Computational Methodology for the Prediction of Functional Requirement Variations Across the Product Life-Cycle

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Problem

- Parts within mechanisms are generally specified for the assembly stage of their life cycle.
- Useful values of Functional Requirements are usually defined under operating conditions (at higher temperature and strains…)
- These 2 occurrences will be referred to as product configurations in this work.
Currently, the study of the functional requirement (FR) is done on an ideal model of the mechanism.

Challenge: How to study FR evolution during the product life cycle?

This work investigates the definition of multiple configurations to integrate part deformation in the FR calculation process.
Illustration of the problem

At Assembly
- Low Temperature (≈20°C)
- No Centrifugal Force on the blades

In Operation
- High temperature
- Important centrifugal force on the blades

How maintain the proper gap between the blades and the frame in these 2 physical states?
Wheel shaft made of Aluminium ($\alpha=1,2 \times 10^{-5}$)
Frame made of steel ($\alpha=2,38 \times 10^{-5}$)
Dimensions defined at 20°C
Parts deformations due to thermal expansion only
Design variables: dimensions of the frame
Sources of functional requirement variations

- Uncertainties due to Tolerances stack-up: analysis of tolerance zones made thanks to existing techniques

- Changing environment (variation of mechanical load or temperature): Elastic strain on parts.
Functional requirements variations across the life-cycle

- Elastic strain

\[
au - al << \overline{A} \quad \Delta (au - al) << \Delta \overline{A} << \overline{A}
\]

\( au, al \) : upper and lower tolerance zone boundaries

- Variation of tolerance zone width is insignificant relatively to mean dimension variation.

S1 At 20°C

S2 At 50°C
# Functional requirements variation across life-cycle

<table>
<thead>
<tr>
<th>Life-cycle stage</th>
<th>Value of Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- 0 +</td>
</tr>
<tr>
<td></td>
<td>Interference possible motion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Life-cycle stage</th>
<th>Δ( j_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial State (S1)</td>
<td></td>
</tr>
<tr>
<td>Final State (S2)</td>
<td>Mean value</td>
</tr>
</tbody>
</table>
Design paradigm: 2 out of 3 of the above elements must be chosen for a design to be fully constrained.
Three approaches (1)

Dimension driven

- Functional Requirements
  - At final stage

- Individual Dimension
  - At initial stage

- Loads: (Temperature, Efforts)
  - At initial and final stages
Three approaches (1)
Dimension Driven

- Known variables
  - Temperature at initial and final stages
  - Individual dimensions at initial stage

- Resulting variable
  - Functional requirements at initial and final stages
  - Individual dimensions at final stage

- Typical Issue
  What will be the value of a given functional requirement after the thermal expansion of the parts?
Three approaches (2) Functional requirement driven

- **Functional Requirements**: At initial stage
- **Individual Dimension**: At final stage
- **Loads**: (Temperature, Efforts) At initial and final stages
Three approaches (2)
Functional Requirement Driven

- Known variables
  - Temperature at initial and final stages
  - Functional requirement at initial stage

- Resulting variable
  - Individual dimension at initial and final stages
  - Functional requirement at final stage

- Typical Issue
  Which dimensions have to be chosen in order to obtain a given value for a functional requirement after thermal expansion?
Three approaches (3)  
Geometry driven

Functional Requirements
At initial and final stages

Individual Dimension
At initial stage

Loads:
(Temperature, Efforts)
At final stage
Three approaches (3)
Geometry driven

- Known variables
  - Functional requirement at initial and final stages
  - Temperature at initial stage

- Resulting variable
  - Temperature at final stage

- Typical Issue
  Which loads are acceptable in order to ensure the respect of a common functional requirement at 2 different stages of the product life cycle.
Example of FR management along the product life cycle

Check of initial Design (Dimension Driven)

Meet Final Functional Requirements

Yes

Redesign to fit final requirements (Functional Requirement Driven)

Meet Initial Functional Requirements

Yes

Calculation of Acceptable Load variation (Geometry Driven)

Product validated
## Calculation 1

### Dimension driven

<table>
<thead>
<tr>
<th>Life-cycle stage</th>
<th>Value of $j_1$</th>
<th>Value of $j_2$</th>
<th>Value of $j_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Interference</td>
<td>0.45</td>
<td>0.6</td>
<td>0.85</td>
</tr>
<tr>
<td>Motion Possible</td>
<td>0.25</td>
<td>0.4</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>0.479</td>
<td>1.010</td>
<td>0.369</td>
</tr>
<tr>
<td></td>
<td>0.279</td>
<td>0.810</td>
<td>-0.031</td>
</tr>
<tr>
<td></td>
<td>0.079</td>
<td>0.610</td>
<td>-0.431</td>
</tr>
</tbody>
</table>

