Qualitative Design of Compact Transmission Mechanisms with Standard Components

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Introduction

- **General context**

  3D machine design from written specifications

- **Purpose of this work**

  A software wizzard for preliminary design of transmission mechanisms

- **Type of mechanisms**

  - High ratio transmissions
  - Multi- stage mechanism
    - Which stage ?
    - In what order ?
    - Where in space ?

- **Summary**

  1 - Basic concepts
  2 - Synthesis method
  3 - Concluding example
Context

References:

- [Chakrabarti and Bligh 96]
  Synthesis of transmission mechanisms with multiple I/O
  Combination of mechanical modules
  Orthogonality restrictions

- [Kota and Chiou 92]
  Synthesis method for compound mechanisms
  Qualitative matrix representation

- [Joskowicz and Sacks 93]
  Kinematic analysis of gear boxes and transmissions

- [Forbus, Nielsen and Faltings 91]
  Qualitative kinematics and dynamics for analysis of complex mechanisms

Previous works:

- [Fauroux and Sartor 97]
  Qualitative synthesis method for exploring domain of feasible solutions

- [Fauroux, Sanchez, Sartor and Martins 98]
  Fuzzy logic evaluation of solution

The idea:

- Improving synthesis method for transmission mechanisms
  - Including qualitative analysis of solutions for getting a better characterization
Method Architecture

Requirements
- I/O relative orientations
- Efficiency
- Speed ratio
- Sense of rotation
- Stage number

Domain of potential solutions

Domain of feasible solutions complying with design rules

Ordered list of solutions
- CAD models

Exploration
Generate combinations of mechanisms

Elimination
Apply design rules

Sorting
Find best solutions sorted by quality

+ - A method improving creativity
- Exhaustive exploration of feasible solutions

- - Qualitative solutions are too vague
  Many equivalent good solutions
  How to differentiate them?
Qualitative Solutions

- Qualitative solutions are too vague
  - Qualitative shape of parts
  - Relative ordering of parts (connectivity)
  - Not the final dimensions
  - Not the final orientations

Good qualitative solutions are often not easy to differentiate
- Qualitative solutions give a good start to designers...
- ...but need to be enriched in information

Example: 1008 solutions and 8 rated N° 1
Which to choose?

Idea: try to reproduce human mind
Standard Orientations

- Enriching the model by orientating stages
- 4 standard values: $0^\circ / 90^\circ / 180^\circ / 270^\circ$
  - Strong assumption but corresponding to the vast majority of industrial mechanisms
  - Permits a fast exploration of mechanism layouts
  - May be refined later

A given mechanism can take a great number of layouts
- 2 angles
- 4 values per angle
- 16 combinations
Standard Orientations

0°/0°

0°/90°

0°/180°

0°/270°

90°/0°

90°/90°

90°/180°

90°/270°

180°/0°

180°/90°

180°/180°

180°/270°

270°/0°

270°/90°

270°/180°

270°/270°

Horizontal

Compact
Mechanism Compactness

- **Compactness**: a way for differentiating solutions
- Compact = fits the available space
  - No spoilt space inside
  - No big parts crossing outside

- **Not Compact**
  - Space is horizontal
  - Mechanism is vertical
  - Mechanism is totally outside

- **Compact**
  - Mechanism has good overall orientation
  - Mechanism has good proportions

Available space

Input

Output

Specified output

Available space

Output = Specified output

Input
Standard Mechanisms (1/2)

- **Semi-dimensioned** mechanisms

  **Example:** cylindrical gear
  - Diameters have given values - > Fixed ratio
  - Pitch diameter or tooth width may be kept undefined

- **Cylindrical gear sets**
  - Opposite shafts / Shafts on the same side
  - Ratios 1, 2 or 4
  - Dimensions: 4R, 6R, 10R

- **Bevel gear sets**
  - Two shaft settings for reversing sense of rotation
  - Ratios 1, or 2
  - Big wheels are expensive so ratios are limited
Standard Mechanisms (2/2)

**Internal cylindrical gear sets**
- Opposite shafts / Shafts on the same side
- Ratio 2 gives part interference with shafts on the same side
- Ratios 3 or 5
- Dimensions: 6R or 10R
- With same overall dimension, internal gear sets reduce more than external ones

**Worm gear sets**
- Great ratios but efficiency sometimes small
- Two shaft settings
- Ratios 8, 16 or 32
- 4 threads / 32 teeth, ratio 8, efficiency 85%
- 1 thread / 16 teeth, ratio 16, efficiency 75%
- 1 thread / 32 teeth, ratio 32, efficiency 67%
- Number of threads $\uparrow \Rightarrow$ ratio $\downarrow$ but efficiency $\uparrow$
- Number of teeth $\uparrow \Rightarrow$ ratio $\uparrow$, dimensions $\uparrow$ but efficiency $\downarrow$
Exploration

