Mechanism Feasibility Design Task

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Last Week

Systems Modelling in Simulink

- Demo: Stopping the simulation at a specific point
- Demo: Adding damping to a system
- Demo: Four-bar mechanism

Where you should be at:

- Mechanism modelled in Simulink
- Evaluated a range of motors, gear ratios and level of damping

Product Design Specification

Concept Design

Concept Selection

Stage-Gate

Deployment Modelling

Motor, Gear Ratio & Damping Selection

Gearbox Design

Types of Gear

Spur

- Applications
  - Low/Moderate speed environments (Pitch Line Velocity < $25ms^{-1}$)
  - Engines, Power Plants, Fuel Pumps, Washing Machines, Rack & Pinion mechanisms
- Pros
  - Can transmit large amounts of power (50,000kW)
  - High Reliability
  - Constant Velocity Ratio
  - Simple to Manufacture
- Cons
  - Initial contact is across entire tooth width leading to higher stresses
  - Noise at high speeds
  - Can't transfer power between non-parallel shafts

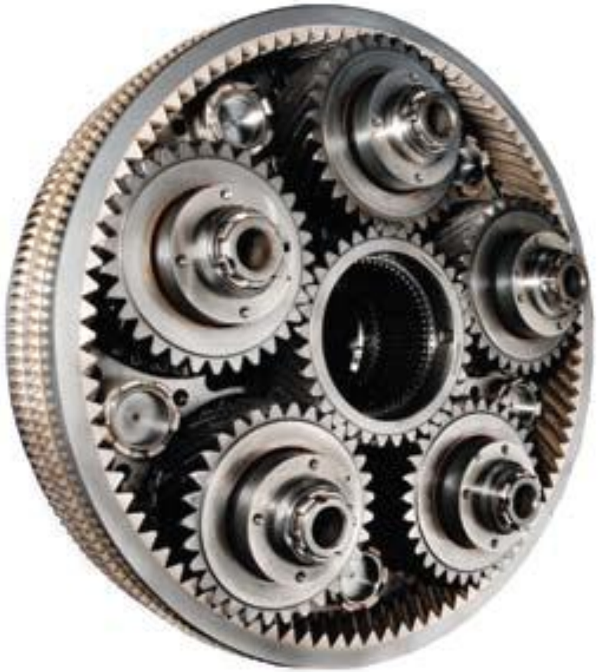
Helical

- Applications
  - High speed environments (> 25ms^{-1})
  - Automotive industry
  - Elevators, conveyors
- Pros
  - Smoother running compared to spur
  - Higher load transfer per width of gear compared to spur
  - Typically longer maintenance cycles
- Cons
  - Thrust bearings required to counter axial forces
  - Greater heat generation compared to spur due to gear mating
  - Typically less efficient than spur gears

Herringbone

- Applications
  - 3D Printers
  - Heavy Machinery
- Pros
  - Smoother power transmission
  - Resistant to operation disruption from missing/damaged teeth
- Cons
  - Difficult to manufacture and hence more expensive

Epicyclic



- Applications
  - Lathes, hoists, pulley blocks, watches
  - Automatic Transmissions
  - Hybrid Vehicles (engine and motor)
- Pros
  - Higher efficiency
  - Higher power density
  - Accurate gearing
  - Packaging (Achieve higher ratios in the same area)
  - In-line input-output shafts
- Cons
  - Loud operation
  - High accuracy manufacturing required to ensure equal load sharing

