International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 04 Issue: 04 | April -2020 ISSN: 2582-3930

Introduction to Aerospike and its Performance

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Abstract:

In the aeronautical world, an aerospike can refer to one of two rocket components – both of which have rich meaning for our database.

The first component, the drag-reducing aerospike, was a thin, antenna-like structure mounted on the nose cone of a rocket. This aerospike – picture an upside down martini glass stuck on the rocket's nose – increased the rocket's range at supersonic speeds by reducing drag. The aerospike allowed the projectile to go faster and further, carry a larger payload, and achieve greater stability. Sounds a lot like the Aerospike database.

The second component, the aerospike engine, is a type of rocket engine that maintains its aerodynamic efficiency across a wide range of altitudes. It uses much less fuel at low altitudes, where most missions have the greatest need for thrust. Unlike a traditional engine, this engine adjusts to changing air pressure as the rocket ascends. It never needs to be jettisoned, meaning there is only one rocket stage required. The aerospike engines being developed today are lighter weight and reusable, which makes them much more cost effective for space tech companies such as SpaceX to deploy.

I. Introduction

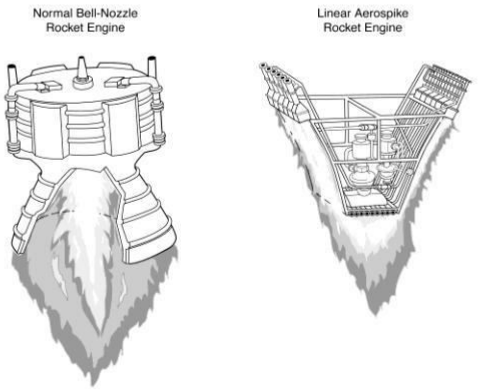
The Aerodynamic Spike (Aerospike) is a deployable drag reducing mechanism stowed within the nose fairing of the Trident I submarine launched ballistic missile. This mechanism maximizes missile performance within the limited envelope available by transforming the aerodynamic characteristics of a blunt, space efficient nose fairing into a More streamlined shape. The Aerospike mechanism is comprised of three subsystems which perform three separate and distinct functions: The mechanical inertial initiator (I2) discriminates the correct missile flight acceleration and initiates a gas generator; the gas generator provides the energy for deployment, and boom segments which once deployed and locked, establish a region of separated flow which provides the induced drag reduction. The Aerospike is required to be maintenance- and service-free over a ten year design life. Initiation and Deployment of the Aerospike occurs just after the missile is launched; after the missile leaves the atmosphere the Aerospike is jettisoned along with the nose fairing approximately 2 minutes after missile launch.

[NASA's Marshall Space Flight Center]

Principle:

A normal rocket engine uses a large "engine bell" to direct the jet of exhaust from the engine from the surrounding airflow and maximize its acceleration – and thus the thrust. However the proper design of the bell varies with external conditions: one that is designed to operate at high altitudes where the air pressure is lower needs to be much larger and more tapered than one designed for low altitudes. The losses of using the wrong design can be significant. For instance the Space Shuttle engine can generate a specific impulse of just over 4,400 N·s/kg in space, but only 3,500 N·s/kg at sea level. Tuning the bell to the average environment in which the engine will operate is an important task in any rocket design.

The aerospike attempts to avoid this problem. Instead of firing the exhaust out a small hole in the middle of a bell, it instead uses several small (small = suffer from friction) under expanded, wrong pointed bells. This leads to shock waves, whose energy can mostly be converted to thrust with the help of a cone or wedge-shaped protrusion, the "spike". The spike forms one side of a "virtual bell", with the other side being formed by the airflow past the spacecraft – thus the aero-spike.