**Stage “Si” @ 20°C**

**Stage “Sf” @ 50°C**
## Calculation 2
### Functional Requirement driven

<table>
<thead>
<tr>
<th>Life-cycle stage</th>
<th>Value of $j_1$ (-)</th>
<th>Interference</th>
<th>Motion Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage “Si” @ 50°C</td>
<td>0.45</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>0.471</td>
<td>0.271</td>
<td>0.071</td>
</tr>
<tr>
<td>Stage “Sf” @ 20°C</td>
<td>0.09</td>
<td>-0.110</td>
<td>-0.310</td>
</tr>
<tr>
<td></td>
<td>1.381</td>
<td>0.981</td>
<td>0.581</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value of $j_2$ (-)</th>
<th>Interference</th>
<th>Motion Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>0.9</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>0.071</td>
<td>-0.110</td>
<td>-0.310</td>
</tr>
</tbody>
</table>
# Calculation 3
## Geometry driven

<table>
<thead>
<tr>
<th>Life-cycle stage</th>
<th>Value of $j_1$</th>
<th>Value of $j_2$</th>
<th>Value of $j_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage &quot;Si&quot; @ 20°C</td>
<td>- 0 +</td>
<td>- 0 +</td>
<td>- 0 +</td>
</tr>
<tr>
<td></td>
<td>Interference</td>
<td>Interference</td>
<td>Interference</td>
</tr>
<tr>
<td></td>
<td>Motion Possible</td>
<td>Motion Possible</td>
<td>Motion Possible</td>
</tr>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>0.3</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>0.1</td>
<td>0.45</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.45</td>
<td>0.25</td>
<td>0.6</td>
<td>0.85</td>
</tr>
<tr>
<td>0.25</td>
<td>0.05</td>
<td>0.4</td>
<td>0.45</td>
</tr>
<tr>
<td>0.05</td>
<td></td>
<td>0.2</td>
<td>0.05</td>
</tr>
</tbody>
</table>

| Allowable final temperature | 91.0°C | 25.9°C | 22.8°C |


Conclusion

- High-level management of Functional Requirement along the product life-cycle.

- Investigation of typical design scenarios involving loads and functional requirements variations.

- Use of multiple configurations of the mechanism for studying product evolution along life cycle.
Perspectives & Further Work

- Use of a parametric representation for 3D extension.
  - Dimension chains viewed as vector loops
  - Deformations viewed as variations on vectors’ lengths and orientations
- Results from Finite Elements calculation used to quantify dimension variations
- Integration within a PLM based framework representation
Computational Methodology for the Prediction of Functional Requirement Variations Across the Product Life-Cycle

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Discussion

Calculs de :
Tolérancement
Assemblabilité
Mobilité
Jeu minimum

Paramètres de conception

Modèle Géométrique CAO

Spécifications Fonctionnelles (GPS)

Vectorisation
SATT / EGRM

Simulation Éléments Finis

Maillages résultats
Paramètres de calcul

Modèle CAO Déformé
Definitions and concepts

- Nominal dimension: $A$
- Tolerance: $[al;au]$
- Mean dimension: $\bar{A} = A + \frac{au + al}{2}$
- Dimension chain: $j1 = B - A$
- Calculation of functional requirement values
Uncertainties on Functional Requirements

- For all dimensions tolerance zones are 0.2mm width
- Uncertainties on Functional Requirements are deduced thanks to dimension chains relation
  - $j1$ has a 0.4mm width uncertainty zone
  - $j2$ has a 0.4mm width uncertainty zone
  - $j3$ has a 0.8mm width uncertainty zone
Functional requirements variation across life-cycle

- Width of uncertainty for Functional Requirement is not varying along life cycle
- Loads variations affect the mean value of the Functional Requirement

- Tolerance analysis/synthesis made once at the initial stage.
- Variations due to the changing environment are evaluated on the mean values
Further Work

- Use of a deformed mesh to deformed BRep transfer. [Louhichi]
- Association of the deformed mechanism to an ideal and FR compatible “neighbour”.
- Calculation of the distance between deformed and associated parameterisation vectors
- Deduction of minimal functional requirement [Serré]
Discussion : Contribution du LISMMMA?

- Utilisation des relations de dépendance en 3D comme équation pour caractériser des conditions fonctionnelles.

- Pour les mécanismes iso-statiques ?
Three kind of calculations

### Dimension driven
- Choice of functional requirement under study and extraction of the corresponding dimension chain
- Extraction of individual dimensions along dimension chain
- Calculation of mechanical deformations
- Integration of calculated deformations in the corresponding mean dimension
- Calculation of final functional requirement value with dimensions updated values
- Comparison of the results with designer intent or with specifications at final stage.