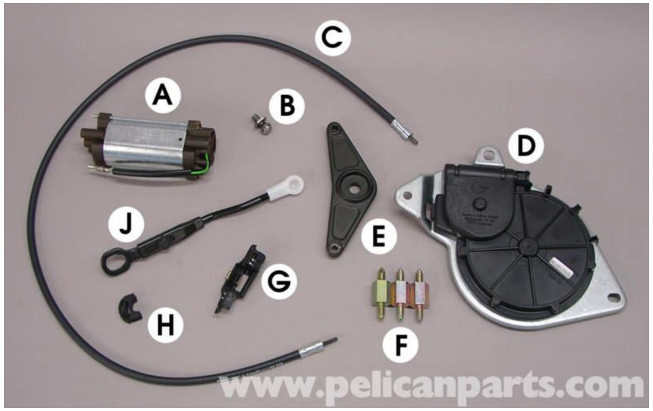
Worm

- Applications
  - Elevators, hoists
  - Packaging equipment
  - Rock Crushers
  - Tuning Instruments
- Pros
  - Near silent and smooth operation
  - Self-locking
  - Occupy less space of equivalent spur gear ratio
  - High velocity ratio can be attained within a single step (approx. 100:1)
  - Absorb shock loading
- Cons
  - Expensive to manufacture
  - Higher power losses compared
  - Greater heat generation due to increased teeth contact

Bevel

- Applications
  - Differential drives (e.g. vehicles)
  - Hand drills
  - Assembly machinery
- Pros
  - Change direction of power transmission
- Cons
  - Difficult to manufacture
  - Precision mountings

Car Convertible Roof

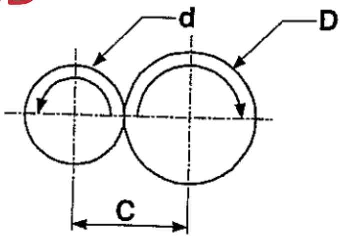


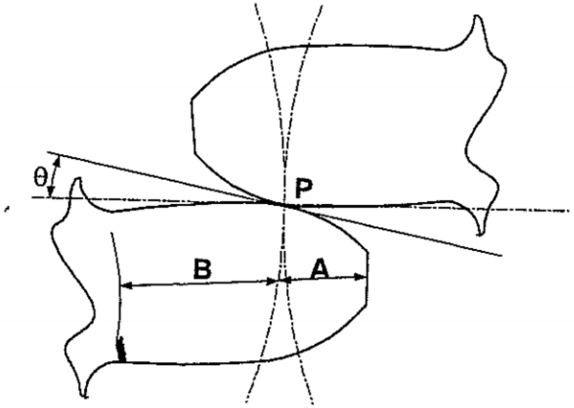
- Worm Gear to Multi-Stage Gearbox
- We will solely design a multi-stage spur/helical gear set

Gear Definitions

Gear Definitions

- Pinion
  - Smaller Gear
  - (n, d) = number of teeth, PCD
- Wheel
  - Larger Gear
  - (N, D) = number of teeth, PCD





Gear Definitions

- Velocity Ratio

$$VR = \frac{N}{n} = \frac{D}{d}$$

- Examples
  - Pinion has 20 teeth and Wheel has 40

$$VR = \frac{40}{20} = 2$$

  - If connected to a wheel of 60 and pinion of 20

$$VR = \frac{40}{20} \times \frac{60}{20} = 6$$

Gear Definitions

- Limiting Velocity Ratios

Type of gear pair	VR lower limit	VR upper limit
Worm and wheel	5	60
All others	1	5

- Pinion and wheel efficiency (η)

95-96% per stage

Gear Definitions

- Module (M)

$$M = \frac{d}{n} = \frac{D}{N}$$

- Addendum (A)

