MATH AND SCIENCE @ WORK

AP* PHYSICS Student Edition

SPACE SHUTTLE LAUNCH MOTION ANALYSIS

Background

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

The space shuttle follows a specific trajectory during a mission. The Flight Dynamics Officer (FDO, pronounced “Fido”) in the Space Shuttle MCC is responsible for monitoring the trajectory. They must know exactly where the space shuttle is and where it is going at all times during the mission. The trajectory of the space shuttle is unique for each flight and is broken into four phases: ascent, entry, orbit, and rendezvous.

Figure 1: Space Shuttle Discovery at lift-off during STS 121

Figure 2: Viewed from the Banana River Viewing Site, Space Shuttle Discovery heads toward Earth orbit and rendezvous with the International Space Station (ISS) on 28 August, 2009 during STS 128.

The first phase is the ascent phase which begins at lift-off and ends as the space shuttle reaches orbit. Since the space shuttle has a mass of approximately 2 million kg (weight of about 4.4 million lbs) when on the launch pad, a very powerful propulsion system is needed to launch it into orbit. The main propulsion system consists of the External Tank (ET) and the Space Shuttle Main Engines (SSMEs). This system, together with the Solid Rocket Boosters (SRBs), supplies the force (thrust) needed to accelerate to the speed of approximately 7.85 km/s that is required to attain orbit. Within 1 minute of launch the space shuttle breaks the sound barrier. The stress on the vehicle and the crew increases as the space shuttle accelerates. To ensure their safety, the acceleration of the space shuttle must be kept below 3 g (3 times the acceleration due to gravity). The space shuttle continues to accelerate along its trajectory until Main Engine Cutoff (MECO). It only takes approximately 8 minutes and 30 seconds for the space shuttle to reach MECO, which occurs around 104 km (56 miles) above the surface of the Earth. The ET is dropped away to break up and land in the ocean. Approximately 30 minutes later, the orbiter performs a final rocket engine firing to reach an orbital altitude of around 320 km (200 miles) above Earth.

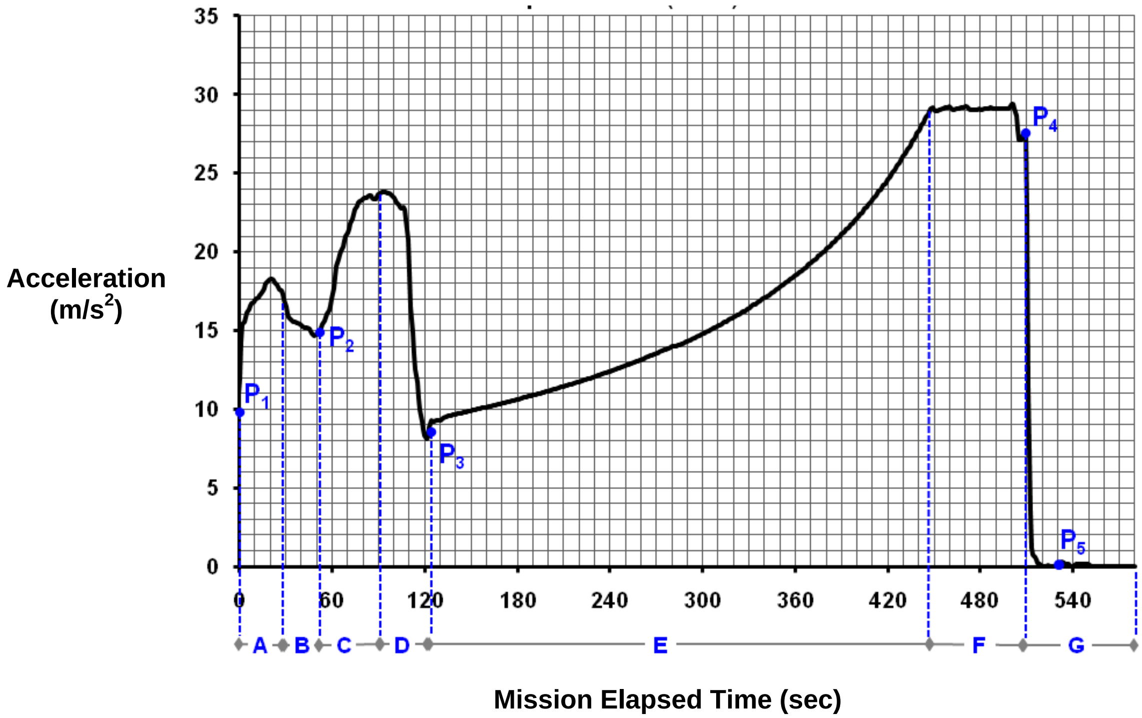
During the ascent phase, the FDO flight controllers work closely with the Propulsion (PROP) officer and the Booster flight controller who are both responsible for monitoring the propulsion of the space shuttle. In addition, there are several support teams for the FDO position located in backrooms of the MCC. These support teams are constantly engaged in intensive computational processing starting with the ascent phase and continuing throughout the entire mission. The FDO flight controller continues to work closely with the backroom support teams and other flight controllers in the Space Shuttle MCC throughout the mission to meet the mission objectives and to ensure crew safety.

Problem

The Ascent Team, one of the backroom teams associated with FDO, has provided the acceleration data of the space shuttle during the launch of Space Transportation System (STS) 121. As the space shuttle lifts off from the launch pad and ascends into orbit, the motion along its flight path appears to be smooth. Although one might intuitively perceive the space shuttle as maintaining a constant acceleration during its climb into orbit, it actually experiences varying accelerations during this period. The final orbital speed of the space shuttle is approximately 28,000 km/hr (17,500 mph). Graph 1 provides an acceleration-time profile for the launch ascent phase of STS 121. The motion is modeled as linear motion. For purposes of this problem, centripetal or orbital motions are neglected in this model, therefore the acceleration is assumed to affect only the speed of the shuttle. The space shuttle has an initial speed of 0 m/s and distance is measured from the launch pad.

Note: Throughout this problem, when the terms “acceleration” and “displacement” are used, they are referring to the magnitude component of the vectors only.

Mission Elapsed Time (MET) vs. Acceleration



Graph 1: Acceleration profile of STS 121 during the ascent phase.

A. The following events take place during the launch of a space shuttle. Compare the rates of change of acceleration in Graph 1 and determine which event occurs at the marked time periods (A through G) and points (P_1 through P_5).

______ External Tank separation

______ Aerodynamic stress on the spacecraft in atmospheric flight is at its highest (Max Q)

______ Space Shuttle Main Engines provide smoothly changing acceleration

______ Throttle down

______ On orbit

______ Throttle up

______ Main Engine Cutoff

______ Solid Rocket Boosters burning out

______ Negative rate of change of acceleration (large air drag)

______ Constant acceleration (3 g's)

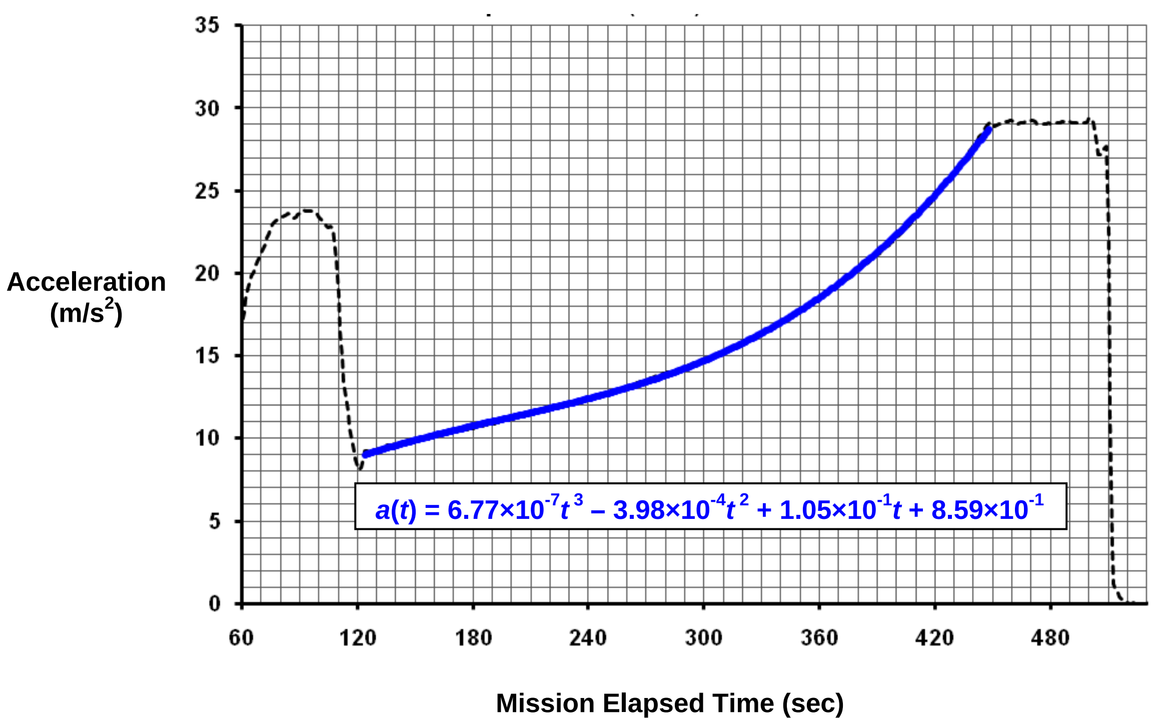
______ Solid Rocket Booster separation

______ Space shuttle lift-off

B. Identify the initial acceleration value at $t = 0$ s from Graph 1and explain why the acceleration is not 0 m/s^2?

During the timeframe $t = 124$ s through $t = 446$ s the space shuttle's main engines produce a very smooth change in acceleration. Graph 2 shows how this period of changing acceleration can be best modeled by the expression: $a(t) = (6.77 \times 10^{-7})t^3 - (3.98 \times 10^{-4})t^2 + (1.05 \times 10^{-1})t + (8.59 \times 10^{-1})$.

Mission Elapsed Time (MET) vs. Acceleration with Trendline



Graph 2: Acceleration profile of STS 121 showing the trendline for the time period t=124 s to t = 446 s.

C. Write an expression that represents the change in speed (Δv) experienced by the space shuttle during the time period $t = 124$ s to $t = 446$ s and then evaluate the expression to determine the value.

D. If the speed of the space shuttle at t = 124 s is approximately 974 m/s, write an expression that represents change in displacement along the ascent path during the time period t = 124 s through t = 446 s and evaluate the expression to determine the value.

The displacement expression derived from the acceleration expression will not yield an altitude measurement but a distance along the flight path. (This is because the data used to produce the Mission Elapsed Time (MET) vs. Acceleration graph is a composite resultant of all three axis accelerometers on the space shuttle.)

E. Notice that the acceleration between t = 446 s and t = 500 s remains constant at approximately 3 g (g = 9.8 m/s^2). See Graph 2. Maintaining the acceleration at 3 g limits the physical stress endured by the astronauts. Make a sketch of the speed-time graph for this time period.

F. Determine the speed of the space shuttle at Main Engine Cutoff (MECO) occurring at t = 500 s.