- Combinatorial exploration
- Global **hybrid** configuration counter:
  - Stage nature (base $N_{\text{MaxM}}$)
  - Stage orientation (base 4)

<table>
<thead>
<tr>
<th>Stage nature counter</th>
<th>Stage orientation counter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>$O_1$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$O_2$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$O_3$</td>
</tr>
<tr>
<td>$S_{\text{MaxM}}$</td>
<td>$O_{\text{MaxM}}$</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Nature</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 2</td>
<td>000° 090° 180° 270°</td>
</tr>
<tr>
<td>$N_{\text{MaxM}}$</td>
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</tbody>
</table>
Elimination Rules

- The domain of configurations increases greatly
- Elimination rules can be refined
- Limitation of the number of stages with orthogonal shafts
- Good efficiency \( \eta_C \geq \eta_S \) with \( \eta_C = \prod_{i=1}^{N_{\text{Max}}} \eta_i \)
- Good speed ratio \( U_S - \Delta U \leq U_C \leq U_S + \Delta U \) with \( U_C = \prod_{i=1}^{N_{\text{Max}}} U_i \)
- Good rotation sense
- Good absolute orientation of output shafts

\[ \tilde{Z}_{OC} = \tilde{Z}_{OS} \quad \text{with} \quad \tilde{Z}_{OC} = \prod_{i=1}^{N_{\text{Max}}} \mathbb{R}_i \tilde{Z}_{IC} \]

- Correct relative I/O locations

\[ \gamma = \langle \overrightarrow{P_{IC}} \overrightarrow{P_{OC}}, \overrightarrow{P_{IS}} \overrightarrow{P_{OS}} \rangle < 90^\circ \]

\[ \text{with} \quad P_{OC} = \prod_{i=N_{\text{Max}}}^{1} c_i P_{IC} \]

- Qualitative and non dimensional
Sorting Criteria (1/2)

- Best configurations should be sorted first
- Five performance functions
  - Mechanism nature quality
    - Power transmission ability
    - Fabrication cost
    - Mounting cost
  - Overall proportion quality
    - From 0 (perfect fitting)
    - To infinity (infinite extension along one axis)

\[
F_P = \left| \frac{a}{A} - \frac{b}{B} \right| + \left| \frac{b}{B} - \frac{c}{C} \right|
\]

Overall dimensions of a mechanism configuration

Specifications

- \( A \)
- \( B \)
- \( C \)

- \( Z_{IS} \)
- \( Z_{OS} \)
- \( Z_{OC} \)
- \( Z_{IC} \)
Sorting Criteria (½2/2)

- Five performance functions

- **Input location quality**
  \[ F_I = \left( \frac{|NX_{IC} - NX_{IS}| + |NY_{IC} - NY_{IS}| + |NZ_{IC} - NZ_{IS}|}{3} \right) \]

  with
  \[ NX_{IC} = \frac{X_{IC} - X_{MinC}}{X_{MaxC} - X_{MinC}} \]
  and
  \[ NX_{IS} = \frac{X_{IS} - X_{MinS}}{X_{MaxS} - X_{MinS}} \]

  - \(NX_{IC}\) represent the non-dimensional position in % of \(P_{IC}\) along the specification box
  - \(F_I = 0\) for an input perfectly fitting specifications
  - \(F_I = 1\) for an input diagonally opposed to requirements

- **Output location quality**

- **Relative I/O location quality**
  \[ F_{IO} = 1 - \cos(\gamma) \]

  - \(F_{IO} = 0\) when relative I/O location perfectly fits specifications
  - \(F_{IO} = 1\) when I/O is very far from expected
Example

Design of the following mechanism:
- Orthogonal I/O shafts
- Efficiency > 90%
- Speed ratio around 47
- Reversing sense
- No more than 4 stages

Results:
- 10 240 000 combinations
- Less than 5 seconds on a PIII 650 Mhz
- No solutions with $\Delta U = 0$
- 5723 solutions with $\Delta U = 1$ (space reduced by a factor 2000)
- Most of time spent in Exploration and Elimination phases
- High efficiency of qsort method (average running time $N \cdot \log(N)$)

Example: $10^6$ combinations sorted in 10 seconds
- Time may be cut down by changing elimination rule order

Example: Orientation rule from first to last place
Computing time from 45 to 4 seconds

Demo
Conclusion

A new method for designing transmission mechanisms with **standard components** and **standard orientations**.

**Advantages**
- Standard components: more precise and **realistic** particularly for transmission ratio and efficiency.
- Solutions are **better defined** with more qualitative information.
- Realistic diameters and part orientations.
- **Compact** mechanisms are exhibited.
- Divides by **several thousands** the initial combination space.

**To be Improved**
- Elimination rules may be refined.
- Sorting criteria may be refined.
- Faster computations with large databases.

**An efficient tool for suggesting ideas to designer with exhaustivity.**