[NASA's Marshall Space Flight Center]

The "trick" to the aerospike design is that as the spacecraft climbs to higher altitudes, the air pressure holding the exhaust against the spike decreases. This allows the exhaust to move further from the spike, and the virtual bell automatically expands in just the right way. In theory the aerospike is slightly less efficient than a bell designed for any given altitude, yet it vastly outperforms that same bell at all other altitudes. The difference can be considerable, with typical designs claiming over 90% efficiency at all altitudes.

History:

The first serious studies of spike nozzles were performed in Germany in conjunction with the development of the turbojet engine. Engines, like those used on the Messerschmitt Me 262 shown below, utilized a plug center body to vary the throat area for better performance.

[NASA's Marshall Space Flight Center]

1950s through 1970s:

NASA, the United States Air Force, and Rocketdyne together spent over $500 million on the development of aerospike engines during the 1950s, 1960s, and 1970s. The development effort, conducted by the NASA Lewis Research Center (now known as NASA Glenn) in Cleveland, OH, and by Rocketdyne's Nevada test facility, tested aerospike engines ranging in size from subscale cold-flow models to a full-scale 250,000 lb thrust engine. These tests included 73 ground tests of full-sized engines totaling over 4000 seconds of operation.

Similar work was underway in West Germany from 1965 to the early 1970s in support of a heavy lift launch vehicle called Neptune. The propulsion arrangement for this concept consisted of a "toroidal plug nozzle" that behaved much like an aerospike with primary and secondary flows.

[NASA's Marshall Space Flight Center]

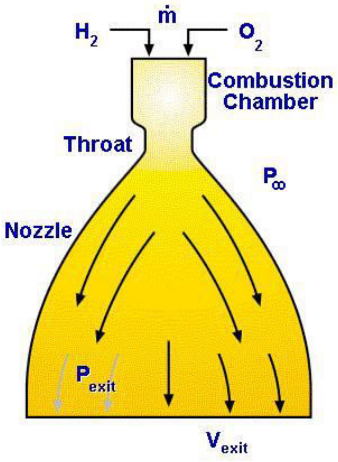
Current Development:

The early NASA and Rocketdyne research efforts have led to the development of the XRS-2200 linear aerospike engine that was to be used on the X-33 test vehicle. Four of these engines, subscale versions of those planned for the VentureStar vehicle, were built. Two were installed on the X-33 while the other two were being used in ground tests at the NASA Stennis Space Center in Mississippi. Each engine employed 20 combustion chambers, ten aligned on the end of each ramp centerbody, to produce 206,400 lb of thrust at sea level. The full-sized RS-2200 engine intended for the VentureStar was to have 14 combustion chambers (7 per side) to produce 431,000 lb of thrust. The maximum specific impulse of these engines is estimated at 455 seconds. The first two test engines began test-stand testing at NASA Stennis in September 1999. The test program called for 41 firings: 6 initial firings to develop ignition sequencing, 8 to analyze engine performance at different power levels, 11 firings of two separate flight-rated engines, and 16 firings of the two flight-rated engines together.

Linear Aerospike SR-71 Experiment (LASRE)

Aerospike Nozzle:

Simply put, the nozzle is the component of a rocket or air-breathing engine that produces thrust. This is accomplished by converting the thermal energy of the hot chamber gases into kinetic energy and directing that energy along the nozzle's axis, as illustrated below.



Simple representation of a rocket nozzle [from Rocketdyne, 1999]

Although simplified, this figure illustrates how a rocket nozzle works. The propellant is composed of a fuel, typically liquid hydrogen (H_2), and an oxidizer, typically liquid oxygen (O_2). The propellant is pumped into a combustion chamber at some rate $\dot{m}$ (mdot) where the fuel and oxidizer are mixed and burned. The exhaust gases from this process are pushed into the throat region of the nozzle. Since the throat is of less cross-sectional area than the rest of the engine, the gases are compressed to a high pressure. The nozzle itself gradually increases in cross-sectional area allowing the gases to expand. As the gases do so, they push against the walls of the nozzle creating thrust.