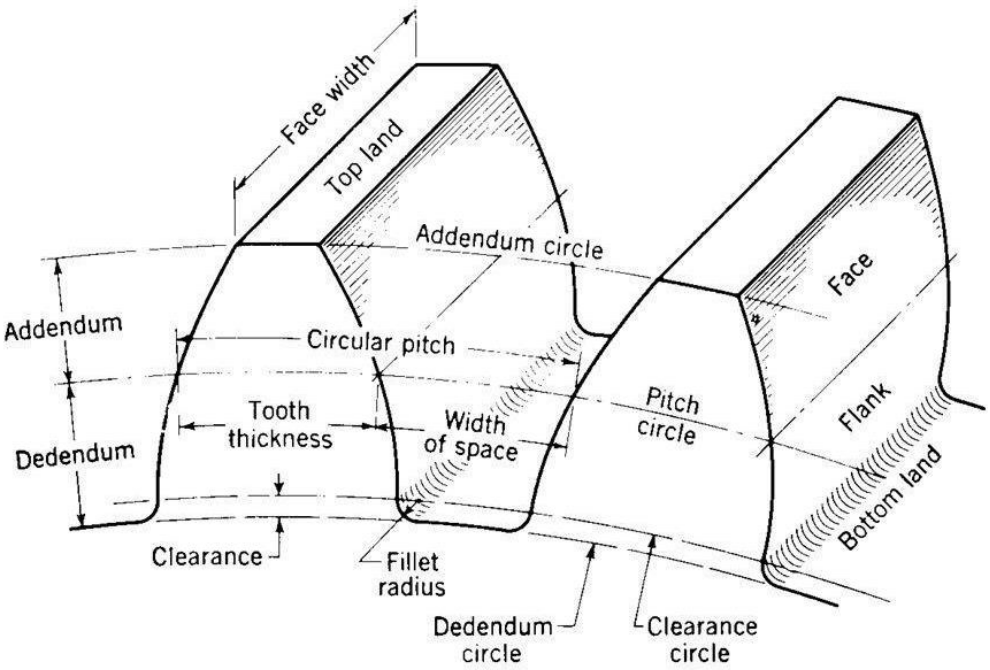
$$A = M$$

- Dedendum (B)

$$B = 1.25M$$

- Tooth depth

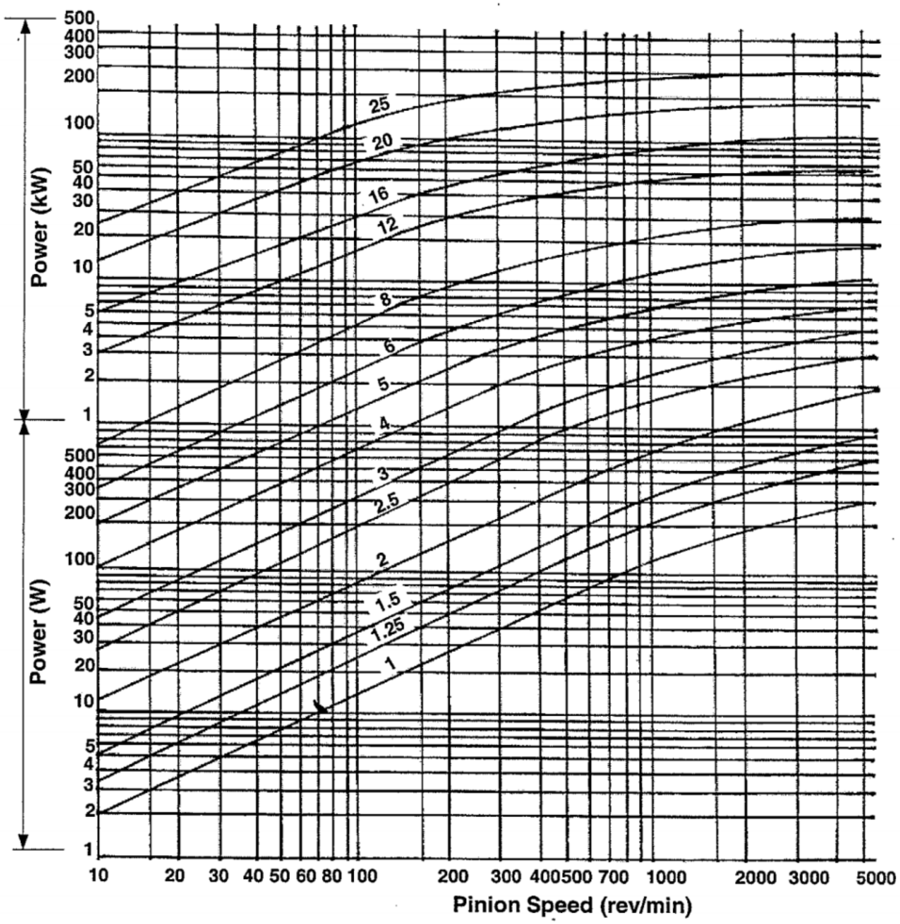
$$A + B = 2.25M$$



Module Selection Charts

Example:

- Pinion Speed = 200rev/min
- Power = 200W



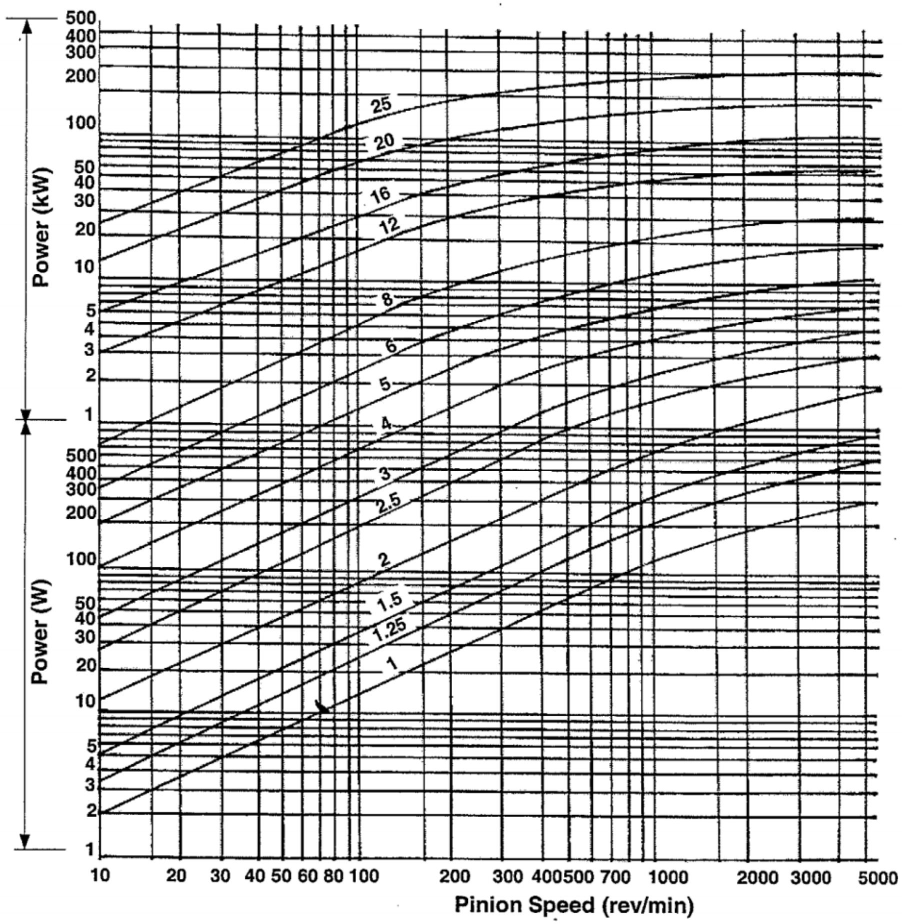
Module Selection Charts

Example:

- Pinion Speed = 200rev/min
- Power = 200W

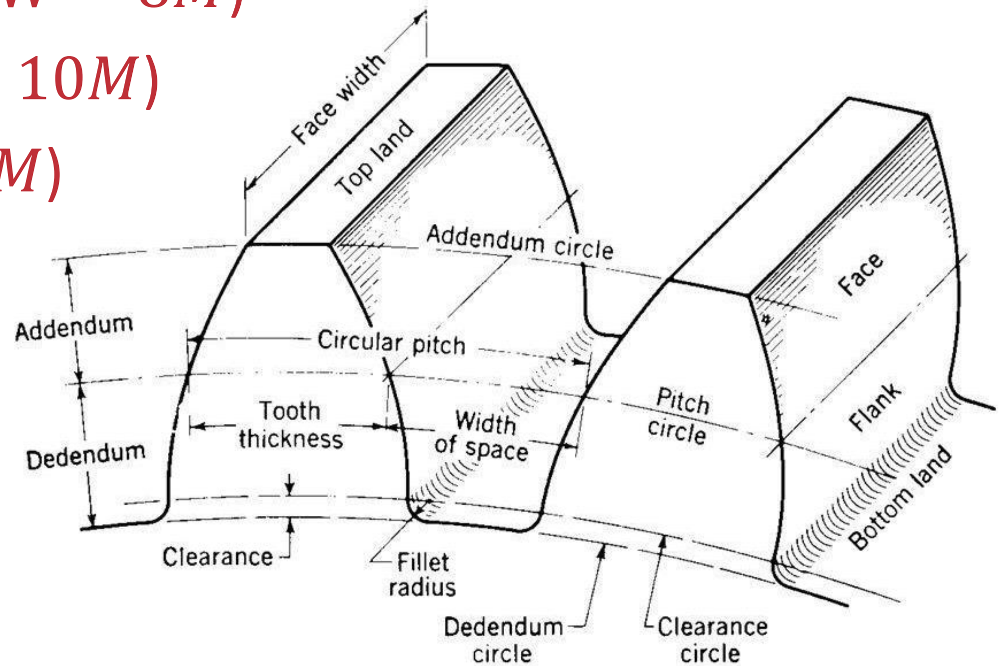
Answer:

- Modules > 2.5



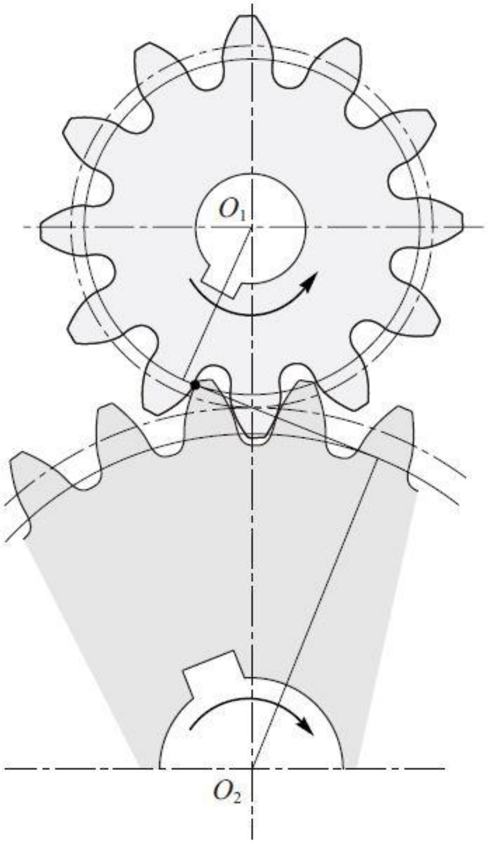
Gear Definitions

- Face Widths
  - Relatively light loads ($W = 8M$)
  - Moderate loads ($W = 10M$)
  - Heavy loads ($W = 12M$)



Gear Definition - Teeth Hunting

- Transmission forces are often cyclical
- Some teeth may experience higher forces than others
- Having the teeth hunt distributes the cyclic loading across all the teeth in gear
- Uniform wear
- Also, maximise the number of cycles before two damaged gears will mesh with one another



Gear Definition - Teeth Hunting

Determining Hunting Tooth Frequencies

1. Calculate the common factors (CF) between the teeth
2. Looking for the highest common factor (12)
3. Hunting Tooth Frequency (HTF)

$$HTF = \frac{GMF \times CF}{n \times N}$$

GMF = gear mesh frequency

Gear Definition - Teeth Hunting

Determining Hunting Tooth Frequencies

Example:

2000rpm, 24 pinion teeth, 84 wheel teeth

Gear Definition - Teeth Hunting

Determining Hunting Tooth Frequencies

1. Calculate the common factors (CF) between the teeth

Example:

2000rpm, 24 pinion teeth, 84 wheel teeth

Pinion (24 Teeth)	Wheel (84 Teeth)
1 x 24	**1** x 84
2 x **12**	**2** x 42
3 x 8	**3** x 28
4 x **6**	**4** x 21
	6 x 14
	7 x **12**

Gear Definition - Teeth Hunting

Determining Hunting Tooth Frequencies

1. Calculate the common factors (CF) between the teeth
2. Looking for the highest common factor (=12 in this case)

Example:

2000rpm, 24 pinion teeth, 84 wheel teeth

Pinion (24 Teeth)	Wheel (84 Teeth)
1 x 24	**1** x 84
2 x **12**	**2** x 42
3 x 8	**3** x 28
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	6 x 14
	7 x **12**

