Anticipatory Systems in Thermal Errors Compensation (TEC) of Machine Tool

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Abstract
The errors of machine tools on product arise from some source types which directly affect the structure of machine, the tool, the piece and the translation systems. An accurate design can control many of these sources but the thermal ones are yet critical. Many solutions were proposed to control them from the design state either by hardware or by software. The software methods are based on processing the temperature signals of the structure till to compensate the error between piece and tool. The AA. have performed many particular solutions and in the recent years they have experimented TEC by fuzzy system whose rules vary by a neural network or by an anticipatory model.
Keywords: Anticipation, Temperature, Errors, Machine, Compensation

1 Introduction

The demand for high machining accuracy has increased through the factory automation. The geometric errors of machine tools arise from some source types, which directly affect the machine, the tool, the piece and the translation systems. Although an accurate design can control many of these sources, the thermal ones are still critical, because they vary their position and intensity in the working volume and over time.
The goal of the research should be to help the machine tool designer through hardware and/or software design criteria: on the one hand for reducing the thermal deformation of the structure and on the other hand for compensating the residual errors, that are unavoidable with the current design techniques and materials, by TEC (Thermal Error Compensation) methodology.
The TEC methodology is based on the knowledge or anticipation of the errors and on its correction by the working program of the machine tool numerical control.

2. Some contributions to the problem solution

The studies to control the thermal errors date from many years ago mainly from the mid-sixties when the introduction of computer numerical control (CNC) of machine

tools allowed the flexible automation of the machining process (Koenigsberger, 1970[1]; Stute,1971[2]; Sata et Al.,1973[3]; Tlusty,1973[4]; Spur et Fischer, 1968[5],1969[6]; Bryan,1982[7]; Wiele et Al.,1981[8]; Srivasava et Al,1995,[9]).
Many solutions were proposed to control the structural deformations from the design state either by hardware (Bryan,1990[10]; Cotta Ramusino,1985[11]; Bryan,1968[12], 1972[13]; Okushima,1973[14]; Weck,1975[15]; Attia et Kops,1979 [16][17]; D'Addea et Quaranta,1981[18]; Donmez,1985[19]; Venugopal,1986[20]), e.g. geometry and structural anisotropy, or by software (Bryan,1990[10]; Dufour et Groppetti,1981[21]; D'Addea et Al.,1985[22]; Chen,1991[23],1993[29]; Soons et Al.,1992 [24]; Hatamura, 1993[25]; Chiappulini et Al.,1991[26]).
The methods based on the hardware design of machine tools are mainly used in the correction of errors that depend on deformations caused by their own weights or by the additional mobile ones.
Two kinds of mobile weights hardware corrections are used as "contrasting pretensioning" and "balancing" with opposite loads (Koenigsberger,1970[1]; Tlusty, 1973[4]; D'Addea et Quaranta,1981[18]; Dufour et Groppetti, 1981[21]).
The sensitivity to thermo-geometric symmetry has increased also with the development and diffusion of calculation methods with finite elements modules.
The spindle is the most important module between the active sources and many attempts were made in the past to reduce the thermal exchange with the structure and at the same time many attempts were also made to limit the temperature variation of the structure by an extra exchange of heat with fluid medium (BryanJ et Al,1968[13]). Some authors (Tlusty,1973[4]; D'Addea et Quaranta,1981[18]) have underlined that the prevalent lengthening of the spindle is not the only spindle error and the components in the other axes are not always negligible.
The software methods (Bryan,1990[10]; D'Addea et Al,1985[22]; Chen,1991[23]; Hatamura,1993[25]; Chiappulini et Al.,1991[26]; Dehaes et Al,1996[27]; Chen, 1993[29]; Mou et Al,1995[30]) are more recent and are based on the structure temperature signals, their processing to obtain the value of the main components of error at tip of tool and their correction by compensation in the work program of numerical control.
The studies have been growing since the beginning by searching to apply an ideal model to yield the deformations as a function of temperatures. These methods yielded some success but the machine tools are always in a transient state: speeds and working parameters and thermal exchanges are variable over time and with the position of mobile parts at the extent that the thermal condition results from the history of the heating and cooling alternance over time (thermal memory). The main problem is checking in the structure the points from which to draw the signals (D'Addea et Al,1985[22]; Huang,1995[33]; D'Addea,1998[35]). Although the problem was not at all overcome, the correlation between temperature and deformation improved by the use of FEM modules and when the knowledge based systems, as neural network, fuzzy systems and so on, were introduced (Dehaes et Al,1996[27]; Weck et Al.,1995[31]; Srinivasa et Ziegert, 1997[34]; D'Addea, 1998[35],1999[37]; Zadeh, 1973[38]; Mamdani, 1977, [39]; Chen et Al.,1977, [40]; Kloke et Al.,1997, [41]; Cusimano et

D'Addea,1997,[42]; Revilla et Arana,1994,[43]; Moriwaki et Zhao,1992,[44]; Yang et Al., 1995[45]; Mou,1997,[46]).
In a new recent attempt, the correction was made by controlling the thermal exchange so as to have continuously the same temperature rate (Fraser et Al.,1998,1999[36]).

3 Using the fuzzy rules to define the Homogeneous Transformation Matrix (HTM) coefficients in TEC system

For designing a thermal error compensation (TEC) system of machine tools it is necessary to compute in real time the errors and to vary the machining program so as to reduce these errors. Till now the main problem is how to compute the thermal errors of the structure.
Machine tools have rigid modules which are linked by fixed or mobile restraints to form a closed kinematic chain from the piece to the tool, Fig.1. The homogeneous transformation matrix (HTM) allows to get the transfer of deformations in the chain between the piece and the tip of the tool, Fig.1. The approach is not new (Srivastava,1995,[9]) but is new the calculation of the coefficients.

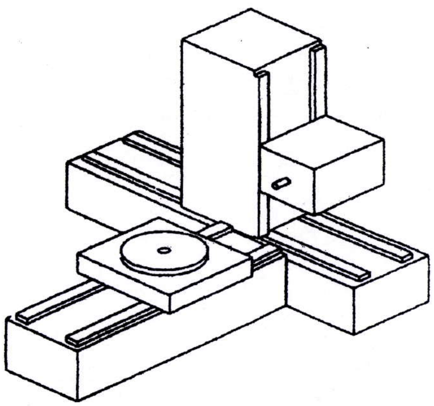

Fig.1 Five axis machining centre

The innovation, supported by extensive field testing, is considering "a priori" the coefficients of transformation matrix as time and position variables: and this specification helps us to obtain a higher precision. In fact using compensation of the global (in the sense of complete machine) thermo-deformation errors by software, also by fuzzy or neural-net or by both techniques, it is difficult to find reliable rules all in the

range of running and the machining conditions for categorising the knowledge are critical (Dehaes,1996[27]; Revilla,1994[43]; Moriwaki,1992[44]), because the thermo-deformations of the mechanical systems of the structure are mutually interactive.
The attributing vice-versa a level of position and time variation to any coefficient of homogeneous transformation matrix help us to obtain a better definitions of the local deformation and a more useful design of the knowledge tests or of the inference rules.
The machine tool used in this application is a medium size five axes NC machining centre with three translation axes (X,Y,Z) ad two rotation (A,B), parallel to the Y and Z, Fig.1.
The homogeneous transformation matrix application using the synthetic description of machine joints help us to find the components of the error in the main directions X,Y,Z, Fig.2.