Mathematically, the ultimate purpose of the nozzle is to expand the gases as efficiently as possible so as to maximize the exit velocity (v_{exit}). This process will maximize the thrust (F) produced by the system since the two are directly related by the equation

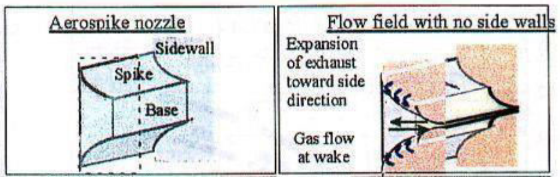
$$F = \dot{m}\, v_{exit} + (p_{exit} - p_{\infty})\, A_{exit}$$

where

F	thrust force
$\dot{m}$	mass flow rate
v_{exit}	exhaust gas velocity at the nozzle exit
p_{exit}	pressure of the exhaust gases at the nozzle exit
p_{∞}	ambient pressure of the atmosphere
A_{exit}	cross-sectional area of the nozzle exit

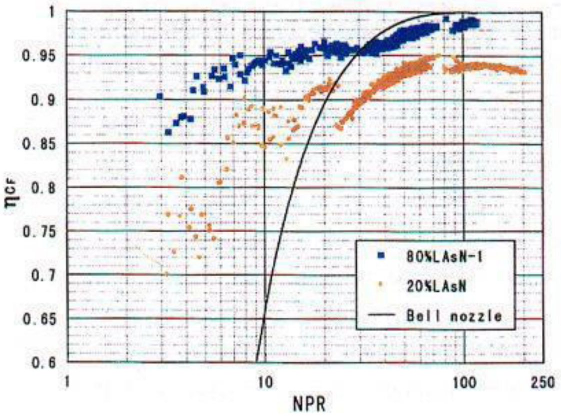
Performance & Losses:

When we first introduced altitude compensation, we compared a theoretical aerospike nozzle with a bell nozzle and an ideal nozzle. According to theory, the aerospike should meet or exceed the performance of the bell at all altitudes, thanks to its inherent altitude compensation characteristics. However, experimental data shows that these predictions are not necessarily true, for many potential sources of losses exist in the design of a practical engine, as illustrated below.



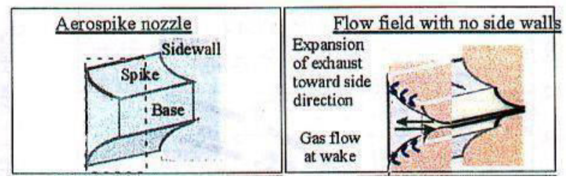
[From Tomita et al, 1999]

The most important cause of these losses is the elimination of the full-length isentropic spike previously discussed. The following graph indicates the loss in performance resulting from the replacement of a "full" (80%) spike by a truncated (20%) spike.



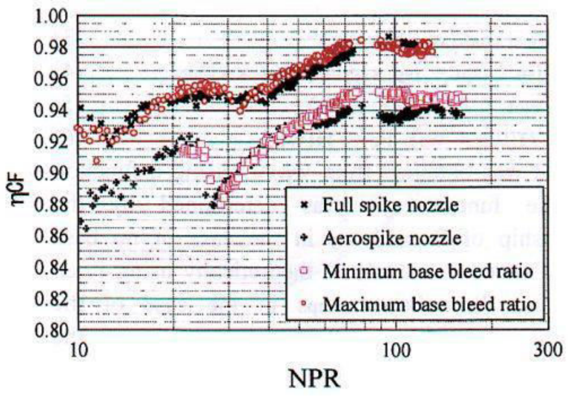
[From Tomita et al, 1998]

Even though the aerodynamic spike does behave similarly to an actual spike, performance will still be lost due to oblique shock formation and the transition from an open to a closed wake. The effect of this transition can be seen in the above figures in the sudden decrease in thrust efficiency at pressure ratios around 20-30. Another important loss results from the replacement of an annular nozzle by a linear one. In a linear engine, exhaust may flow to the side of the engine rather than along its axis, as illustrated in the following figure. Other typical sources of performance loss are usually functions of individual designs, such as the type of thrusters employed and their arrangement, but these are beyond the scope of this discussion.



