(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
15 November 2012 (15.11.2012)

WIPO | PCT

(10) **International Publication Number**
WO 2012/153157 A2

(51) **International Patent Classification**: Not classified

(21) **International Application Number**: PCT/HU2012/000035

(22) **International Filing Date**: 8 May 2012 (08.05.2012)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
P1100243 9 May 2011 (09.05.2011) HU

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title**: METHOD FOR OPTIMIZING CUTTING FORCES IN A MILLING PROCESS AND COMPUTER-CONTROLLED MILLING MACHINE USING THE SAME METHOD

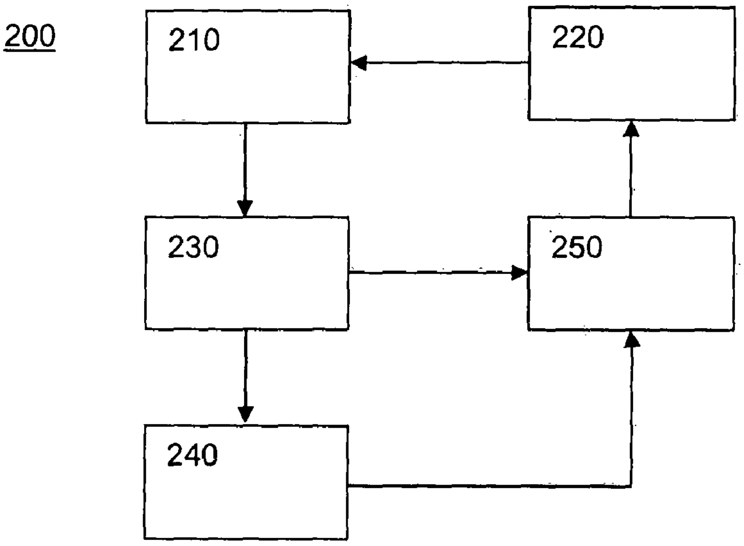

Fig. 4

(57) **Abstract**: The present invention relates to a computer-controlled milling machine comprising a milling tool (210) for machining a workpiece, a measuring unit (230) for measuring the cutting forces exerted by the milling tool (210) to the workpiece, a simulation module (240) for simulating the milling process to determine a contact area between the workpiece and the milling tool (210) by using a multi-dexel representation of the workpiece, a prediction module (250) for receiving the milling force measurements and the simulated geometrical data, and for generating predicted cutting forces from the measured cutting forces and the simulated cutting forces, and a control unit (220) for receiving the predicted cutting forces and for adjusting the operational parameters of the milling process according to the predicted cutting forces so as to reach optimum values for the actual cutting forces acting to milling tool (210).The invention also relates to a method of optimizing cutting forces in a milling process using the aforementioned computer-controlled milling machine.

Method for optimizing cutting forces in a milling process and computer-controlled milling machine using the same method

The present invention relates to a method for optimizing cutting forces in a milling process and computer-controlled milling machine using the same method.

For improving the effectiveness of milling processes, the prediction of cutting forces plays an important role. The accurate knowledge of the particular forces to be applied for the milling tool gives the basis of the feed rate optimization, which leads to a reduction of machining time while increasing the tool lifetime.

Two computing models are commonly applied for the instant cutting force prediction, one is the so called MRR (Material Removal Rate) model, which is rather simple, and the other one is the more sophisticated mechanistic model.

In the MRR model, which is introduced, for example, in *K.K. Wang, Solid modeling for optimizing metal removal of 3_D NC end milling, Journal of Manufacturing Systems 7/1 (1998) 57-65*, it is assumed that the cutting forces are proportional to the amount of the material momentary being removed. The main disadvantage of this method is that it provides only average force values without showing the direction of the forces, instead of determining instantaneous force vectors, which would be necessary to exactly determine wearing, deflection or chattering of the milling tool. However, owing to its simplicity and robustness, the MRR method is widely used in computer-aided machining (CAM) systems for feed rate optimization.

The mechanistic model incorporates the geometrical attributes of the cutting process into the simulation. It extends the fundamental cutting force equations, which describe the effect of shearing and ploughing along an elemental cutting edge, to the complex geometry of the milling tool. The original theory of the mechanistic modelling has been further developed to the conditions of milling in several ways. Many of the researchers have been focusing on the exact description of the geometrical relations during the cutting process. Analytical solutions were born for face milling (see e.g. *K.A. Desai, P.K.Agarwal, P.V.M. Rao, Process geometry modeling with cutter runout* *for milling of curved surfaces, International Journal of Machine Tools & Manufacture 49 (2009) 1015-1028*), ball-end milling (see e.g. *P.Lee, Y. Altintas, Prediction of ball-end milling forces from orthogonal cutting data, International Journal of Machine Tools & Manufacture 36 (1996) 1059-1072*), and also for general-end cutters and inserted cutters. Due to the recent development of the simulation technologies, the way of determination of the contact area between the workpiece and the milling tool has also been changed. The use of analytical calculations has been replaced by approximating methods, including the most commonly applied z-map (see e.g. *G.M. Kim, P.J. Cho, C.N. Chu, Cutting force prediction of sculptured surface ball-end milling using Z-map, International Journal of Machine Tools & Manufacture 40 (2000) 277-291*) and other techniques, which involve the swept volume of not only the whole milling tool but each of the cutter teeth into the computation.

In case of the mechanistic model, however, the determination of the cutting force coefficients is a critical issue. For getting coefficients which are independent from the cutting conditions, the evaluation of a set of experiments with well-defined technological parameters is usually proposed. Such a solution is disclosed, for example, in the US Pat. No. 7,050,883.

Though various solutions have been elaborated to simplify the tests with reservation of accuracy and generality, the main problem related to the coefficients has not been solved yet. The known solutions are valid only for a certain workpiece materials and milling tool geometries, however, these parameters usually change during the machining process due to the wearing of the tool, thus setting up any usable database of coefficients, even for the most common cases, is practically impossible. This causes that the mechanistic cutting force model, in spite of being more accurate and providing more information than the MRR model, has not been used in practice.

It is therefore an object of the present invention to provide an improved method for determining the cutting forces to be applied to the tool in a milling process by using an enhanced mechanistic force model for calculating the various force coefficients and by continuously measuring the real cutting forces exerted by the tool to the workpiece during machining.

It is another object of the present invention to allow the use of a milling tool of any shape and the application of any kind of feeding path for the milling tool without restrictions in respect of milling geometry and accuracy.

It is also an object of the present invention to provide a method for determining the cutting forces in a milling process wherein the cutting force coefficients can be adapted to the wearing, the deflection or other changes of the tool during the milling process.

These and other objects are achieved by a method for optimizing cutting forces in a milling process of machining a workpiece by means of a milling tool, the method comprising the steps of:

- in a tool coordinate system, continuously measuring the real three-dimensional cutting force exerted by the milling tool to the workpiece,
- simulating the milling process to determine a contact area between the workpiece and the milling tool by using a multi-dexel representation of the workpiece,
- for each elementary section of an entire turn of the milling tool, predicting a forthcoming instantaneous elementary cutting force from said measured cutting force, said calculated cutting force being determined using a plurality of cutting force coefficients resulted from a mechanistic force model of the milling tool, wherein the mechanistic force model is provided with geometrical information of said contact area obtained from the milling process simulation, and wherein the prediction uses a predetermined look-forward period,
- determining the predicted instantaneous cutting force components for an entire turn of the milling tool for each cutting edge, and
- according to the predicted cutting force, adjusting the operational parameters of the milling process so as to reach an optimum value for the actual cutting force acting to the milling tool.

The above object are further achieved a computer-controlled milling machine comprising

- a milling tool for machining a workpiece,
- a measuring unit for measuring the cutting forces exerted by the milling tool to the workpiece,

- a simulation module for simulating the milling process to determine a contact area between the workpiece and the milling tool by using a multi-dexel representation of the workpiece,
- a prediction module for receiving the milling force measurements and the simulated geometrical data, and for generating predicted cutting forces from the measured cutting forces and the simulated cutting forces, and
- a control unit for receiving the predicted cutting forces and for adjusting the operational parameters of the milling process according to the predicted cutting forces so as to reach optimum values for the actual cutting forces acting to milling tool.

The present invention will be now described through preferred embodiments thereof with reference to the accompanying drawings, in which

Figures 1a to 1c schematically illustrate the head of a milling tool with depicting the geometrical and mechanical parameters used in the mechanistic force model,

Figure 2 is a flow diagram depicting the basic steps of the method according to the invention,

Figure 3 illustrates organization of a memory block used in the simulation of the cutting forces, in a preferred embodiment of the method according to the invention,

Figure 4 is a schematic block diagram of the computer-controlled milling machine according to the invention,

Figures 5a and 5b illustrate a milling test configuration with ball-end cutter and a cylindrical workpiece in a perspective view and a schematic view, respectively,

Figure 6a to 6f show test results of the examined milling test configuration illustrated in Figures 4a and 4b, using 0 s force prediction delay, and

Figure 7a to 7f show test results of the examined milling test configuration illustrated in Figures 4a and 4b, using 0,5 s force prediction delay.

With reference to Figures 1a to 1c, a cutting force prediction method will be first introduced as a first aspect of the present invention. This method abandons applying the prior art force prediction models, in which elementary force components are numerically integrated along the active parts of the cutting edge. Instead, elementary (average) force components are calculated for a plurality of elementary (i.e. arbitrarily small) surface segments of the contact area between the tool and the workpiece, and then these elementary forces are summed along a cutting edge for a particular section of the entire turn of the tool. The surface segments, more particularly their geometrical parameters, are obtained directly from a multi-dexel description of the workpiece volume, which is continuously simulated during the milling process. A suitable method for generating the multi-dexel representation of the workpiece is disclosed in *B. Tukora, T. Szalay, Fully GPU-based volume representation and material removal simulation of free-form objects (Innovative Developments in Design and Manufacturing: Advanced research in virtual and rapid prototyping (2009) 609-614)*, which is incorporated herein as a reference.

As Figures 1a to 1c illustrate a ball-end milling tool, the cutting force prediction method will be detailed below for ball-end tools, however, the method can be easily adapted to general-end milling tools. The cutting force coefficients can be determined from instantaneous or average orthogonal forces measured on the tool during multi-axis machining, irrespectively of whether instantaneous or average estimated forces are calculated.

The cutting force prediction method is based on the mechanistic force model presented in *P.Lee, Y. Altintas, Prediction of ball-end milling forces from orthogonal cutting data, International Journal of Machine Tools & Manufacture 36 (1996) 1059-1072*. In this model, a cutting edge is described as a sequence of linear segments. For each elementary edge segments a tangential, a radial and an axial elementary force component, dF_t, dF_r and dF_a, respectively, are calculated as shown in Eq. 1.

$$\begin{cases} dF_t(\theta,z) = K_{te}dS + K_{tc} \cdot t_n(\Psi,\theta,\kappa)db \\ dF_r(\theta,z) = K_{re}dS + K_{rc} \cdot t_n(\Psi,\theta,\kappa)db \\ dF_a(\theta,z) = K_{ae}dS + K_{ac} \cdot t_n(\Psi,\theta,\kappa)db \end{cases} \qquad (1)$$

where K_{te}, K_{re}, K_{ae} (N/mm) are the edge specific coefficients, K_{tc}, K_{rc}, K_{ac} (N/mm2) are the shear specific coefficients, dS (mm) is the length of an elementary edge section of a cutting edge, t_n (mm) is the undeformed chip thickness, and db is the projected length of the edge segment in the direction of the cutting velocity (also referred to as the chip width).

The force components related to the tool coordinate system (x, y, z) can be obtained by Eq. 3 resulted by the transformation in Eq. 2.