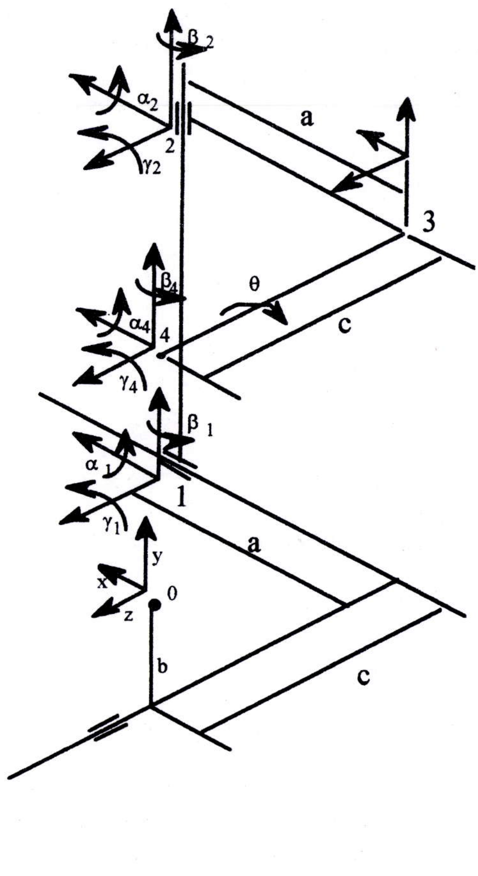

Fig 2- Closed force chain from piece to tool

This approach has allowed some years ago to obtain relevant results by application of a rigid method that describes the instantaneous error at tip of tool as function of the temperatures $(T_1, T_2, ... T_i ..... T_n)$ and the position P(x,y,z) in the working volume (X,Y,Z), Fig.2.
So, when $[H]_{i,j}$ and $[\Phi]_{i,j}$ are the matrices for translation of origin and rotation:

$$[H]_{0,4} = [H]_{0,1} \cdot [\Phi]_{0,1} \cdot [H]_{1,2} \cdot [\Phi]_{1,2} \cdot [H]_{2,3} \cdot [\Phi]_{2,3} \cdot [H]_{3,4} \cdot [\Phi]_{3,4} \quad (1)$$

where, following the scheme of Fig.2, the first coordinate transformation is from origin 0(000) at the base of upright, point 1 (x+a,-b,-c), while the rotations are $\alpha_1, \beta_1, \gamma_1$.
The origin of the second reference is point 2 (x+a,y,-c) and rotations $\alpha_2, \beta_2, \gamma_2$; the spindle sleeve is the third reference, point 3 (x, y,-c) and rotations are negligible and so the fourth point on the spindle tip 4 (x,y,x)and rotations $\alpha_4, \beta_4, \gamma_4$. The spindle axis excites a rotation around the main axes and also a linear error $\Delta\varepsilon$ $(\Delta x, \Delta y, \Delta z)$ as in Fig.3.

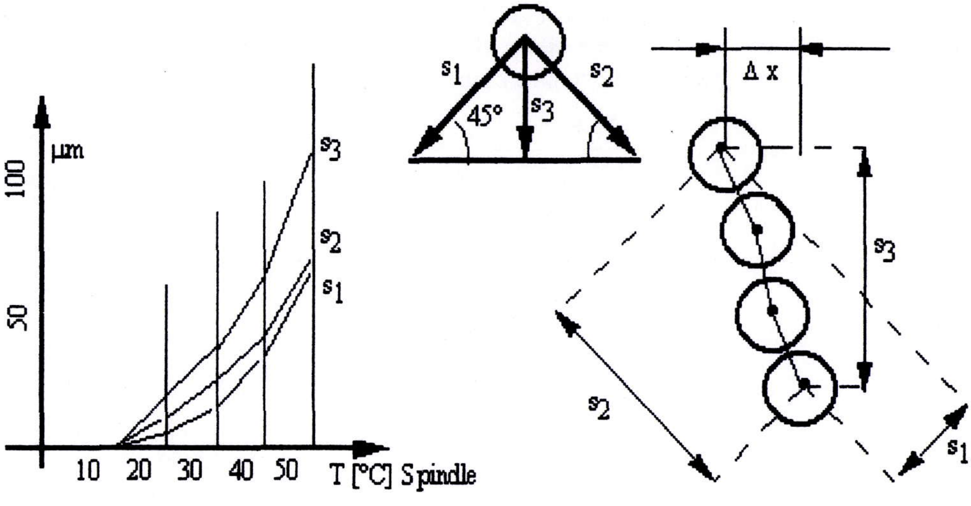

Fig.3 Displacement of spindle nose ($s_3 = \Delta y$)

If the radial dimensions of the tool are overlooked and the rotations around the axes are small enough to disregard the second order terms, the corrections are:

$$\varepsilon_x = \varepsilon_{xx}(x, T_{xi}) + \varepsilon_x(y, T_{yi}) + (c+z)(\beta_1+\beta_2) + a\,\gamma_1 + \Delta x\,(T_{mk}) + \text{superior order terms}$$

$$\varepsilon_y = \varepsilon_{yy}(y, T_{yi}) + \varepsilon_y(y, T_{yi}) + (c+z)(\alpha_1+\alpha_2) + a\,(\gamma_1+\gamma_2) + \Delta y\,(T_{mk}) + \ldots \quad (2)$$