[From Tomita et al, 1999]

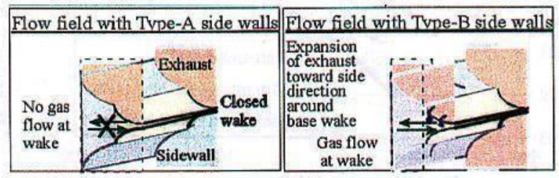
Many researchers working on the X-33 and similar projects in other countries are currently conducting a great deal of research into methods of alleviating these performance losses. The most important of these, already mentioned several times, is the introduction of a secondary flow aft of the nozzle base, or a base bleed. The pivotal question surrounding the secondary flow is how great it should be. Research has shown that too small a bleed has no impact on performance while too large a bleed can have a detrimental effect on overall performance.



[From Tomita et al, 1999]

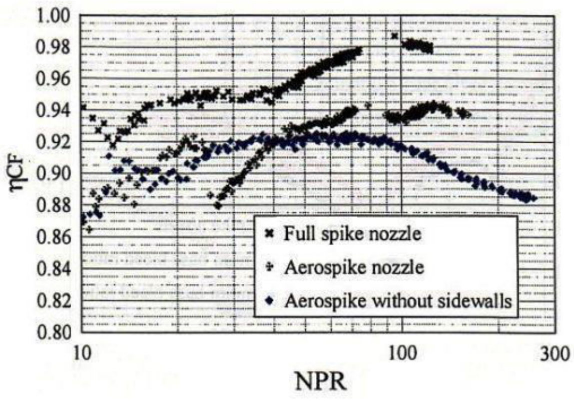
Some experimental results are provided above comparing the full spike, aerospike without base bleed, and aerospike with minimum base bleed (0.3% of the primary flow) and maximum base bleed (2.4%). Beyond a bleed of about 3%, performance begins to suffer because the base flow actually re-circulates too quickly. As indicated in the above figure, the maximum bleed results in far better performance, matching the full spike over a very large range of operating pressures.

The same study also looked at the use of endplates, or sidewalls, along the aerospike, as illustrated below. Two types of sidewalls were evaluated, one extending well into the base flow region and another extending only to the end of the center body.



[From Tomita et al, 1999]

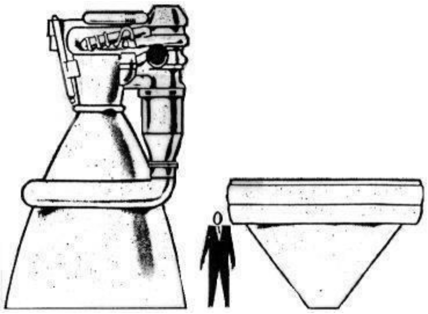
The experimental results shown below indicate that the use of these walls does increase the base pressure, and thus the thrust coefficient, but the shorter walls do not increase performance nearly as much as those extending into the secondary flow region.



[From Tomita et al, 1999]

ADVANTAGES:

1. **Nozzle:** Shortened nozzle length for the same performance, or increased performance (higher expansion area rations) for a given length.

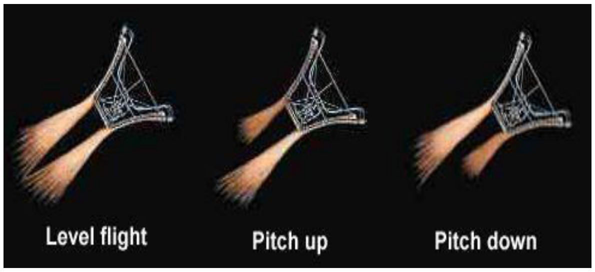


[From Berman and Crimp, 1961]

2. **Performance:** