2.72 Elements of Mechanical Design
Spring 2009

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Schedule and reading assignment

Quiz

- Quiz – HTMs

Topics

- Principles of exact constraint
- Bearing layout exercises
- Spindle shaft constraint/bearing layout

Reading assignment

- Chapter 11 in Shigley and Mischke
  - Read sections 11.1 – 11.6, 11.9
  - Skim sections 11.7 – 11.8, 11.10 – 11.12

- This is 40ish pages, but most of it is pictures/graphs/examples
Principles of exact constraint
Under, exact and over constraint

Constraints are fundamental to mechanical design
- A mechanical designers goal is to control, i.e. to constrain, parts so that they are where they are supposed to be.

Exact constraint:
- There should be one constraint for each degree-of-freedom that is constrained.

Under constraint
- Too few constraints, part is not held in all the directions it needs to be

Over constraint
- Too many constraints, some constraints may fight each other when trying to do the same job.
Mechanical constraints

We want to learn how to model and design each

We first need to know:

- How they should be used
- What their functional requirements are

How they should be used and their FRs depend upon:

- How they are laid out
- Dos and don’ts

Learn to lay them out right

- Use this to obtain their Functional Requirements
- Then do the detailed design of each
Rigid components have 6 degrees-of-freedom
We will represent an ideal constraint as a line

$6 - C = R$

$C = \# \text{ of Non-Redundant Constraints}$

$R = \# \text{ of Independent Degrees of Freedom}$

Example:

$6 - 2\text{ constraints} = 4\text{ DoFs}$

Courtesy John Hopkins, MIT

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Constraints, compliance and motion

Exact constraint: Achieve desired motion

- By applying minimum number of constraints
- Arranging constraints in correct constraint topology
- Adding constraints only when necessary

For now:

- Start with ideal constraints
- Considering small motions
- Constraints = lines

Focus on rigid stage attached to ground

- What do we mean by rigid?
- What do we mean by constraint? - Stiffness ratios
The benefits of exact constraint

Parts of machines are now always the same strength and stiffness.

Large, stiff components have a tendency to “kill” their smaller counterparts when they are connected so that they are forced to fight.

Exact constraint design helps to prevent fights, therefore all your parts live in harmony.

Penalties for over constraint

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Constraint examples

More examples:

1. 
2. 
3. 
4. 
5. 
6.
Exact constraint practice
Mechanical constraints: Some bearing types

**Sliding**
- Bushings
- etc…

**Radial rolling**
- Radial
- Shallow groove
- Deep groove (Conrad)
- Angular contact
- Tapered
Examples drawn from your lathe
Example: Carriage constraint

Assume these are bushings as in your lathe.
Example cont.
Example cont.

Thermally Induced growth
Practical embodiment

Flexure that is stiff in y and z, yet compliant in x
Group exercise – Carriage constraints

Identify the motions that you desire for the carriage and the minimum # of constraints that are needed to yield only these motions.

Identify the constraints from each bearing set and determine how they act in concert to yield the desired motions.
Constraint layouts and thermal stability
Avoiding over constraint

How to deal with the thermal growth issue

- The shaft typically gets hotter than the housing because the housing has better ability to carry heat away
- Whether the outer or inner race are fixed, matters…

Constraining front and rear bearings

- One bearing set should be axially and radially restrained
- The other bearing set should ONLY have radial restraint
Examples: Good or bad

Outer race fixed \textit{axially}, if shaft heats is this bad?

- Think about what happens to the preload…
Examples: Good or bad

Outer race fixed *axially*, if shaft heats is this bad?

- Think about what happens to the preload…

This is the back-to-back config.

It should be used when the outer race is not rotating.
Examples: Good or bad

Assume the outer race does not rotate

Sliding permitted

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Examples: Good or bad

Assume the outer race does not rotate

Sliding permitted

Gear

Gear

Nut

Spacer

Shaft

Chuck

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Examples: Good or bad

Assume the outer race does not rotate

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Examples: Good or bad

Assume the outer race does not rotate

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Examples: Good or bad

Assume the outer race does not rotate

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Examples: Good or bad

Assume the outer race does not rotate

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Examples: Good or bad

Good

- Front set constrained radially and axially
- Rear set constrained only radially

But, sliding means some gap must exist and therefore one must precision fabricate if a small gap is desired.
Examples: Good or bad

Bad

- Front set constrained only radially
- Rear set constrained only radially

This design will not work if axial loads are to be applied along both directions
Examples: Good or bad

Good

- Front set constrained radially and $\frac{1}{2}$ axially
- Rear set constrained radially and $\frac{1}{2}$ axially

BUT, adding a spring increases part count/cost

Axial stiffness values (left vs. right) will be different
Examples: Good or bad

BAD

- Front set is constrained only ½ axially
- Rear set is constrained only ½ axially

This design will not work if axial loads are to be applied along both directions.
Examples: Good or bad

BAD

- Front set is constrained ½ axially and radially
- Rear set is constrained ½ axially and radially

At high speeds/loads, thermal growth may kill the bearing sets

- Like a double face-to-face…
Examples: Good or bad

Bad

- Front set constrained radially and $\frac{1}{2}$ axially
- Rear set constrained radially (if flexure is of proper stiffness)

Assume the outer race does not rotate

Left bearing set is not in the back-to-back configuration

Shaft can pop out…
Group exercise
Group exercise – Spindle constraints

The spindles you have seen use tapered roller bearings.

First, sketch a layout from one of the previous lathes and diagnose its layout.

Second, generate and sketch a different way to constrain the spindle shaft.