MSFC-2025

(From Acknowledgements)

ACKNOWLEDGMENTS

2.8.2 Space Shuttle Solid Rocket Motor Nozzle Internal Flow

Each Space Shuttle is boosted by two solid rocket motors (Figure 2-16a), which are 126 feet long and 12 feet in diameter. Figure 2-16 (b) shows an enlarged upper cross section of the nozzle. Combustion products entering the nozzle experience maximum compression at the throat where the nozzle internal diameter is minimal. Aft (to the right) of the throat, nozzle diameter increases. Gases exiting the throat expand, increase in velocity, and generate thrust.

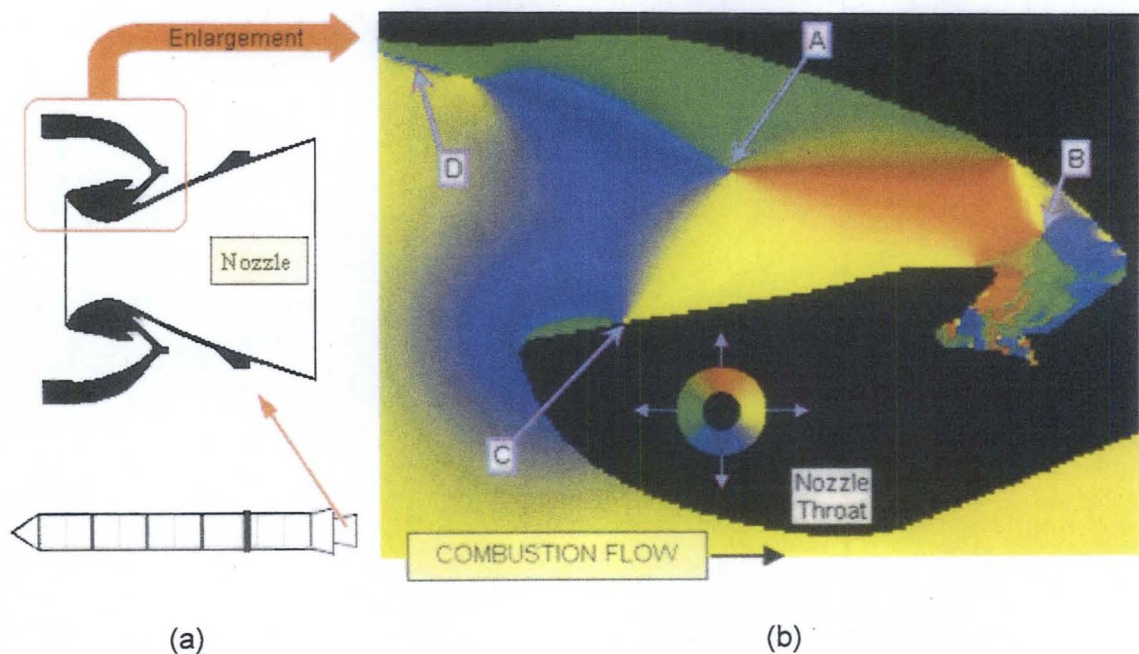(a)   (b)

Figure 2-16, Illustration of the Space Shuttle Booster, Nozzle, and Nozzle Internal Combustion Flow. (a) Space Shuttle solid rocket motor booster and section view of nozzle. (b) Enlarged nozzle section, the red-green-blue-yellow (RGBY) color wheel indicates direction, and circular data image of internal combustion flow. Interesting features include two counter-rotating vortices A and B, flow impingement on the nozzle surface at C, and a narrow particle shear zone at D.

The flow direction shown in Figure 2-16 (b) was computed with FLUENT computational fluid dynamics software (FLUENT 2008), for the Space Shuttle solid rocket motor nozzle at 67 sec from ignition (Permission documentation given after the Appendices). The dataset comprises 30,351 observations of five variables; node

identification, axial and radial coordinates in meters (m), and axial and radial velocity components in m/sec). With direction of the flow aft (right) equal to yellow, upward equal to red, forward (left) equal to green, and down equal to blue, the large counterclockwise pattern in the cavity above the nozzle throat and centered at point A indicates a counterclockwise flow. The smaller pattern at the right end of the cavity and centered at point B indicates a clockwise flow. These two vortices mesh like oppositely rotating gears. At point C, combustion products flowing down impact the nozzle outboard surface and rapidly turn forward. Point D is a high shear zone where particle breakup occurs. The circular data image easily shows much more structural information than a vector plot, which is frequently used for these data, would be able to show. In particular, a vector plot easily could miss the narrow high shear zone at Point D.

