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Algorithm for Modeling the Thermo-Mechanical Field Dynamics, Based on B-Spline Functions, with Application to Machining System

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ABSTRACT

Manufacturing systems adaptive control, having as final purpose products fabrication in conditions of maximum efficiency and by respecting required quality (precision) specifications, can be done only by permanently identifying these systems. Manufacturing systems identification is realized, in fact, by identifying characteristic fields. Because process conditions continuously change during manufacturing, it appears the necessity of modeling system dynamics. This paper presents a specific tool, designed to enable manufacturing systems thermo-mechanical fields dynamics modeling, based on B-spline functions. A numerical application, in the case of a lathe vibrations field is also presented.

***Keywords**: thermo-mechanical fields, dynamics, modeling algorithm, B-spline functions.*

1. Introduction

Manufacturing systems adaptive control, having as final purpose products fabrication in conditions of maximum efficiency and by respecting required quality (precision) specifications, can be done only by permanently identifying these systems.

Manufacturing systems identification is realized, in fact, by identifying their characteristic fields, no matter if talking about geometric fields (manufacturing errors field), mechanical fields (forces, stresses or strains) or thermic fields; these fields identification is grounded on mathematical models.

Having in view that, during the manufacturing process, its evolving conditions permanently change, it appears the necessity of modeling not only the characteristic fields, but also theirs dynamics.

In dedicated literature, concerning technological systems identification, there are presented different types of characteristic fields models, analytical (based on laws governing the involved phenomena) or numerical (built-on by using the Finite Elements Method, the Element-Free Galerkin Method or Hybrid Neural-Fuzzy methods).

Although the influence of thermo-mechanical fields, generated by manufacturing processes, onto manufacturing precision is analyzed and different methods to calculate and compensate the errors (in concrete situations) are suggested, an exhaustive approach on manufacturing systems characteristic fields dynamics modeling, with general character, cannot be found and neither a specific mathematical tool dedicated to it.

From upper exposed arguments, it appears the necessity and the utility of conceiving a specific tool to allow manufacturing systems thermo-mechanical fields and their dynamics modeling; together to "on-machine" measuring techniques this will lead to an efficient adaptive control of mechanical manufacturing processes.

2. B-Spline functions

A B-spline function is a polynomial segmental function, which can be expressed by using a basic set of functions ($N_{i,k}(t)$) on each interval, referred to a set of nods.

Basic functions are chosen on such a manner as the number of backing intervals is as smaller as possible and the modification of a node position implies changes concerning only its neighborhood.

The set of k+1 consecutive intervals on which a k-order B-spline function is not null is considered as its support.

Basic B-spline functions can be iteratively generated as it follows:

$$N_{i,1}(t)=\begin{cases}1, t\in[t_i,t_{i+1});\\ 0, in\ other\ cases.\end{cases} \quad (1)$$

$$N_{i,k}(t)=\frac{t-t_i}{t_{i+k-1}-t_i}N_{i,k-1}(t)+ \\ +\frac{t_{i+k}-t}{t_{i+k}-t_{i+1}}N_{i+1,k-1}(t), \forall k\geq 2. \quad (2)$$

By using basic B-spline functions, a *k*-order B-spline function can be written as

$$f(t)=\sum_{i=1}^{n}d_i N_{i,k}(t), \quad (3)$$

on $(t_i)_{i=\overline{1,n+k}}$ set of nods.

This sum calculus can be efficiently done by using the iterative relation (2), which enables to express *f(t)* relative to basic B-spline functions, having an order smaller by one. This is further leading to the possibility of elaborating an algorithm to be used when calculating the coefficients vector to evaluate a B-spline function value, depending on its initial control points.

3. Algorithm for Modeling Thermo-Mechanical Fields Dynamics

Let’s considering a certain type of thermic or mechanical field, characterized by a function defined on a 3-D domain, $f = f(x,y,z)$. We also suppose that *f* function values can be measured in a great number of points, *N*, owning to its definition domain.

Our final purpose is to find an algorithm for characterizing considered field dynamics, by monitoring the values of f function in only a few (*n*) points, conveniently chosen from all *N* points (from practical reasons, it is very difficult to realize too many measurements during a certain manufacturing process).

From the very beginning we assume that considered field has a coherent evolution in time [1] – its values may change, but its map keeps the same general pattern.

A four-steps algorithm is further suggested, to solve the enounced problem.

