem, and then using sample failure data produced by Monte Carlo simulations, they established a machine assembly reliability function using a radial basis function and a linearization technique to solve the inverse reliability function [21]. Pang analyzed the influence of machining error, structural deformation, joint clearance and hinge wear on the reliability of kinematic accuracy of the planar linkage mechanism [23]. Using a low-speed discontinuous contact model and a high-speed continuous contact model, Zhang analyzed the influence of joint clearance on the kinematic accuracy of the crank slider mechanism [24]. To improve upon existing kinematic reliability methods, Wang et al. proposed a hybrid dimension reduction method (HDRM) to better handle the dependent joint clearance variables. A slider–crank mechanism was to demonstrate validity of the proposed methodology [25]. Liu et al. analyzed the reliability of the high-speed punch crankshaft using finite element analysis software with probability design function (PDS ANSYS module) [26].

Zheng et al. used Solid Works to build the solid model of high-speed precision press prototype and imported Adams to build a rigid model of virtual prototype. The model of gap contact collision was established by using Hertz contact stiffness theory and considering damping effect. After the main linkage was flexible, a parametric rigid flexible coupling virtual prototype model with clearance was established. They set the appropriate parameters of the simulation based on the dynamic simulation of the prototype model, influencing rules of clearance, speed and load on the dynamic precision of dead press, which can provide reference for the optimal combination of parameters under the dead point precision [27].

Based on the Darren Bell principle, Li established the dynamic statics equations of the mechanism, carried out the dynamic simulation of the mechanism in ADAMS and established the three-dimensional model of the drive mechanism in solid works. As an example to multi-rod drive, he analyzed the influence of manufacturing errors, elastic deformation, clearance and other factors and their coupling effects on the reliability of slider motion accuracy, precision machining,

Fig. 1 JF-75G-300 press driving mechanism. **a** Diagram of driving mechanism, **b** Crank slider mechanism



driving mechanism optimization of stiffness, backlash [28].

The second part of this paper uses the punch JF75G-300 as an example to establish a reliability model of the kinematic accuracy of a crank slider mechanism and to determine the function of the BDC motion precision reliability of the press. The third section analyzes the factors that influence reliability, including the machining error, elastic deformation and joint clearance. A Monte Carlo simulation of the BDC dynamic precision of the high-speed press is carried out in the fourth and fifth sections. In the sixth section, a physical experiment is carried out using the JF75G-300 punch press. The seventh section presents a concluding summary by comparing simulation results with experimental results.

2 Kinematic accuracy of crank slider mechanism’s reliability calculation model

The diagram of driving mechanism of JF75G-300 press is shown in Fig. 1a. In order to simplify the calculation model, the crank slider mechanism of the left half part is analyzed only for the symmetry of the mechanism, as shown in Fig. 1b.

Assume that the crank OA is r , the link AB is l , the crank angular velocity is ω , the nominal force travel time is $[t_0, t_f]$ and $t_f \geq t_0$, the bottom dead center time of press is t_1 . So the ideal value for the output displacement of point B of the slider crank mechanism is:

$$y_B^*(t) = r \cos(\omega t) + \sqrt{l^2 - r^2 \sin^2(\omega t)}$$

Taking the machining error, the axial elastic deformation of the link and the clearance of joint A and joint B into consideration, the actuals length of the crank and

link are R and L , respectively. so the actual value of the output displacement of point B of the slider is:

$$y_B(t) = R \cos(\omega t) + \sqrt{L^2 - R^2 \sin^2(\omega t)}$$

And the output displacement error of the point B of the slider is:

$$\Delta y_B(t) = y_B(t) - y_B^*(t)$$

The mean value of the output displacement error is:

$$\mu_{\Delta y_B}(t) = \left(\cos(\omega t) - \frac{R \sin^2(\omega t)}{E} \right) \mu_{\Delta R} + \frac{L}{E} \mu_{\Delta L} \tag{1}$$

In (1), $E = \sqrt{L^2 - R^2 \sin^2(\omega t)}$

The variance of output displacement error is:

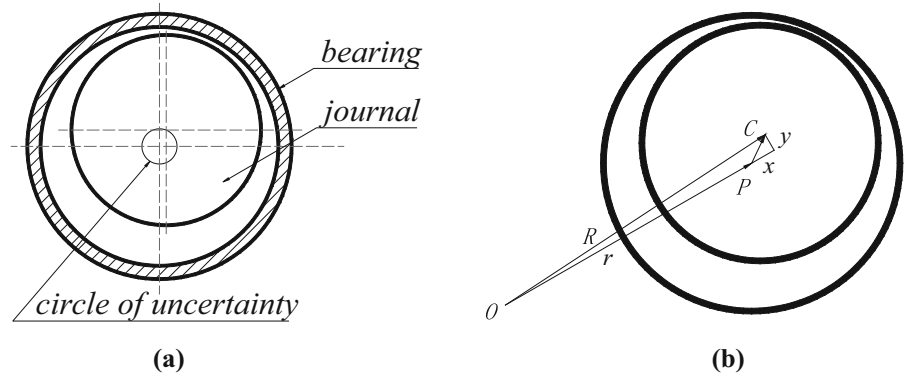
$$\sigma_{\Delta y_B}^2(t) = \left(\frac{\partial y_B}{\partial r} \right)^2 (\sigma_{\Delta R}^2 + \sigma_{x_1}^2) + \left(\frac{\partial y_B}{\partial l} \right)^2 (\sigma_{\Delta L}^2 + \sigma_{x_2}^2) \tag{2}$$

In (2), ΔR and ΔL are the actual rod length error of crank and link, respectively. x_1 and x_2 are the local coordinates of the center of the pin in the long direction of the rod in the effective length model of joint O and joint A, respectively.

It is generally believed that the output displacement error of mechanism is always obey normal distribution of normal distribution. According to the definition of the reliability of the motion precision of the mechanism, we get Eq. (3).

$$R(t) = \Phi \left(\frac{-\varepsilon - \mu_{\Delta y_B}(t)}{\sigma_{\Delta y_B}(t)} \right) \leq \frac{\Delta y_B(t) - \mu_{\Delta y_B}(t)}{\sigma_{\Delta y_B}(t)} \leq \frac{\varepsilon - \mu_{\Delta y_B}(t)}{\sigma_{\Delta y_B}(t)} \tag{3}$$

Fig. 2 Model with joint clearance. **a** Joint clearance, **b** Effective connection model



In (3), ε is the limit displacement error of the slider B.

Substituting Eqs. (1) and (2) into Eq. (3), and taking $t = t_1$, we can get the reliability of press of BDC motion precision of press, as shown in Eq. (4).

$$R(t_1) = \Phi \left(\frac{-\varepsilon - \mu_{\Delta y_B}(t_1)}{\sigma_{\Delta y_B}(t_1)} \leq \frac{\Delta y_B(t_1) - \mu_{\Delta y_B}(t_1)}{\sigma_{\Delta y_B}(t_1)} \right) \leq \frac{\varepsilon - \mu_{\Delta y_B}(t_1)}{\sigma_{\Delta y_B}(t_1)} \tag{4}$$

Time-varying reliability of mechanism motion precision refers to the probability of mechanism motion precision which conforms to a prescribed motion within a range of motion. The Poisson process theory is used to model and solve the variant reliability of press dead position in nominal power stroke interval $[t_0, t_f]$ in this paper.

The event “motion accuracy of mechanism failure K times in the range of motion $[t_0, t_f]$ ” is recorded as $\{N(t_0, t) = k\}$, According to the Poisson process theory, the failure model of mechanism motion accuracy is proposed as follows:

- (1) It is independent within the non-overlapping motion range.
- (2) It does not occur two times or more failure in a sufficiently small range of motion, that is, $k \leq 1$.
- (3) For a sufficiently small range of motion Δt , there is $P\{N(t_0, t_f) = 1\} = \lambda \Delta t + o(\Delta t)$, when the Δt approaches to zero, and $o(\Delta t)$ is the higher-order infinitesimal of Δt .

According to the Poisson process theory, the probability of mechanism motion precision of failure k times in $[t_0, t_f]$ can be obtained as shown in Eq. (5).

$$P_k(t_0, t_f) = P \{N(t_0, t) = k\} = \frac{\left[\int_{t_0}^{t_f} \lambda(t) dt \right]^k}{k!} e^{-\int_{t_0}^{t_f} \lambda(t) dt} \tag{5}$$

It can be obtained by condition (3).

