Mechanics Activity: Dynamics of a Shuttle Launch

Go to the following website and watch the first two and half minutes of the launch of a shuttle mission to the International Space Station.

http://www.nasa.gov/multimedia/videogallery/index.html?collection_id=14717

After watching the launch, find the following information about the shuttle transport system (STS). http://www.nasa.gov/returntoflight/system/system_STS.html may be a good place to start.

Launch Weight of STS: ____________________

↘

Convert to SI units (if necessary) (show work): _____________________

Mass of STS at liftoff (in kg): _________________________

Thrust provided by Solid Rocket Boosters (SRBs) at lift-off: ____________________________

↘

Convert to SI units (if necessary): _______________________________

Maximum sea level thrust of main engines: ___________________________

↘

Convert to SI units (if necessary): _______________________________

Using the information above, answer the following questions about the forces at work during the launch.

1. Draw a free body diagram for the shuttle just after launch. Assume that air resistance is negligible.

2. If the main engines initially provide 65% of their maximum thrust in acting with the SRB's, what will be the initial upward acceleration of the shuttle?

3. After the solid rockets are jettisoned, the main engines provide thrust which accelerates the Shuttle from 3,000 mph to over 17,000 mph in just six minutes to reach orbit. At this point in the launch, when the shuttle has lost much of mass in the form in the fuel, assume an average mass of the orbiter and External Tank (ET) of 230,000 kg.
    a. What acceleration (in m/s^2) does this correspond to?

    b. Draw a free body diagram corresponding to this situation. Remember that air resistance is no longer negligible.

    c. If the main engines provide 10×10^6 N of thrust (on average) during this portion of launch, what is the average force of air resistance?

Extension/Research questions:

1. What is the chemical reaction that fuels the shuttle? What is its byproduct?

2. What is the speed of the shuttle in low Earth orbit (LEO)? At this speed, how long will it take the shuttle to cross over the Pacific Ocean? (At its widest point, the Pacific Ocean stretches 19,800 km from East to West.)

3. It takes a total of 8.5 minutes for the shuttle to go from the launch pad at rest to Low Earth orbit (at the speed found in #2 above). What is the average acceleration during this period? Is the acceleration actually constant? Why or why not?

4. The maximum payload the shuttle can carry to low earth orbit is 53,600 pounds, while the maximum payload to a higher, geotransfer orbit is 8,390 pounds. Why are these different?

Teacher Notes
Mechanics Activity: Dynamics of a Shuttle Launch

This worksheet is meant to give students a real world example of dynamics and Newton's Laws. While the actually problem of a rocket launch is one requiring calculus, students can get a feel for the physics at work using simple algebraic expressions of Newton's Laws and free body diagrams. Students first research the shuttle to find the relevant data on masses and thrusts.

Students may need to be told that a thrust is just an upward force. These forces are sometimes reported in MN, or MegaNewtons, or 10^6 N. There is a lot of great information both the NASA page linked in the worksheet on the Space Shuttle Wikipedia entry.

Go to the following website and watch the first two and half minutes of the launch of the most recent shuttle mission.

http://www.nasa.gov/multimedia/videogallery/index.html?collection_id=14717

After watching the launch, find the following information about the shuttle transport system (STS). http://www.nasa.gov/returntoflight/system/system_STS.html may be a good place to start.

Launch Weight of STS: _4.5 million pounds__
↘
Convert to SI units (if necessary) (show work): ___2.0×10^7 N

4.5×10^6 lbs x (1 kg / 2.2 lbs) x (9.8 N / kg) = 2.0×10^7 N

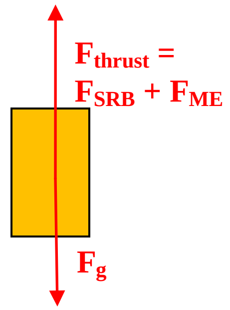
Mass of STS at liftoff (in kg): ___2.04×10^6 kg_______

Thrust provided by Solid Rocket Boosters (SRBs) at lift-off: ____25×10^6 N_______
↘
Convert to SI units (if necessary): ______________________________

Maximum sea level thrust of main engines: 5.255×10^6 N
↘
Convert to SI units (if necessary): ______________________________

Using the information above, answer the following questions about the forces at work during the launch.

