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SURVEY OF THE DOMINANT ERROR TYPES AT PARALLEL KINEMATICS MACHINE TOOLS

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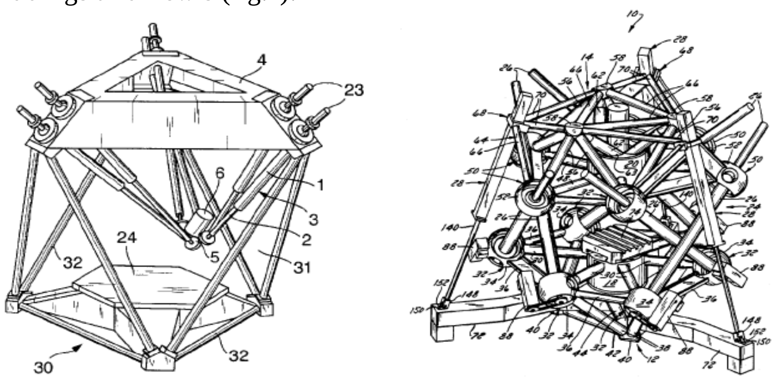
ABSTRACT:
Theoretically parallel kinematics machine tools should be very accurate and rigid due to their closed loop structure and no error accumulation characteristics. Unfortunately, these theoretical presumptions have not been confirmed in practice. This paper gives a survey of the types of errors which significantly decrees the expected accuracy of the parallel kinematics machine tools.
KEYWORDS:
parallel kinematics, machine tools, errors, accuracy

1. INTRODUCTION

Parallel kinematics manipulators have attracted the attention in research institutions and industry due to their high theoretical structural rigidity and high accuracy due to the closed kinematic loops and no error accumulating characteristics.

The first prototypes of parallel kinematics machine tools were introduced to the public in 1994 by Ingersoll and Ginddings and Lewis (fig.1).



a) b)

Figure 1. Schemes of parallel kinematics machine tools
a) ingersoll's "octahedral hexapod b) giddings & lewis' "variax"

Although more than 10 years passed since the first commercial kinematics machine tools were introduced, they are not widely accepted in the industry. From the beginning of their appearance it became obvious that implementation of their theoretical capabilities in practice introduces many new problems. Accuracy of the parallel kinematics machine tools has became one of their main weaknesses.

But, what is different between theory and practice?

For the control and theoretical investigations generally a simplified model based on several assumptions is used. The assumptions are [10]:

- each joint has one centre point for all rotational degrees of freedom,
- these centres are precisely known,
- the linear actuators move with only one degree of freedom and pass exactly through the joint centres,
- the leg length can be read without errors, and
- no internal and external loads effect on the manipulator.

But these assumptions will easy fail for a real machine tool due to manufacturing and assembly errors, kinematic errors in the actuators and joints, elastic deformations due to the gravity, thermal deformations, limited sensor accuracy, control errors and others.

In the following will be given several most dominant errors which have a greatest influence on the parallel kinematics machine tools accuracy.

2. TYPES OF ERRORS

On the accuracy of the parallel kinematics machine tools have influence a various types of errors. Because the occurring errors are partially dependent on the dynamics and process forces during the machining, should be made differentiation between static and dynamic errors [7].

Static errors are errors not dependent on the dynamics and process forces, whereas the source of dynamic errors is in the machining method.

2.1. Static and quasi-static errors

When the accuracy of any machine tool is specified, usually only the static accuracy is considered. This provides only insufficient information as to what will be the machine tool accuracy during the machining process. A high static accuracy is a basic requirement for machine tool operation, especially in the smoothing and positioning processes. In the following several static errors are described.

2.1.1. Kinematic and transformation errors

Manufacturing and assembly errors of the joints and actuators introduce kinematic errors. Only errors in the local direction of leg are of importance [9]. Straightness and angular errors of the actuator as well as an offset of the leg in a joint orthogonal to the strut direction could be neglected as second order terms.