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \frac{P_1(t, t + \Delta t)}{\Delta t} \tag{6}$$

If $k = 0$, the probability of mechanism motion precision that does not failure in the range of motion can be obtained as shown in Eq. (7).

$$P_0(t_0, t_f) = e^{-\int_{t_0}^{t_f} \lambda(t) dt} \tag{7}$$

Taking $k = 1$ and substituting Eq. (6) into Eq. (5), the time-varying reliability of slider in $[t_0, t_f]$ can be obtained as Eq. (8).

$$R(t_0, t_f) = R(t_0) * e^{-\int_{t_0}^{t_f} \lambda(t) dt} \tag{8}$$

3 Determining the distribution parameters of reliability influencing factors

The dynamic precision of BDC of high-speed precision press is mainly affected by machining error R_c , elastic deformation ΔL and joint clearance L_0 . It is generally believed that machining error R_c and elastic deformation ΔL of component λ are follow normal distribution [23].

$$\begin{cases} \Delta L \sim N(\mu_{\Delta L}, \sigma_{\Delta L}^2) \\ L_0 \sim N(\mu_{L_0}, \sigma_{L_0}^2) \end{cases} \tag{9}$$

As shown in Fig. 2, point P is the hole center, point C is the pin center, R is the effective length, r is the

length of the rod, x and y are the local coordinates of the center of the pin that is in the hole, and the center of the pin is randomly distributed in the circle of uncertainty.

Assuming the external diameter of the pin is d_1 , and the internal diameter of the bushing is d_2 , the radial clearance of the joint is as Eq. (10).

$$R_c = \frac{d_2 - d_1}{2} \tag{10}$$

d_1 and d_2 can be checked by GB/T1801-2009. Substituting d_1 and d_2 into Eq. (10),

$$\begin{cases} R_{cmax} = (d_{2max} - d_{1min})/2 \\ R_{cmin} = (d_{2min} - d_{1max})/2 \end{cases} \tag{11}$$

The radial clearance R_c follows the normal distribution for the batched mechanism, so assume the value of confidence probability is 99.73%. So the joint clearance follows the normal distribution.

$$\begin{cases} \mu_{R_c} = (R_{cmax} + R_{cmin})/2 \\ \sigma_{R_c} = (R_{cmax} - R_{cmin})/6 \end{cases} \tag{12}$$

4 Using the Monte Carlo simulation method to simulate the reliability of dynamic precision

The Monte Carlo simulation can avoid some complex probability analysis, and the simulation samples produced are very similar to the samples which truly observed, so this paper uses the Monte Carlo method to simulate the accuracy reliability of the mechanism movement.

According to the infinite divisibility of continuous time, press machine nominal force travel time $[t_0, t_f]$ is divided into n moments.

$$t_j = t_0 + j * \frac{t_f - t_0}{n - 1} \quad (j = 0, 1, \dots, n - 1)$$

Assuming the instantaneous state of the mechanism motion accuracy at the t_j time in i times simulation is S_{ij} , and S_{ij} is performed as shown in the formula (13).

$$S_{ij} = \begin{cases} 1, & |y_B(t_j) - y_B^*(t_j)| \leq \varepsilon \\ 0, & |y_B(t_j) - y_B^*(t_j)| > \varepsilon \end{cases} \tag{13}$$

Therefore, the instantaneous state matrix S of the kinematic accuracy of the mechanism can be obtained.

$$S = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1j} & \cdots & S_{1n} \\ S_{21} & \ddots & \cdots & \cdots & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ S_{i1} & S_{i2} & \cdots & S_{ij} & \vdots & S_{in} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{Nj} & \cdots & S_{Nn} \end{bmatrix} \tag{14}$$

Therefore, the time-varying state of the kinematic accuracy of the mechanism can be expressed as formula (15).

$$S'_{ij} = \prod_{j=1}^j S_{ij} \tag{15}$$

By observing the N groups of sample value of motion precision within each time in the nominal force travel time $[t_0, t_f]$, we can get the time-varying state matrix S' of the mechanism motion precision.

$$S' = \begin{bmatrix} S'_{11} & S'_{12} & \cdots & S'_{1j} & \cdots & S'_{1n} \\ S'_{21} & \ddots & \cdots & \cdots & \cdots & S'_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ S'_{i1} & S'_{i2} & \cdots & S'_{ij} & \vdots & S'_{in} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ S'_{N1} & S'_{N2} & \cdots & S'_{Nj} & \cdots & S'_{Nn} \end{bmatrix}$$

5 Analysis on the simulation results of BDC dynamic precision reliability

JF75G-300 is a classic high-speed press in China, which was manufactured by Xuzhou Forging Machine Tool Group Co., Ltd.. Its major parameters are shown in Table 1. The error distribution parameters which are obtained by analyzing the reliability factors of JF75G-300 punch press are shown in Table 2, and the Carlo Monte simulation of BDC dynamic precision reliability at different speeds is performed.

