Introduction to Aerospace Engineering

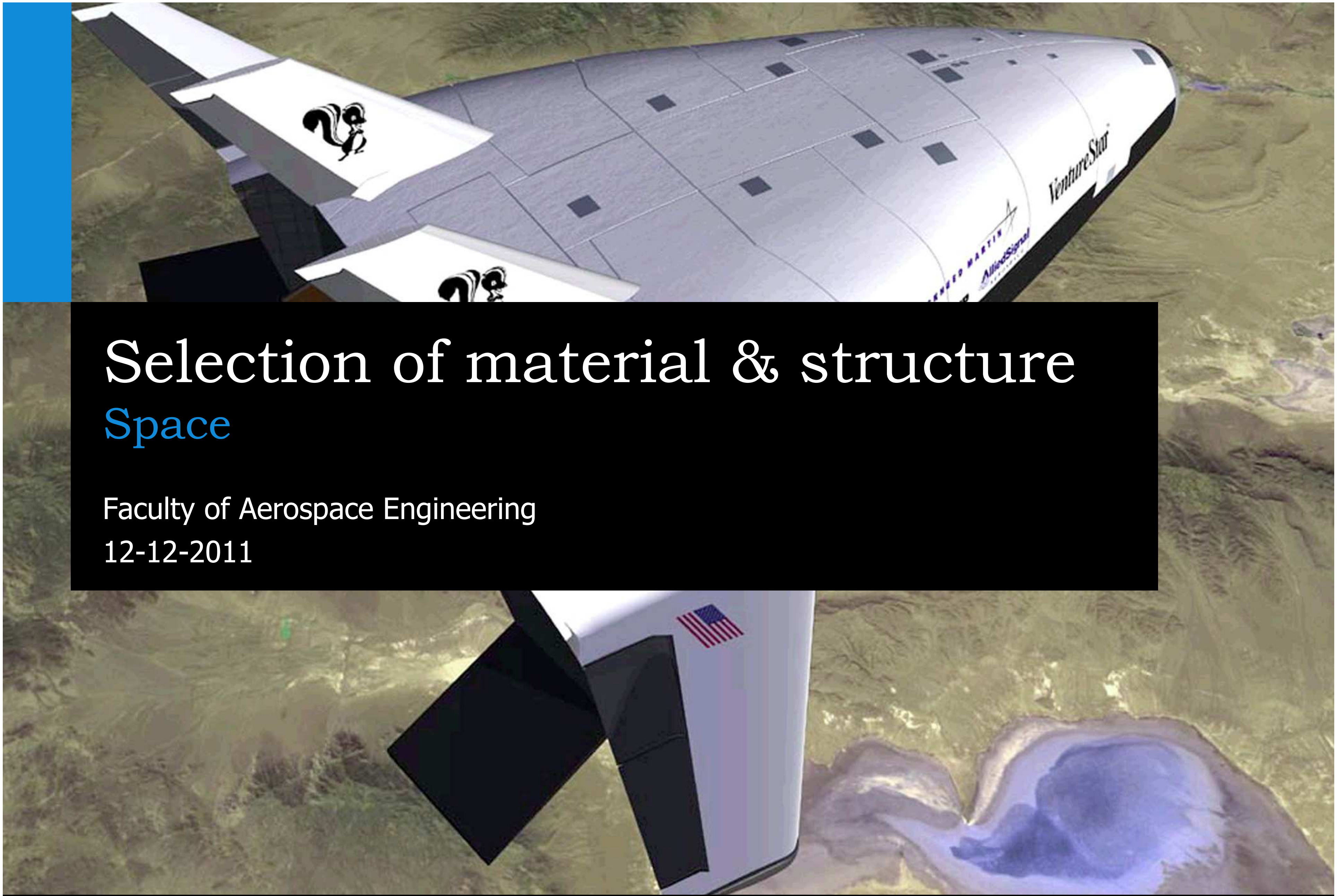
Lecture slides

Selection of material & structure

Space

Faculty of Aerospace Engineering

12-12-2011



TU Delft Delft University of Technology

Challenge the future

Learning objectives

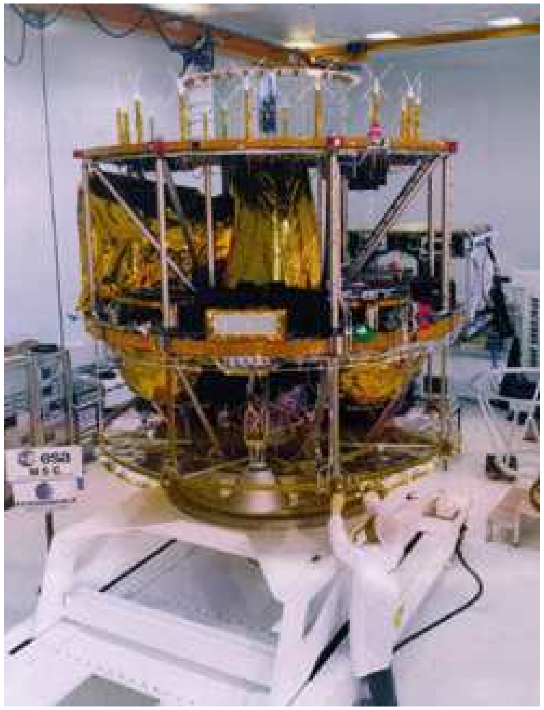
Student should be able to...