$$\varepsilon_z = \varepsilon_{zz}(z, T_{zi}) + \varepsilon_z(x, T_{xi}) + \varepsilon_z(y, T_{yi}) + a\,(\beta_1+\beta_2) + \alpha_1 y + \Delta z\,(T_{mk}) + \ldots$$

where x, y, z are the current co-ordinates in the work volume and T_{xi}, T_{yi}, T_{zi}, are the temperatures; T_{mk} the temperatures on the spindle sleeve; $\varepsilon_{xx}(x, T_{xi})$, $\varepsilon_{yy}(y, T_{yi})$, $\varepsilon_{zz}(z, T_{zi})$ the linear errors along the axes; $\varepsilon_x(y, T_{yi})$, $\varepsilon_y(y, T_{yi})$, $\varepsilon_z(x,T_{xi})$, $\varepsilon_z(y, T_{yi})$ the cross errors in X, Y, Z, as a result of the deflection of upright; $(c+z)(\beta_1+\beta_2)$, $(c+z)(\alpha_1+\alpha_2)$, $a\,(\beta_1+\beta_2)$ the errors along X,Y,Z as results of rotations in the joints and in the upright $((\alpha_i, \beta_i, \gamma_i) = f(T_{xi}, T_{yi}))$.

We can't measure the temperature in all the points of the structure so the methods of compensation are generally based on the selection of a number of key points by which we can describe the deformation state.

The key points were found by a long experimental process also integrated with a FEM (finite element method) model. The problem demands numerous tests in various working conditions which take account of the environment and the thermal state within the structure. This results in lead times which are incompatible with the needs of modern manufacturing and commercialisation of production machines.

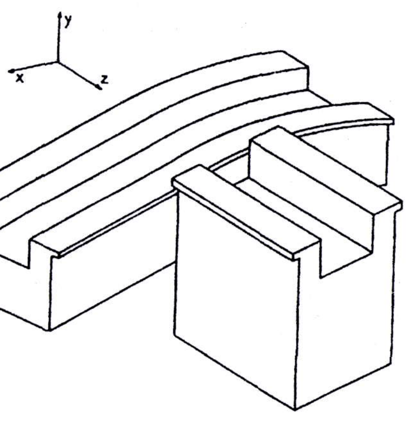

Fig.4 Thermo-deformation of the base

From many years the idea has been pursued of using during design phase simplified calculation instruments to accelerate the process of forecasting and generating compensation rules. FEM calculation methods are now relatively widely used, making them an useful initial support.

Research recently undertaken by the Authors has shown that it is possible to move from an initial FEM thermo-deformation model, Figg.4, 5, 6 to one which approximates real machine behaviour.

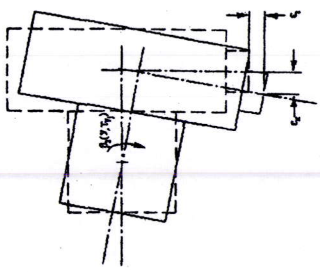

Fig.5 Thermo-deformation (torsion) of the upright (Y axis)

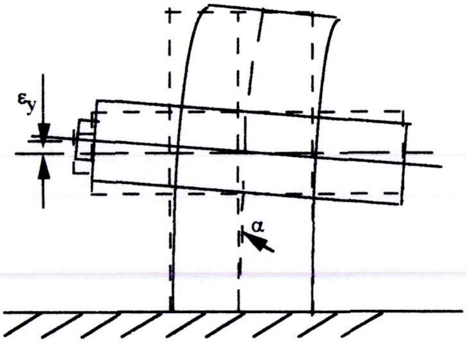

Fig.6 Thermo-deformation of the upright (bending)

This result was obtained comparing the temperature maps and the geometrical errors in the initial model with the real ones and modifying the model to obtain with some approximation the same maps with the same thermal loads. Tuning is also limited to a number of representative cases and is therefore not too time consuming. Such a model eases and accelerates recognition of other situations, e.g. transient state, and the overlapping of external and internal thermal variation allows to find key temperatures, i.e. those points which give a reliable fitting of thermo-deformation links.
An other solution was found using the neural network approach but the results were only partially satisfactory, also probably because of the difficulties in categorising the knowledge (Moriwaki et Zhao,1992[44]; Revilla et Arana,1994[43]; Yang et Al.,1995 [45]; Dehaes et Al.,1996[27]; Mou,1997[46]).
The recent approaches start from the assessment that the description of the deformation state as a function of key temperatures is only an approximation, because we don't know the effective global thermal distribution in the structure; so, it is necessary to describe the deformation state in a flexible and qualitative manner, by some thermal key points.
This method is followed in some recent applications using a fuzzy system, based on the rules coming from the experimental tests and from FEM model so as in the application presented in the CASYS '99 paper (D'Addea,2000[37]).
The validation of the model and the selection of temperature key points are the experimentation engagements or loads: so the tests categorising is an important as basic approach.