Figure 3 shows the BDC position of JF75G-300 high-speed press under different speed with no load by the Monte Carlo simulation. Figures 4, 5, 6 and 7 show the BDC position error of JF75G-300 high-speed

Table 1 Major parameters of JF75G-300 high-speed press

Power source	Nominal pressure	Slider travel	Control form	Stroke times
Pneumatic transmission	3000 KN	300 mm	Numerical control	400/min

Table 2 Distributed parameter of elastic deformation at different speeds

Item	Design value (mm)	Rotational speed (r/min)	Elastic deformation ΔL (mm)	Machining error L_0 (mm)	Joint clearance R_C (mm)
Crank	15	150	$N(3.01 \times 10^{-4}, (1.50 \times 10^{-5})^2)$	$N(0.04, 0.008172^2)$	$N(0, 0.00212^2)$
		200	$N(3.66 \times 10^{-4}, (1.83 \times 10^{-5})^2)$		
		250	$N(4.53 \times 10^{-4}, (2.27 \times 10^{-5})^2)$		
		300	$N(5.62 \times 10^{-4}, (2.81 \times 10^{-5})^2)$		
Link	170	150	$N(3.41 \times 10^{-3}, (1.70 \times 10^{-4})^2)$	$N(0.042, 0.014^2)$	$N(0, 0.013^2)$
		200	$N(4.15 \times 10^{-3}, (2.07 \times 10^{-4})^2)$		
		250	$N(5.13 \times 10^{-3}, (2.57 \times 10^{-4})^2)$		
		300	$N(6.37 \times 10^{-3}, (3.18 \times 10^{-4})^2)$		

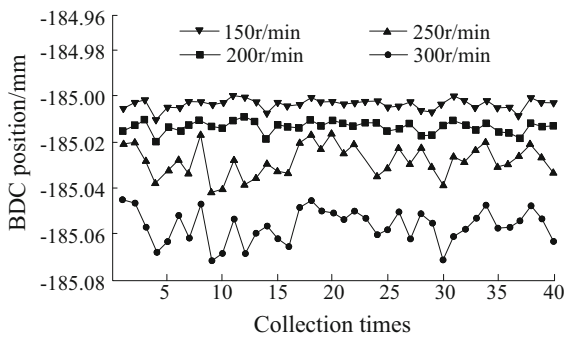


Fig. 3 Positions of down dead point at different speeds

press under different speed with no load by the Monte Carlo simulation.

Figure 3 shows that with the increase in speed with on load, the BDC position gradually shifts downward, and the BDC position fluctuation increases. Figures 4, 5, 6 and 7 show that the slider displacement error under different speed approximately follows the normal distribution. With the increase in velocity of press, the distribution of errors is more dispersed, the variance increases, the fluctuation of displacement error increases obviously and the BDC precision reduces.