- Describe the basic steps in dimensioning a spacecraft structure
- Design simplified structure for minimum natural frequency requirements

Spacecraft structures

Typical structures

- Spacecraft
  - Struts
  - Central cylinder
- Launch vehicle
  - Fairings
  - Stage structure
  - Thrust structure
  - Adaptors



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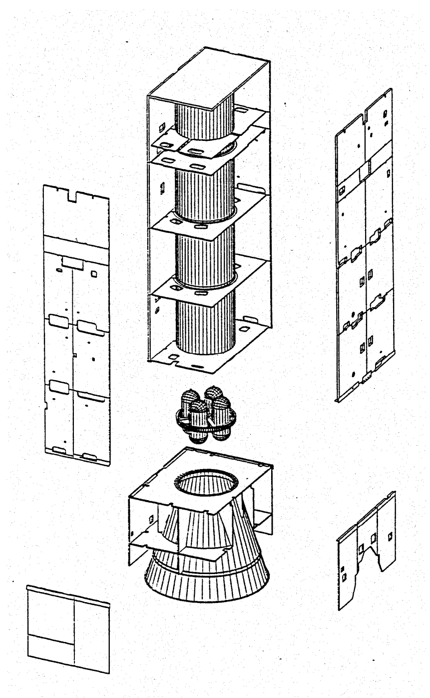
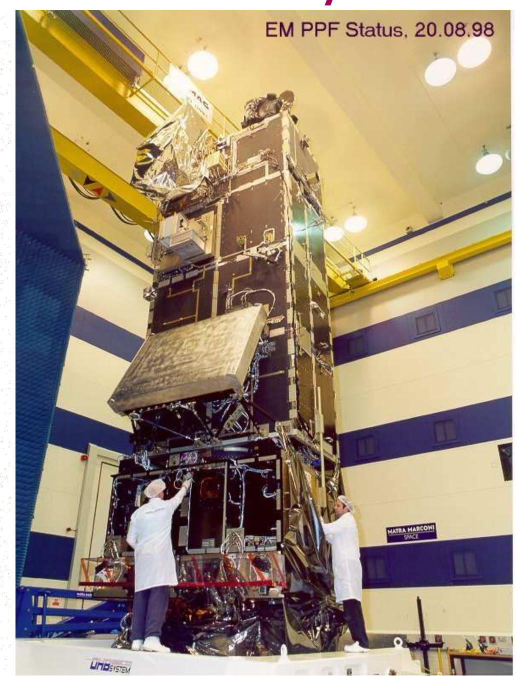
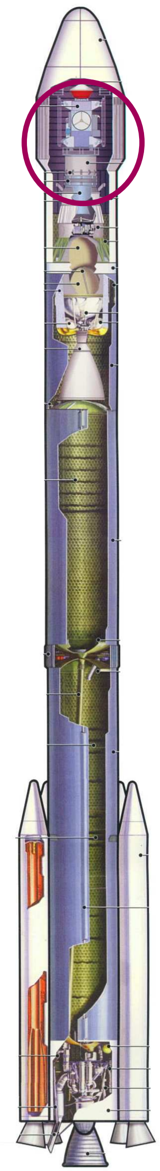


See Envisat in study collection!





- Characteristics
  - Central thrust-load-bearing member (cone/cylinder)
  - All systems attached at strong points directly, or by combinations of Struts/Platforms/Shear webs

Spacecraft structures

Typical structures

- Spacecraft
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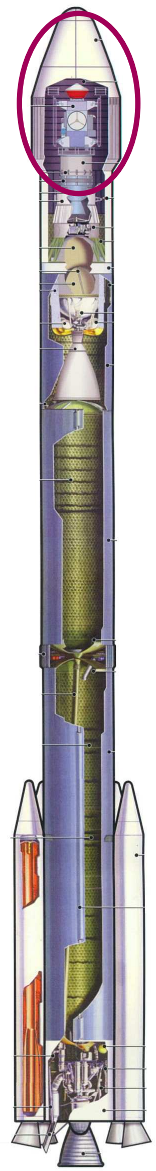

Spacecraft structures

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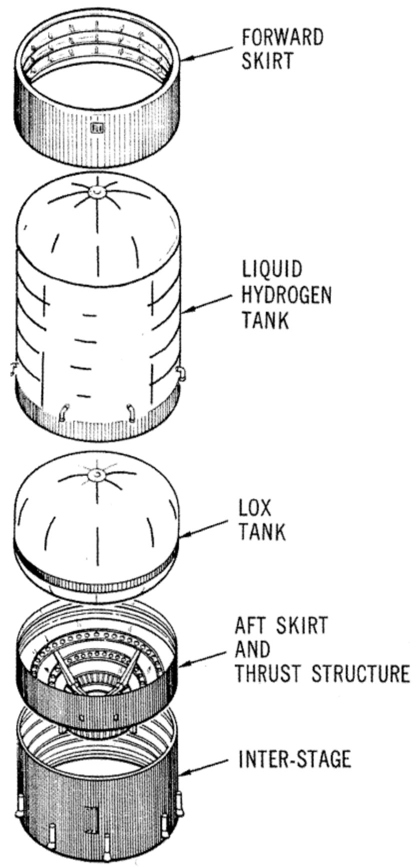
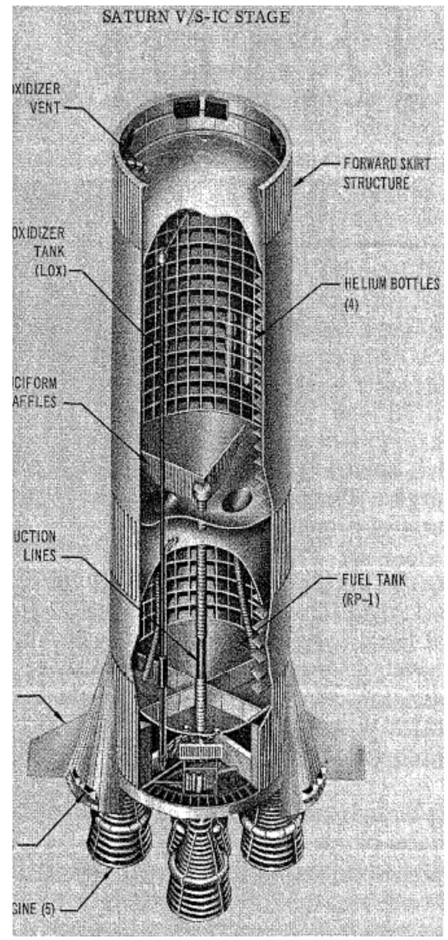
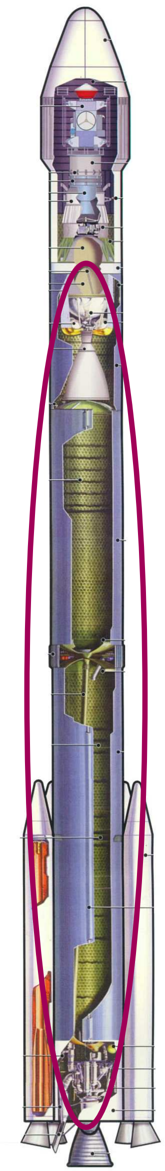


Saturn V S-II Second Stage Subassemblies





Spacecraft structures

Typical structures

- Spacecraft
- Launch vehicle
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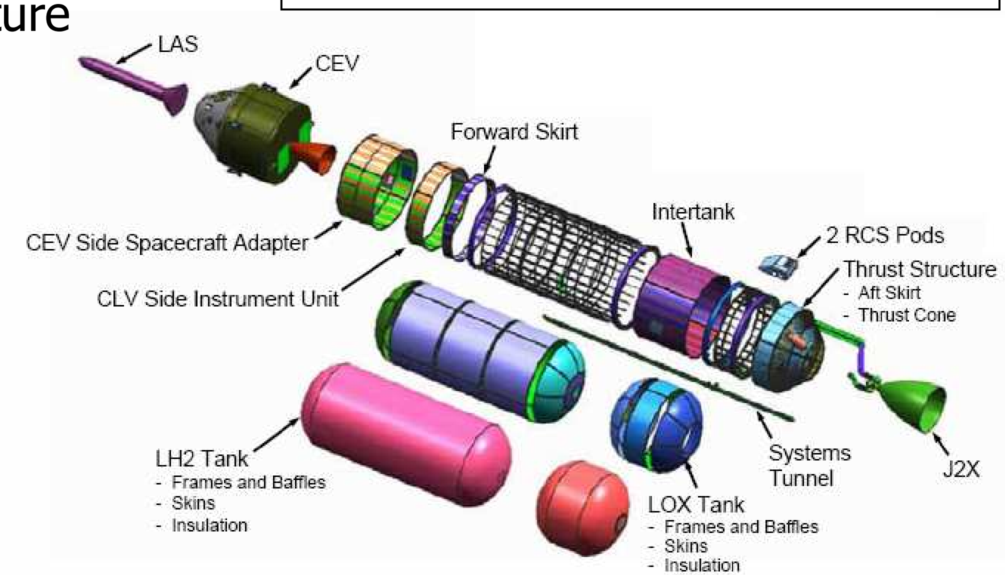
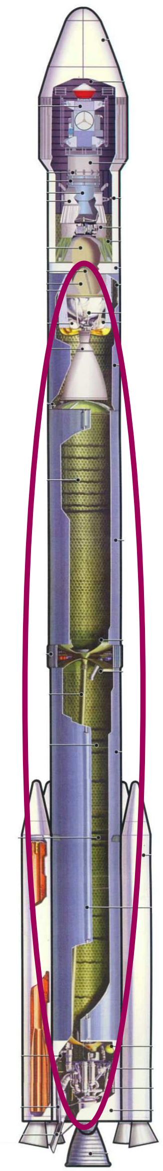
    - Thrust structure
    - Adaptors

- Semi-monocoque (load bearing skin internally stiffened)
- External skin, internal tanks separated by longerons and cricular stiffeners





Spacecraft structures

Typical structures

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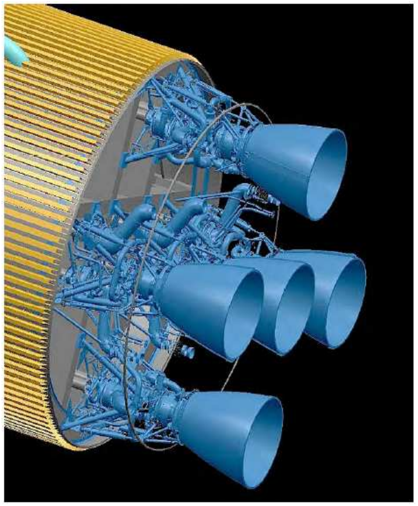
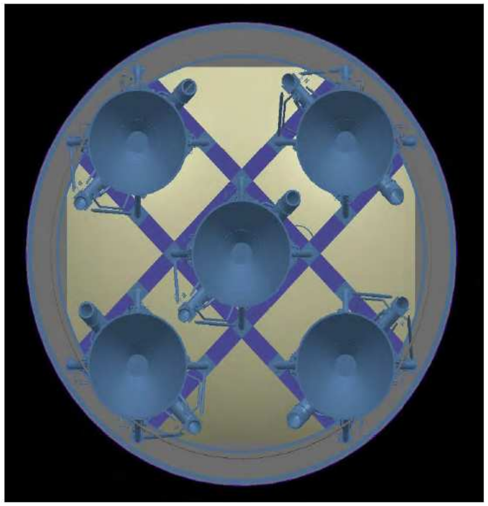
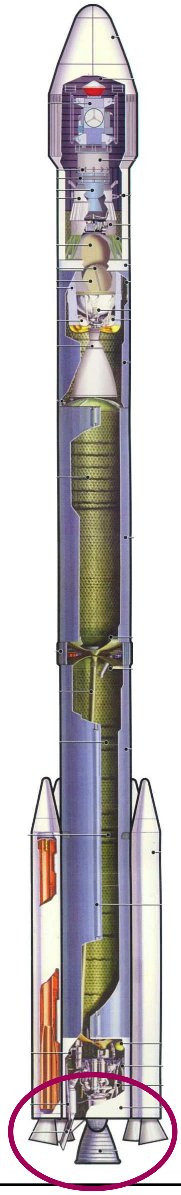
  - Stage structure
  - Thrust structure
  - Adaptors

Example: ARIANE 5 ~ 1200 tons of thrust!!







Spacecraft structures

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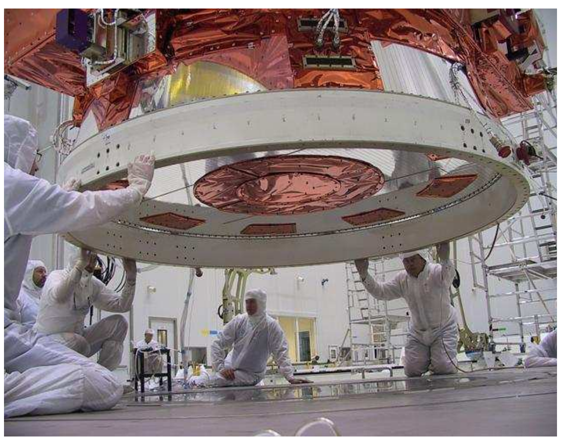

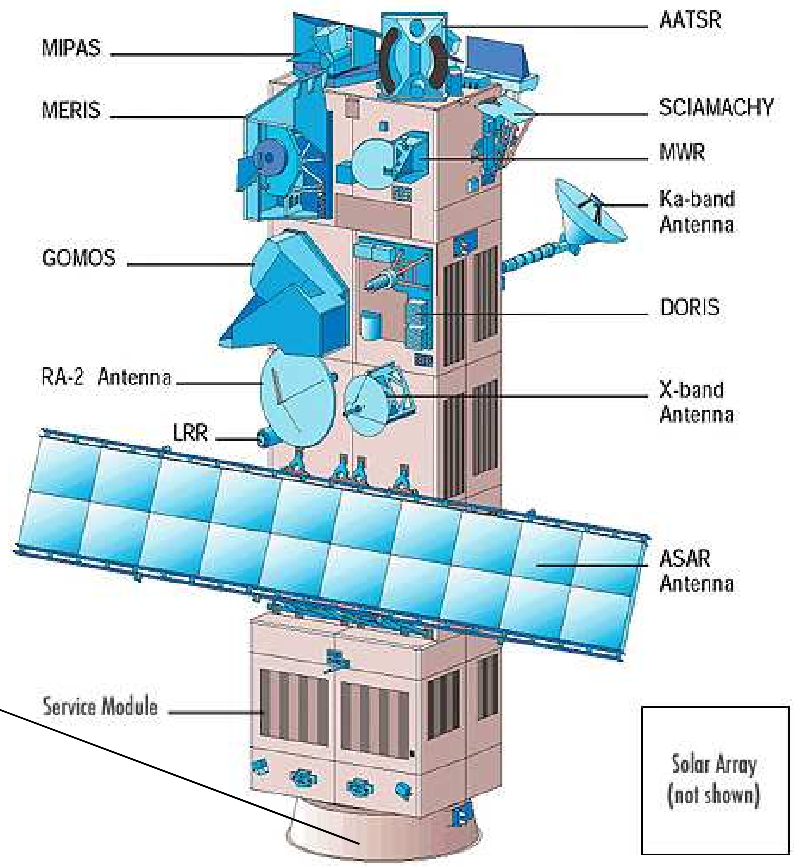

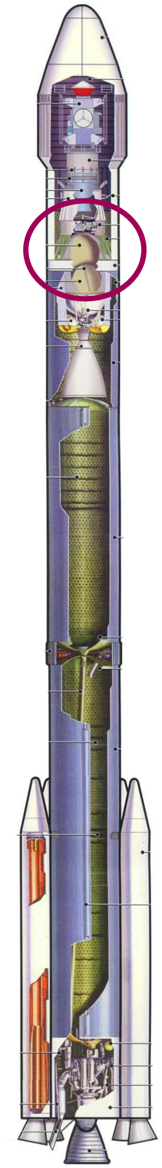

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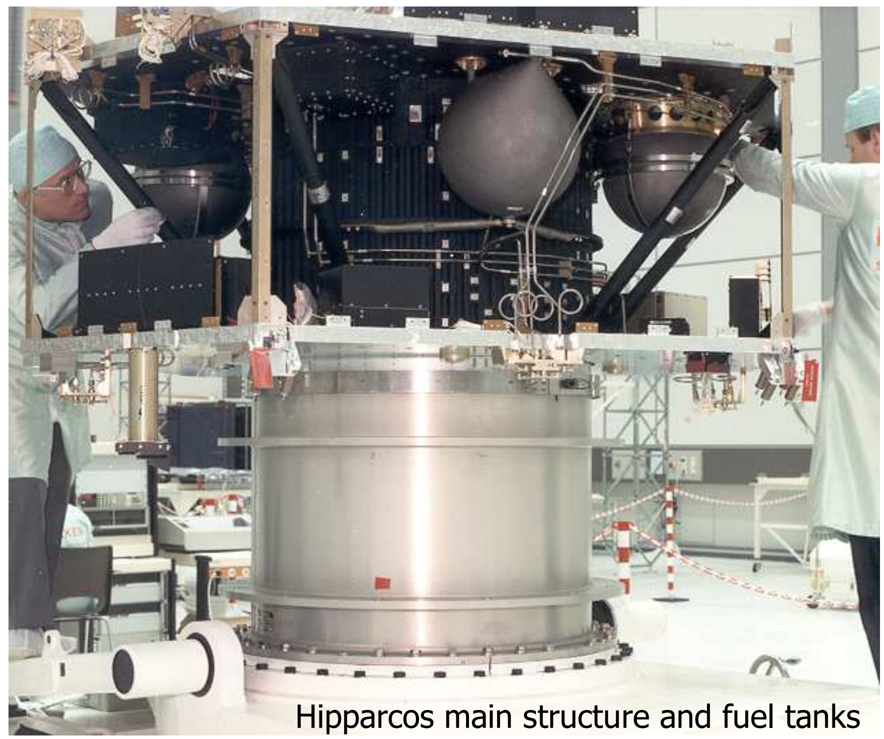
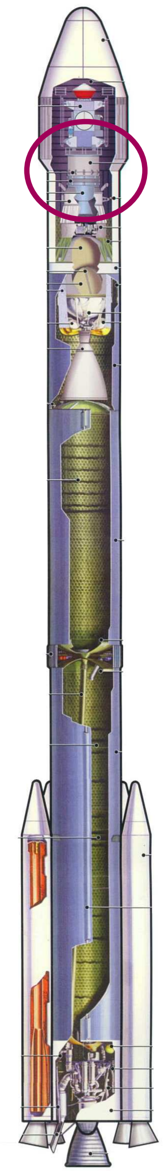


Hipparcos main structure and fuel tanks



Spacecraft structures

Mission requirements

- Minimum mass
- High stiffness
- Withstand the loads (= high strength)

- Accommodate payload + equipment
- High reliability
- Low cost
- Accessibility, manufacturability

Material selection criteria

Material properties

C. R. corrosion resistance
S. C. C. stress corrosion cracking

Caution: There is considerable variation of the properties of materials according to conditions (ageing, temper, form and structure orientation). Consult manufacturers' data

	Density (kg/m^3)	Young's modulus E(GPa)	Yield strength f(MPa)	Selection criteria E/ρ	$E^{1/2}/\rho$	$E^{1/3}/\rho$	f_y/ρ	Thermal expansion (μm/m K^{-1})	Fracture toughness (MPa m)	Fatigue strength (MPa)	Comment
Aluminium alloy											
6061.T6	2700	68	276	24	2.9	1.5	98.6	23.6	186	97	Good C.R
7075.T6	2800	71	503	26	3.1	1.5	186.3	23.4	24	159	Prone to SSC in T6 Form
Magnesium alloy											
A2 31B	1700	45	220	26	3.9	2.1	129.4	26			Prone to SCC
ZK 60 A.T5 extrn	1700	45	234	26	3.9	2.1	137.6	26		124	
Titanium alloys											
T1-6A1-4V (annealed)	4400	110	825	25	2.4	1.1	187.5	9	75	500	
(solution treated and aged)			1035						42	690	
Beryllium alloys											
S 65 A	2000	304	207	151	8.7	3.4	103.5	11.5			Hot pressed sheet } Low fracture toughness
SR 200 E			345								
Ferrous alloys											
INVAR		150	275/415					1.66			Low expansion Ferromagnetic
Stainless steel AM 350 (SCT850)	7700	200	1034	26	1.84	0.8	134.3	11.9	40/60	550	
304L Ann	7800	193	170	25	1.8	0.7	21.8	17.2			Austenitic
Composites											
KEVLAR 49 0°	1380	76*	1379†	55	6.3	3.1	999.3	−4			Structure members
(Aramid fibre) 90°	1380	5.5	29.6	4	1.7	1.3	21.4	57			Pressure vessels Rocket casings
Graphite epoxy sheets (undirectional) GY70/934	1620	282	586	174	10.4	4.0	361.7	−14.7 (Longitudinal) 29.7 (Transverse)			Sheet
Column ref. (see text)	A	B	C	D	E	F	G	H	I	J	

*Tensile modulus
†Tensile strength

Material selection criteria

Frequency

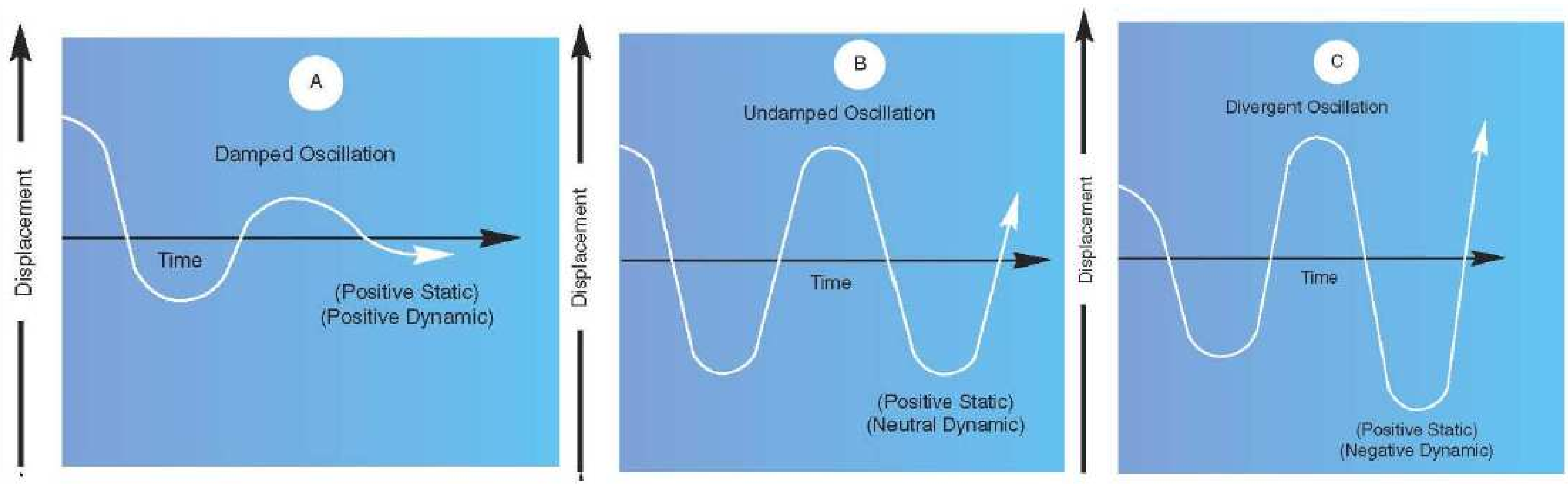
- Limiting the natural frequencies of spacecraft is essential to avoid resonance between launch vehicle and spacecraft

- Low dynamic coupling results in lower loads for spacecraft

Material selection criteria

Natural frequency

- Oscillations can be damped or excited
  - Example: aerodynamic flutter



(recall the flutter of horizontal & vertical tail planes)

Material selection criteria

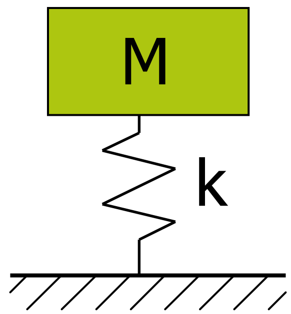
Frequency

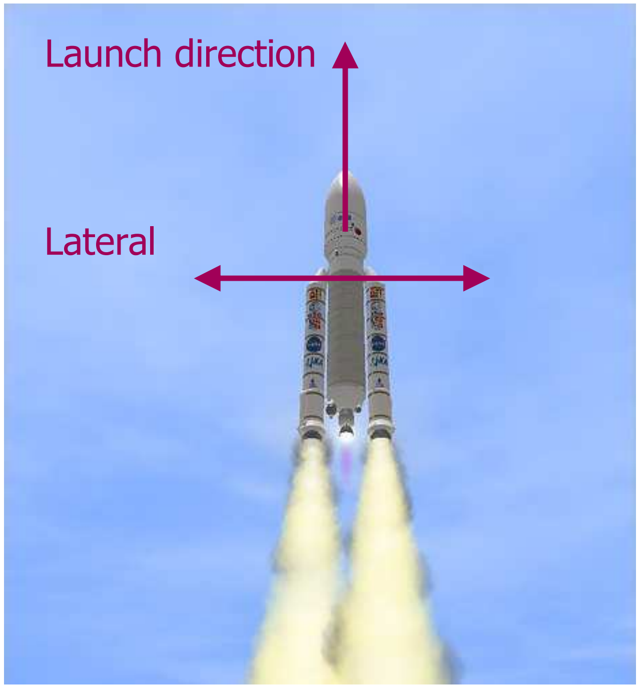
- Requirements are launcher dependent:
- ARIANE 4
  - Launch direction >31 Hz
  - Lateral >10 Hz
- STS
  - Launch direction >13 Hz
  - Lateral >13 Hz

Natural Frequency [Hz]

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

k = stiffness = load/deflection





Material selection criteria

Frequency

- Dimensioning the primary structure
- First
  - Lowest natural frequencies > minimum required natural frequencies!
- Then
  - Design for quasi-static loads

Material selection criteria

Natural Frequency [Hz]

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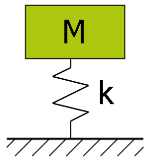
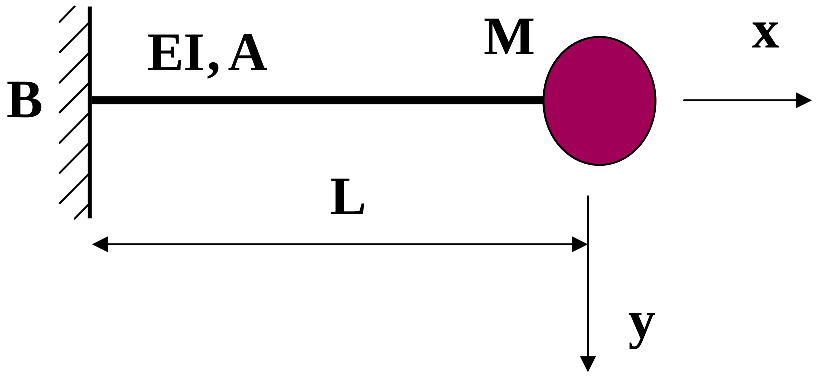
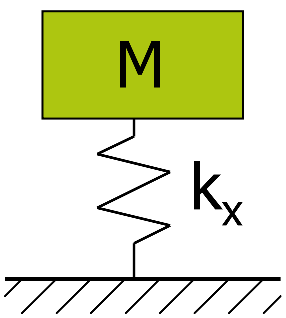


Frequency – Example on stiffness sizing

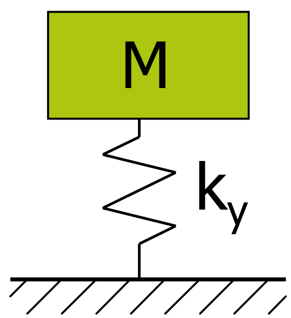
- Mass concentrated at end of clamped beam



- Define single degree of freedom system



$$k_x = \frac{EA}{L}$$



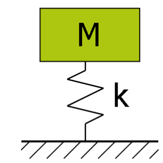
$$k_y = \frac{3EI}{L^3}$$

Material selection criteria

Natural Frequency [Hz]

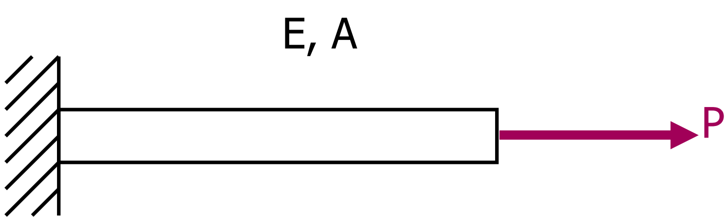
$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

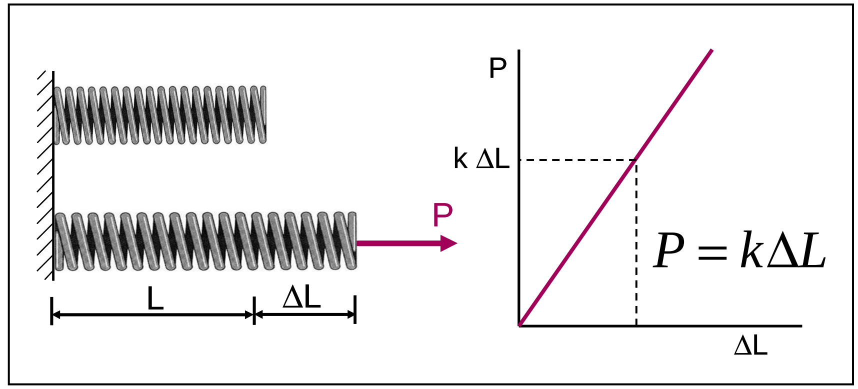
k = stiffness = load/deflection



Frequency – Example on stiffness sizing

- Axially loaded beam



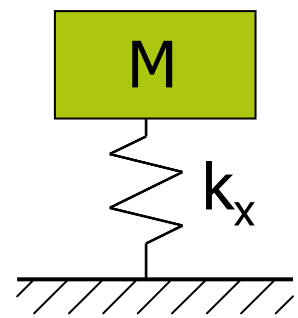


- Strain

$$\varepsilon = \frac{\Delta L}{L} = \frac{P}{EA} = \frac{\sigma}{E}$$

- Elongation

$$\Delta L = P\frac{L}{EA}$$



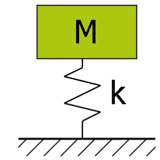
$$k_x = \frac{EA}{L}$$

Material selection criteria

Natural Frequency [Hz]

