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Analyzing feasibility of field measurements by Digital Image Stereo Correlation in restrictive conditions: Application to flexible work-piece vibrations during High Speed Machining

Faisabilité de la mesure de champs par stéréo corrélation d’images en conditions restrictives: Application aux vibrations de pièces minces en Usinage Grande Vitesse

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I. Context and goal

II. Digital Image Stereovision in machining

III. Machining tests and Measurements analysis method

IV. Conclusions and perspectives
I. Context and goal

*Thin plates milling = high risk of chatter*

- Weight reducing
  → thin plates
  → reduced stiffness compared to tool

- More and more resistant materials
  → Increased cutting forces

**Results**

- Broken tools
- Scraped pieces
- Polishing

**Costs**

**Risks**
Scientific motivation

I. Context and goal

TOOL VIBRATIONS
- No loss of material
- Constant characteristics
- No modes transitions

THIN PART VIBRATIONS
- Loss of material
- Nodes and antinodes
- Many modes transitions
  → Evolutionary behavior

… Scientists own deep knowledge

Complex scientific enigmas
I. Context and goal

Material removal problematic

Loss of information on finished part

Vibratory modes must be measured **during** machining

**Punctual sensors** do not see the whole part

**Necessity of displacement field measurement during machining**
II. Digital Image Stereovision in machining

Very high cutting frequencies → combination of 6 sensors

Limitations

Machining center access
Cameras snapping frequency: 5 images / second

Displacement fields only allow to study permanent vibrations
II. Digital Image Stereovision in machining

**Stereo correlation measurement**

![Diagram](image)
II. Digital Image Stereovision in machining

**Stereo correlation measurement**

- **Step 1:** Grey pattern painting
- **Step 2:** Sample framing
- **Step 3:** Sharpness searching
- **Step 4:** Cameras calibrating
- **Step 5:** Test measuring
- **Step 6:** Calculus parameters adjusting
- **Step 7:** Physical points processing

*No works about setting phases (2 and 3) + reduced accessibility*

-> *We developed a setting method*
II. Digital Image Stereovision in machining

**Stereo correlation device setting parameters**

**Parameters to be adjusted**
- Equipment choice
- Shutter time
- Objective
- Diaphragm
- Lighting device
- Angle between cameras
- Measurement distance
- Cameras spacing

**Constraints**
- Vibration frequency
- Machining center accessibility
- Poor ambient light
- Part’s horizontal framing
- Part’s vertical framing
- Parts sharpness
- Angle stereovision angle
  - . . .

**Analysis work: cameras spacing impact on sample sharpness**

Cameras spacing

- raises the Depth of Field (DOF), AND
- makes the D. o F. first plan cross the part

- **Parameter effet may reverse**
- **Interaction of all the parameters**
Analytical formalizing of constraints

« ... The grey pattern must sharply appears during the whole machining... »

\[ FQ > FU' \]

\[
\frac{0.35 \times 2 \times f^2}{F_{number} \times C_{confusion}} \times ((0.5 \times B)^2 + A^2) - \frac{0.5^2 \times L \times B - (\Delta - \delta) \times A}{((0.5 \times B)^2 + A^2)^{1/2}} > 0
\]
II. Digital Image Stereovision in machining

**Problem synthesis**

*Machining center accessibility*

\[ A > A_{\text{min}} \]

*Cameras spacing*

\[ B < B_{\text{max}} \]

*Stereo correlation angles*

\[ 2 \cdot A \cdot \tan \alpha_{\text{min}} - B \leq 0 \]

\[ B - 2 \cdot A \cdot \tan \alpha_{\text{max}} \leq 0 \]

*Right border framing*

\[
\frac{(0.5 \cdot B)^2 + A^2 + (\Delta - \delta) \cdot A - 0.5^2 \cdot L \cdot B)^{\text{horiz}}}{((0.5 \cdot B)^2 + A^2)^{1/2}} - 0.5^2 \cdot B \cdot L \cdot A^{\text{horiz}} - 0.5^2 \cdot B \cdot A \leq 0
\]

*Left border framing*

\[
\frac{[A^3 + (0.5 \cdot B)^2 + A + (\Delta - \delta) \cdot (A^2 - (0.5 \cdot B)^2) + 0.5^2 \cdot B \cdot L \cdot A]^{\text{horiz}}}{(0.5 \cdot B)^2 + A^2} - 0.5^2 \cdot B \cdot A \leq 0
\]