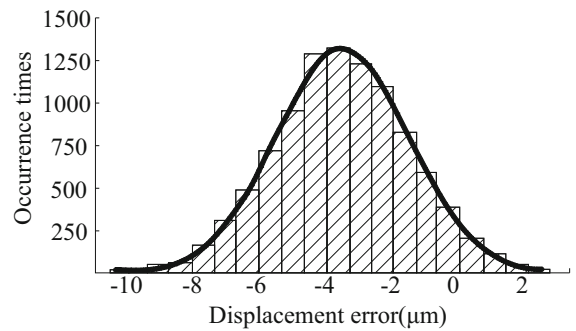


Fig. 4 Distribution of displacement error histogram for BDC at 150 spm

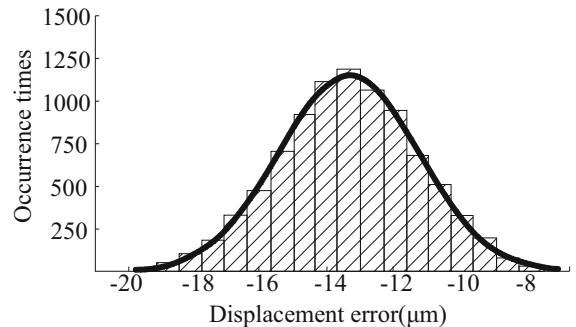


Fig. 5 Distribution of displacement error histogram for BDC at 200 spm

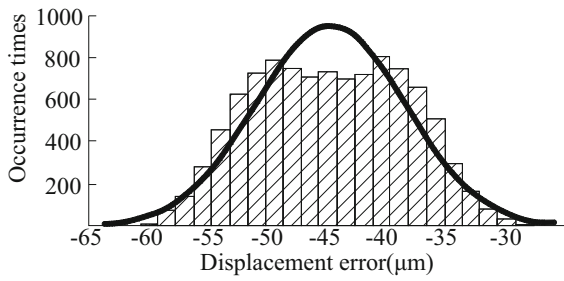


Fig. 6 Distribution of displacement error histogram for BDC at 250 spm

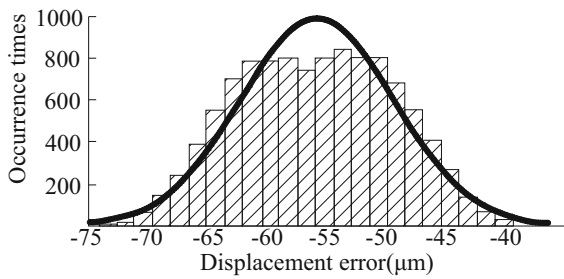


Fig. 7 Distribution of displacement error histogram for BDC at 300 spm

6 Experimental validation of BDC dynamic precision reliability

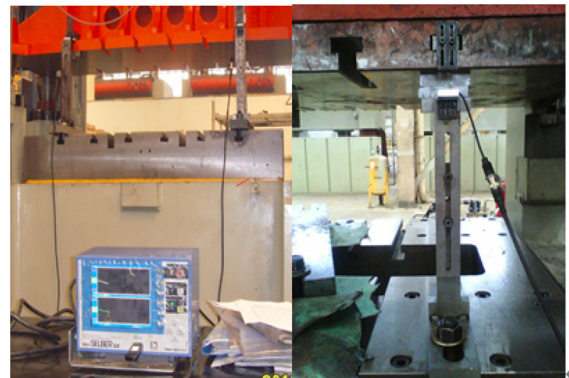
The press and the measuring system for the test is shown in Fig. 8. The proximity body is fixed on the slider, and the sensor is fixed on the test fixture. The measurement procedure is as follows: Place the slider to BDC, fix the proximity body on the lower surface of the slider and adjust the height of test fixture so that the distance between the sensor and the proximity body is about 1.5 mm, and then fix the test fixture with a nut. After starting the punch press, make it work for a period of time to reach the thermal balance, and then begin to measure, and the distance and the data file name of the sensor and the proximity body should be recorded each time before the measurement.

The dynamic precision of JF75G-300 high-speed press is measured with no load under different speed, and the thermal equilibrium data are statistics and analyzed. Forty thermal equilibrium data are taken from each measurement data; we can get the BDC position as shown in Fig. 9.

Taking 10000 measurement data from each thermal equilibrium datum, the initial position, data of the maxi-



(a)



(b)

Fig. 8 Photographs of experimental site by JF75G-300 high-speed press. **a** JF75G-300, **b** test site and sensor arrangement

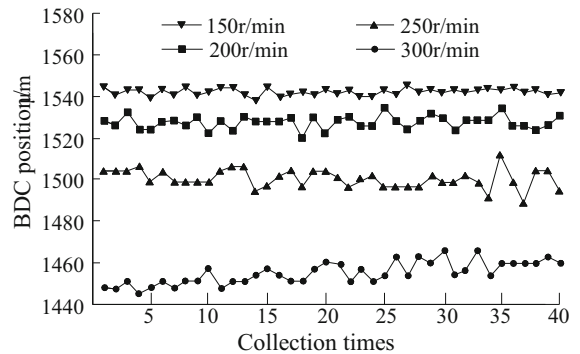


Fig. 9 Positions of BDC at different speeds

imum and minimum, mean μ and variance σ of the measuring data with different speed are shown in Table 3.

Figures 10, 11, 12 and 13 show the distribution histogram of 10,000 thermal equilibrium data for 150, 200, 250 and 300 spm, respectively.