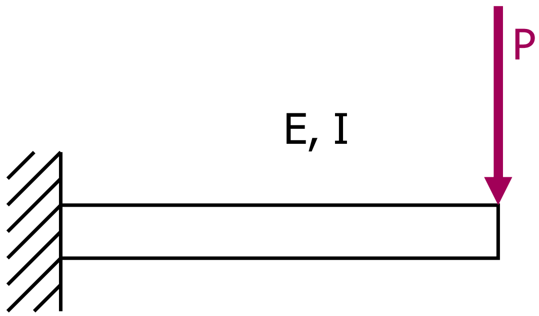
$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

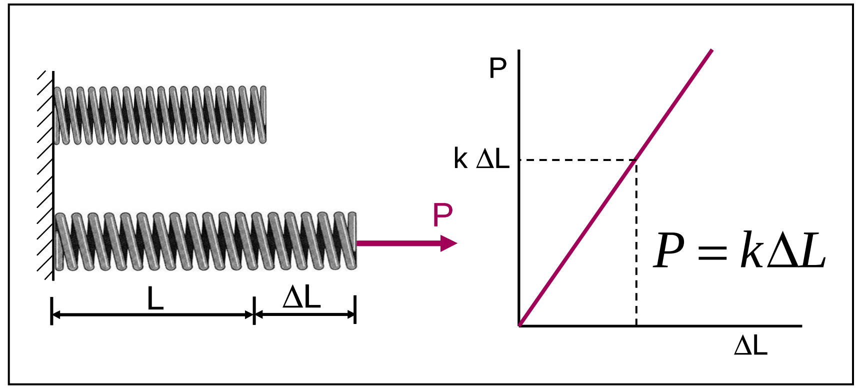
k = stiffness = load/deflection



Frequency – Example on stiffness sizing

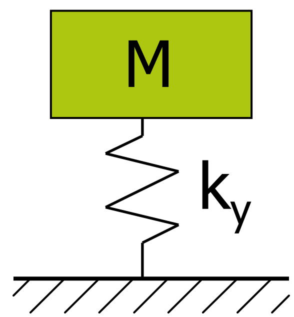
- Laterally loaded beam





- Deflection

$$\delta = \frac{PL^3}{3EI}$$



$$k_y = \frac{3EI}{L^3}$$

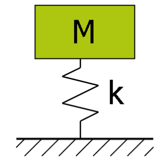
Material selection criteria

Frequency – Example on stiffness sizing

Natural Frequency [Hz]

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

k = stiffness = load/deflection

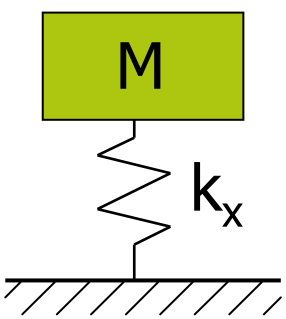


- The natural frequency is

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad [Hz]$$

- Which means for the stiffness

$$\frac{3EI}{L^3} \geq \left(2\pi f_n\right)^2 M \qquad \frac{EA}{L} \geq \left(2\pi f_n\right)^2 M$$



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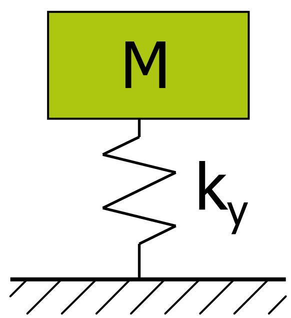


$$k_y = \frac{3EI}{L^3}$$

SMAD III, Fig. 11-42

Equations 11-57,11-58

Material selection criteria

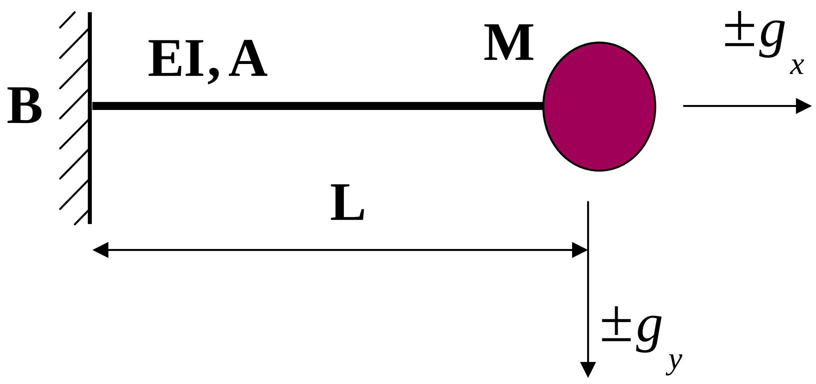
Frequency

- Dimensioning the primary structure
- First
  - Lowest natural frequencies > minimum required natural frequencies!
- Then
  - Design for quasi-static loads

Sizing Example Strength

Frequency – Example on stiffness sizing

- Maximum stress at clamping



Structure/geometry

- Define I and A

Material

- Select material with E

- Axial $\sigma_x = \frac{g_x M}{A} = \frac{F}{A}$
- Lateral $\sigma_y = \frac{g_y MLy}{I} = \frac{FLy}{I}$

$$\sigma_{tot} = \sigma_x + \sigma_y \leq \sigma_{allowable}$$

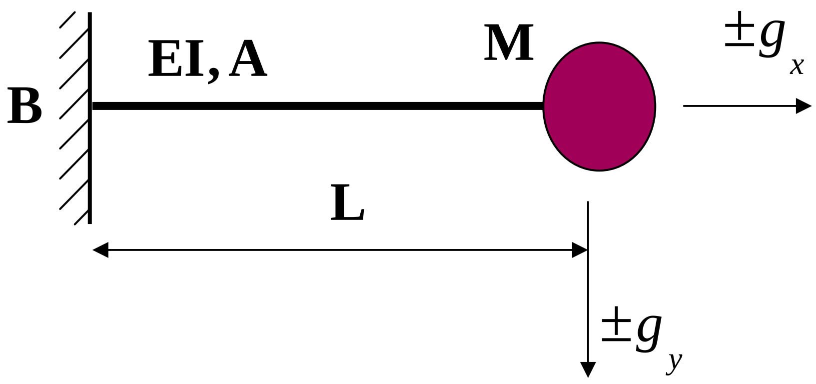
SMAD III

Equations 11-48,11-49

Sizing Example Strength

Frequency – Example on stiffness sizing

- Buckling load



Structure/geometry

- Define I and L

Material

- Select material with E

$\Rightarrow$ Bending stiffness EI!

- Euler $F_{euler} = \dfrac{\pi^2 EI}{4L^2} \leq g_x M$

SMAD III

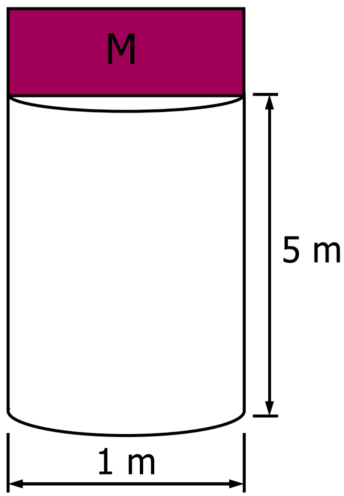
Equations 11-48,11-49

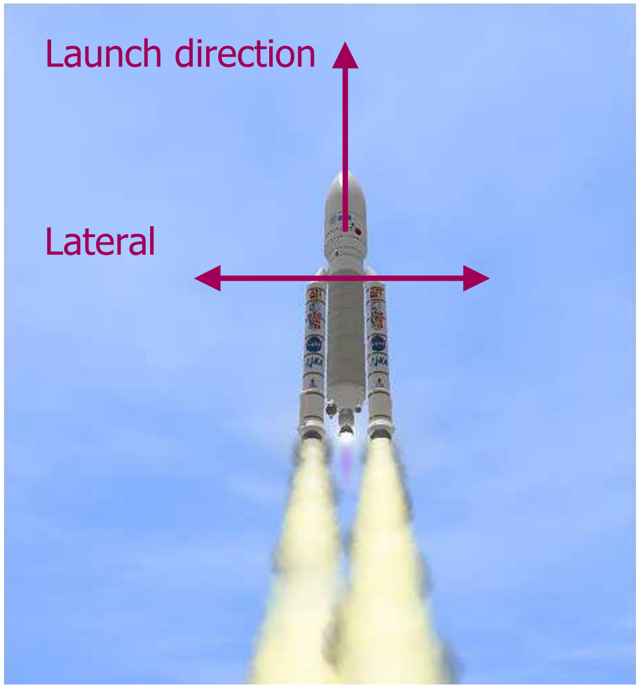
Material selection criteria

Example

- Required wall thickness
- ARIANE 4
  - Launch direction >31 Hz
  - Lateral >10 Hz

- Conditions
  - M=250 kg
  - E = 72 GPa (aluminium)
  - Max. axial acceleration = 6 g (launch load)
  - Payload = point mass
  - $M_{cylinder} = 0$



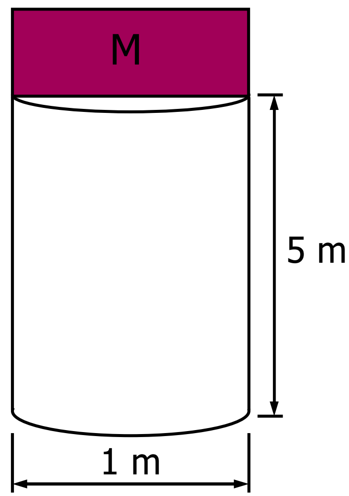


Material selection criteria

Example

- Required wall thickness (frequency)
  - Launch direction >31 Hz

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \geq 31 Hz$$



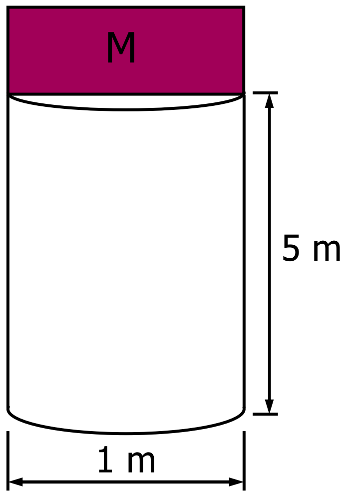
  - With m=250 kg

$$k = \frac{EA}{L}$$

$$\Rightarrow \quad A \geq \frac{mL}{E}\left(2\pi f_1\right)^2$$ with $$A = 2\pi rt$$ $\Rightarrow$ t~1 mm

Material selection criteria

Example



- Required wall thickness (quasi-static loads)
  - Axial acceleration = 6 g
  - Lateral direction = 1.5 g

- Axial $\sigma_x = \frac{g_x M}{A} = \frac{F}{A}$
- Lateral $\sigma_y = \frac{g_y MLy}{I} = \frac{FLy}{I}$

$$\sigma_{tot} = \sigma_x + \sigma_y \leq \sigma_{allowable}$$

- With $\sigma_{allowable} = \sigma_{ultimate}$ / safety factor $\Rightarrow$ A & I

Summary

Space

- Typical spacecraft & launch vehicle structures
- Steps in dimensioning a spacecraft structure
  - Natural frequency
  - Quasi-static loads
- Example simplified structure for minimum natural frequency requirements