2.8.3 Space Shuttle Solid Rocket Motor Nozzle Vectoring Circular Time Series

Nozzle vector direction angle is the angle a nozzle points to in the plane perpendicular to the motor axis. Figure 2-17 (a) shows the RGBY color wheel coding direction. Figure 2-17 (b) (Permission documentation given after the Appendices) shows the direction angle of a subset of nozzles for the time period from 5 sec to 23 sec after ignition. The complete dataset comprises about 3,000 observations. Other variables are orbital altitude in nautical miles (nm) and angle in degrees of the Space Shuttle trajectory relative to the Earth equatorial plane. Each narrow horizontal band of colors indicates a circular time series of direction angle with time increasing from left to right. The observations (horizontal strips) were vertically sorted to show structures hidden by alpha-numeric ordering of the observations and by variation. The horizontal strips are sorted first by location of the nozzle (left side then right side of the motor), second by angle of the Space Shuttle trajectory to the equatorial plane, and last by orbital altitude. In Figure 2-17 (b), the prominent red horizontal band shows that the left side rocket

nozzle tends to vary about the 0-degree location (red), and the overall blue horizontal band above the red band shows that the right side rocket nozzle tends to vary about the 180-degree location (blue). Given the rotated assembly of the rocket motors, the red and blue directions mean that the left and right nozzles tend to be pointed toward Earth.

The blue vertical band at about 10 sec shows the turning of the left side nozzle to initiate the Space Shuttle roll maneuver as illustrated in Figure 2-18. The roll maneuver orients the cargo bay towards the Earth to satisfy communication, scientific, and Space Shuttle engineering requirements and provides the astronauts with a spectacular view of Earth (Brown 2003). The nonrandom diagonal structures between about 14 sec and 23 sec, which were revealed by sorting the observations by inclination and orbital altitude, show that nozzle vectoring following initiation of the roll maneuver is affected by inclination and altitude.

