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A New Error Analysis and Accuracy Synthesis Method for Shoe Last Machine

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Abstract: In order to improve the manufacturing precision of the shoe last machine, a new error-computing model has been put forward to. At first, Based on the special topological structure of the shoe last machine and multi-rigid body system theory, a spatial error-calculating model of the system was built; Then, the law of error distributing in the whole work space was discussed, and the maximum error position of the system was found; At last, The sensitivities of error parameters were analyzed at the maximum position and the accuracy synthesis was conducted by using Monte Carlo method. Considering the error sensitivities analysis, the accuracy of the main parts was distributed. Results show that the probability of the maximal volume error less than 0.05 mm of the new scheme was improved from 0.6592 to 0.7021 than the probability of the old scheme，the precision of the system was improved obviously, the model can be used for the error analysis and accuracy synthesis of the complex multi-embranchment motion chain system, and to improve the system precision of manufacturing.

Keywords: Monte Carlo method, Multi-rigid body, Error analysis, Accuracy synthesis.

1. Introduction

In the present machine precision analysis and machine precision synthesis field, there are many more attentions to precision analysis than precision synthesis. Qiang Lu [1] took consideration about manufacturing tolerance and pair mating space, utilized Mentkaluo method to make precision synthesis for six legs parallel machine. Lin Ma [2] constructed mapping relationship between parts manufacturing precision and moving flatform position by spacing vector chained model. According to sensitivity analysis, under the given cutter position error condition, and make parts manufacturing error weighting spacing as aims, some papers makes a precision synthesis for parallel machine: Qin Zhang [3] make use of multi-body theory as base, researched geometric precision error, thermal deformation error and loading error, and make relative experiment, got obvious achievement. Jianzhong Fu [4] construct structure thermal dynamic error neural net model. Okafor [5] make error analysis for vertical machining centre based on multi-body theory. To multi –dimensions chain of shoe last, the paper deduces system error transform matrix, and builds error synthesis computing model based on multi-body theory, and discusses the error distribution regularity and error parameter sensitivity of working space.

2. Spacing Error Model of Shoe Last

2.1. Topology System and Movement Structure of System

Analysing system structure, Numerical control shoe last machine has tree representation multi-body system, just like Fig. 1.

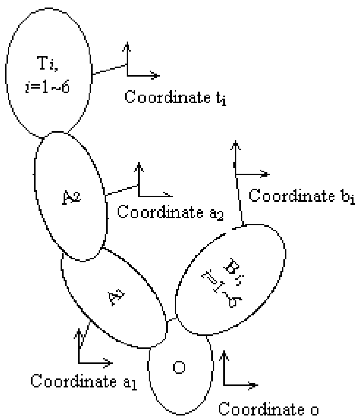


Fig. 1 Topological structure of system.
O-base; A_1-*z*; A_2-*x* direction working platform;
T_i, *i*=1~6 - *x* direction working platform six cutters;
B_i, *i*=1~6 – *c* direction six revolving working piece.

In the system, 6 cutters T_i and corresponding revolving parts B_i construct 6 working space, it is decided by manufacturing ways. The whole system is construct from base to parts （O—B_1, O—B_2, O—B_3, O—B_4, O—B_5, O—B_6） and from base to cutters (O—A_1—A_2—T_1, O—A_1—A_2—T_2, O—A_1—A_2—T_3, O—A_1—A_2—T_4, O—A_1—A_2—T_5, O—A_1—A_2 — T_6). According to Topological structure, a movement structure sketch is established, like Fig. 2.

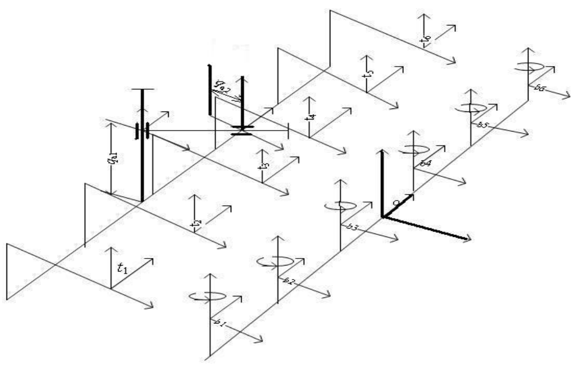


Fig. 2. Movement structure sketch of shoe last machine tool.