Figure 9 shows, with the increase in velocity of press under on load, the BDC position gradually shifts down-

Table 3 Statistical results of measured data at different speeds

Number of strokes (spm)	Initial position (μm)	Average value (μm)	Variance	Maximum (μm)	Minimum (μm)
150	1584	1542.2	0.0020	1547	1536
200	1564	1524.6	0.0034	1530	1517
250	1543	1493.7	0.0037	1501	1487
300	1518	1445.8	0.0029	1452	1437

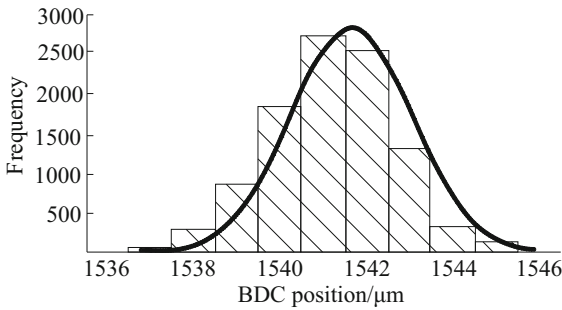


Fig. 10 Distribution of BDC position histogram at the speed of 150 spm

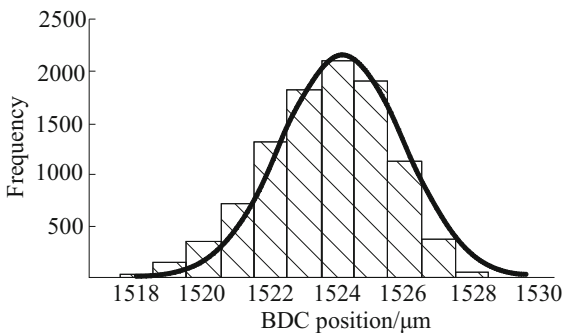


Fig. 11 Distribution of BDC position histogram at the speed of 200 spm

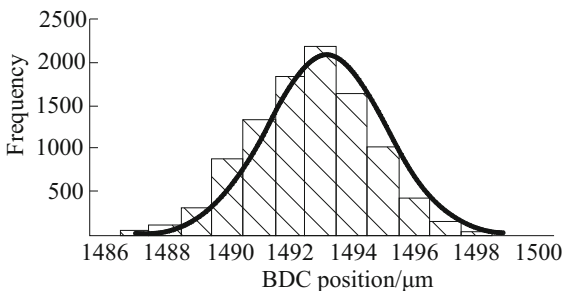


Fig. 12 Distribution of BDC position histogram at the speed of 250 spm

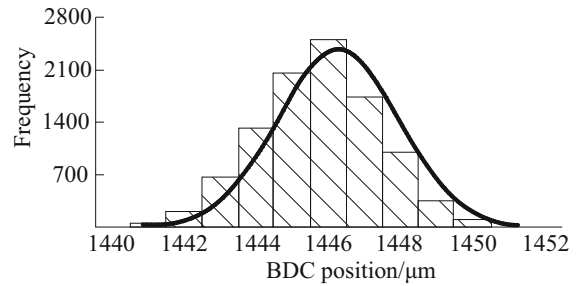


Fig. 13 Distribution of BDC position histogram at the speed of 300 spm

ward. The BDC position under different speed fluctuation in certain error band, and with the increase in speed, the bigger the fluctuation value is.

Figures 10, 11, 12 and 13 show that BDC precision measurement data under different velocities with no load approximately allow normal distribution, and with the increase in speed, the BDC position shifts downward, and the wave momentum increases, and the BDC precision decreases.

When the speed at 150 spm, the maximum value is $1547\ \mu\text{m}$, the minimum value is $1536\ \mu\text{m}$, the fluctuation of the data is $11\ \mu\text{m}$, the mean value of BDC position is $1542.2\ \mu\text{m}$, and the variance is 0.0020.

When the speed at 200 spm, the maximum value is $1530\ \mu\text{m}$, the minimum value is $1517\ \mu\text{m}$, the fluctuation of the data is $13\ \mu\text{m}$, the mean value of BDC position is $1524.6\ \mu\text{m}$, and the variance is 0.0034.

When the speed at 250 spm, the maximum value is $1501\ \mu\text{m}$, the minimum value is $1487\ \mu\text{m}$, the fluctuation of the data is $14\ \mu\text{m}$, the mean value of BDC position is $1493.7\ \mu\text{m}$, and the variance is 0.0037.