Figure 2-17 (c) is an enlargement of one sequence of nozzle data in Figure 2-17 (b) near the tail of the arrow connecting Figures 2-17 (b) and (c).
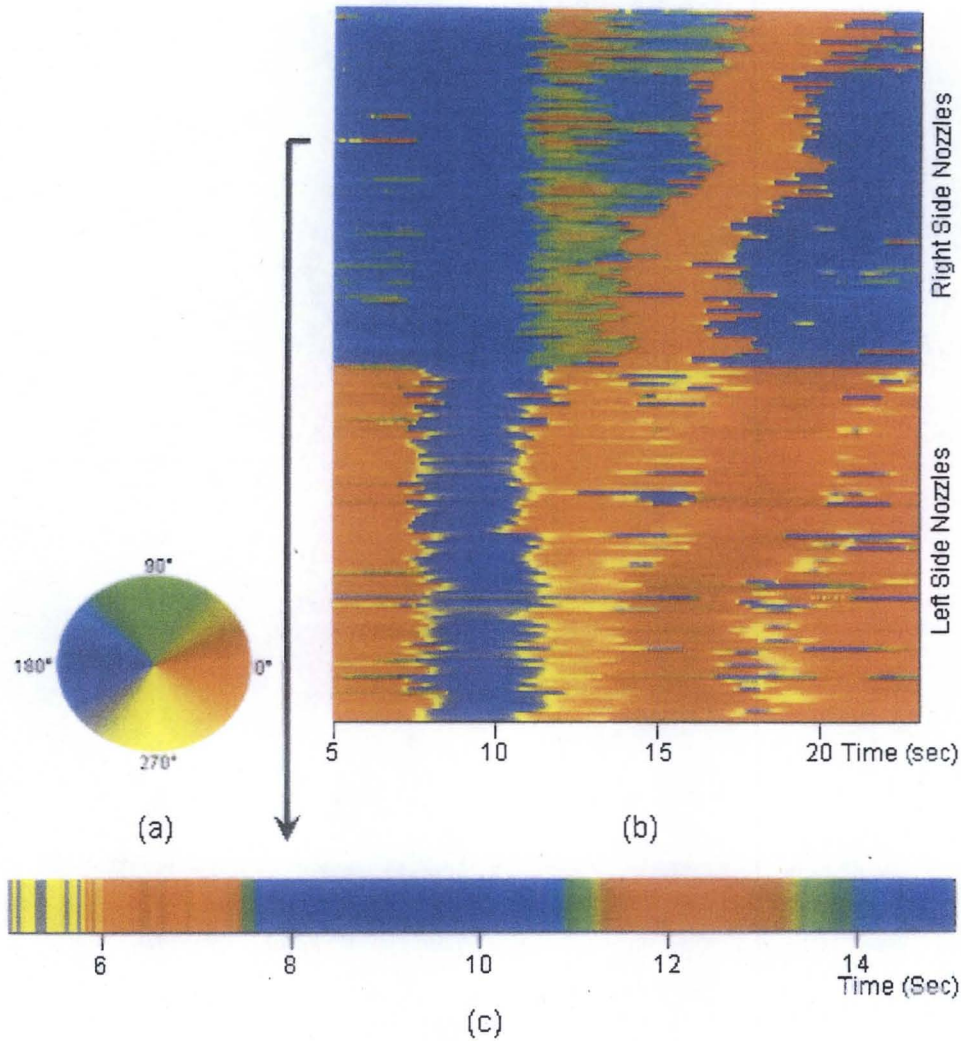
Figure 2-17, Time Series of the Space Shuttle Booster Nozzle Direction Angle. Direction angle is the direction the nozzle is pointing toward in a plane perpendicular to the booster axis. (a) RGBY color wheel, (b) Circular time series families, and (c) Enlargement of one time series. The vertical and diagonal structures in (b) reflect roll maneuver as influenced by inclination and altitude.
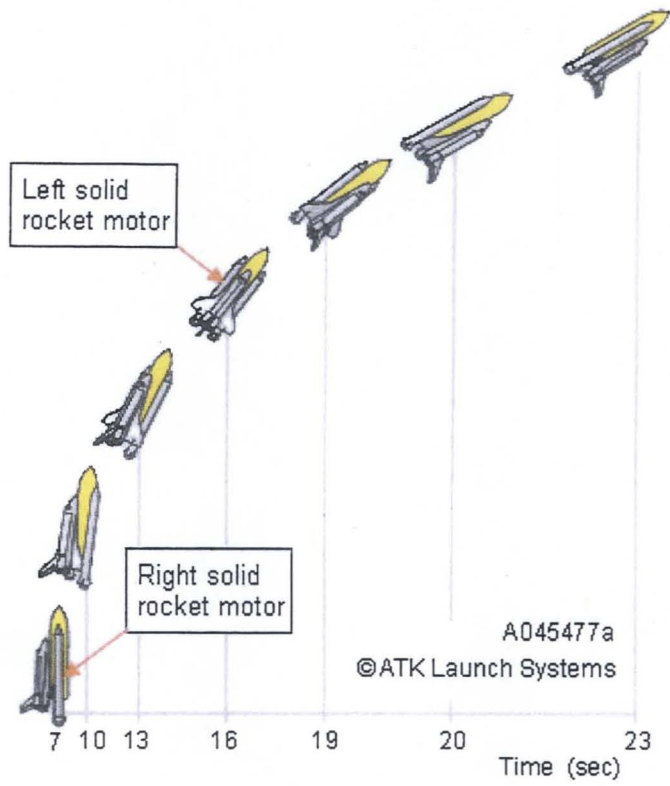
Figure 2-18, Illustration of the Space Shuttle Roll Maneuver Versus Time from Ignition. The time scale is nonlinear to show rotation in equal angular increments.