However, straightness and angular errors of the leg become very important if they introduce errors of integrated metrology systems, e.g. caused by Abbey's effect especially under bending load caused by the weight of the actuator itself. These effects can be drastically reduced by a proper design and placement of sensor system.

Transformation errors occur by deviations of the kinematic model within the control and real machine tool kinematics. There two reasons fore transformation errors. The first is simplification of the kinematic model and the second is fact that the model parameters are not known exactly.

Typical simplifications of the kinematic model are for example the neglected offsets between the axes of cardan joints and the unevenness of linear axes. If these refinements are taken in account the effort for calculating the transformation becomes significantly higher so they can not be calculated anymore in presently available controls.

The geometric parameters used in the transformation are identified by calibration. The main difference between the calibration of parallel kinematic machines and the calibration of serial kinematic machines lies in the very high number of geometric parameters at parallel kinematic machines. The method for calibration of parallel kinematic machines consists of measurement the position and orientation of the tool centre point at several points in the workspace. Afterwards, the geometric parameters of the kinematics are determined by a numerical optimization.

The accuracy achieved with this optimization depends on various factors Measuring method used for determining the position of tool centre point during the calibration plays an important role. Because of nonlinear coupling of all parameters a one-dimensional measurement, as for example, x component of the tool position or the distance between tool tip and fixed point, could be enough. But if we know the positions and orientations of the tool centre point in the measuring points, a higher accuracy will be achieved by calibration.

Another important factor is the number of measuring points and requirement the measuring points to be spread over the whole workspace. The more measuring points are used, the real geometric parameters can be better determined by averaging.

Maximum magnitude of the kinematic and transformation errors could reach 0.1-0.5 mm [1].

2.1.2. Gravitational errors

The weight of the tool platform leads to elastic deformations of the real machine tool structure due to the flexibility of machine kinematics and machine components

For example, there are several highly compliant joints, such as universal- and ball-joints, ballscrew, nut and supporting bearings, in the driving mechanism (fig.2).

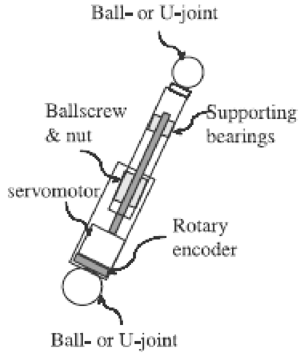


Figure 2. Example of one leg of a hexapod based parallel kinematic machine tool [3]

At the serial kinematics machine tools deformation caused by gravity is approximately constant in the entire workspace and therefore is the best automatically to be considered already with calibration. But gravitation forces in parallel kinematics machine tools have very significant effect due to the non-constant stiffness in the workspace. This error could reach maximum values up to the 0.5-1 mm [1]. Typical values are about 0.2 mm [4].

One possibility to reduce the gravitation errors is the compensation in numerical control unit based on elastic model. Here even quite simple models lead to very good results. Usually it is enough to calculate with uncomplex lumped masses for the tool platform and for the actuators. But elastic models need the exact stiffness of the kinematic components. Therefore the stiffness of the struts should be measured before assembling the machine.

2.1.3. Thermal errors

Thermal errors are another important source that significantly decreases the accuracy of the parallel kinematics machine tools. Thermal deformations happen with a high time constant and result in slowly changing quasi-static errors.

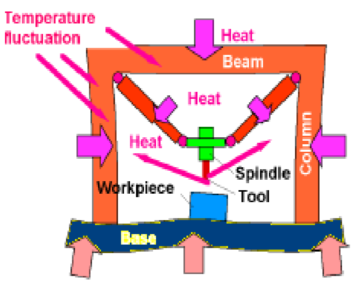


Figure 3. Thermal expansion of the moving platform and The base frame [6]

There are different sources of thermal drift under working conditions. The major error source is the thermal expansion of the legs due to the heat generated in ball screw drives [2]. These errors can be drastically reduced if thermal invariant direct measurement systems are used.

