MATH AND SCIENCE @ WORK

AP* PHYSICS Educator Edition

SPACE SHUTTLE ORBITAL DOCKING SYSTEM

Instructional Objectives

Students will

- analyze the components of the space shuttle and International Space Station docking system;
- evaluate torque and energy; and
- determine work and separation velocity.

Degree of Difficulty

For the average AP Physics C student, this problem is at a moderate to advanced difficulty level. Integration and differentiation techniques are required on some parts.

Class Time Required

This problem requires 60 minutes.

- Introduction: 5 minutes
- Student Work Time: 45 minutes
- Post Discussion: 10 minutes

Background

This problem is part of a series of problems that apply Math and Science @ Work in NASA's Space Shuttle Mission Control Center.

Since its first flight in 1981, NASA has used the space shuttle for human transport, the construction of the International Space Station (ISS), and to research the effects of space on the human body. One of the keys to the success of the Space Shuttle Program is the Space Shuttle Mission Control Center (MCC). The Space Shuttle MCC at NASA Johnson Space Center uses some of the most sophisticated technology and communication equipment in the world to monitor and control the space shuttle flights.

Within the Space Shuttle MCC, teams of highly qualified engineers, scientists, doctors, and technicians, known as flight controllers, monitor the systems and activities aboard the space shuttle. They work together as a powerful team, spending many hours performing critical simulations as they prepare to support preflight, ascent, flight, and re-entry of the space shuttle

Grade Level
11-12

Key Topic
Springs

Degree of Difficulty
Physics C: Mechanics: Moderate to Advanced

Teacher Prep Time
10 minutes

Class Time Required
60 minutes

Technology
Calculator

AP Course Topics
Newtonian Mechanics:
- Kinematics
- Newton's laws of motion
- Work, energy, power
- Systems of particles, linear momentum
- Circular motion and rotation

NSES
Science Standards
- Physical Science
- Science and Technology

and the crew. The flight controllers provide the knowledge and expertise needed to support normal operations and any unexpected events.

Following a successful launch, the space shuttle's orbiter arrives at the same orbit and within visual contact of the International Space Station (ISS) in order to rendezvous with the ISS. From the Space Shuttle MCC, the Mechanical, Maintenance, Arm, and Crew Systems (MMACS) flight controllers monitor the docking and undocking process between the two vehicles. Because the space shuttle and ISS are both pressurized vehicles traveling in a vacuum, it is extremely critical that upon docking, a secure connection is achieved. This occurs through the use of a docking mechanism between the space shuttle and ISS. This mechanism consists of two pieces: the Orbital Docking System (ODS), which is connected to the space shuttle (see Figure 1), and the Pressurized Mating Adaptor (PMA), which is permanently mounted on the ISS (see Figure 2).

Figure 1: Space shuttle payload doors have opened, revealing the Orbital Docking System.

Figure 2: Space Shuttle Atlantis docks with the ISS.

At rendezvous, both the space shuttle and the ISS have an orbital velocity of 28,000 km/hr (approximately 17,500 mph). Their relative translational velocities, however, are zero. As the docking process begins, the space shuttle uses its thrusters to approach the ISS at a relative speed of 0.0325 m/s (0.1 ft/s). MMACS flight controllers monitor the docking process and follow procedures to reduce the impact between the two massive vehicles.

Where there is a collision, there is an energy transfer. Because both the space shuttle and ISS together are effectively one isolated system, and since energy is conserved, the energy of impact must remain within the system. For this reason, the ODS is constructed to damp out the energy of collision, as well as perfectly align the docking rings of both vehicles. This ensures an ideal seal between the space shuttle and the ISS. The ODS performs an amazing feat of engineering in passively damping energy and realigning the space shuttle to the PMA of the ISS, using both torsional and compression/extension springs. The torsional springs are at work during docking, contributing to the damping of impact energy and alignment, while the compression/extension springs are in use during undocking, providing an initial push to separate the two vehicles.