When the speed at 300 spm, the maximum value is $1452\ \mu\text{m}$, the minimum value is $1437\ \mu\text{m}$, the fluctuation of the data is $15\ \mu\text{m}$, the mean value of BDC position is $1445.8\ \mu\text{m}$, and the variance is 0.0029.

Table 4 shows the calculation results of Monte Carlo simulation data and experimental measurement data of

Table 4 Instantaneous reliability of kinematic accuracy at different speeds

Sample number (N)	Allowable error ε (mm)	Rotation rate (r/min)	$R_1(t)$	$R_2(t)$
10,000	0.015	150	1	1
		200	1	1
		250	0.9683	0.9805
		300	0.9215	0.8594

BDC dynamic precision, which $R_1(t)$ and $R_2(t)$ are, respectively, the Monte Carlo simulation result and test result of BDC dynamic precision reliability on JF75G-300 press under different speed. Table shows that with the increase in the speed of the press, $R_1(t)$ reduces from 1 to 0.9215, $R_2(t)$ decreases from 1 to 0.8594, and the trend of the changes is similar.

7 Conclusions

By establishing a reliability model of the BDC dynamic precision of the high-speed press, the influence of kinematic pair clearance, elastic deformation and machining error was analyzed. The BDC position of no load at different stamping speeds was gained determined using the JF75G-300 high-speed punch as an example for Monte Carlo simulation. Using JF75G-300 the unloaded BDC position was experimentally recorded at different stamping speeds and compared to simulation results. Conclusions are as follows:

- (1) The simulation and experimental results are in good agreement with each other. The dynamic accuracy of high-speed press can be analyzed by the dynamic precision reliability model.
- (2) Within the nominal capacity range of the press, increasing the forming speed results in downward shift in BDC position and positional fluctuations increase continuously, and the inertial force of the mechanism also increases, leading to elastic deformation of the connecting rod mechanism.
- (3) The fluctuation of the displacement curve of the press during high-speed operation is much higher than that of the displacement curve at low speed. The effect of clearance on the motion precision is larger when the speed of the press is increased.
- (4) Increasing the speed of the main shaft gradually reduces the precision of the press motion. This phe-

nomenon is related to the elastic deformation of the component.

Acknowledgements The research is funded partially by Post-doctoral Science Foundation of China (2016M601800), Science and Technology Foundation of Outstanding Young Talents of Nanjing Agricultural University (YQ201605), the Fundamental Research Funds for the Central Universities fund (KYZ201760) and the six major talent summit in Jiangsu Province (2015-zbzz-011).

Compliance with ethical standards

Conflict of interests The authors declare that there are no competing interests regarding the publication of this paper.

References

1. Lu, X.J., Ke, Z.M., Zhu, S.H., Zhou, J.: Research on bottom dead center (B.D.C) of high speed precision press. *Forg. Stamp. Technol.* **35**(1), 87–92 (2010)
2. Chen, Y., Sun, Y., Chen, C.: Dynamic analysis of a planar slider-crank mechanism with clearance for a high-speed and heavy load press system. *Mech. Mach. Theory* **98**, 81–100 (2016)
3. Zheng, E.L., Jia, F., Zhu, S.H.: Thermal modelling and characteristics analysis of high speed press system. *Int. J. Mach. Tools Manuf.* **85**(7), 87–99 (2014)
4. Lu, X.J., Zhu, S.H., He, G.J., Ji, Y., Zhang, Y.: Kinematic analysis of multi-link high-speed presses. *Chin. J. Mech. Eng.* **11**, 1297–1301 (2011)
5. Zheng, E.L., Zhou, X.: Modelling and simulation of flexible slider-crank mechanism with clearance for a closed high speed press system. *Mech. Mach. Theory* **74**(6), 10–30 (2014)
6. He, C.K.: Influencing factors analysis of dynamic accuracy for high-speed precision press. *China Met. Form. Equip. Manuf. Technol.* **49**(6), 13–16 (2014)
7. Flores, P., Leine, R., Glocker, C.: Modelling and Analysis of Rigid Multi-body Systems with Translational Clearance Joints Based on the Non smooth Dynamics Approach// *Multi-body Dynamics*, pp. 107–130. Springer, Netherlands (2011)
8. Li, Ye-jian, Sun, Yu., Wang, Shuan-hu: Dimensional synthesis for multi-linkage of high-speed mechanical press. *Procedia Eng.* **81**, 1639–1644 (2014)