Gear Definition - Teeth Hunting

Determining Hunting Tooth Frequencies

1. Calculate the common factors (CF) between the teeth
2. Looking for the highest common factor (=12 in this case)
3. Hunting Tooth Frequency (HTF)

$$HTF = \frac{GMF \times CF}{n \times N}$$

Where GMF is the gear mesh frequency (GMF)

$$GMF = rpm \times n$$

Example:

2000rpm, 24 pinion teeth, 84 wheel teeth

Pinion (24 Teeth)	Wheel (84 Teeth)
1 x 24	**1** x 84
2 x **12**	**2** x 42
3 x 8	**3** x 28
4 x **6**	**4** x 21
	6 x 14
	7 x **12**

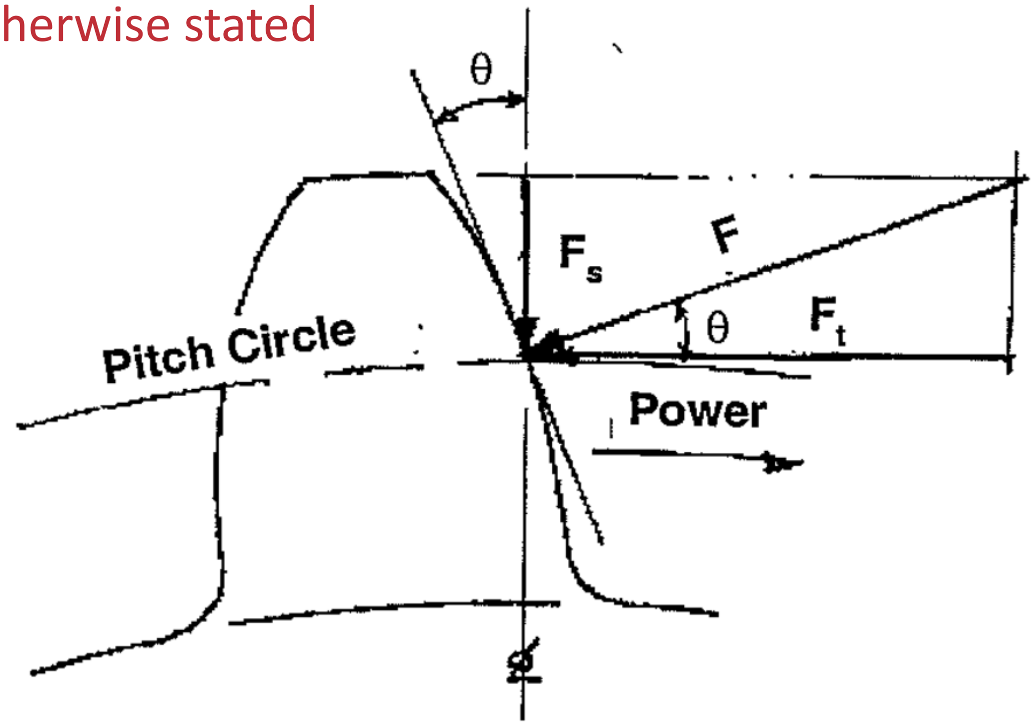
$$\frac{(2000 \times 24) \times 12}{24 \times 84} = \frac{48000 \times 12}{24 \times 84}$$

$= 285.7$ clashes per min

Gear Forces

Spur Gear Forces

- Pressure Angle (θ)
  - Typically 20 degrees unless otherwise stated
- Tangential Force (F_t)
  - $F_t = \frac{2T}{d}$
  - T = Torque (Nm)
- Separating Force (F_s)
  - $F_s = F_t \tan\theta$
- Resultant Force (F)
  - $F = \sqrt{F_t^2 + F_s^2}$



Helical Gear Forces

- Tangential Force (F_t)
  - Same as for Spur
  - $F_t = \frac{2T}{d}$
  - T = Torque (Nm)
- Separating Force (F_s)
  - $F_s = \frac{F_t \tan\theta}{\cos\alpha}$, α = helix angle (assume 20 degrees unless otherwise stated)
- Axial Force (F_a)
  - $F_a = F_t \tan\alpha$
- Resultant Force (F)
  - $F = \sqrt{F_t^2 + F_s^2}$

Example Gearbox

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

Gear Stage	**1**	**2**	**3**
VR			
Combined VR			
Module			
Pinion Teeth			
Pinion PCD (mm)			
Wheel Teeth			
Wheel PCD (mm)			
Hunting Tooth Frequency			
Efficiency			
Pinion Speed (rev/min)			
Wheel Speed (rev/min)			
Pinion Torque (Nm)			
Wheel Torque (Nm)			
Pinion Forces			
Tangential Force (kN)			
Separating Force (kN)			
Resultant Force (kN)			

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

1. Put in the initial conditions

Gear Stage	**1**	**2**	**3**
VR			
Combined VR			
Module			
Pinion Teeth			
Pinion PCD (mm)			
Wheel Teeth			
Wheel PCD (mm)			
Hunting Tooth Frequency			
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)			
Pinion Torque (Nm)	104.70 *(1)*		
Wheel Torque (Nm)			
Pinion Forces			
Tangential Force (kN)			
Separating Force (kN)			
Resultant Force (kN)			

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

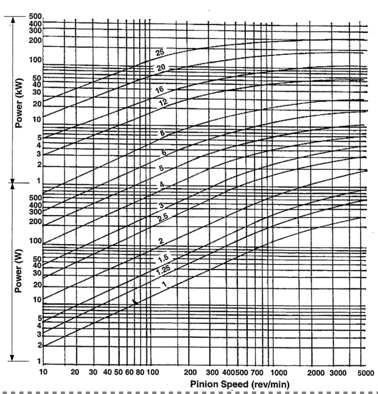
1. Put in the initial conditions
2. Make an initial guess at the VR for each stage to generate the correct combined VR

Gear Stage	**1**	**2**	**3**
VR	5.00 *(2)*	5.00 *(2)*	5.00 *(2)*
Combined VR	5.00 *(2)*	25.00 *(2)*	125.00 *(2)*
Module			
Pinion Teeth			
Pinion PCD (mm)			
Wheel Teeth			
Wheel PCD (mm)			
Hunting Tooth Frequency			
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)			
Pinion Torque (Nm)	104.70 *(1)*		
Wheel Torque (Nm)			
Pinion Forces			
Tangential Force (kN)			
Separating Force (kN)			
Resultant Force (kN)			

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

1. Put in the initial conditions
2. Make an initial guess at the VR for each stage to generate the correct combined VR
3. Determine Module



Gear Stage	1	2	3
VR	5.00 *(2)*	5.00 *(2)*	5.00 *(2)*
Combined VR	5.00 *(2)*	25.00 *(2)*	125.00 *(2)*
Module	2.00 *(3)*		
Pinion Teeth			
Pinion PCD (mm)			
Wheel Teeth			
Wheel PCD (mm)			
Hunting Tooth Frequency			
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)			
Pinion Torque (Nm)	104.70 *(1)*		
Wheel Torque (Nm)			
Pinion Forces			
Tangential Force (kN)			
Separating Force (kN)			
Resultant Force (kN)			

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

1. Put in the initial conditions
2. Make an initial guess at the VR for each stage to generate the correct combined VR
3. Determine Module
4. Calculate Pinion/Wheel PCDs & Hunting Tooth Frequency

Gear Stage	**1**	**2**	**3**
VR	5.00 *(2)*	5.00 *(2)*	5.00 *(2)*
Combined VR	5.00 *(2)*	25.00 *(2)*	125.00 *(2)*
Module	2.00 *(3)*		
Pinion Teeth	19.00 *(4)*		
Pinion PCD (mm)	38.00 *(4)*		
Wheel Teeth	95.00 *(4)*		
Wheel PCD (mm)	190.00 *(4)*		
Hunting Tooth Frequency	200.00 *(4)*		
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)			
Pinion Torque (Nm)	104.70 *(1)*		
Wheel Torque (Nm)			
Pinion Forces			
Tangential Force (kN)			
Separating Force (kN)			
Resultant Force (kN)			

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

1. Put in the initial conditions
2. Make an initial guess at the VR for each stage to generate the correct combined VR
3. Determine Module
4. Calculate Pinion/Wheel PCDs & Hunting Tooth Frequency
5. Wheel Speed and Torques
   - Note: Efficiency loss