### Functional requirement driven
- Choice of functional requirement under study and extraction of the corresponding dimension chain
- Specification of initial functional requirement
- Distribution of functional requirement: deduction of initial dimension values
- Calculation of parts deformations
- Deduction of final values for individual dimensions
- Optional calculation of functional requirement at final stage
- Comparison of the results with designer intent or with specifications at final stage.

### Geometry driven
- Choice of functional requirement under study and extraction of the corresponding dimension chain
- Specification of initial and final values for functional requirement
- Distribution of functional requirement: deduction of initial dimension values
- Calculation of thermo-mechanical load variations from initial to final condition
- Optional Calculation of final dimensions
Calculation 1
Dimension driven

What will be the value of a given functional requirement after thermal dilatation of the parts?

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_i = 20°C$</td>
<td>$j_1 = [0.079 ; 0.479] mm$ at 50°C</td>
</tr>
<tr>
<td>$t_f = 50°C$</td>
<td>$j_2 = [0.610 ; 1.010] mm$ at 50°C</td>
</tr>
<tr>
<td>$e_1 = 60^{±0.1} mm$ at 20°C</td>
<td>$j_3 = [-0.431 ; 0.369] mm$ at 50°C</td>
</tr>
<tr>
<td>$e_2 = 1440^{±0.1} mm$ at 20°C</td>
<td>$e_3 = 60^{±0.1} mm$ at 20°C</td>
</tr>
<tr>
<td>$e_3 = 60^{±0.1} mm$ at 20°C</td>
<td>$b_2 = 1439.7^{±0.1} mm$ at 20°C</td>
</tr>
<tr>
<td>$b_1 = 60.3^{±0.1} mm$ at 20°C</td>
<td>$b_1 = 60.043$ at 50°C</td>
</tr>
<tr>
<td>$b_2 = 1440.218$ at 50°C</td>
<td>$b_2 = 1440.218$ at 50°C</td>
</tr>
<tr>
<td>$b_3 = 60.8^{±0.1} mm$ at 20°C</td>
<td>$b_3 = 60.322$ at 50°C</td>
</tr>
<tr>
<td>$b_3 = 60.8^{±0.1} mm$ at 20°C</td>
<td>$b_3 = 60.822$ at 50°C</td>
</tr>
</tbody>
</table>
### Calculation 2
#### Functional requirement driven

Which dimension has to be chosen in order to obtain a given value of a functional requirement after thermal dilatation?

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_i = 50^\circ C$</td>
<td>$e_{160}$ at 20°C</td>
</tr>
<tr>
<td>$t_f = 20^\circ C$</td>
<td>$e_{21440}$ at 20°C</td>
</tr>
<tr>
<td>$j_1 = [0.05 ; ; 0.45] \text{ mm}$ at 50°C</td>
<td>$e_{21440}$ at 20°C</td>
</tr>
<tr>
<td>$j_2 = [0.2 ; ; 0.6] \text{ mm}$ at 50°C</td>
<td>$b_{160.27}$ at 20°C</td>
</tr>
<tr>
<td>$j_3 = [0.05 ; ; 0.85] \text{ mm}$ at 50°C</td>
<td>$b_{21440.109}$ at 20°C</td>
</tr>
<tr>
<td>$e_1 = 60.043^{\pm 0.1} \text{ mm}$ at 50°C</td>
<td>$b_{160.87}$ at 20°C</td>
</tr>
<tr>
<td>$e_2 = 1441.028^{\pm 0.1} \text{ mm}$ at 50°C</td>
<td>$j_1 = [0.071 ; ; 0.471] \text{ mm}$ at 20°C</td>
</tr>
<tr>
<td>$e_3 = 60.043^{\pm 0.1} \text{ mm}$ at 50°C</td>
<td>$j_2 = [-0.310 ; ; 0.09] \text{ mm}$ at 20°C</td>
</tr>
<tr>
<td>$b_1 = 60.293^{\pm 0.1} \text{ mm}$ at 50°C</td>
<td>$j_3 = [0.581 ; ; 1.381] \text{ mm}$ at 20°C</td>
</tr>
<tr>
<td>$b_2 = 1440.628^{\pm 0.1} \text{ mm}$ at 50°C</td>
<td></td>
</tr>
<tr>
<td>$b_3 = 60.893^{\pm 0.1} \text{ mm}$ at 50°C</td>
<td></td>
</tr>
</tbody>
</table>
Simple application case: Hypothesis

- Wheel shaft made of Aluminium ($\alpha=1,2 \times 10^{-5}$)
- Frame made of steel ($\alpha=2,38 \times 10^{-5}$)
- Dimension known at 20°C
- Deformation of parts due to thermal dilatation only

Design variables: dimensions of the frame

\[
\begin{align*}
  j_1 &= b_1 - e_1 \\
  j_2 &= e_2 - b_2 \\
  j_3 &= b_2 + b_3 - e_2 - e_3
\end{align*}
\]