The fuzzy technique is used to compensate the uncertainty of the links between temperatures and deformations, so as to rotations of mobile joints affecting greatly the final errors by the amplification of the arms.
The fuzzy system indeed processes the signal by the rigid rules and this design liability doesn't fit the need to define all the thermo-deformational states. To redesign a wholly flexible system, the rules of the fuzzy systems must be varied in accordance with different conditions as dissipation, thermal exchanges, warming up and so on.

4 Changing the fuzzy rules by neural-net or anticipatory systems in HT matrix to compute the thermo-structural errors

The rules of the fuzzy system that allow to compute the HTM coefficients can be revised and varied to control the errors arising from the position of the thermal sources and from the structure thermal memory. The key temperatures describe in a correct but limited manner the structure deformations, because they give us an approximated figure of the real machine thermal state. On the basis of this analysis a good interpretation comes from the fuzzy connection of thermal state with deformation state also through the necessary variation of rules in the matrix according to a high variation of the thermo-deformational state.

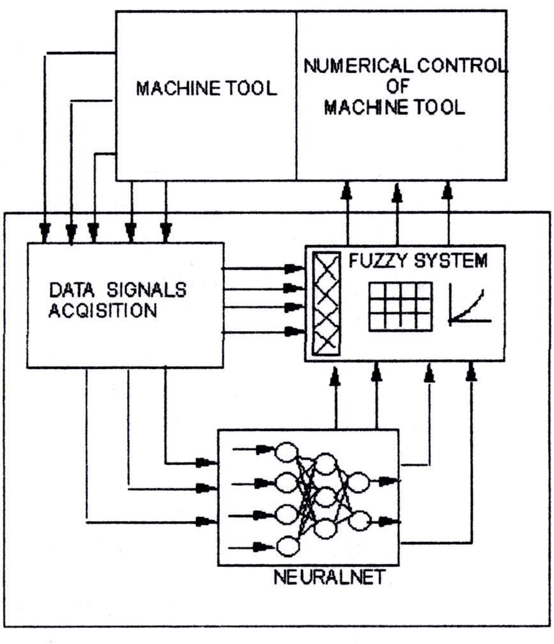

Fig.7 Information System of TEC (neuralnet)

In a first case, the rule revision can be obtained by a recursive knowledge based algorithm so as a neural networks approach is increasingly common. This method is far from a direct application of neural network to the total error of axis and the results are already satisfactory.

The author was reporting about an application of this type to control the structure errors of a gear cutting machine in the CASYS '99 paper (D'Addea, 2000[37]).

Using this compensation method based on a three-layer feed forward multi-inputs multi-outputs network, the correspondence over long periods between the calculated and measured thermo-deformation was very high.

The information system, Fig.7, based on temperature key signals and on categorised experience is varying the shape or the slope of control plane or the universe of discourse.

The variation of the universe of discourse (Cusimano et D'Addea, 1997[42]) was attributing more or less weight to the temperature variables in the fuzzy transformation.

Recently, to select the fuzzy rules system, the authors have been trying an algorithm based on the anticipation of the probable states of the structural thermo-deformation.

This algorithm defines the thermal state at the time $(t+\Delta t)$ of the machine structure $T_{ji}(t+\Delta t)$ (where $j = x,y,z$; $i = 1,2, \ldots n$) function of the ..... $T_{ji}(t-2\Delta t)$, $T_{ij}(t-\Delta t)$, $T_{ji}(t)$ states as well as the probable states $T_{ji}(t+2\Delta t)$, ..., $T_{ji}(t+n\Delta t)$.

On the basis of this new probable state, the membership of variable $T_{ji}(t)$ and/or the syntax of the fuzzy rules so as the control plane can be modified, Fig 8.

The rotations $(\alpha_i, \beta_i, \gamma_i)$ and the linear errors (ε_i) coming from the thermo-deformational scenario are the outputs of the fuzzy compensation system, giving us the probable new assesment of the structure.