Gear Stage	**1**	**2**	**3**
VR	5.00 *(2)*	5.00 *(2)*	5.00 *(2)*
Combined VR	5.00 *(2)*	25.00 *(2)*	125.00 *(2)*
Module	2.00 *(3)*		
Pinion Teeth	19.00 *(4)*		
Pinion PCD (mm)	38.00 *(4)*		
Wheel Teeth	95.00 *(4)*		
Wheel PCD (mm)	190.00 *(4)*		
Hunting Tooth Frequency	200.00 *(4)*		
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)	200.00 *(5)*		
Pinion Torque (Nm)	104.70 *(1)*	497.33 *(5)*	
Wheel Torque (Nm)	497.33 *(5)*		
Pinion Forces			
Tangential Force (kN)			
Separating Force (kN)			
Resultant Force (kN)			

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

1. Put in the initial conditions
2. Make an initial guess at the VR for each stage to generate the correct combined VR
3. Determine Module
4. Calculate Pinion/Wheel PCDs & Hunting Tooth Frequency
5. Wheel Speed and Torques
   - Note: Efficiency loss
6. Pinion & Wheel Forces

Gear Stage	**1**	**2**	**3**
VR	5.00 *(2)*	5.00 *(2)*	5.00 *(2)*
Combined VR	5.00 *(2)*	25.00 *(2)*	125.00 *(2)*
Module	2.00 *(3)*		
Pinion Teeth	19.00 *(4)*		
Pinion PCD (mm)	38.00 *(4)*		
Wheel Teeth	95.00 *(4)*		
Wheel PCD (mm)	190.00 *(4)*		
Hunting Tooth Frequency	200.00 *(4)*		
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)	200.00 *(5)*		
Pinion Torque (Nm)	104.70 *(1)*	497.33 *(5)*	
Wheel Torque (Nm)	497.33 *(5)*		
Pinion Forces			
Tangential Force (kN)	5.51 *(6)*		
Separating Force (kN)	2.01 *(6)*		
Resultant Force (kN)	5.86 *(6)*		

Three Stage Gearbox Design Example

A three-stage spur gearbox is to provide a 1:125 total gear ratio for a motor providing 500W @ 1000 rev/min.

1. Put in the initial conditions
2. Make an initial guess at the VR for each stage to generate the correct combined VR
3. Determine Module
4. Calculate Pinion/Wheel PCDs & Hunting Tooth Frequency
5. Wheel Speed and Torques
   - Note: Efficiency loss
6. Pinion & Wheel Forces
7. Repeat Steps 3-6 for the next stages

Gear Stage	**1**	**2**	**3**
VR	5.00 *(2)*	5.00 *(2)*	5.00 *(2)*
Combined VR	5.00 *(2)*	25.00 *(2)*	125.00 *(2)*
Module	2.00 *(3)*		
Pinion Teeth	19.00 *(4)*		
Pinion PCD (mm)	38.00 *(4)*		
Wheel Teeth	95.00 *(4)*		
Wheel PCD (mm)	190.00 *(4)*		
Hunting Tooth Frequency	200.00 *(4)*		
Efficiency	0.95 *(1)*	0.95 *(1)*	0.95 *(1)*
Pinion Speed (rev/min)	1000.00 *(1)*		
Wheel Speed (rev/min)	200.00 *(5)*		
Pinion Torque (Nm)	104.70 *(1)*	497.33 *(5)*	
Wheel Torque (Nm)	497.33 *(5)*		
Pinion Forces			
Tangential Force (kN)	5.51 *(6)*		
Separating Force (kN)	2.01 *(6)*		
Resultant Force (kN)	5.86 *(6)*		

Gearbox Design

Design Report

- Gearbox Design
  - Discuss the process you have taken to design the gearbox
  - Compare a spur and helical gearbox that meets your criteria (not just gear ratio but also your PDS)
  - Rationale behind your chosen design
  - Gear arrangement and space optimisation
  - Could perform checks on minimum shaft sizes & bearings

This Week

- Generate an initial spur and helical gear set to drive your mechanism
- Select type and refine gears
    - Evaluate against forces, packaging and suitability for the application
    - You may have to compromise on your ideal gear ratio from your deployment modelling
    - Make sure you record you rationale

Happy Easter