In the sketch, coordinate O is corresponding to based fixed coordinate, coordinate a1 and a2 are corresponding to z direction and x direction moving coordinate respectively; t_i(i=1,2,…,6) are corresponding to 6 fixed cutters coordinate; b_i(i=1,2,…,6) are corresponding to 6 revolving parts coordinate. And the domain between linear displacement of z direction and base coordinate O is q_{a1} [0,350], the domain between linear displacement of x direction and base coordinate O is q_{a1} [-150, 0], the domain of b_i is [0, 360].

2.2. System Error Models

Take consideration of Topology and movement ways, the paper construct error model by multi-body system theory. From reference [6], in multi-body system, any 2 adjacent rigid body, if their corresponding coordinate are a1 and a2, and their relationship can be contacted as following: a random point in a1, al coordinate can be presented as homogeneous coordinate p_{a1}, p_{a2} and a transform matrix T_{a1a2}, like equation (1):

$$p_k = [\, p_{k_x}\, p_{k_y}\, p_{k_z}\, 1]^T = T_{a_1a_2} \cdot p_{a_2} \,, \tag{1}$$

Make use of this transform procedure to shoe last system like Fig. 1 the transform matrix of parts coordinate b_i and cutters coordinate t_i can be presented equation (2):

$$\boldsymbol{T}_{\mathrm{b_it_i}} = \boldsymbol{T}_{\mathrm{b_io}} \cdot \boldsymbol{T}_{\mathrm{oa_1}} \cdot \boldsymbol{T}_{\mathrm{a_1a_2}} \cdot \boldsymbol{T}_{\mathrm{a_2t_i}}; \quad \mathrm{i} = 1, 2, \cdots, 6 \,, \tag{2}$$

The equation doesn't take consideration error influence. Now think about linear error between coordinate 1 and k's position (including x, y, z): $e_{kl_x}, e_{kl_y}, e_{kl_z}$, angular error: $\varepsilon_{kl_x}, \varepsilon_{kl_y}, \varepsilon_{kl_z}$, and adopt first order approximation, the relationship between actual transform matrix $\boldsymbol{T}_{\mathrm{a_1a_2}}$ and nominal transform matrix $\boldsymbol{T}_{\mathrm{a_1a_2}}$ is equation (3):

$$\boldsymbol{T}_{\mathrm{a_{a_1a_2}}} = \boldsymbol{T}_{\mathrm{a_1a_2}} \cdot (\boldsymbol{I} + \Delta \boldsymbol{T}_{\mathrm{a_1a_2}}) \,, \tag{3}$$

In the equation (3):

$$\Delta \boldsymbol{T}_{\mathrm{a_1a_2}} = \begin{bmatrix} 0 & -\varepsilon_{\mathrm{a_1a_{2z}}} & \varepsilon_{\mathrm{a_1a_{2y}}} & \mathrm{e}_{\mathrm{a_1a_{2x}}} \\ \varepsilon_{\mathrm{a_1a_{2z}}} & 0 & -\varepsilon_{\mathrm{a_1a_{2x}}} & \mathrm{e}_{\mathrm{a_1a_{2y}}} \\ -\varepsilon_{\mathrm{a_1a_{2y}}} & \varepsilon_{\mathrm{a_1a_{2x}}} & 0 & \mathrm{e}_{\mathrm{a_1a_{2z}}} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

I is 4×4 unit matrix.