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = \begin{bmatrix} -\cos(\kappa)\cos(\Psi) & \sin(\Psi) & -\sin(\kappa)\cos(\Psi) \\ -\cos(\kappa)\sin(\Psi) & -\cos(\Psi) & -\sin(\kappa)\sin(\Psi) \\ \sin(\kappa) & 0 & -\cos(\kappa) \end{bmatrix} \begin{bmatrix} dF_r \\ dF_t \\ dF_a \end{bmatrix}, \tag{2}$$

$$\begin{cases} dF_x = -dF_r\cos(\kappa)\cos(\Psi) + dF_t\sin(\Psi) - dF_a\sin(\kappa)\cos(\Psi) \\ dF_y = -dF_r\cos(\kappa)\sin(\Psi) - dF_t\cos(\Psi) - dF_a\sin(\kappa)\sin(\Psi). \\ dF_z = dF_r\sin(\kappa) - dF_a\cos(\kappa) \end{cases} \tag{3}$$

The contact area between the workpiece and the milling tool is composed of a plurality of elementary surface segments that are associated with the intersections of the workpiece's dexels and the surface of the tool's swept volume. Let $\Delta F_{xyz,j}$ denote the three-dimensional cutting force that acts to an elementary cutting edge at the *j*th intersection point of the workpiece dexels and the tool surface, presuming that this elementary edge segment produces unit chip thickness, i.e. $db = 1$. From Eq. 1 and Eq. 3:

$$\begin{cases} \Delta F_{t,j} = K_{te}dS_j + K_{tc}\cdot t_{n,j} \\ \Delta F_{r,j} = K_{re}dS_j + K_{rc}\cdot t_{n,j}, \\ \Delta F_{a,j} = K_{ae}dS_j + K_{ac}\cdot t_{n,j} \end{cases} \tag{4}$$

$$\begin{cases} \Delta F_{x,j} = -\Delta F_{r,j}\cos(\kappa_j)\cos(\Psi_j) + \Delta F_{t,j}\sin(\Psi_j) - \Delta F_{a,j}\sin(\kappa_j)\cos(\Psi_j) \\ \Delta F_{y,j} = -\Delta F_{r,j}\cos(\kappa_j)\sin(\Psi_j) - \Delta F_{t,j}\cos(\Psi_j) - \Delta F_{a,j}\sin(\kappa_j)\sin(\Psi_j). \\ \Delta F_{z,j} = \Delta F_{r,j}\sin(\kappa_j) - \Delta F_{a,j}\cos(\kappa_j) \end{cases} \tag{5}$$

where $t_{n,j}$ is determined on the basis of the removed portion of the dexels in the actual simulation step, and dS_j for ball-end tool is:

$$dS_j = \sqrt{1 + \frac{\cos^4(\kappa_j)}{\tan^2(\varphi)}}. \tag{6}$$

Furthermore, let us divide a whole turn of the rotating milling tool into P elementary sections (sections of a circle), so that the turning angle of the tool will be $2\pi/P$ during each elementary circle section. The average force components acting to a particular cutting edge while sweeping through the *k*th elementary circle section can be determined as:

$$\boldsymbol{F}_{xyz,k} = \sum_j \left(\Delta \boldsymbol{F}_{xyz,j} \cdot \frac{S_j P}{2\pi r_j}\right) \text{ for every } j \text{ to which } \frac{2\pi}{P} k \leq \theta_j < \frac{2\pi}{P}(k+1), \tag{7}$$

where S_j is the surface area of the *j*th elementary surface segment of the contact area (along the cutting edge concerned) and $2\pi r_j/P$ is the length of the elementary circle section along which the point of the edge, which touches the *j*th intersection point, sweeps during the elementary surface segment. If P is equal to 1, than $\boldsymbol{F}_{xyz,0}$ gives the average force vector which acts to the particular cutting edge during a whole turn of the tool. The greater the number of the elementary circle sections is, the more the force values approach the instantaneous forces. The forces acting along other cutting edges can be calculated in the same way, considering that the related spindle rotation angle must be increased with the angle between the first and *i*th cutting edge.

The formulation of Eq. 7 allows to simultaneously calculate the force components associated with different elementary surface segments for a whole turn, which is preferably carried out by means of a general-purpose graphics processing unit (GPGPU). It is obvious for a skilled person that Equations 1 to 3, and thus Equations 4 to 7 can be applied not only to a ball-end milling tool (leading to Eq. 7), but also to general-end milling tools, depending on the calculation method of dS.

As disclosed in the prior art (e.g in *A. Lamikiz, L.N. Lopez de Lacalle, J.A. Sanches, U. Bravo, Calculation of the specific cutting coefficients and geometrical aspects in sculptured surface machining, Machining Science and Technology 9 (2005) 411-436*), the most accurate estimation of the cutting force can be achieved by using constant ploughing coefficients and polynomial shearing coefficients depending on the position of the elementary surface segment in the z-direction (see Figures 1a to 1c). The shearing coefficients may be expressed as follows:

$$\begin{aligned} K_{tc} &= K_{tc0} + K_{tc1} \cdot z + K_{tc2} \cdot z^2 + \cdots + K_{tcn} \cdot z^n \\ K_{rc} &= K_{rc0} + K_{rc1} \cdot z + K_{rc2} \cdot z^2 + \cdots + K_{rcn} \cdot z^n . \\ K_{ac} &= K_{ac0} + K_{ac1} \cdot z + K_{ac2} \cdot z^2 + \cdots + K_{acn} \cdot z^n \end{aligned} \qquad (8)$$

Substituting Eq. 4, 5 and 8 into Eq. 7, the x-component of the cutting force for the *k*th elementary circle section is:

$$F_{x,k} = \left\{ \begin{aligned} &\textstyle\sum_j \Big(\big(K_{re} dS_j + \big(K_{rc0} + K_{rc1} \cdot z_j + K_{rc2} \cdot z_j^2 + \cdots + K_{rcn} \cdot z_j^n \big) t_{n,j} \big) \big(-\cos(\kappa_j) \cos(\Psi_j) \big) \Big) \\ &\qquad + \textstyle\sum_j \Big(\big(K_{te} dS_j + \big(K_{tc0} + K_{tc1} \cdot z_j + K_{tc2} \cdot z_j^2 + \cdots + K_{tcn} \cdot z_j^n \big) t_{n,j} \big) \sin(\Psi_j) \Big) \\ &+ \textstyle\sum_j \Big(\big(K_{ae} dS_j + \big(K_{ac0} + K_{ac1} \cdot z_j + K_{ac2} \cdot z_j^2 + \cdots + K_{acn} \cdot z_j^n \big) t_{n,j} \big) \big(-\sin(\kappa_j) \cos(\Psi_j) \big) \Big) \end{aligned} \right. . \qquad (9)$$

Let us denote the $K_{tc0}, K_{tc1}, \cdots, K_{tcn}, K_{rc0}, K_{rc1}, \cdots, K_{rcn}, K_{ac0}, K_{ac1}, \cdots, K_{acn}$ components in Eq. 8 as $\mathrm{K}_0 \ldots \mathrm{K}_{3(n+2)}$, respectively. In this case, Eq. 9 can be written as follows:

$$F_{x,k} = \textstyle\sum_s \Lambda_s \mathrm{K}_s \, , 0 \le s \le 3(n+2), \qquad (10)$$

wherein the Λ_s values can be directly gained from the cutting geometry in every simulation step performed to determined the actual contact area between the workpiece and the milling tool. The form of Eq. 10 allows to determine the K_s cutting force coefficient components using the least square (LS) method. Let Q denote the difference between the calculated force and the measured force. As Q has to be minimized during a given measuring sequence, the following expression can be written for each K_s.

$$\frac{\partial Q}{\partial K_s} = \sum_k \left(2\Lambda_s\Lambda_0 K_0 + 2\Lambda_s\Lambda_1 K_1 + \cdots + 2\Lambda_s\Lambda_t K_t - 2\Lambda_s F_{x,k\,m}\right) = 0. \quad (11)$$

Eq. 11 describes a linear equation system of $t = 3(n + 2)$ equations, which can be solved by using the Gaussian elimination method for every K_s, resulting in:

$$\begin{cases} K_0 \sum_k 2\Lambda_0\Lambda_0 + K_1 \sum_k 2\Lambda_0\Lambda_1 + \cdots + K_t \sum_k 2\Lambda_0\Lambda_t = \sum_k 2\Lambda_0 F_{x,k\,m} \\ \vdots \\ K_0 \sum_k 2\Lambda_t\Lambda_0 + K_1 \sum_k 2\Lambda_t\Lambda_1 + \cdots + K_t \sum_k 2\Lambda_t\Lambda_t = \sum_k 2\Lambda_t F_{x,k\,m} \end{cases} \quad (12)$$

It should be noted that the above K_s coefficients can be determined by measuring the x-directional cutting force component only. Nevertheless, for the y and z-directional cutting force components, similar equations can be created in the same way, and those may also be involved in the computations of the cutting force coefficients so as to improve the accuracy of the cutting force estimation.

The form of the proposed force equations allows to express the shearing and ploughing cutting force coefficients in such a way that they can be determined from measured forces even in case of continuously altering cutting geometry. This makes it possible to determine the coefficients and to estimate the forthcoming forces in the same time, during the actual manufacturing process. To this end, an appropriate look-forward algorithm is proposed that will be described later.

Now, reference is made to Figure 2 in order to describe the basic steps of a method for optimizing cutting forces in a milling process, in accordance with the present invention.

In step S100, the real three-dimensional cutting forces exerted by the milling tool to the workpiece are measured in a tool coordinate system (shown in Fig. 1a). Measurements of the real cutting forces are carried out in a conventional manner by means of an appropriate measuring device coupled to the milling tool.

In step S110, the milling process is simulated to determine the actual contact area between the workpiece and the milling tool by using a multi-dexel representation of the workpiece. In each simulation step, various geometrical parameters of the elementary surface segments of the contact area, such as t_n and position of the elementary surface segments, are computed. For an exact simulation of the milling process, it is preferred that position of the milling tool is also measured continuously and forwarded to the simulation module.

Using the geometrical information of the milling tool and the workpiece produced by the simulation, for each elementary section of an entire turn of the tool an elementary cutting force of the milling process is predicted on the basis of the measured cutting force in step S120. The calculated cutting force is determined from a plurality of cutting force coefficients that are determined from the mechanistic force model of the milling tool, the mechanistic model using all necessary geometrical information of the contact area obtained from the simulation of the milling process.

Next, in step S130, the predicted cutting force components are determined for an entire turn of the tool for each cutting edge. In this step, the elementary cutting force components associated with the subsequent elementary circle sections of a turn of the tool may computed simultaneously, which makes it possible to significantly reduce the computing time, thus allowing a real time prediction of the cutting force.

Finally, in step S140, the operational parameters (e.g. the feed-rate) of the milling process are adjusted according to the predicted cutting force so as to reach an optimum value for the actual cutting force acting to the milling tool. Although the cutting force adjustment may be carried out immediately (i.e. without substantial delay) after the force prediction, adjustment of the actual cutting forces is preferably delayed by a predetermined time period, i.e. a so-called look-forward period, after the prediction of the cutting force in order to reduce the required computational power. In practice, a delay ranging from a few tenths of a second up to a few seconds seems to be appropriate for most milling processes. A preferred range of the look-forward period includes 0,1 to 2 seconds, and a more preferred range of the look-forward period includes 0,5 to 1 second. The aforementioned zero delay is preferably used only for test purposes to validate the simulation model.

As the method of the determination of the coefficients does not require keeping to special cutting conditions during the measuring sequence, it can be applied directly at the machining process, just before the cutting forces are needed to be predicted. The best result can be reached if the elapsed time between the coefficient determination and the force prediction is short. To this end, continuous cutting force measurements and a synchronized simulation are carried out in the course of the milling process, wherein the forthcoming cutting forces are instantly predicted with an appropriate look-forward algorithm as described below.

A proposed look-forward algorithm for the cutting force adjustment will now be described with reference to Figure 3, in which an exemplary organization of a memory block used in the simulation of the cutting forces is illustrated.

As shown in Figure 3, three pointers may be used to point to various locations in the memory block, namely a *simulation_time_pointer*, a *manufacturing_time_pointer* and a *time_window_pointer*.

The *simulation_time_pointer* is synchronized with the simulation of the milling process and the cutting force estimation process, this latter also being performed in the simulation module. The simulation always goes ahead of the manufacturing, i.e. the current time of the simulation is ahead of the current time of the manufacturing. In every simulation step, actual values for the geometrical parameters of the workpiece and the milling tool, i.e. the Λ_S values, are calculated and pushed into the memory block at the position of the *simulation_time_pointer*. On the basis of the cutting geometry provided by the milling process simulation and the calculated cutting force coefficients (when they already exist), updated cutting forces are predicted and if necessary, the feed rate is adjusted accordingly, thus providing a feed rate optimization. For example, when according to the estimated cutting forces, an increased feed rate can be used without causing damage for the tool, whereas in case the estimated cutting forces are qualified as excessive, the feed rate of the tool should be reduced. (If the feed rate is changed, updated values thereof should be also written into the memory block.)

When a delay is applied between the cutting force estimation and the force adjustment of the milling tool, which is a preferred way of milling, the estimated cutting force is regarded as a predicted cutting force.

After the real cutting forces have been measured, their values may be put into the memory together with the related Λ_S values at the *manufacturing_time_pointer*, and all these values may be added to the matrix which describes the linear equation system of Eq. 12. The actual cutting force coefficients K_S are determined at this time by solving the matrix. (It should be noted that the geometrical data have already been added to the matrix at the simulation phase, which is antecedent to the measurement of the actual cutting forces.)

The *time_window_pointer* may be optional. After a certain elapsed time the Λ's and the measured force values can be subtracted from the matrix describing Eq. 12, so they do not take part in the force coefficient calculation any more. In this way the force coefficients may be adapted to the altering machining conditions (e.g. caused by tool wearing) during long manufacturing processes as well.

Theoretically, the aforementioned look-forward algorithm makes it possible also to conclude to the degree of wearing of the milling tool through the observation of the changes in the values of the force coefficients during a milling process.

In a second aspect, the present invention relates to a computer-controlled milling machine. As shown in Figure 4, which schematically illustrates the configuration of a milling machine 200 according to the invention, a CNC milling tool 210 is numerically controlled by a control unit 220, in which a conventional CAM software is used for setting the operational parameters of the tool (e.g. rotational speed of the spindle, feed-rate, position of the milling end, etc.) to perform the milling processes.

To obtain the instantaneous cutting force exerted by the milling tool 210 to the workpiece (not shown), a measuring unit 230 is coupled to the milling tool 210. The measuring unit may comprise any suitable measuring device.

The milling process is continuously simulated in a simulation module 250 to determine the contact area between the workpiece and the milling tool. The simulation module 240 uses a multi-dexel representation of the workpiece to calculate the actual values of the geometrical parameters of the elementary surface segments of said contact area. To achieve the most accurate simulation as possible, the simulation module 240 is coupled to the measuring unit 230 to collect certain pieces of position information with respect to the milling tool 210.

A prediction module 250 is used to generate estimated cutting forces from the measured cutting forces and the simulated cutting forces. To this end the prediction module is coupled to the measuring unit 230 and the simulation module 240.

The control unit 220 is adapted for receiving the predicted cutting forces from the prediction module 250 and for adjusting the operational parameters of the milling process according to the predicted cutting forces so as to reach optimum values for the actual cutting forces acting to milling tool 210. The control unit 220 is preferably configured to perform the cutting force adjustments using a predetermined delay after receiving the predicted cutting forces, resulting in a predictive cutting force adjustment.

Either or both of the simulation module 240 and the prediction module 250 may be integrated into the control unit 220 in the form of additional software. The advantage of executing the force calculations (i.e. prediction) within the control unit 220 is that some important information is still not available at the off-line state, but it can be gained during the machining process. This means that the control unit 220 may take over certain functions that conventionally belong to the CAM software. The integration of these functions may hide some difficult software technology problems.

Example

For validating the above introduced mechanistic force model, different tests have been completed, wherein a well-machinable AlMgSi1 aluminium alloy blank was cut with cooling by a two-fluted HSS ball-end cutter having 12 mm diameter, 30° nominal helix angle and 0° rake angle. The milling processes were performed on a Kondia B640 machining center with NCT control. The cutting forces were measured by a Kistler 9257B dynamometer. The sampling rate was set to 3000Hz; ±1000N measuring range and no filtering were applied to a connected Kistler 5019 Multichannel Charge Amplifier.

A GPGPU-based machining simulation was run on a NVIDIA Geforce 480GTX graphics card as fast as the real machining process. The simulation was off-line due to technical limitations, i.e. the measured force values were first stored by the Kistler's Dynoware software and then they were read from a text file for the computations. In spite of this, the simulation software perceived and computed as if direct connection had been established with the measuring system. The cutting force coefficients were determined on the basis of instantaneous measured forces.

The applied method required the knowledge of the exact tool positions and spindle turning positions during the whole machining process. The measurements showed that the difference between the programmed and real spindle speed was about 0.46%, while the real feed rate followed the programmed feed-rate at about 2% accuracy. The test configuration enclosed only the measuring of the three force components (along the three tool axes x, y and z) as a function of time, meaning that subsequent manual adjustments were needed for the exact synchronization of the simulation and the machining process.

In Figure 5a and 5b, one of the test configurations is illustrated in a perspective view and a simplified schematic view, respectively, for a rather simple milling process, in which a multi-axis machining was tested with continuously changing cutting geometry along the tool path. A slot with a maximum depth of 4 mm was milled into a cylindrical blank, at 45 degrees to its symmetry axis. The cutting parameters applied in this test are listed in Table 1.

Spindle speed (S)	Cutting speed (v_c)	Feed rate (F)	Feed per tooth (z_f)	Radial depth of cut (a_e)	Axial depth of cut (a_p)
3200 rpm	120 m/min	512 mm/min	0.08 mm	6 mm	4 mm

Table 1.

At first, the look-forward period was set to zero second, which means that the forces were predicted just for the same moment when they were measured. In reality, howvere, there would be no point of this, it has been performed only for validating the simulation model. Figures 6a to 6f show the measured and predicted forces along each tool axis, respectively, during the machining process in this case. In the figures, it can be observed that the predicted force values flutter at the beginning of the milling process due to the lack of the *a priori* knowledge of the cutting force coefficients. However, after a very short time (ca. 0,5 second in this example), when enough information has been gained and consumed for the calculation of the cutting force coefficients, the curves of the predicted forces tend to approach the curves of the measured forces with rather high accuracy.

In Figures 7a to 7f, the result of the same test configuration using a 0.5 second look-forward period can be seen. In this case, the simulation precedes the real machining, and the cutting forces are predicted by 0.5 second in advance to their measurement. In the first 0.5 second the force prediction does not provide any result due to the lack of the measured values. After this period the predicted force values shortly approach the measured force values and application of a look-forward period of 0.5 second did not significantly reduce the accuracy of the method.

Although in the foregoing, several preferred embodiments of the method and the milling machine according to the invention have been illustrated, the present invention is not in any way limited to the exemplary embodiments shown in the description and the drawings and many variations thereof are possible within the scope of the invention defined by the appended claims.

Claims

1. A method for optimizing cutting forces in a milling process of machining a workpiece by means of a milling tool, the method comprising the steps of:

- in a tool coordinate system, continuously measuring the real three-dimensional cutting force exerted by the milling tool to the workpiece (S100),
- simulating the milling process to determine a contact area between the workpiece and the milling tool by using a multi-dexel representation of the workpiece (S110),
- for each elementary section of an entire turn of the milling tool, predicting a forthcoming instantaneous elementary cutting force from said measured cutting force, said calculated cutting force being determined using a plurality of cutting force coefficients resulted from a mechanistic force model of the milling tool, wherein the mechanistic force model is provided with geometrical information of said contact area obtained from the milling process simulation and wherein the prediction uses a predetermined look-forward period (S120),
- determining the predicted instantaneous cutting force components for an entire turn of the milling tool for each cutting edge (S130), and
- according to the predicted cutting force, adjusting the operational parameters of the milling process so as to reach an optimum value for the actual cutting force acting to the milling tool (S140).

2. The method according to claim 1, wherein look-forward period of the prediction ranges between 0,1 to 2 seconds, preferably between 0,5 to 1 second.

3. The method according to claim 1 or 2, wherein the elementary cutting force components associated with the subsequent elementary sections of a turn of the tool are computed simultaneously.

4. A computer-controlled milling machine comprising

- a milling tool (210) for machining a workpiece,
- a measuring unit (230) for measuring the cutting forces exerted by the milling tool (210) to the workpiece,

- a simulation module (240) for simulating the milling process to determine a contact area between the workpiece and the milling tool (210) by using a multi-dexel representation of the workpiece,
- a prediction module (250) for receiving the milling force measurements and the simulated geometrical data, and for generating predicted cutting forces from the measured cutting forces and the simulated cutting forces, and
- a control unit (220) for receiving the predicted cutting forces and for adjusting the operational parameters of the milling process according to the predicted cutting forces so as to reach optimum values for the actual cutting forces acting to milling tool (210).

5. The milling machine according to claim 4, wherein the control unit (220) is adapted to adjust the cutting force to the predicted cutting force after a predetermined look-forward period upon receiving the predicted cutting force.

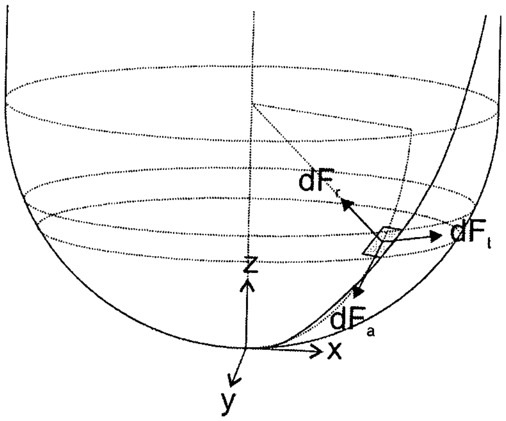

Fig. 1a

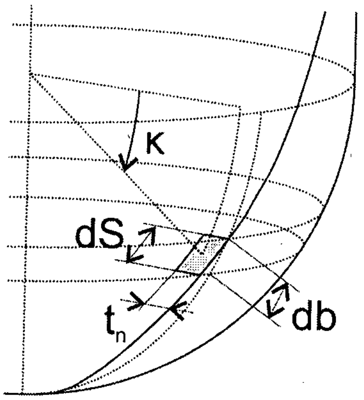

Fig. 1b

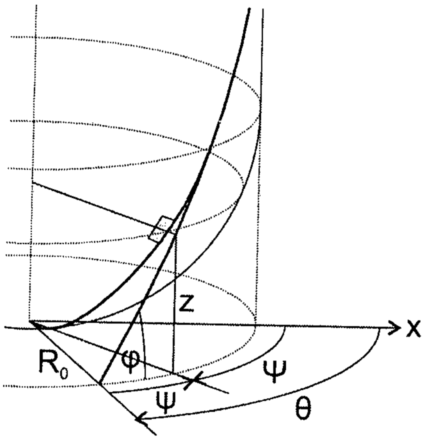

Fig. 1c

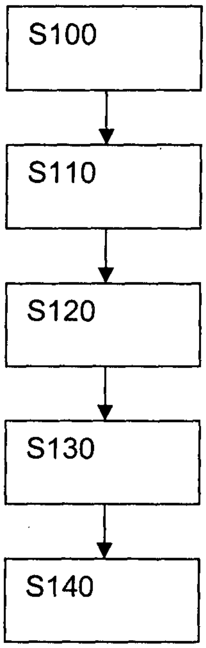
S100
S110
S120
S130
S140

Fig. 2

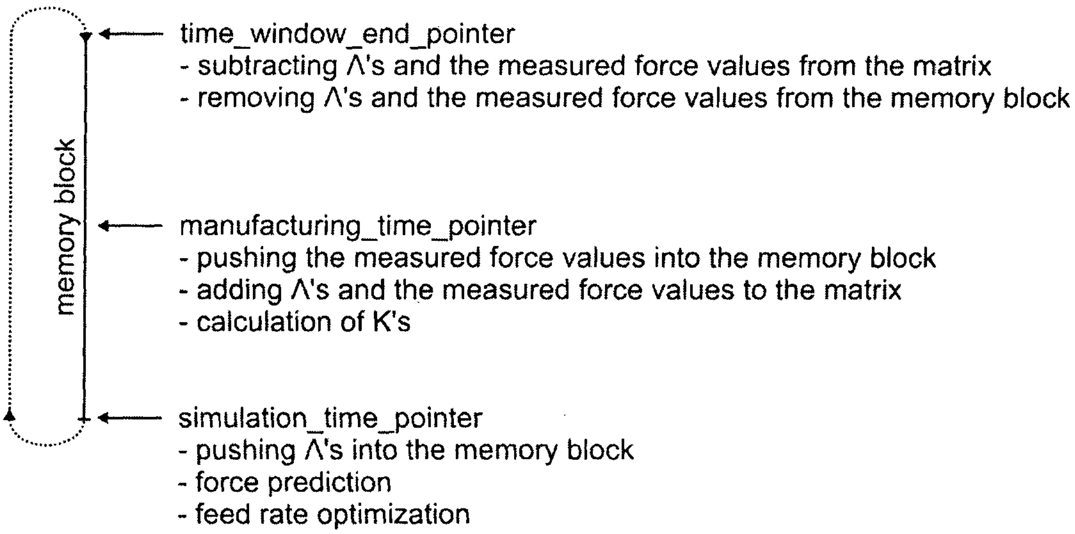
memory block
time_window_end_pointer
- subtracting Λ's and the measured force values from the matrix
- removing Λ's and the measured force values from the memory block
manufacturing_time_pointer
- pushing the measured force values into the memory block
- adding Λ's and the measured force values to the matrix
- calculation of K's
simulation_time_pointer
- pushing Λ's into the memory block
- force prediction
- feed rate optimization

Fig. 3

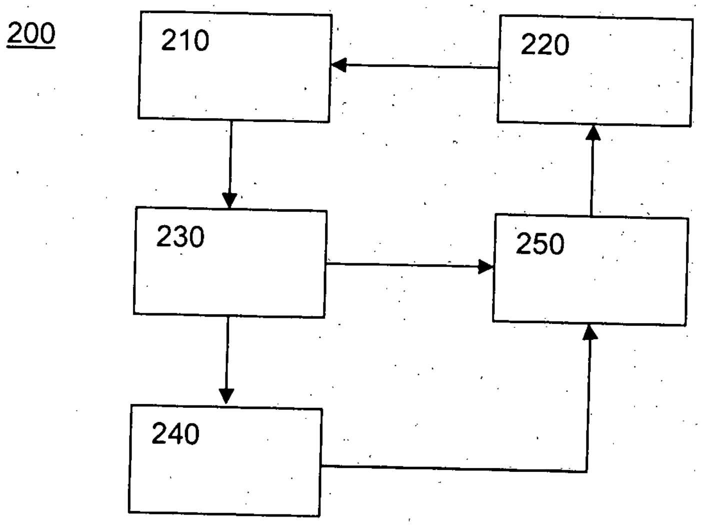

Fig. 4

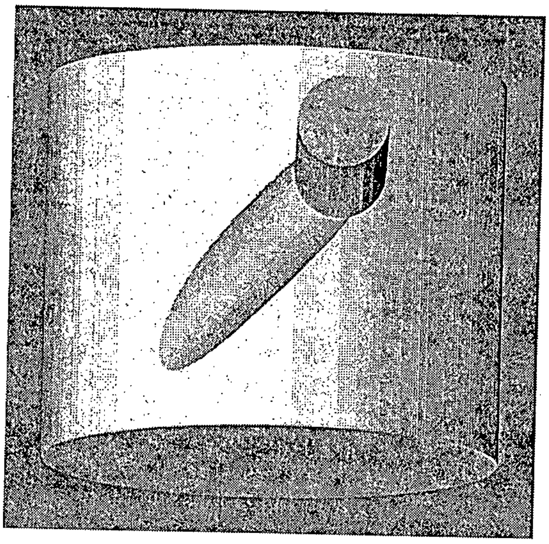

Fig. 5a

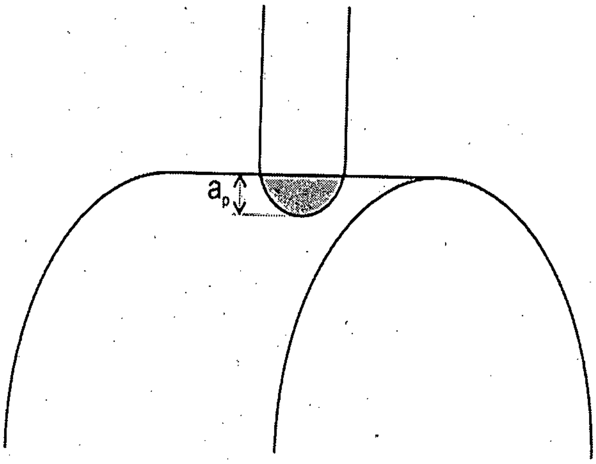

Fig. 5b

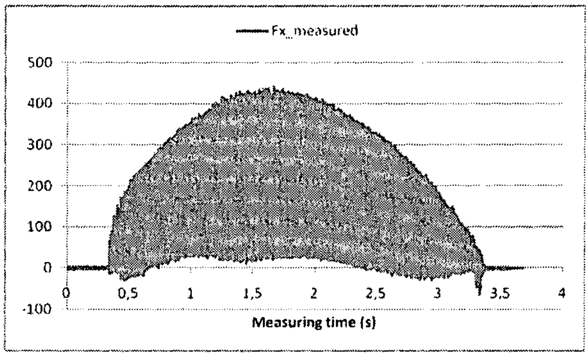

Fig. 6a

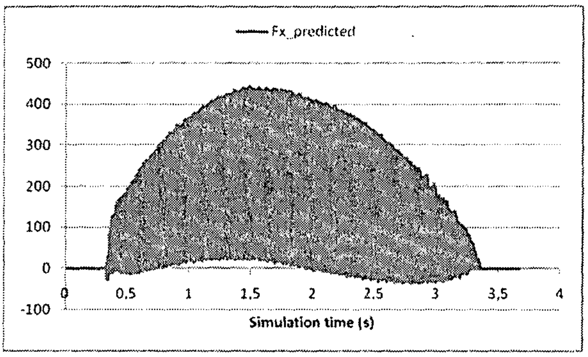

Fig. 6d

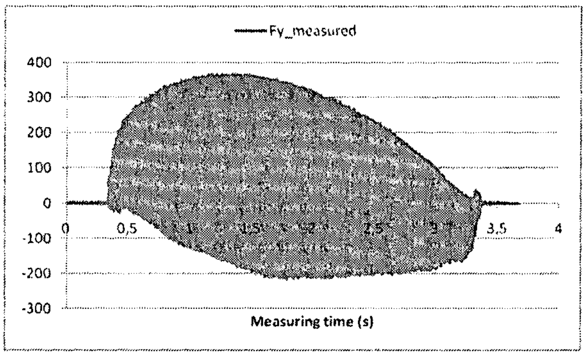

Fig. 6b

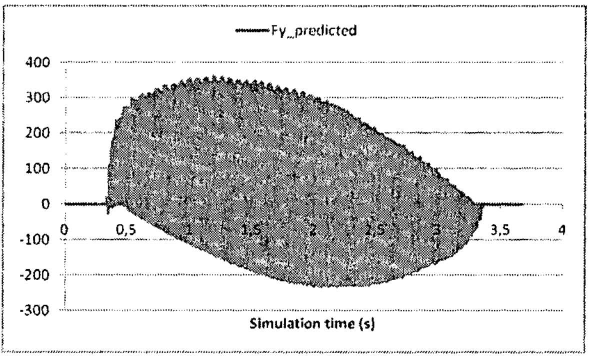

Fig. 6e

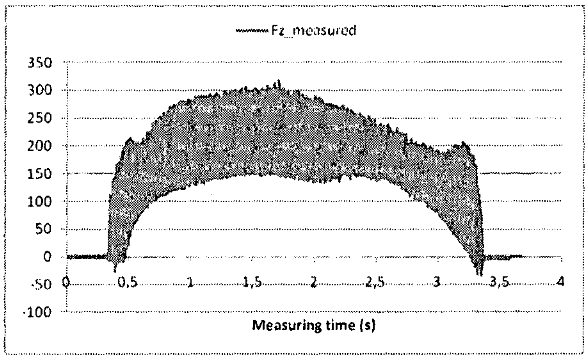

Fig. 6c

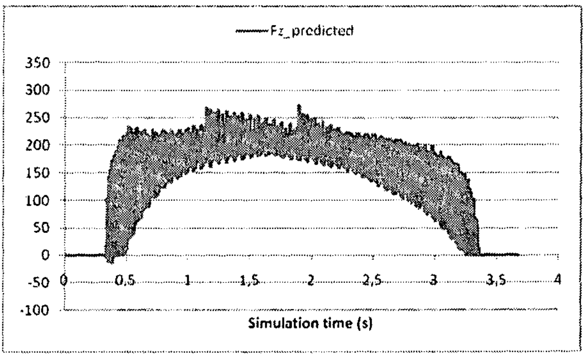

Fig. 6f

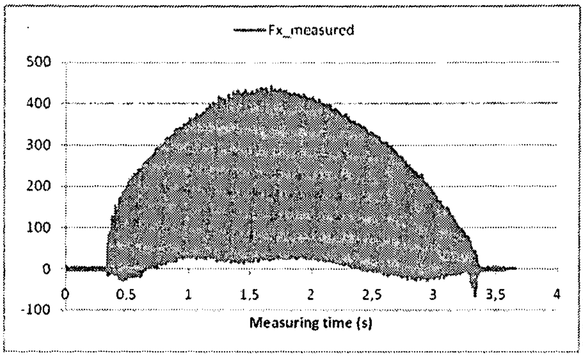

Fig. 7a

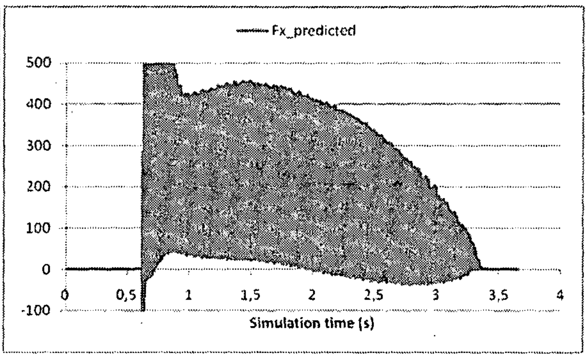

Fig. 7d

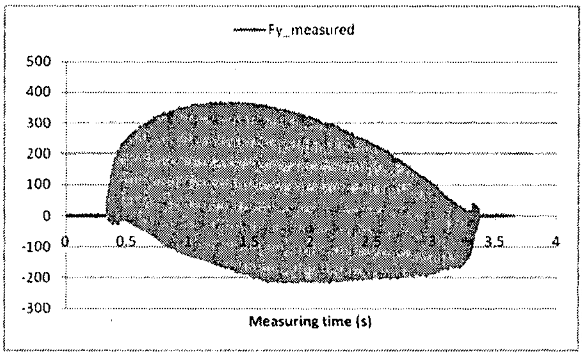

Fig. 7b

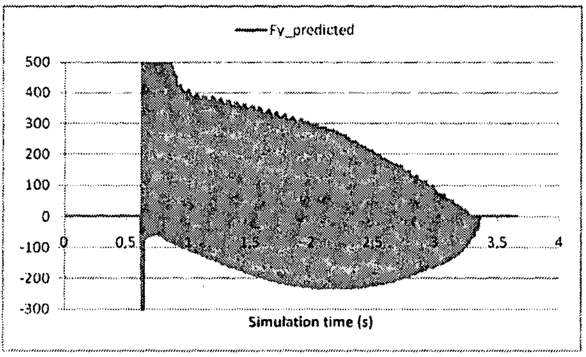

Fig. 7e

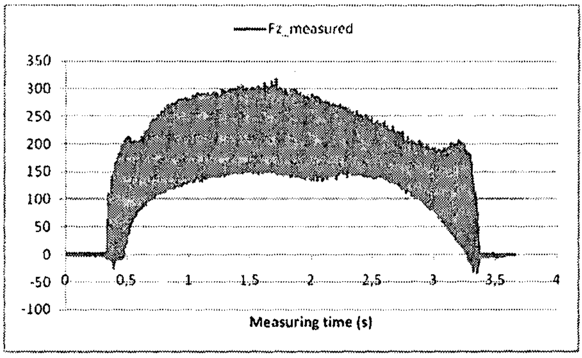

Fig. 7c

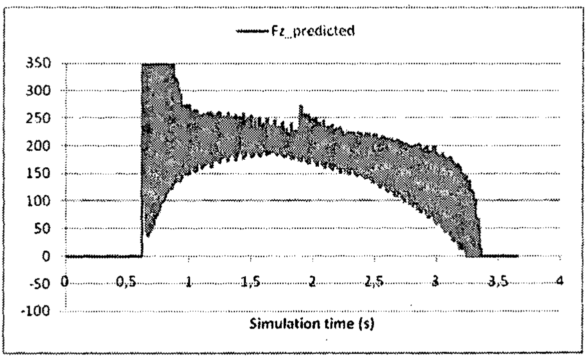

Fig. 7f