STOCHASTIC TOLERANCE ANALYSIS OF THE MODULAR FIXTURE SYSTEMS WITH GRID PATTERN HOLES

Prof. dr. ing. Tudor PĂUNESCU,
„Transilvania" University, Braşov

Cadru didactic la Universitatea „Transilvania" din Braşov, Facultatea de Inginerie Tehnologică, catedra TCM, cu preocupări în domeniile: dispozitive pentru maşini unelte, robotică industrială şi sisteme flexibile de fabricaţie. A publicat peste 90 de articole cu caracter ştiinţific şi este autor sau coautor la 6 cărţi în edituri centrale şi 5 pe plan local.

REZUMAT. Analiza preciziei sistemelor modulare pentru dipozitivele de prindere a pieselor pe maşini unelte este dificilă datorită varietăţii mari a tipurilor de seturi modulare, dar şi pentru că se operează cu lanţuri demensionale spaţiale, multidimensionale şi puternic neliniare. În această lucrare sunt propuse: o metodă de comparare a preciziei geometrice a seturilor modulare cu suprafeţe cilindrice de poziţionare şi orientare precisă a modulelor de reazem, modele matematice pentru cele două tipuri dominante de asamblare a modulelor. Cu ajutorul metodei de simulare Monte Carlo sunt comparate preciziile geometrice a celor mai importante sisteme modulare existente pe piaţă.

Cuvinte cheie: sisteme modulare, dispozitive de prindere, maşini-unelte, metoda Monte Carlo.

ABSTRACT. The geometrical accuracy analysis of the modular fixture systems is a difficult task because there are various kinds of modular locating systems and the dimensional chains are spatial, multi-dimensional and nonlinear. In this paper, a comparing method for the position & orientation errors of the most popular modular systems with holes and dowels, several stochastic models of the locating modules resolved with the Monte Carlo simulation method are proposed.

Keywords: modular locating systems, stochastic models, Monte Carlo method.

1. INTRODUCTION

The geometrical accuracy analysis of the modular fixture systems (MFS) is a difficult task because:

- there are various kinds of MFS: holes and dowels, T slots, hybrid systems based on holes and dowels or T slots with interfaces for other one system;
- the grid pattern holes systems are most popular, but the variety of the technical solutions is great: multi-functional holes (Carr Lane, Kipp, IMAO, AMF), alternate centering holes with threaded holes (Nabeya), pins are rigid bodies (Carr Lane, Kipp, IMAO) or elastic bodies working with zero clearances (AMF), pins are separate parts or modules and pins are un-separated (Norelem);
- the shapes and functions of locating modules are various, for example standard Kipp set has not edge supports, but AMF and Nabeya MFSs have a lot of such supports.

Because the MFS with holes and dowels offer several advantages over T slots system: many more positional possibilities, more security, repeated setups are easier, if grid pattern holes are damaged, these are repairable, the present paper focuses on the first systems.

Workpiece location relative to the cutting tool is affected by the accuracy of part placement in the fixture. The major sources of errors include fixture and workpiece geometric errors and elastic deformations of the fixture and workpiece due to fixturing forces. In this approach, only geometrical models of positioning modules are considered.

Various methods for determination of workpiece location have been developed, based on: small screw theory, meta functions and nonlinear, implicit contact constraints, variational methods, sequential methods that mimics the actual placement of a workpiece in a fixture, deterministic or stochastic approaches [KAN 01, RAN 03, SHA 99]. In my opinion, the most realistic results can be obtained working with the stochastic models of workpiece-fixture system.

Statistical tolerance design is accepted by industry, particularly if the parts can be reassigned to other assemblies if they fail to assemble or function (this is the case of modular fixtures).

Generally, the usual methods for tolerance analysis are: the worst case method (WCM) and statistical methods such as the root sum square method and the

Monte Carlo simulation (MCS). Monte Carlo is a simulation method that attempts to model the randomness that occurs in reality. The last methods assume a distribution of each individual dimension and can generate a more reasonable tolerance than WCM, because it assumes extreme conditions that rarely happen.

2. ASSEMBLY SCHEMES

The grid pattern holes MFS mainly use two locating principles of modules:

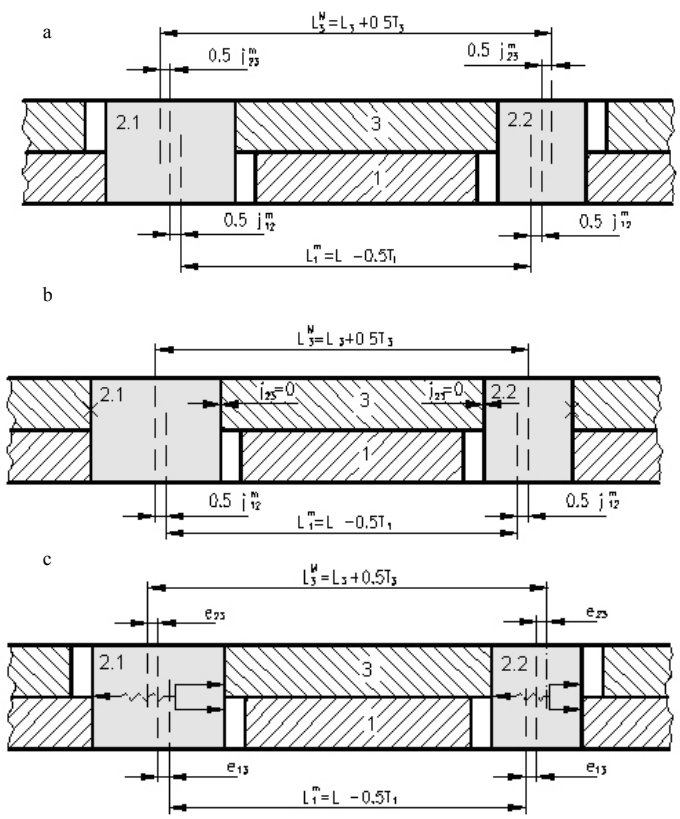
- if the locating module has a symmetry axis (locating pins, locating-support pins, support cylinders) one hole – one pin – one hole (1H1P1H) assembly is used;
- if the locating module has not a symmetry axis (single and double edge supports, vee blocks) the assembly scheme is two holes-two pins-two holes (2H2P2H).

Three 2H2P2H assemblies are used by the actual MFS:

- the pins are rigid bodies, locational clearance fits between the pins and holes (Carr Lane, Kipp, IMAO, Nabeya), shown in fig.1a;
- the pins are rigid bodies, force fits between the pins and the holes of mounted module, and locational clearance between the pins and the holes of base module (Norelem), fig 1b;
- the pins are the elastic bodies (AMF), shown in figure 1c.

Above, the 2H2P2H assemblies are shown in the worst case of the tolerances.

Notations: *1* – base module; *2* – centering pin (locating screw, round pin, rigid sleeve, slotted sleeve); *3* – mounted module; L – centre distance between the two holes or two pins; T_1, T_3 – tolerance of centre distance between the two holes of the module 1, respectively 3; m – minim; M – maxim; j_{ij} – clearance between the hole i and the pin j; Δ – the feasible assembly index [PAU 08] (if $\Delta \geq 0$ then the system has total interchangeability else partial interchangeability). The feasibility of 2H2P2H modular assembly and Δ index result for the worst case, assuming that $D_{11} = D_{31}$, $D_{12} = D_{32}$, $d_{21} = d_{22}$ (nominal diameters of holes and pins are equal), and the limits are equal respectively.



$$\Delta = j_{12}^m + j_{23}^m - 0.5 \cdot (T_1 + T_3) \geq 0$$

$$\Delta = j_{12}^m - 0.5 \cdot (T_1 + T_3) \geq 0$$

$$d_2^m \leq d_2 \leq d_2^M$$

$$d_2^M = D + \frac{2 \cdot (ES_3 + ES_1) - T_1 - T_3}{4}$$

$$d_2^m = D + \frac{2 \cdot (EI_3 + EI_1) - T_1 - T_3}{4}$$

Fig. 1. 2H2P2H assemblies frequently used and the feasible assembly indexes.

3. PROBLEM AND ITERATIVE ALGORITHM DESCRIPTIONS

The problem: comparing the location accuracy of the most popular MFS with grid pattern holes. In this paper, the 2H2P2H assembly is detailed because the 1H1P1H is trivial and were presented in [PAU 05].

Suppose that the workpiece has a low ratio of height to length, therefore is possible to simplify the 3D geometrical model to a 2D.

The input variables are: position tolerance of grid pattern (TPp), upper and lower limits of holes (ES,Ei) and pins (es,ei). The distributions of dimensional parameters are normal.

The model of the 2H2P2H assembly is based on four coordinate systems (CS_i, $i = 0...3$):

– CS_0 is the global CS, the origin is the center of the left circle, X0 axis links the centers.

– CS_1 is the local CS, attached to real positions of the centering holes of the mounted module 1.

– Local CS_2 is attached to pins.

– CS_3 is the local CS, attached to holes of the workpiece.

The proposed algorithm simulates the 2D assembly process of two modules. The algorithm for 2H2P2H assembly, shown in figure 1,*a*, is described below:

1. The CS_1 is generated: error-vector V_{1i}, $i = 1, 2$ is introduced to express the actual location of an axis 1.i, the module of V_{1i} describes the distance of the 1.i axis relative to its true position ($V_{1i} = 0…TPp1/2$), α_{1i} dictates the direction of V_{1i}. It is assumed that the random variable α_{1i} has a uniform distribution from 0 to 2π.

2. The random diameters of holes 1.1, 1.2 and the random diameters of pins 2.1, 2.2 are generated.

3. The CS_2 is generated: error-vector V_{2i}, $i = 1, 2$ is introduced to express the actual location of the pin axis 2.i, the module of V_{2i} describes the distance of the 2.i axis relative to the axis 1.i of the holes 1.i ($V_{2i} = 0…j_{2i}/2$, where j_{2i} is the clearance), α_{2i} is the direction of V2.i, it has a uniform distribution from 0 to 2π.

4. The geometrical parameters of the module 3 are generated: the random diameters of holes 3.1, 3.2 and centre distance between the two holes of the module 3.

5. If the assembly is not feasible $\Delta<0$ then go to step 1 else continue.

6. The random position and orientation of module 3 are generated like the well known Buffon's needle experiment, but the dropping area is limited. If the assembly is not feasible go to step 1 else continue.

7. The effective coordinates of centers O_{31} and O_{32} can be easy calculated by the following coordinate transformations: $CS_3 \rightarrow CS_2 \rightarrow CS_1 \rightarrow CS_0$.

8. The steps 1…7 are repeated n>250000, and the results are statistical processed.

For the model and algorithm of 2H2P2H assembly, shown in figure 1,*c*, see [PAU 07].

4. THE MONTE CARLO APPROACH

With MCS, random 2H2T2H components are generated in accordance with their engineering drawings. You can see in table 1 the results of most popular MFS simulations with MCS. Sample size $n = 10^6$, normal distribution of the geometrical parameters, confidence interval = 0.9973 are adopted.

In table 1, ε_x, ε_y, ε_{xy}, ε_α are the errors of the CS_3 (ε_x, ε_y, ε_{xy} the position errors of the hole 3.1, ε_α – orientation error of X3 axis), IT grades refer to the holes, pins and the center distances between the holes, * – 1H1P1H errors for AMF rigid sleeve, ** – 1H1P1H errors for AMF slotted sleeve.

Analyzing the 2H2P2H and 1H1P1H geometrical errors we can conclude:

- the modular kits are ordered from the most accurate MFS to the most imprecise: AMF M12 → Nabeya M12 → Norelem M10 → Halder M12 → Kipp M12 → Carr Lane standard;
- except the AMF modular kit that uses the special elastic slotted sleeves, the second MFS (Nabeya M12) and the third (Norelem M10) have Δ <0. As you see, the minimum errors can be achieved if the feasibility condition of 2H2P2H assembly is neglected. Because the rate of rejected assemblies is very small such combinations of tolerance zones are acceptable.

Table 1

	Modular system	Δ [mm]	IT grade	2H2P2H				1H1P1H
				ε_x [mm]	ε_y [mm]	ε_{xy} [mm]	ε_α [deg]	ε_{xy} [mm]
1	Halder M12	0	5,6	0.02699	0.03609	0.03771	0.04935	0.03898
2	Kipp M12	0.024	5,6,7	0.04972	0.06214	0.06469	0.12365	0.05352
3	Nabeya M12	-0.018	4,5,6	0.01253	0.01499	0.01615	0.01712	0.02092
4	Norelem M10	-0.008	6	0.02363	0.02776	0.03092	0.06939	0.04321
5	Carr Lane std.	0.005	7,8	0.04572	0.06247	0.06542	0.10760	0.07134
6	AMF M12	-	6,7	0.01444	0.00861	0.01474	0.00806	0.04039*
								0.01244**

4. CONCLUSIONS

A Monte Carlo simulation approach to 2D statistical tolerance analysis of the most popular modular fixture systems with holes and dowels has been developed. The results can be used to the choice of the optimum modular kit, if the criterion is the position and orientation errors of the 2H2P2H and 1H1P1H modular assemblies.

REFERENCES

[KAN 01] **Kang Y.** *Computer Aided Fixture Design Verification*. Ph.D. Dissertation, Worcester Polytechnic Institute, December 2001.

[PAU 05] **Păunescu T.** *A Monte Carlo Approach of Modular Fixture Systems Accuracy*. Part 2. The Monte Carlo Simulation. Second International Conference „Mechanics and Machine Elements", University of Sofia, November 3-5, 2005, 300-304.

[PAU 07] **Păunescu T, Păunescu R.** *Analiza preciziei geometrice realizate de dispozitivele de prindere modulare cu sisteme de poziționare și orientare compensatoare de joc*. Buletinul AGIR, anul XII, nr. 4, oct. – dec. 2007, 88-92.

[PAU 08] **Păunescu T, Bulea H, Păunescu R.** *Dispozitive modulare. Modele matematice*. Vol. II. Editura Universității „Transilvania" din Brașov, 2008, ISBN 978-973-598-319-2 Vol.2-2008.

[RAN 03] **Raghu A, Melkote S. N.** *Prediction of workpiece location error due to fixture geometric errors and fixture-workpiece compliance*, Proceedings of IMECE'03 2003 ASME International Mechanical Engineering Congress &Exposition Washington, November 16-21, 1-8.

[SHA 99] **Shan A, Roth R. N & Wilson R. J**. *A New Approach to Statistical Geometrical Tolerance Analysis*. International Journal of Advanced Manufacturing Technology 15, 1999, 222-230.