*Vertical framing*

\[
\frac{(0.5 \cdot B)^2 + A^2 + (\Delta - \delta) \cdot A - 0.5^2 \cdot L \cdot B)^{\text{vertic}}}{((0.5 \cdot B)^2 + A^2)^{1/2}} - 0.5^2 \cdot B \cdot L \cdot A^{\text{vertic}} - 0.5^2 \cdot B \cdot A \leq 0
\]

*Right border sharpness*

\[
\frac{0.35 \cdot 2 \cdot \frac{f^2}{r_{\text{stop}}^{\text{confusion}}}}{(0.5 \cdot B)^2 + A^2} - \frac{0.5^2 \cdot L \cdot B - (\Delta - \delta) \cdot A}{((0.5 \cdot B)^2 + A^2)^{1/2}} > 0
\]

*Left border sharpness*

\[
\frac{0.65 \cdot 2 \cdot \frac{f^2}{r_{\text{stop}}^{\text{confusion}}}}{(0.5 \cdot B)^2 + A^2} - \frac{(\Delta + \delta) \cdot A + 0.5^2 \cdot L \cdot B}{((0.5 \cdot B)^2 + A^2)^{1/2}} > 0
\]

\[ \{ A ; B ; f ; F_{\text{stop}} ; \Delta ; \delta ; L ; l \} \]

*To be chosen by the scientist*
II. Digital Image Stereovision in machining

Graphical solution chart

Includes the measurement technique, the sensors characteristics, the lighting, the part dimensions, the machine, ...
II. Digital Image Stereovision in machining

**Method synthesis**

- **Interesting benefits**
  - Optimal settings choice **before** tests
  - A complex experimental **problem simplified**
  - **Fast** chart plotting
  - Can include human factor, cameras dissymetry, …
  - May be **transposed** to other process
  - Setting time and material cost **reduction**

- **Limitations**
  - Needs to consider ambient light « in situ » to choose diaphragm aperture
III. Machining tests and Measurements analysis method

**Measurements during radial milling tests**

Repetition tests with 8 snaps / test

$Ap = 6 \text{ mm}$

$N = 10900 \text{ rot/ min}$
III. Machining tests and Measurements analysis method

**Measurements analysis method**

Modal analysis

Interpolation with polynomials

\[ f_1(\alpha_1, x, y) = \alpha_1 \cdot (a_{1,9} x^9 y^9 + \cdots + a_{1,0} x^0 y^0) \]
\[ f_2(\alpha_2, x, y) = \alpha_2 \cdot (a_{2,9} x^9 y^9 + \cdots + a_{2,0} x^0 y^0) \]
\[ \cdots \]
\[ f_6(\alpha_6, x, y) = \alpha_6 \cdot (a_{6,13} x^{13} y^{13} + \cdots + a_{6,0} x^0 y^0) \]

**Modes weights**

Measurement of cutting force

\[ f_0(\alpha_0, x, y)_{\text{outside}} = \alpha_0 \cdot (a_{0,9} x^9 y^9 + \cdots + a_{0,0} x^0 y^0) \]

Modal shapes + static deflection

\[ S(x, y)_{\text{outside}} = \sum_{i=1}^{6} f_i(\alpha_i, x, y) + f_0(\alpha_0, x, y)_{\text{outside}} \]

**Interpolation of Measured shape**

20 N < F < 30 N
III. Machining tests and Measurements analysis method

**Some analysis results**

- Part's structural modes of the free part (FEM)
- Vibratory shapes from cameras
- Vibratory shapes from laser vibrometer
- Mean cutting force
- Animated modes

**Dissimilarities**

- Frequencies
- Shape

**Not vibratory shapes**

**Mean cutting force**

**Similarity**

**Modes weights**
Conclusions

- Better knowledge of the stereocorrelation for machining tests
  - Setting phase analysis
  - Analytical formalization
  - Feasibility charts
  - Important novel results for measurement

- Specific analysis method developed to investigate real vibration modes
  - Surface roughness doesn’t give all the elements
  - Displacement fields helped to find differences between supposed and real modes
Perspectives

- Setting Islands for stereo correlation
  - More experimental validations of setting islands
  - Transposal to 3D parts

- High speed measurements
  - Many snaps at the cutting tooth scale
  - Finished surface roughness simulation

- Take into account the tool presence
  - Precisely identify tool contact evolution
  - Finite Elements Models with tool presence

Future cooperation in Lebanon ? ? ?
Call for abstracts: Beirut Energy Forum
26 – 27 September 2013

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