Also, in parts coordinate b_i, the actual position of cutter coordinate t_i can be contacted by matrix $\boldsymbol{T}_{\mathrm{a_{b_it_i}}}$:

$$\boldsymbol{T}_{\mathrm{a_{b_it_i}}} = \boldsymbol{T}_{\mathrm{b_it_i}} \cdot (\boldsymbol{I} + \Delta \boldsymbol{T}_{\mathrm{b_it_i}}) \,, \tag{4}$$

In the equation (4):

$$\Delta \boldsymbol{T}_{b_i t_i} = \begin{bmatrix} 0 & -\varepsilon_{b_i t_{iz}} & \varepsilon_{b_i t_{iy}} & e_{b_i t_{ix}} \\ \varepsilon_{b_i t_{iz}} & 0 & -\varepsilon_{b_i t_{ix}} & e_{b_i t_{iy}} \\ -\varepsilon_{b_i t_{iy}} & \varepsilon_{b_i t_{ix}} & 0 & e_{b_i t_{iz}} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Continue use transform matrix $\boldsymbol{T}_{a_1 a_2}$, actual position of cutters t_i in the coordinate b_i can be presented (5):

$$\boldsymbol{T}_{a_{b_i t_i}} = \left[(\boldsymbol{I} + \Delta \boldsymbol{T}_{b_i o}) \boldsymbol{T}_{b_i o} \right] \cdot \left[(\boldsymbol{I} + \Delta \boldsymbol{T}_{oa_1}) \boldsymbol{T}_{oa_1} \right] \cdot \left[(\boldsymbol{I} + \Delta \boldsymbol{T}_{a_1 a_2}) \boldsymbol{T}_{a_1 a_2} \right] \cdot \boldsymbol{T}_{a_2 t_i} (\boldsymbol{I} + \Delta \boldsymbol{T}_{a_2 t_i}), \quad (5)$$

From (5), sub-items of equation (4) can be solved.

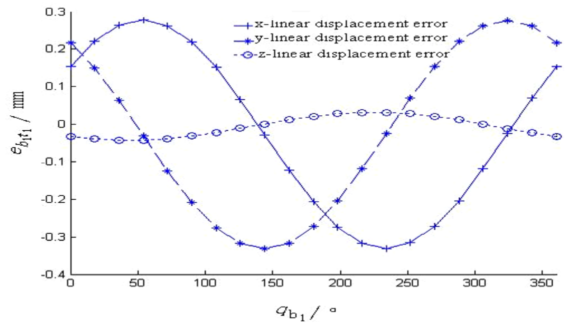
3. Distribution and Sensitivity of Spacing Error in Shoe Last

3.1. The Law of Space Error in Shoe Last

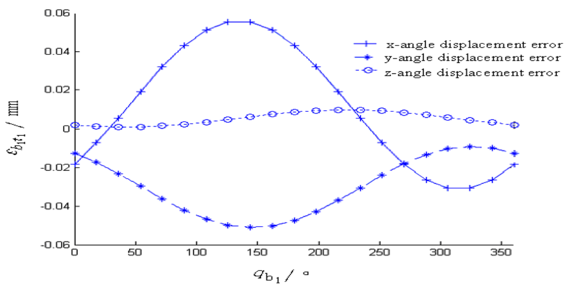
The system error matrix is computed by function totaldelta_find01 (q_{a1}, q_{a2}, q_{b1}), argument q_{a1} is the position alteration of z direction working platform, the span is [0,350]; q_{a2} is the position alteration of x direction working platform, the span is [-150, 0]; q_{b1} is angle of part revolving, the span is [0, 360°].

Fig. 3(a), (b), (c) present the influence to system by angle of part revolving. Fig. 3(a) shows the liner displacement error $\varepsilon_{b_i t_i}$ alteration with the part revolving angle q_{b1}, x direction and y direction linear displacement errors are cosine change with the working part revolving, when the part is at the angle 54° and 234°, the linear displacement error of x direction reaches maximum; when the part is at the angle 144° and 324°, the error of y direction reaches maximum; Fig. 3(b) shows the angle displacement error $e_{b_i t_i}$ alteration with the part revolving angle q_{b1}, when the part is at the angle 126° and 144°, x direction and y direction angle error are maximum. Fig. 3(c) shows general linear displacement error $\left| e_{b_1 t_1} \right|$ alteration with part angle's change ,when part revolve at angle 198°, the general linear displacement error reaches to maximum value: 0.3434 mm.

