Lecture Module 5: Introduction to Attitude Stabilization and Control

Lectures 1-3

Stability is referred to as a system’s behaviour to external/internal disturbances (small) in/from equilibrium states. For example, position of rest of a simple pendulum at vertically down location is a stable equilibrium state. This is because when disturbed from this position, pendulum comes back to its state of equilibrium after a while. A ball at the bottom of a bowl is another example of a stable equilibrium state of the ball, while a ball on top of an inverted bowl is an example of an unstable equilibrium state of the ball. Satellite in our case is example of another physical system similar to a ball and the task of attitude stabilization is to make sure that satellite’s attitude is stable under influence of external torques. If not, any small disturbance torque acting on the satellite will change its orientation (attitude) forever and take it away from the mission specific attitude. The task of re-orienting satellite’s attitude from one stable equilibrium attitude to another is known as attitude maneuvering or attitude control. Both the operations may need a torque producing device on the satellite, for example, a jet thrust acting at a distance from satellite’s center-of-mass.

As you would guess, when a small external disturbance torque acts on a satellite in equilibrium, satellite utilizes the input energy to change its attitude (orientation) to an attitude different from the equilibrium attitude. In order to bring the satellite back to its original equilibrium attitude, it is important to get rid of the disturbance energy as quickly as possible. Physical mechanism of dissipation of energy is known as damping. As stated above, a satellite needs to be stable in its mission specific attitude (orientation) by design or it has to be provided with artificial stability using a control system onboard. Even without an active control system onboard, dissipation of disturbance energy or damping can be achieved by using dampers on a satellite. Please note that a satellite made of elastic material may itself possess some damping characteristics, but that may not be sufficient to bring back the satellite to its equilibrium attitude as quickly as possible, as desired.

We have seen in previous lectures, a satellite/spacecraft undergoes periodic motions when disturbed from its equilibrium position under influence of disturbance torques. For a spin-stabilized spacecraft (spacecraft spinning about its major or minor principal axis), this periodic motion around equilibrium attitude is rotational and is known as nutation. For a gravity gradient stabilized spacecraft, the periodic motion around equilibrium attitude is oscillatory and is known as libration. Cause of these motions are additional external
(environmental) torques or internal torques, due to for example, separation of part from the satellite or re-orientation of some parts. Damping mechanisms for a satellite are characterized by control of undesired nutational and libration motions. We learn about some passive techniques (by design or onboard damping mechanisms) of attitude stabilization first and then we will discuss some active control devices onboard a satellite for attitude stabilization and maneuvering.

**Figure 5.1**: A dumbbell shaped satellite in an orbit around Earth.

**Gravity Gradient Stabilization**: This is a passive attitude stabilization technique for a Earth pointing satellite which makes use of gravity gradient. In order to understand the principle behind gravity gradient stabilization technique, let us consider a dumbbell satellite with its center of mass going around Earth in a circular orbit as shown in the Fig. 5.1. The equal masses $m_1$ and $m_2$ experience different forces when not aligned along the local vertical. The centrifugal force on mass $m_1$ is larger than the centrifugal force on mass $m_2$ in a deviate position from the local vertical. The centrifugal forces acting on the two masses are different even when they are aligned with the local vertical, however, in this situation both the forces pass through the center of mass. In the deviate position the difference in centrifugal forces at mass $m_1$ and $m_2$ result in a restoring torque.
For a satellite body of arbitrary shape with moments of inertia $I_x$ about yaw-axis $x$ (along local vertical), $I_y$ about roll-axis $y$ (along the orbit) and $I_z$ about pitch-axis $z$ (completing right handed orthogonal $x$-$y$-$z$ axis system as shown in Fig. 5.2), conditions for stability can be arrived at (see Ref. [1] for detailed analysis) as:

**For roll-yaw stability**: pitch axis must be the minor or major principal axis, i.e., $I_z$ must be largest or smallest of all three.

**For pitch stability**: $I_y > I_x$

Therefore, $I_z > I_y > I_x$ OR $I_y > I_x > I_z$

In general, it is best to design satellites operating in a gravity gradient such that $I_z > I_y > I_x$

**Homework Exercise**: Discuss the kind of bodies that will satisfy the above conditions? Discuss the stability of dumbbell shapes satellite based on above conditions. Also, argue based on previous stability analysis, if this conditions above are true in general.

**Figure 5.2**: A satellite in an orbit around Earth.
Various damping mechanism

Undesired nutation or libration motions can be damped by active or passive devices. Active techniques make use of feedback control systems requiring continuous attitude sensing, whereas passive techniques do not need active attitude sensing and measurements and are driven by motion itself to dissipate energy.