Another important source is the drift of joints due to the thermal expansion of the moving platform and the base frame caused by internal or external thermal loads (fig. 3). The platform is mainly thermally loaded by the heat of cutting process and heat generated of spindle bearings. The frame is mainly influenced by changes in the ambient temperature and this could be source of great errors. The heat generated by the actuators due to power loss influence on the rise of the temperature in the legs and the frame of parallel kinematics machine tool.

The most effective measure against thermal errors is the cooling of thermally effective kinematics components.

Another possibility to reduce errors caused by thermal deformations is the temperature measurement of the components and the compensation of the resulting deformation using a thermal model. Because of the limited accuracy of the thermal model and high number of the needed temperature sensors, this procedure is restricted in regard to the achievable machine accuracy, especially since the thermal model for the parallel kinematics machine tools is very complex [5].

Thermal errors could reach values up to the 0.5 mm.

2.2. Dynamic errors

When we have machining at low speed and low process forces the static and quasi-static errors determine the machine accuracy. Such a process is for example smoothing process which is normally driven at a very low feed rate and requires high accuracy. But smoothing is only possible if the contour of the workpiece is very close to the final contour. In order to achieve this the preceding machining phases should have been executed accurately to a certain degree.

Especially with high-speed machining with parallel kinematics machine tools the dynamic errors have a much stronger impact than the static errors. Reason for dynamic errors are drive errors e.g. tracking error and coupled oscillations, elastic deformations of the machine kinematics through process forces or inertial forces and natural vibrations of the machine. Whether there is an effect and how strong will be the impact of these error sources depends on the process forces and acceleration and velocity. High process forces are the reason for drive errors due to a low disturbance (dynamic) stiffness of the drives. A Low stiffness of the machine kinematics results in big errors when process forces and dynamics (speed and acceleration) are high. Lower stiffness of the machine kinematics enables bigger errors which are result from deformations of process and inertial forces.

Other dynamic errors like the errors caused by natural vibrations cannot be directly attributed to the machining force or the acceleration even they only occur during the process.

2.2.1. Errors from elastic deformations

Elastic deformation errors result from the limited stiffness of the machine tool, when it is loaded with force. Besides the already mentioned static gravitation errors, also the machining force and the inertial forces caused by acceleration motion, lead to deformations those results in considerable errors. The stiffening of the machine kinematics very often is found to be impossible, due to the limits of the required lightweight construction. An estimation of the occurring errors by the calculation of stiffness, process forces and inertial forces in real-time can only is based on highly simplified models. Usually, this is not very successful method.

Errors from elastic deformations could reach values of up to 0.1 mm [7].

2.2.2. Errors from natural vibrations

Errors from natural vibrations are often based on the stiffness of the machine kinematics. The natural vibration with the lowest frequency plays the most important role, since, it is the upper limit for the dynamics of a machine tool. It is extremely difficult to suppress the natural vibrations by means of elastic model in the numerical control

These errors could reach values of 0.05 mm.

2.2.3. Drive errors

A requirement for high-speed machining with parallel kinematic machine tools is highly dynamic drives which demonstrate low contouring errors at high speed and acceleration. They have to deal with the operating point-dependent load and with the coupling of the drives which can in worse case excite each other to oscillate [8].

Typical drive errors are the width of backlash when the velocity inverses the direction, the velocity proportional contouring error depending on the control parameters and deviations due to the disturbance forces. At linear direct drives the disturbance (dynamic) stiffness depends primarily on the control parameters of the drive controller and for ball screw drives also the mechanical stiffness of the drive playas an important role.

Drive errors could be reduced or eliminated only by improvements in the drive control.

Typical values of drives errors could be up to 0.01 mm.

3. CONCLUSION

In this paper different types of errors which significantly decrease the parallel kinematics machine tools accuracy are given. The static errors are caused by manufacturing and assembly errors, non-exact transformation and by the deformations of the machine kinematic through weight forces. Quasi-static errors are result of thermal deformation of machine tool. Dynamic errors occur only during the manufacturing processes and depend on the velocity, the acceleration and the process forces. Dynamics errors are deformations caused by inertia and process forces, natural oscillations and drive errors.

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