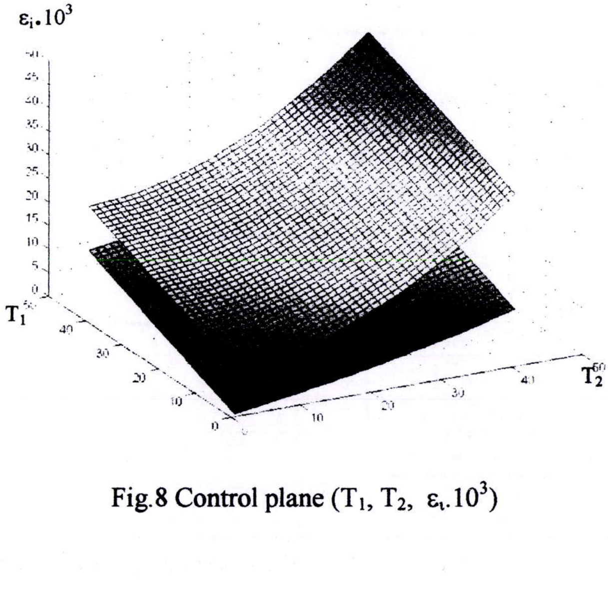

Fig.8 Control plane (T_1, T_2, $\varepsilon_i.10^3$)

The logic occurrence is coming from the physical considerations:
-measuring the deformations in a thermal reference ($\varepsilon_{xx}(x,T_{xi}(0))$, $\varepsilon_{yy}(y,T_{y,i}(0))$, $\varepsilon_{zz}(z,T_{zi}(0))$)
-thermal data acquisition in real time $T_{xi}(t)$, $T_{yi}(t)$, $T_{zi}(t)$
-selection of thermal signals, universe of discourse, rules of syntax to transform the input signals (temperature, position of the axes at working point) to output signals (ε_{xx}, ε_{yy}, ε_{zz}, $\varepsilon_x(x,T)$, $\varepsilon_y(y,T_i)$, $\varepsilon_z(z,T_i)$, α_i, β_i, γ_i) to obtain the output corrections (ε_x, ε_y, ε_z) when they are as inputs to the transformation matrix
-a change of the rules syntax of the fuzzy system between the key temperatures T_i and the deformation on the base of the algorithm:

$$T_i(t+\Delta t) = f(\ldots T_i(t-2\Delta t), T_i(t), T_i(t+\Delta t), T_i(t+2\Delta t)\ldots p_i) \quad (2)$$

where p_i is the parameter that defines the evolution probability of the temperatures,. This association between temperatures and linear or rotational deformations

$$\varepsilon_{ji}, \alpha_{ji}, \beta_{ji}, \gamma_{ji} \text{ corresponding to } T_{ji}$$

is lik a scenario from which, Fig.9

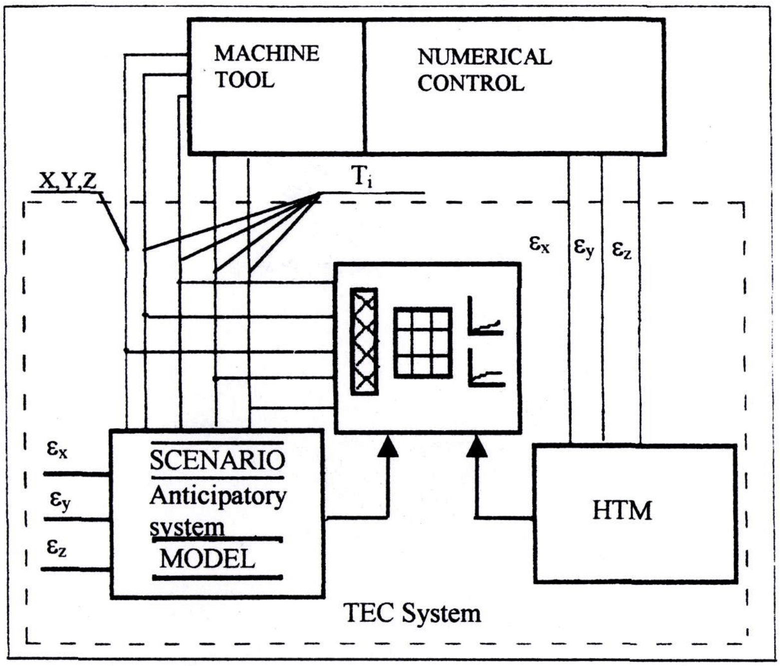

Fig 9 Fuzzy system with variable rules in thermally compensated machine tool

-Computing ε_x, ε_y, ε_z by HT Matrix and changing of machining program in NC machine tool.