Passive nutation damping:

Objective of nutation damping is of aligning the nominal spin axis with the angular momentum vector by dissipating the excess kinetic energy associated with nutational motion. For a rigid spacecraft it is possible only if the spin axis is the major axis of the spacecraft. Four major types of passive dampers in use are:

- **Pendulum**: consists of a mass attached to a long elastic rod which is used to absorb the excess energy.
- **Ball-in-tube damper**: A picture of ball-in-tube damper is shown in the figure below.

![Ball-in-tube Nutation Damper](image)

Figure 5.3: Ball-in-tube Nutation Damper (Redrawn from Ref.[1]).

Ball-in-tube dampers consists of a curved tube inside the satellite aligned along the spin axis of spacecraft body. Ends of the tube are energy absorbing dampers. A ball moves inside the curved tube which dissipates the additional energy caused by the disturbance motion. The damper behaves like a centrifugal pendulum with frequency...
of rotation directly proportional to the spin rate of the satellite body. For better damping, the tube may be filled with viscous liquid.

- **Viscous ring damper**: Viscous ring dampers consists of closed tubes with viscous fluids inside (Fig. 5.4). Energy dissipation takes place due to fluid motion inside the tube. Heat pipes (fluid filled aluminium pipe), fiberglass tube filled with mercury are examples viscous ring dampers. The ring can either be placed on the spin axis or any other axis.

![Figure 5.4: Viscous ring nutation damper.](Image)

- **Eddy current damper**: energy dissipation in this case is achieved by moving a conducting plate relative to a magnet. The energy dissipation rate per unit weight due to eddy current in the conductor is much greater than that of the fluid dampers. A typical eddy current damper consists of a Ni/Pt torsion wire parallel to the spin axis. The wire carries a pendulous copper vane which oscillates between the poles of an electromagnet. The drag force is proportional to the velocity of the vane between the poles. The damping constant is given by

\[ c = \frac{KB^2d}{\rho} \]

K in the above relation depends on the shape and size of the poles. \( \rho \) and \( d \) are resistivity and thickness of the vane, respectively, and \( B \) is the magnetic induction
between the magnetic poles. Advantage of Eddy current is that magnitude of the damping constant can be varied by adjusting the strength of the electromagnet.

**Libration damping:**

- **Spring damper:** For gravity gradient satellites, spring libration dampers are very useful for damping librational motion in the plane of the orbit. A sketch of the damper is shown in Fig. 5.5.

![Figure 5.5: Spring libration damper for gravity gradient stabilized satellite.](image)

As the satellite liberates, the spring attached to the antenna boom of the satellite undergoes expansion and contraction resulting in energy dissipation due to high structural damping in the spring.

- **Magnetically Anchored Eddy Current Damper:** This consists of two concentric spheres separated by silicone oil to provide viscous damping. Spheres are free to move relative to each other. The inner sphere is attached to a magnet which aligns itself to Earth’s magnetic field vector. The outer sphere made of pyrolitic graphite (for diamagnetic centering of forces on the inner sphere) and aluminium (for energy dissipation through Eddy currents) is attached to the spacecraft’s boom. The damping torque created by this arrangement is given by

\[
N = c \hat{B} \times \left( \frac{d \hat{B}}{dt} \right)
\]

Where \(c\) is the damping constant and \(\hat{B}\) is the direction of the resultant magnetic field in the body fixed frame. These dampers are strong over wide operational altitudes.
• **Eddy current rods**: Ferromagnetic rods coated with conducting copper sheet fixed along the principal axes of a satellite are used for libration damping. As satellite liberates, eddy currents are generated in the rods because of change in geomagnetic field which effects instantaneous power dissipation in the rod.

**Active nutation damping**

Active nutation damping works on the principle of using a sensor to measure nutation phase and amplitude, and using an actuator to change the angular momentum of the satellite. Various types of sensors and actuators are used for active damping in an open-loop, in which actuator is activated by a ground command, or in a closed loop, which requires a control system onboard. A closed loop control system onboard makes use of the satellite attitude measurements available from attitude sensors with respect to fixed references, determines the error between the sensed attitude and the prescribed attitude and releases a command signal to control actuators to mitigate the error. Such active control systems are based upon feedback control mechanism as shown in the Fig. 5.6.

**Figure 5.6**: Block diagram of an active attitude control system.

**Active nutation damping elements**:

- Magnetic coil
- Gas Jets
- Momentum/reaction wheel
- Control moment gyroscope