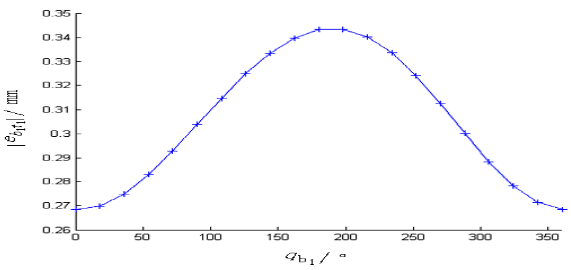
Fig. 4(a), (b) present the error influence induces by z, x direction working platform position variation. Fig. 4(a) shows that: with z working platform move alone positive direction, x direction linear displacement error is negative increasing, y direction linear displacement error is positive increasing, z direction linear displacement is keeping in fixed value. Fig 4(b) shows that: when x direction working platform move alone negative direction, and the error influence is: x direction linear displacement error is keeping in fixed value, y direction linear displacement error is negative increasing, z direction linear displacement error is negative increasing, we can make conclusion: when x direction working platform is far away from part, the general linear displacement error value is big.



(a)



(b)

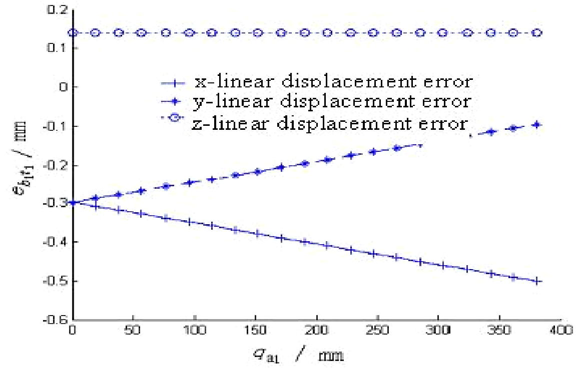


(c)

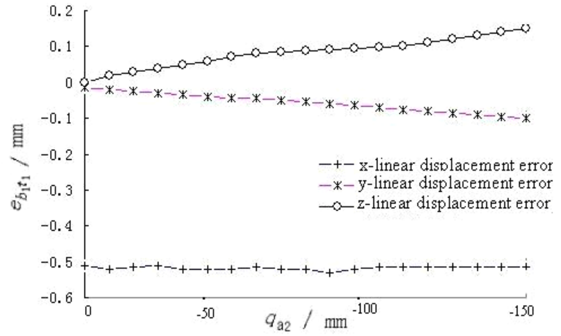
Fig. 3. The Influence to system by angle of part.
(a) The influence of angle to linear displacement error;
(b) The influence of angle to angle displacement error;
(c) General linear displacement with the variation of part.

Fig. 5, is 6 transfer chains 3 coordinate axis direction absolute linear displacement error's comparison. The result indicates that the first transfer chains system error is biggest. In x direction error, difference between $\Delta \boldsymbol{T}_{b_1 t_1}$ and $\Delta \boldsymbol{T}_{b_6 t_6}$ is 0.0665 mm; in y direction, it is 0.0216 mm; in z direction, it is 0.070 mm.

Based on general analysis, system maximum error position is at the first transfer chain, the condition is that: z direction platform move to the highest point, the angle of part is 198°, so, following error sensitivity analysis focus on this position.



(a)



(b)

Fig. 4. The influence to system by *x*-working platform and y-working platform. (a) Error influence induces by *z* direction working platform. (b) Error influence induce by *x* direction working platform.

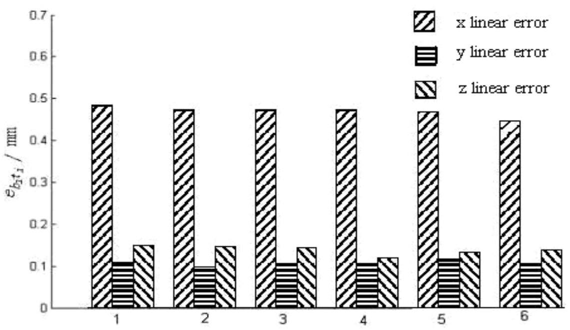


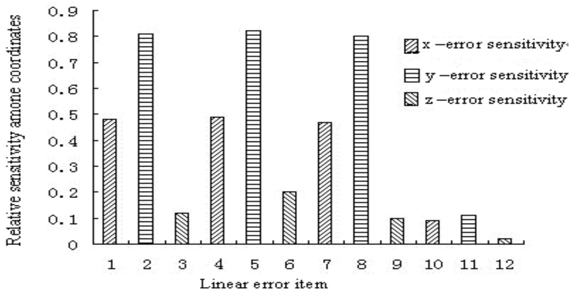
Fig. 5. Comparison of 3 direction absolute linearity error of 6 motion chains.