9. Yang, C.F., Zhang, S., Li, Y.P., Chen, B.S.: Optimization design for six-bar linkage of mechanical press. *J. Dali. Univ. Technol.* **53**(1), 64–70 (2013)
10. Hu, F., Sun, Y., Peng, B.: Dynamic precision analysis and experimental verification of high-speed precision punch press. In: *Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science* (2015)
11. Li, Y., Chen, Gp, Sun, D.Y., Gao, Y., Wang, K.: Dynamic analysis and optimization design of a planar slider-crank mechanism with flexible components and two clearance joints. *Mech. Mach. Theory* **99**, 37–57 (2016)
12. Guan, P.: *Research Simulation for High Speed Press with Multi-body Dynamics*. Nanjing University of Aeronautics and Astronautics, Nanjing (2012)
13. Khemili, I., Romdhane, L.: Dynamic analysis of a flexible slider-crank mechanism with clearance. *Eur. J. Mech. A Solids* **27**(5), 882–898 (2008)
14. Olyaei, A.A., Ghazavi, M.R.: Stabilizing slider-crank mechanism with clearance joints. *Mech. Mach. Theory* **53**(7), 17–29 (2012)
15. Flores, P.: A parametric study on the dynamic response of planar multibody systems with multiple clearance joints. *Nonlinear Dyn.* **61**(4), 633–653 (2010)
16. Hu, F., Sun, Y., Peng, B.: Dynamic characteristics analysis and experimental verification of high-speed precision punch press based on coupled thermal-mechanical model. *Procedia Eng.* **81**, 1651–1656 (2014)
17. Guan, P., Zhao, Y., Wu, H.T.: Study on influence of transmission system on accuracy of bottom dead center (BDC) for high speed press. *China Met. Form. Equip. Manuf. Technol.* **06**, 79–83 (2011)
18. Yang, Z.J., Chen, C.H., Chen, F., Hao, Q., Xu, B.: Reliability analysis of machining center based on the field data. *EKSPLOATACJA I NIEZAWODNOSC Maint. Reliab.* **15**(2), 147–155 (2013)
19. Yang, Z.J., Xu, B., Chen, F., Hao, Q., Zhu, X.: A new failure mode and effects analysis model of CNC machine tool using fuzzy theory. In: *Information and Automation (ICIA), 2010 IEEE International Conference on*, pp. 582–587 (2010)
20. Jili, W., Zhaojun, Y., Fei, C., Guofa, L., Chuanhai, C.: Minimum effort reliability allocation method considering fuzzy cost of punching machine tools. *J. Appl. Sci.* **13**(20), 4107–4113 (2013)
21. Chen, C., Yang, Z., Chen, F., Hao, Q.: Research on reliability modelling method of machining center based on Monte Carlo simulation. *Res. J. Appl. Sci. Eng. Technol.* **5**(8), 2671–2676 (2013)
22. Yang, Z.J., Wang, J.L., Li, G.F., Zhang, X.G.: Reliability growth prediction based on fuzzy analytical hierarchy process for punching machines. *J. Jilin Univ. (Eng. Technol. Ed.)* **44**(3), 686–691 (2014)
23. Pang, H., Yu, T.X., Song, B.F.: Analyses of kinematic accuracy reliability and sensitivity for a planar linkage mechanism. *China Mech. Eng.* **25**(18), 2415–2421 (2014)
24. Zhang, F., Tang, Z.C., Tian, C.Y.: Reliability sensitivity analysis for slider-crank mechanism with clearance. *J. Mach. Des.* **29**(10), 42–45 (2012)
25. Wang, J., Zhang, J., Du, X.: Hybrid dimension reduction for mechanism reliability analysis with random joint clearances. *Mech. Mach. Theory* **46**(46), 1396–1410 (2011)
26. Liu, Y.F., Sun, Y., Zhang, X.Z.: Reliability analysis of crankshaft of high-speed punch based on ANSYS-PDS. *Forg. Stamp. Technol.* **37**(5), 155–157 (2012)
27. Zheng, S.Z., Ding, X.W., Li, C.Z.: Influence analysis of lower dead point precision of high speed press with clearance motion pair. *Machinery* **04**(004), 5270–5276 (2015)
28. Li, G.H.: Reliability study of kinematic accuracy of multi link mechanism in high speed precision press. *Nanjing Agric. Univ.* **09**, 23–86 (2015)