AP Course Topics

Newtonian Mechanics

- Kinematics
    - motion in one dimension

- Newton's laws of motion
  - dynamics of a single particle (second law)
- Work, energy, power
  - work and work-energy theorem
  - forces and potential energy
- Systems of particles, linear momentum
  - conservation of linear momentum, collisions
- Circular motion and rotation
  - torque and rotational statics

NSES Science Standards

Physical Science

- Motions and forces
- Conservation of energy and increase in disorder
- Interactions of energy and matter

Science and Technology

- Abilities of technological design

Problem and Solution Key (One Approach)

The Orbital Docking System (ODS) on the space shuttle principally contains two rings, referred to as the guide ring and the base ring. Three petals on the guide ring each contain a capture latch responsible for the initial soft capture of the ISS. The soft capture first connects the two vehicles, but not rigidly. The base ring houses twelve pairs of structural hooks, which are then used to hard mate the vehicles. This hard mate is a rigid, air tight connection between the two vehicles.

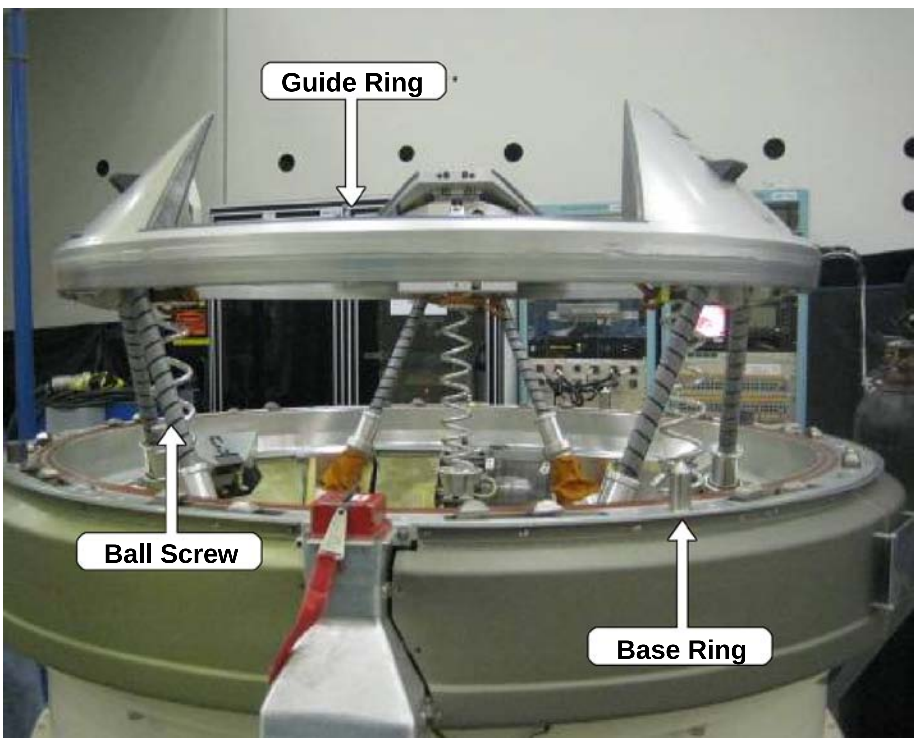

Figure 3: The space shuttle ODS training unit, located at Johnson Space Center in Houston, Texas

The guide ring and the base ring are connected by ball screws, six total, arranged in three pairs. A ball screw consists of a spirally grooved shaft and a ball nut assembly containing ball bearings that run along the grooves in the shaft. A ball screw translates rotational motion into linear motion – similar to the way a nut translates along a screw when turned. The guide ring is drawn towards (or extended away from) the base ring by an electric motor which turns the ball screw assembly. The docking system is aligned when the two rings are parallel to each other.

Although the goal of docking is to have the guide ring of the space shuttle contact the passive docking interface on the ISS symmetrically, this rarely happens. If the guide ring and the base ring are not aligned (parallel), then the load is asymmetrical. If the ball screws were rigidly connected to the structure, any force imparted asymmetrically to the guide ring would cause all ball screws to move simultaneously, with each experiencing varying degrees of force. The rigidity would be detrimental to dissipating the load of docking and would produce a significant oscillation within the space shuttle and ISS system.

Reacting to asymmetrical loading requires each of the ball screws in a pair to be able to move independently. Torsional springs are used to provide compliance in the attachment between pairs of ball screws. (A torsional spring is a type of spring that operates by twisting rather than by compression or extension). Three springs, one for each pair of ball screws and connected by mechanical linkage, allow independent relative motion between the ball screws. The torsional springs independently load (reacting to unbalanced forces) and the mechanical linkage controls the energy being released. These two functions passively result in damping impact energy while realigning the two rings for docking.