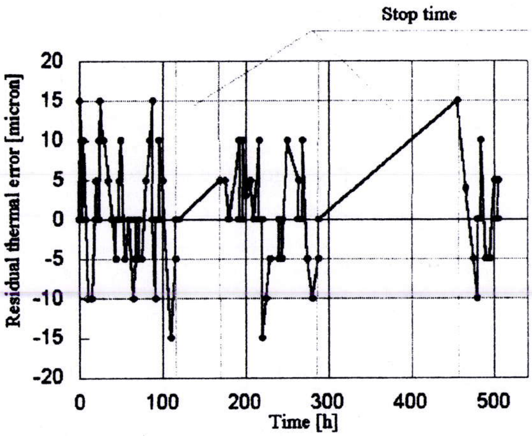

Fig.10 Thermal Error Compensation (stop long time effect) on a medium five axes machine tool

This solution, also more complex than in the variation of the fuzzy transformation on the recursive base, looks for a more precise correction in the transient regime.

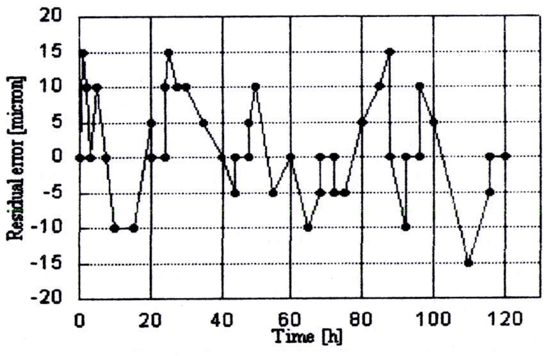

Fig.11 Thermal Error Compensation (short time effect)

This transient state is so common mainly after a long working stop when the links between deformations and key temperatures are particularly weak, because the evaluation of the structure deformation by a little number of temperature points is very difficult in a transient state and also the temperature deformation link is not linear.
The error computed values (ε_x, ε_y, ε_z) are the inputs to the NC (Numerical Control) working program for compensating.
The Fig.10 shows the residual error (vectorial sum of errors along the axes) as a result of a long running time of the medium size five axes NC machine. It makes clear the influence of machine long time stops. According with the Fig.10, the Fig.11 shows the residual errors in a short time (a week) and lights the influence on the residual error of shorter time stops.

5.Conclusions

The problem of thermal deformations of machine tools has been carried out for many years by a number of Authors.
The studies to control and compensate them have recently gained momentum as a result of the pressing needs for greater and better machine productivity that have led essentially to higher working and feeding speeds and a more urgent search for accuracy, reliability and availability.
These contrasting objectives affect the competitiveness both of machine builders as of end-users.
The development of hardware and/or software techniques begins in the product design phase and aims at minimising undesired structural problems which affect repeatability in the time and thus product quality.
After a rapid overview of the present culture, the Authors illustrate an original method of software compensation of thermo-structural errors supported by working applications.
This new methodology of thermal error correction (TEC) shows some advantages:
-the approximated knowledge of the temperature key points define the thermo-deformational regime by the previously tested FEM model of machine;
-the fuzzy data of the temperatures and the deformations are locally linked by flexible rules (knowledge or anticipation based) to define the coefficients of homogeneous transformation matrix (HT matrix);
-the HT matrix links the local regime to all the thermo-deformational state of machine, so the categorising of the knowledge or the anticipation are now easier than in the application of the same techniques to the total machine structure.
The use of the right fuzzy techniques to manipulate uncertain data, the implement of flexible links (neural-net or better anticipation based) to vary the rules of the fuzzy system, that gives all the single coefficients of the homogeneous transformation matrix, helps to achieve good results.
The scheme, also partly proposed in previous papers and supported by briefly indicated field results, is here re-formulated as it seems to have some advantages of time in the

experimental work for the FEM modelling and the fitting performance of thermal error of the structure in the range of transient run of the machine tool .

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