AA 279 C – SPACECRAFT ADCS: LECTURE 12

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Attitude Actuators: Selection and Sizing (1)

Actuator	Performance	Mass (kg)	Power (W)
Thrusters Hot Gas (chemical) Cold Gas (pressure)	Produce torque via force 0.5-9000 N <5 N	Mass and power vary with propellant and functioning principle	
Reaction and momentum wheels	Max torques: 0.01-1 Nm Storage: 0.4-3000 Nms	2-20	Varies with speed 10-100
Control moment gyros	Max torques: 25-500 Nm	>10	90-150
Magnetic torquers	Depends on altitude $5 \cdot 10^{-4} – 5 \cdot 10^{-1}$ Nm	0.4-50	0.6-16

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Attitude Actuators: Selection and Sizing (2)

Parameter	Explanation	Simplified Eqs.
Torque from reaction wheel for disturbance rejection	Control torque must equal worst-case anticipated disturbance torque M_d plus margin ε	$M_c = M_d \varepsilon$
Slew torque for reaction wheels	Maximum acceleration slews θ in time t with no resisting momentum	$M_c = 4I\theta/t^2$ $\theta = (M_d/I)(t/2)^2$
Momentum storage in reaction wheels	Integrate worst-case disturbance torque over full orbit period P and assume max disturbance is accumulated in ¼ orbit	$L = M_d P\ 0.707/4$
Momentum storage in momentum wheels	Stabilization within allowable angular motion θ	$L = (M_d/\theta)(P/4)$
Torque from magnetic torquers	Torque results from interaction between earth's B and satellite D magnetic dipole	$D = M_d/B$

Attitude Actuators: Selection and Sizing (3)

Parameter	Explanation	Simplified Eqs.
Thruster force for external disturbances	The worst case disturbance force M_d needs to be counteracted by the thruster force F through its momentum arm b	$F = M_d/b$
Thruster force for slew rates	Slew profile consists of an angular acceleration α, then coasting, and finally deceleration at α	$Fb = I\alpha$
Fuel needed to complete slew	Fuel mass m depends on thrust, slew time t, and specific impulse I_{sp}	$m = Ft/(gI_{sp})$
Thruster force for momentum dumping	The thrust depends on the stored wheel momentum L, the burn time t, and the momentum arm b	$F = L/(bt)$

Gyroscopic Actuators

- A wheel or rotor can change the distribution of angular momentum vector through an exchange process which fulfils the conservation of the total angular momentum vector in inertial space
  - Momentum Wheel (MW)
    - Nominal relative angular velocity is non-zero
    - Relative angular velocity varies with time
    - Fix spin axis
  - Reaction Wheel (RW)
    - Nominal relative angular velocity is zero
    - Relative angular velocity varies with time
    - Fix spin axis
  - Control Moment Gyro (CMG)
    - Nominal relative angular velocity is non-zero
    - Relative angular velocity does not vary with time
    - Spin axis changes its direction

Differ only by nominal angular velocity, basically identical from a manufacturing perspective

Complex hardware, opposite concept to gyros (satellite reacts to gyro), can provide much larger torques but have shorter life

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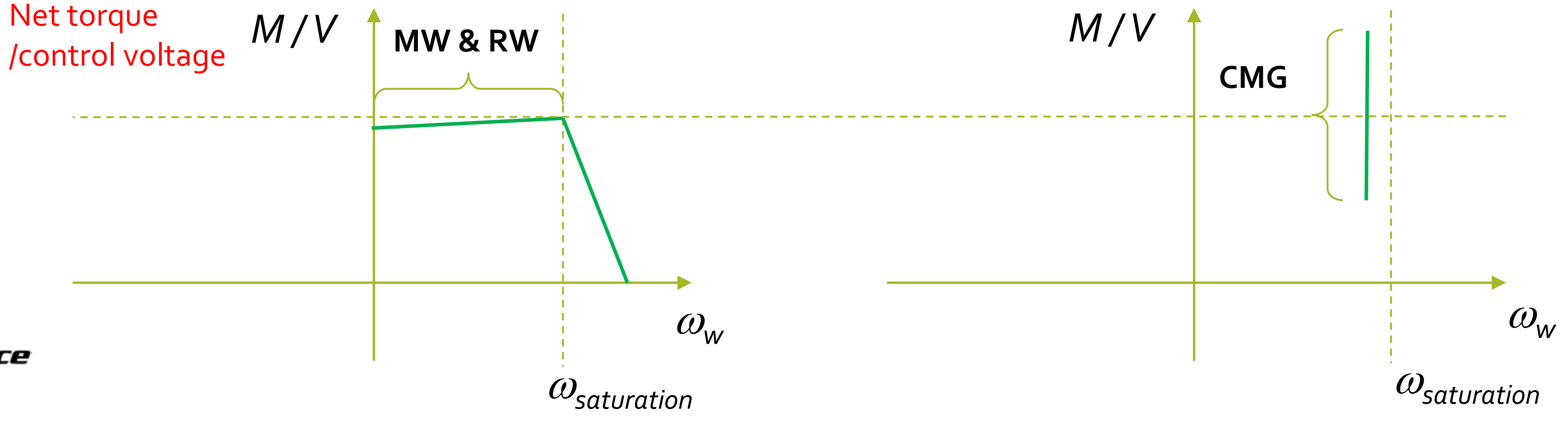
Pros/Cons of Gyroscopic Actuators (1)

- Electric motors are not able to generate a torque when the angular velocity overcomes a certain threshold. In this situation, they saturate and can not accelerate or decelerate

- As a consequence MW and RW are affected by more limitations than CMG which can spin at a high constant angular velocity below the saturation limit and can generate high torques thanks to small variation of spin axis orientation

- To increase the range of operations of MW and RW, one can increase $\dot{\vec{L}}_w$ through an increase of $\boldsymbol{I}_w$ at the cost of higher weights



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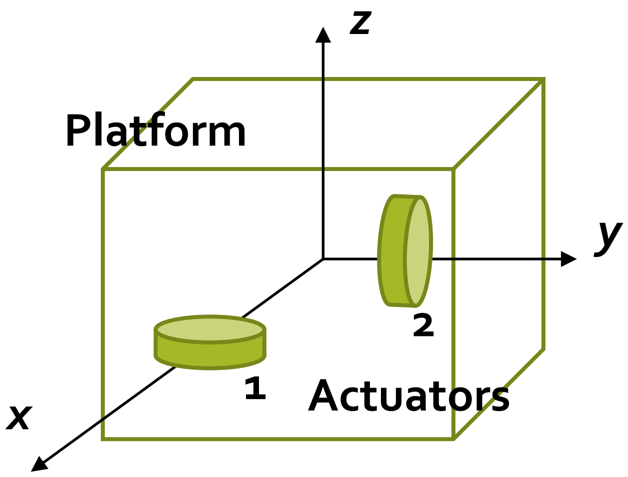
Torque Exchange (1)



- The satellite's platform has the following angular momentum vector

$$\vec{L}_p \quad [3\text{x}1]$$

- The actuators have the following angular momentum vector (relative to platform)

$$\vec{L}_w \quad [n\text{x}1]$$

- The total angular momentum vector of the system is given by

$$\vec{L}_t = \vec{L}_p + \vec{L}_w = \vec{I}\,\vec{\omega} + \vec{A}\,\vec{L}_w$$

Inertia tensor assuming rotors do not rotate

Matrix which brings $\boldsymbol{L}_w$ to the principal axes

[3x1] [3x3] [3x1] [3xn] [nx1]

- From the example in figure

$$\vec{L}_1 = I_1\omega_1\vec{z}\,;\ \vec{L}_2 = I_2\omega_2\vec{y} \Rightarrow \vec{L}_w = \begin{pmatrix} I_1\omega_1 \\ I_2\omega_2 \end{pmatrix}\ ;\ \vec{A} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Torque Exchange (2)

- The Euler equations can be expressed and tailored to the different cases

$$\dot{\vec{L}}_t + \vec{\omega}\,\mathrm{x}\,\vec{L}_t = \vec{M} \Rightarrow \vec{I}\dot{\vec{\omega}} + \dot{\vec{I}}\vec{\omega} + \vec{A}\dot{\vec{L}}_w + \dot{\vec{A}}\vec{L}_w + \vec{\omega}\,\mathrm{x}\,\vec{I}\vec{\omega} + \vec{\omega}\,\mathrm{x}\,\vec{A}\vec{L}_w = \vec{M}$$

MW	≠0	=0	=0	=0	≠0	≠0
RW	≠0	=0	≠0	=0	≠0	=0
CMG	≠0	≠0	=0	≠0	≠0	≠0

Satellite dynamics always present

Does the spin axis change its orientation in principal axes?

Does the wheel change the platform inertia over time?

Does the wheel's speed change over time?

Does the wheel have a non-zero nominal angular velocity?

Pros/Cons of Gyroscopic Actuators (2)

- Despite the saturation disadvantages, MW and RW are much more used than CMG because
  - the control torque is always given about a known axis
  - moving spin axes cause mechanical difficulties
  - the relative geometry between CMGs can become disadvantageous or even singular when two spin axes are aligned

- It is noted that RW typically requires larger power than MW because they encounter static friction at the zero nominal angular velocity

- In general we can re-write the Euler equations and identify the control torque from the actuator terms moved to the right hand side

$$\vec{I}\dot{\vec{\omega}} + \dot{\vec{I}}\vec{\omega} + \vec{A}\dot{\vec{L}}_w + \dot{\vec{A}}\vec{L}_w + \vec{\omega} \times \vec{I}\vec{\omega} + \vec{\omega} \times \vec{A}\vec{L}_w = \vec{M} \Rightarrow$$

$$\vec{I}\dot{\vec{\omega}} + \vec{\omega} \times \vec{I}\vec{\omega} = \vec{M} + \vec{M}_c \; ; \vec{M}_c = \underbrace{-\vec{A}\dot{\vec{L}}_w - \dot{\vec{A}}\vec{L}_w - \vec{\omega} \times \vec{A}\vec{L}_w}$$

- The desired control torque is the output of a feedback loop (control law) and can be obtained through a command to the actuators for realization

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