1. Draw a free body diagram for the shuttle just after launch. Assume that air resistance is still negligible.



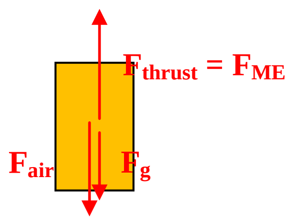
2. If the main engines initially provide 65% of their maximum thrust in acting with the SRBs (acting at full thrust), what will be the initial upward acceleration of the shuttle?

$F_{net} = F_{thrust} - F_g = (25 \times 10^6\ N + 0.65 * 5.25 \times 10^6\ N) - 2.07 \times 10^7\ N = 7.6 \times 10^6\ N$
$F_{net} = ma = 7.6 \times 10^6\ N = (2.04 \times 10^6\ kg)(a);\ a = 3.73\ m/s^2$

3. After the solid rockets are jettisoned, the main engines provide thrust which accelerates the Shuttle from 3,000 mph to over 17,000 mph in just six minutes to reach orbit. At this point in the launch, when the shuttle has lost much of mass in the form in the fuel, assume an average mass of the orbiter and External Tank (ET) of 230,000 kg.
   a. What acceleration (in m/s^2) does this correspond to?

3,000 mph = 1340 m/s
17,000 mph = 7600 m/s
6 min = 360 s
$a = (v_f - v_i) / t = 17.3\ m/s^2$

   b. Draw a free body diagram corresponding to this situation. Remember that air resistance is no longer negligible.



   c. If the main engines provide 10×10^6 N of thrust (on average) during this portion of launch, what is the average force of air resistance?

$F_{net} = ma = F_{thrust} - F_g - F_{air} = 10 \times 10^6 - (230{,}000)*(9.8) - F_{air} = (230{,}000)(17.3)$
$F_{air} = 3.8 \times 10^6\ N$

Extension/Research questions:

1. What is the chemical reaction that fuels the shuttle? What is its byproduct?

The main chemical reaction is the combustion of liquid hydrogen with oxygen, to form a water vapor. It is this water vapor that the shuttle puts into the atmosphere that may contribute to the production of noctilucent clouds and may have an effect of the level of mesospheric ozone in the upper atmosphere.

2. What is the speed of the shuttle in low Earth orbit (LEO)? At this speed, how long will it take the orbiter to cross over the Pacific Ocean? (At its widest point, the Pacific Ocean stretches 19,800 km from East to West.)

The speed necessary for LEO is 7,743 m/s (about 8 km/s). At this speed, the orbiter can cross the widest part of the Pacific Ocean is 19800 km / 8 km/s = 2475 s = 41 minutes

3. It takes a total of 8.5 minutes for the shuttle to go from the launch pad at rest to Low Earth orbit (at the speed found in #2 above). What is the average acceleration during this period? Is the acceleration actually constant? Why or why not?

$v_i = 0$
$v_f = 7700$ m/s
$t = 8.5$ minutes $= 510$ s
$a = \Delta v / t = 7700 / 510 = 15.1$ m/s^2

The acceleration is not actually constant throughout launch for a couple of reasons. For one, as the shuttle goes through the launch process, its speed increases (increasing the air drag), while the atmosphere gets thinner (decreasing the air drag). The effect is a non-constant resistance force on the shuttle that changes the acceleration produced by the engines. Another major factor in the acceleration of the shuttle is its mass, which is constant changing as the shuttle expends its fuel and jettisons unnecessary parts.

4. The maximum payload the shuttle can carry to low earth orbit is 53,600 pounds, while the maximum payload to a higher, geotransfer orbit is 8,390 pounds. Why are these different?

Higher orbits have more potential energy, and that potential energy must be provided by the engines of the shuttle. Because there is only so much fuel the shuttle can carry, if a higher orbit is needed, there must be less mass carried, so that the total amount of energy supplied is limited to what the engines can produce with their payload of fuel.