3.2. Error Sensitivity Analysis

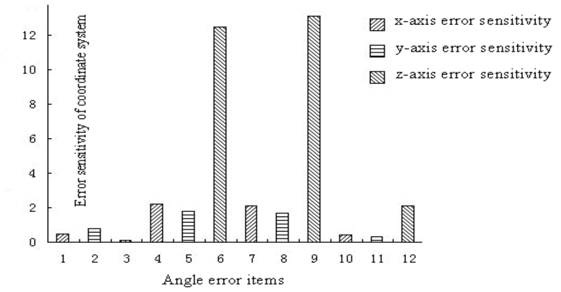
Lin Ma [2], Petel [6] think in whole work space, end point attitude error induced by linear error and angle error is so small that we can ignore it. So, define {***P***} origin point's capacity error as machine error assess standard. Because capacity error between end point cutter and part coordinate is position function, so define e_{V} about any independent error parameter's error sensitivity coefficient is:

$$S_i = \frac{\int_V \frac{\partial(e_{\mathrm{V}})}{\partial \varepsilon'_{p_i}} \mathrm{d}V}{V}, \tag{6}$$

where $\varepsilon'_{\mathrm{p_i}}$ is the independent error parameter, i is the number of relative coordinate.



(a)



(b)

Fig. 6. Bars of error sensitivities.
(a) Linear error sensitivity; (b) angle error sensitivity.

Figs. 6 (a), (b) are linear and angle error sensitivity bar chart which integrated by equation (6). In Fig. 6(a), the first three cylinder coordinate value represent three linear error sensitivity from cutter coordinate t_1 to part coordinate a_2, are expressed by $\mathrm{S_{t_1a_{2x}}, S_{t_1a_{2y}}, S_{t_1a_{2z}}}$. From 4 to 6 cylinder coordinate value represent 3 linear error sensitivity induced by cutter coordinate t_1 and part working coordinate a_2, are expressed by $\mathrm{S_{a_2a_{1x}}, S_{a_2a_{1y}}, S_{a_2a_{1z}}}$. From 7 to 9 cylinder coordinate value represent 3 linear sensitivity induced by part coordinate y direction and base fixed coordinate, are expressed by $\mathrm{S_{a_1o_x}, S_{a_1o_y}, S_{a_1o_z}}$. From10 to 12 cylinder coordinate value represent 3 linear sensitivity induced by part coordinate y direction and base fixed coordinate b_1, are expressed by $\mathrm{S_{b_1o_x}, S_{b_1o_y}, S_{b_1o_z}}$. In Fig. 6(b), the cylinder coordinate values are respectively represented angle error sensitivity of these coordinate system, are expressed by $\mathrm{A_{t_1a_{2x}}, A_{t_1a_{2y}}, A_{t_1a_{2z}}, A_{a_2a_{1x}}, A_{a_2a_{1y}}, A_{a_2a_{1z}}, A_{a_1o_x}, A_{a_1o_y}, A_{a_1o_z}}$.

From Fig. 6 (a), the value of $S_{t_1a_{2y}}$, $S_{a_2a_{1y}}$, $S_{b_1o_y}$ is maximum, indicates that these items linear error sensitivity are maximum value. From Fig 6(b), the value of angle error $A_{a_2a_{1z}}$, $A_{a_1o_y}$ are maximum, indicate the error sensitivities of these angle error.

4. Precision Synthesis

4.1. Random Sampling of Error

When manufacturing a single part, the manufacturing error distributes in tolerance arrange uniformly, and showing Gaussian distribution. Assume the tolerance arrange of every parts of machine is Gaussian distribution, according to theory of 3σ, the standard error is the 1/6, and assume manufacturing error submits Gaussian distribution law, we can reach the dimensional variation sample (Fig. 7) and volume variation sample (Fig. 8).

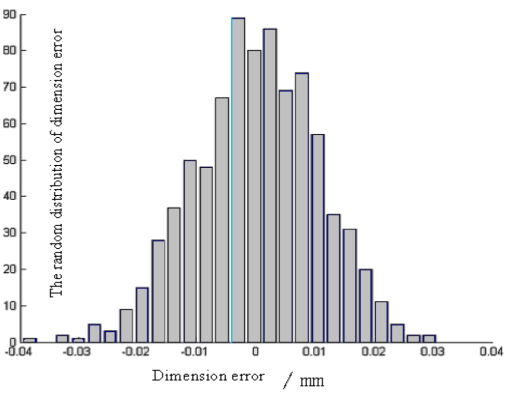


Fig. 7. Dimension error random sample distribution.

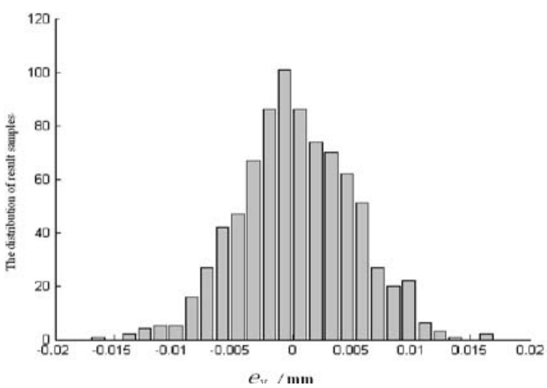


Fig. 8. Calculating sample distribution of volumetric error.

4.2. Mentkaluo Value Simulation

According to precision requirement of Numerical control shoe last machine, the probability of maximum volume error less than 0.05 mm is 0.667. Now, we can make an appreciation to main part's precision scheme of overall design. The primer precision scheme is: the manufacturing precision of cutter support is 8 class, the manufacturing precision of x-sliding guide rail and z-sliding guide rail are 4 class, the manufacturing precision of the worm and worm wheel are 6, the manufacturing precision of speed reducer shell is 7 class, select corresponding 12 linear errors and 12 angle errors samples from 827 samples. Because of randomness of sampling process, the maximum volume error less than 0.05 mm in system maximum error position stabilize at probability 0.63, can't satisfy the system requirement. Reference to sensitivity analysis result, the linear error is biggest between cutter coordinate t_1 and x-working platform, so, the first modification to system is to improve the cutter support precision to 7 class. In stable 1, the first modification was computed 9 times to get the probability where the maximum volume error less than 0.05 mm in system maximum error position.

Table 1. Probability of the most volumetric error Lessing than 0.05 mm.

Compte times	Value *P*		Compute times	Value *P*	
	Way 1	Way 2		way 1	Way 2
1	0.683	0.7017	6	0.6796	0.7314
2	0.6409	0.6917	7	0.6288	0.6915
3	0.6336	0.7215	8	0.6845	0.6843
4	0.6711	0.6823	9	0.6689	0.7103
5	0.6421	0.7043	Avage value	0.6592	0.7021

From Table 1, to improve the cutter support manufacturing precision can increase probability value ***P*** obviously, but still can't reach 0.667, can't satisfy design requirement. According to actual manufacturing condition, and obey the precision equilibrium rule, way 2 is to improve x-sliding guide rail and z-sliding guide rail precision to 3 class, the average of probability is 0.7021, the way 2 precision design satisfy system design requirement, so the precision selection of main parts in numerical control shoe last machine can be determined.

5. Conclusion

(1) The paper builds system error analysis mathematical model based on multi-body theory, and processes error sensitivity analysis and precision synthesis;

(2) The sensitivity analysis result indicates: to improve sliding guide can increase system manufacturing precision obviously;

(3) The Mentkaluo value simulation result can supervise system precision design.

Our method not only solves the allocation of precision in numerical control shoe last machine, but also provides an effective strategy to solve error analysis and precision synthesis of complex topological system.

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