1. The values of *f* function are measured in all *N* points, both in the initial and in the final stage of a certain process.
2. A difference function, Δf, is calculated

$$\Delta f(x,y,z)=f_f(x,y,z)-f_i(x,y,z), \quad (4)$$

where f_f gives the final stage values and f_i – the initial stage values.

3. The difference function is modeled on entire domain, by using B-spline functions and by considering its values in only *n* points; the n points are chosen among all *N* points by using genetic algorithms to find which of them have the greatest influence when characterizing field dynamics.
4. To find the estimated values of *f* function into the final stage, the modeled difference function values are added to *f* initial stage values, in every point from all *N* considered,

$$f_f(x,y,z)=f_i(x,y,z)+\Delta^n f(x,y,z), \quad (5)$$

where $\Delta^n f$ is the function obtained by modeling with B-spline functions.

To evaluate the quality of considered field dynamics modeling, a comparison between f_f calculated and f_f measured values should be done.

4. Numerical Application to a Machining System

The upper presented algorithm was applied to do a SNB 360 lathe vibrations field dynamics modeling. The vibrations were generating by rotating an eccentric body fixed into the self-centering chuck.

To obtain the input data for starting vibration field dynamics modeling, vibrations amplitude was measured in *N* = 53 points from lathe frontal surface (considered as xz plain), chosen on such a manner as all significant zones were considered (fig.1); these points disposition was as it follows:

- 1…25 – on headstock 1;
- 26 – on lathe tool holder 2;
- 27, 28 – on tool holder slide 3;
- 29…32 – on longitudinal slide 4;
- 33, 34 – on tailstock 5;
- 35…42 – on anterior longitudinal guide way;
- 43…50 – on bed 6, under anterior longitudinal guide way;
- 51…53 – on bed 6, on lathe stand 7.

The measurements were done by using a X Viber type device, with piezoelectric transducer, having the following main characteristics:

- sensitivity: 100 mV/g;
- frequency range: 1 – 10,000 Hz;
- resonance frequency: 23,000 Hz;
- measuring temperature: between -50 … +120 ºC;
- dynamics measuring range: > 80 dB.

More measurements series were done: the first one, considered as reference stage, for spindle 600 rot/min rotation speed and a certain eccentricity of the body, *e* (f_1(x,z), tab.1). Then, vibrations frequency was modified, by changing spindle rotation speed to 800 and 1000 rot/min

(f_2(x,z) and f_3(x,z), tab.1). Finally, the amplitude of excitation force was modified by changing rotated body eccentricity to 2*e* and 3*e* (f_4(x,z) and f_5(x,z), tab.1).

Tab. 1

Point No.	x [cm]	z [cm]	f_1(x,z) [μm]	f_2(x,z) [μm]	f_3(x,z) [μm]	f_4(x,z) [μm]	f_5(x,z) [μm]
1	20	90	28	39	32	36	44
2	35	90	30	38	30	35	41
3	50	90	27	35	30	31	37
4	65	90	24	30	29	29	35
5	20	75	26	37	31	32	41
6	35	75	25	33	32	30	36
7	50	75	26	32	31	30	37
8	65	75	23	28	30	30	32
9	20	60	25	35	31	29	35
10	35	60	25	33	30	29	35
11	50	60	24	32	31	27	37
12	65	60	22	28	29	28	34
13	20	45	24	35	30	28	34
14	35	45	24	33	32	29	34
15	50	45	23	31	30	27	33
16	65	45	21	27	30	25	31
17	20	30	23	35	29	27	34
18	35	30	22	33	31	26	32
19	50	30	21	29	30	24	30
20	65	30	19	28	31	23	29
21	5	15	23	36	31	29	34
22	20	15	24	34	30	29	33
23	35	15	22	30	29	24	30
24	50	15	20	28	30	23	29
25	65	15	19	28	29	24	29
26	115	90	19	22	33	22	27
27	115	75	19	24	32	21	25
28	130	75	17	23	39	24	26
29	115	60	19	22	32	21	28
30	130	60	18	20	33	19	28
31	115	45	17	21	32	19	25
32	130	45	15	19	31	20	22
33	145	90	17	21	36	20	24
34	160	90	15	21	36	18	21
35	85	60	21	26	32	25	30
36	100	60	19	23	30	22	28
37	145	60	15	20	33	20	22
38	160	60	14	19	33	18	20
39	175	60	12	18	34	15	17
40	190	60	10	17	33	13	15
41	205	60	7	18	36	10	13
42	220	60	7	22	37	8	10
43	85	45	18	23	29	22	25
44	100	45	17	21	30	21	25
45	145	45	13	17	31	15	19
46	160	45	11	16	31	13	19
47	175	45	10	17	30	13	15
48	190	45	10	17	32	11	12
49	205	45	7	17	34	9	12
50	220	45	6	18	31	7	8
51	205	30	6	15	28	8	9
52	220	30	5	19	31	5	7
53	210	15	5	15	26	6	6

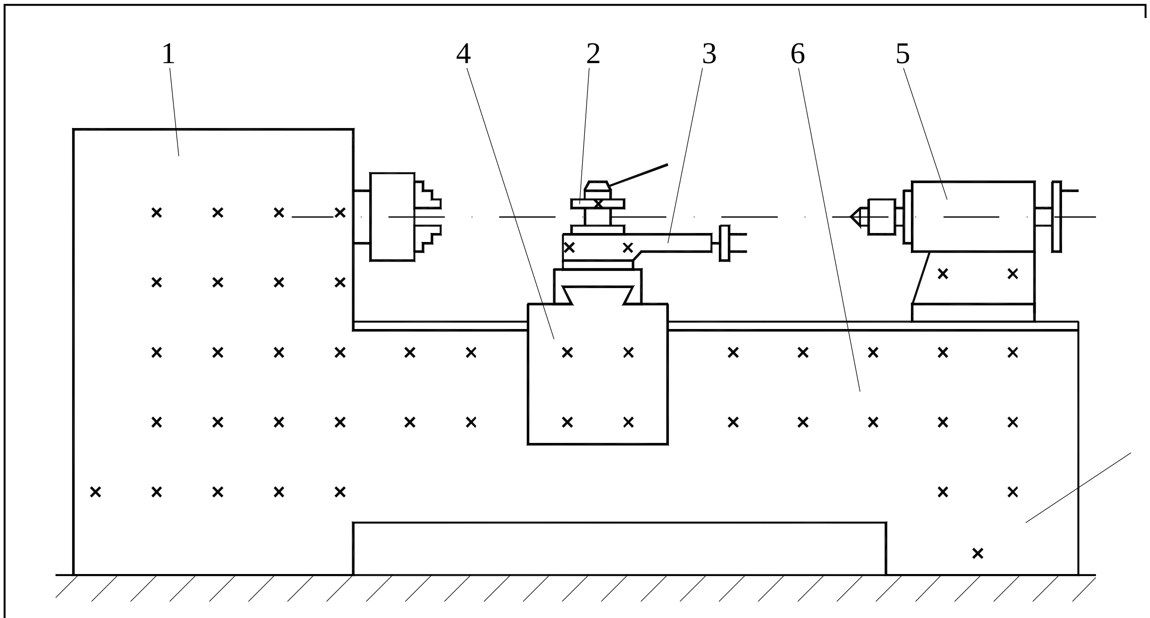

Fig. 1 – Measuring points disposition

Like upper explained, the difference functions were, then, calculated:

$$\Delta f_{1i}(x,z) = f_i(x,z) - f_1(x,z),\ i = 2...5. \quad (6)$$

The four difference functions were modeled by using B-splines, first based on values from n_1 = 25 selected points (fig.2…5), then based on only n_2 = 5 selected points.

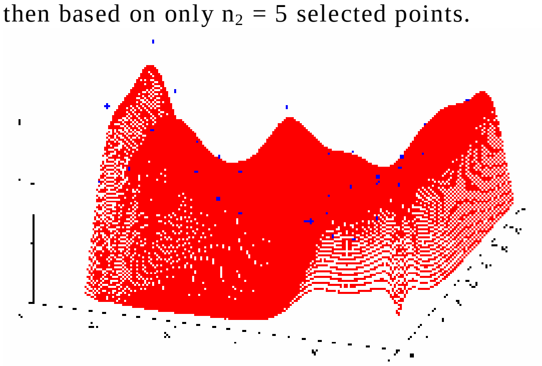

Fig.2 – Δf₁₂ model

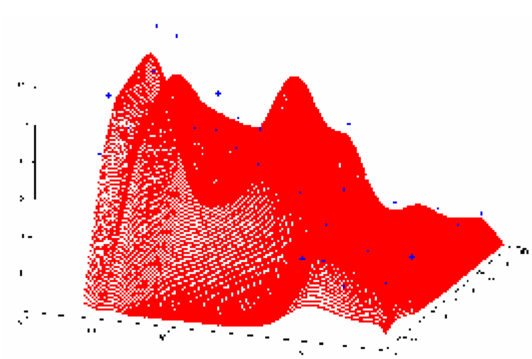

Fig.3 – Δf_{13} model

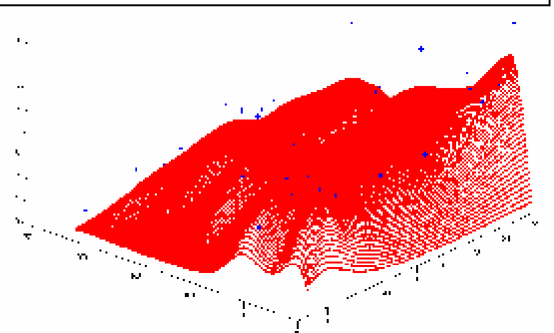

Fig.4 – Δf_{14} model

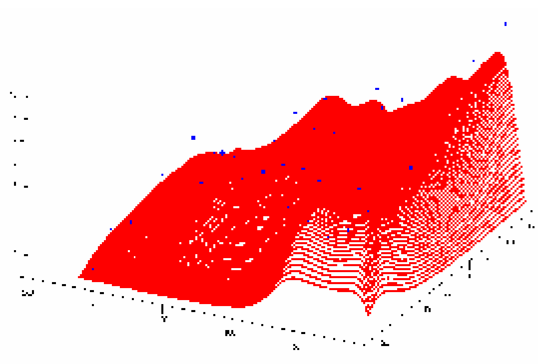

Fig.5 – Δf_{15} model

It is very important to observe if the points chosen by genetic algorithm as best characterizing vibrations field dynamics are (more or less) the same; if the points are quite the same, it means that the manufacturing process can be monitored by making measurements in only a few points.

The positions of chosen points, among all 53 measurement points, when using n = 25 points are shown in Fig.6.

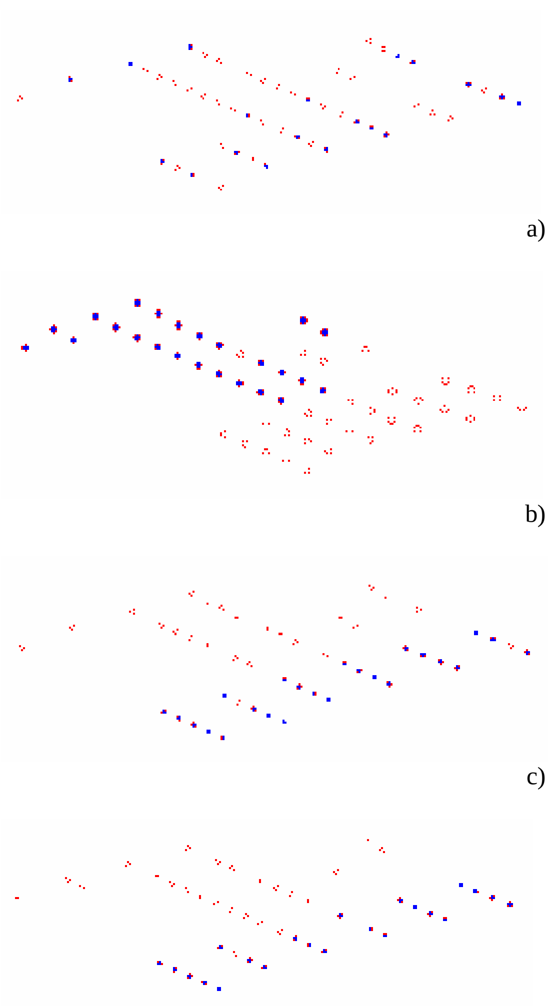

Fig.6 – The points chosen by genetic algorithm to oo Δf_{1i} functions modeling: a- Δf_{12}; b- Δf_{13}; c- Δf_{14}; d- Δf_{15}.

The comparison between vibrations real field, found by measurements and its modeled image (obtained by summing modeled difference function values to the ones from the considered reference stage) was done by calculating the average square deviation between the measured values and those obtained through modeling (in the case of each transition between two stages). The results are shown in Tab.2.

Tab.2

	Standard Deviation			
	$1 \rightarrow 2$	$1 \rightarrow 3$	$1 \rightarrow 4$	$1 \rightarrow 5$
25 points	1.2799	8.9205	0.6133	0.8691
5 points	3.5573	11.1588	0.6274	1.1251

5. Conclusions

By carefully analyzing the results obtained when doing the upper presented numerical application, the following main conclusions may be drawn:

- B-splines functions can be successfully used to realize manufacturing systems thermo-mechanical fields and their dynamics modeling; together to an appropriate graphic soft, suggestive and useful fields images can be obtained;

- The methodology imagined to realize fields’ dynamics modeling is functional; when using a great-enough number of points to construct the difference function, results accuracy is remarkable;

- The results of vibrations field dynamics modeling are totally different in the two considered cases – modifying vibrations frequency versus modifying vibrations excitation force amplitude;

- The disposition of points selected by the genetic algorithm as representative to realize system dynamics modeling substantially changed when passing from first to third oscillation frequency, respect to the transition from first to second oscillation frequency, in both cases (n = 25 or n = 5 points). This can be explained by the fact that one of system’s critical oscillation frequencies is placed between the minimum and the maximum of the frequencies used in the experiment, the system’s vibration mode considerably changing (vibrations field is not coherent between the three stages);

- When only 5 points were used, the error generated by the suggested modeling algorithm is relative higher;

- In the case of modeling vibrations field dynamics at excitation force variation, the positions of selected points remain the same in both situations (n = 25 or n = 5 points) and the precision obtained, even when only 5 points were considered, is very good.

As final conclusion, the dynamics of systems characterized by coherent thermo-mechanical fields can be successfully modeled by using B-spline functions and by measuring their values in only a few points.

Further than that, the new imagined modeling tool, upper presented, together to “on-machine” measuring techniques (which are more and more used in modern manufacturing systems control) could lead to an efficient adaptive control of mechanical manufacturing processes. By realizing an “on-line” dimensional identification, manufacturing errors could be reduced to minimum.

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Algoritm pentru modelarea dinamicii câmpurilor termice şi mecanice pe baza funcțiilor B-Spline cu aplicare în sistemele de fabricație

Rezumat

Conducerea adaptivă a sistemelor de prelucrare, având ca scop final fabricația în condiții de eficiență maximă a unor produse care să satisfacă cerințele de calitate (precizie) prescrise de proiectant, necesită identificarea permanentă a acestor sisteme. Identificarea sistemelor de prelucrare se realizează, de fapt, prin identificarea unor câmpuri caracteristice, fie că este vorba de câmpuri geometrice (câmpul erorilor de prelucrare), mecanice (câmpuri de forțe, tensiuni sau deplasări) sau termice, iar la baza identificării câmpurilor stau modele matematice ale acestora. Având în vedere faptul că, pe parcursul procesului de prelucrare, condițiile de desfăşurare ale acestuia se modifică în mod continuu, pe lângă modelul static al câmpurilor caracteristice trebuie să existe şi posibilitatea de modelare a dinamicii câmpurilor. În lucrările de specialitate dedicate identificării sistemelor tehnologice, sunt prezentate diferite tipuri de modele, analitice sau numerice. Deşi influența câmpurilor termo-mecanice, generate de procesele de prelucrare, asupra preciziei de prelucrare este analizată şi se propun diferite modele care să permită calculul şi compensarea erorilor de prelucrare (pentru diferite cazuri concrete), nu există o abordare exhaustivă, cu caracter general, asupra modelării dinamicii acestor câmpuri şi nici vreun produs matematic special dedicat acestei modelări. Lucrarea de față propune un instrument specific, care să permită modelarea câmpurilor termo-mecanice ale sistemelor de prelucrare şi a dinamicii acestora şi care, asociat cu tehnicile de măsurare „on-machine", să permită o conducere adaptivă, eficientă, a proceselor de prelucrare mecanică. O aplicație numerică referitoare la câmpul vibrațiilor unui strung, este, de asemenea, prezentată.

Algorithme pour modeler la dynamique des champs thermomécanique, basé sur des fonctions B-Spline, avec application au systèmes d'usinage

Résumé

La commande adaptive des systèmes d'usinage mécanique, ayant comme but final la production en conditions d'efficience maximisée et de qualité nécessite l'identification continue de ces systèmes. L'identification des systèmes d'usinage se fait, en effet, par l'identification des champs caractéristiques, soit qu'il s'agit de champs géométriques, mécaniques ou thermiques. En tenant compte que durant le processus de fabrication les conditions de déroulement se changent en permanence, il est nécessaire un instrument qui peut réaliser la modélisation de la dynamique de ces champs. Ce papier propose un tel instrument, lequel, associe à des techniques de mesure «on-machine», permettra la commande adaptive, des processus de fabrication mécanique. Une application numérique, concernant les champs de vibrations d'un tour, est aussi exposée.