A. The ODS docking petals (triangle veins) in Figure 4 are clearly visible, beneath which is housed a torsional spring for each set of ball screws. In the figure, petal 2 is located in the front left. Petal 1 is located in the front right; and petal 3 is in the center-back. The torsional springs are referred to by their petal location accordingly.

Figure 4: The mounted ODS as seen looking through the space shuttle cargo bay windows

I. If the torsional spring constant, κ, for all three torsional springs is $0.51\,\frac{N\cdot m}{rad}$, determine the magnitude of the net restoring torque upon docking if spring 1 is displaced 70.°, spring 2 is displaced 24°, and spring 3 is displaced 215°.

$$\Sigma\tau = \kappa\theta_1 + \kappa\theta_2 + \kappa\theta_3$$

$$\theta_1 = 70° = 1.2\ rad$$
$$\theta_2 = 24° = 0.42\ rad$$
$$\theta_3 = 215° = 3.75\ rad$$

$$\Sigma\tau = \left(0.51\,\tfrac{N\cdot m}{rad}\right)\left(1.2\ rad + 0.42\ rad + 3.75\ rad\right)$$
$$\Sigma\tau = 2.7\ N\cdot m$$

II. How much total energy is stored by the three torsional docking springs?

$$\Delta U = \Sigma\,\tfrac{1}{2}\kappa\theta^2$$
$$\Delta U = \tfrac{1}{2}\left(0.51\,\tfrac{N\cdot m}{rad}\right)\left[\left(1.2\ rad\right)^2 + \left(0.42\ rad\right)^2 + \left(3.75\ rad\right)^2\right]$$
$$\Delta U = 4.0\ J$$

III. Explain what happens to this stored energy.

This energy is slowly released through the mechanical linkage to realign the space shuttle's guide ring to the base ring, effectively damping out the system and eliminating any vibrational motion between vehicles.

B. Figures 5 and 6 depict the compression/extension undocking springs located on the base ring of the ODS. There are two more identical springs located on the passive ring of the ISS. Once the impact energy of docking has damped out and the rings are aligned, the guide ring on the space shuttle is retracted by turning the ball screws. As the guide ring is retracted, the base ring on the ODS draws closer to the passive ring on the ISS. When the two rings are close enough, the undocking springs start to compress. This process continues until the two passive rings are flush with one another.

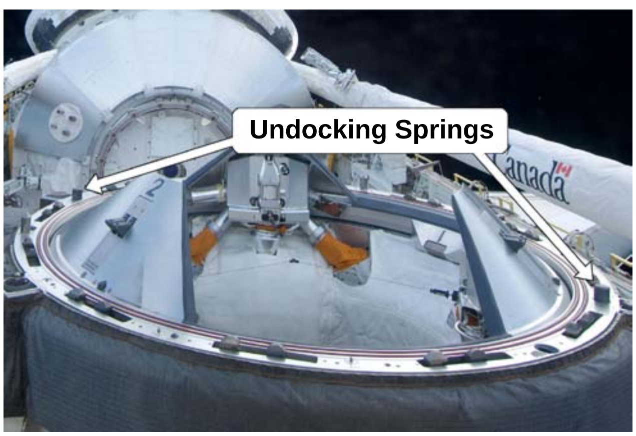

Figure 5: Entire view of the undocking springs on the space shuttle's ODS

Figure 6: Close-up view of an undocking spring on the ODS training unit

I. The undocking springs behave ideally, having a spring constant of 16,092 N/m. Determine the work done by the ball screws to compress all four undocking springs if one uncompressed spring measures 0.030 m.

$$W = \int_{x_i}^{x_f} F_x dx$$

$$x_i = 0\ m$$

$$x_f = 0.030\ m$$

$$W = 4\left[\int_0^{0.030\ m} (F)dx\right] = 4\left[\int_0^{0.030\ m} (kx)dx\right]$$

$$W = 4\left(16{,}092\ \tfrac{N}{m}\right)\int_0^{0.030\ m} xdx$$

$$W = 4\left(16{,}092\ \tfrac{N}{m}\right)\left[\tfrac{1}{2}(0.030\ m)^2 - \tfrac{1}{2}(0\ m)^2\right]$$

$$W = 29\ J$$

II. Using Newton's 2nd law, write a differential equation to represent the acceleration of the space shuttle produced by the undocking springs. Do not solve.

$$\vec{F}_{springs} = \frac{d\vec{p}_{shtl}}{dt} = \frac{d}{dt}(m\vec{v}_f - m\vec{v}_i)_{shtl}$$

$$v_i = 0\ \tfrac{m}{s}$$

$$\vec{F}_{springs} = m_{shtl}\frac{dv_f}{dt}$$

$$\frac{F_{springs}}{m_{shtl}} = \frac{dv}{dt}$$

Since $a_{shtl} = \frac{dv}{dt}$, *the differential equation* $\frac{dv}{dt} = \frac{F_{springs}}{m_{shtl}}$ *represents the acceleration of the space shuttle.*

III. The spring acts on both the space shuttle and the ISS simultaneously, but because of their different masses, the distance through which the spring acts on each vehicle is different. Determine the change in velocity experienced at undocking by the space shuttle and by the ISS given the mass of the space shuttle, m_{shtl}, is 93,975 kg and the mass of the ISS, m_{ISS}, is 369,900 kg.

Work from spring goes to changing kinetic energy of the space shuttle and ISS.

$$W = \frac{1}{2}m_{shtl}\cdot \Delta v_{shtl}{}^2 + \frac{1}{2}m_{ISS}\cdot \Delta v_{ISS}{}^2$$

Conservation of momentum:

$$(m_{shtl} + m_{ISS})v_i = m_{shtl}v_{f,shtl} + m_{ISS}v_{f,ISS}$$

$$v_i = 0\ \tfrac{m}{s}$$

$$0 = m_{shtl}v_{f,shtl} + m_{ISS}v_{f,ISS}$$

$$v_{f,ISS} = -\frac{m_{shtl}v_{f,shtl}}{m_{ISS}}$$

Use substitution in the work equation and solve for the change in velocity.

$$W = \frac{1}{2} m_{shtl} \cdot \Delta v_{shtl}^{\ 2} + \frac{1}{2} m_{ISS} \cdot \left(-\frac{m_{shtl} \Delta v_{shtl}}{m_{ISS}} \right)^2$$

$$W = \frac{1}{2} m_{shtl} \cdot \Delta v_{shtl}^{\ 2} + \frac{1}{2} \left(\frac{m_{shtl}^{\ 2} \Delta v_{shtl}^{\ 2}}{m_{ISS}} \right)$$

$$W = \frac{1}{2} \Delta v_{shtl}^{\ 2} \cdot \left(m_{shtl} + \frac{m_{shtl}^{\ 2}}{m_{ISS}} \right)$$

$$\Delta v_{shtl} = \sqrt{\frac{2W}{m_{shtl} + \frac{m_{shtl}^{\ 2}}{m_{ISS}}}}$$

Substitute known values for work and mass to find the change in velocity of the space shuttle.

$$\Delta v_{shtl} = \sqrt{\frac{2(29\ J)}{93{,}975\ kg + \frac{(93{,}975\ kg)^2}{369{,}900\ kg}}}$$

$$\Delta v_{shtl} = 0.022\ \frac{m}{s}$$

Use conservation of momentum to solve for the change in velocity of the ISS.

$$\Delta v_{ISS} = -\frac{m_{shtl} \Delta v_{shtl}}{m_{ISS}}$$

$$\Delta v_{ISS} = -\frac{(93{,}975\ kg) \cdot (0.022\ \frac{m}{s})}{369{,}900\ kg}$$

$$\Delta v_{ISS} = -0.0056\ \frac{m}{s}$$

Scoring Guide

Suggested 15 points total to be given.

Question		Distribution of points
A	*6 points*	3 points for part I: 1 point for summing three torsional spring contributions 1 point for converting displacements from degrees to radians 1 point for correct value of net torque 2 points for part II: 1 point for summing each torsional spring's energy contribution 1 point for the correct magnitude of stored energy 1 point for part III: for correctly explaining energy is used to realign rings
B	*9 points*	2 points for part I: 1 point for correct expression to determine work done 1 point for correct value of work done 2 points for part II: 1 point for using Newton's 2nd Law relating force and momentum 1 point for recognizing $\frac{dv}{dt} = a$ 5 points for part III: 1 point for conservation of momentum expression 1 point for substitution into the work-energy theorem 1 point for the correct value of the change in velocity of the space shuttle 1 point for determining the change of velocity of the ISS 1 point for acknowledging the change of velocities of space shuttle and ISS are opposite

Contributors

This problem was developed by the Human Research Program Education and Outreach (HRPEO) team with the help of NASA subject matter experts and high school AP instructors.

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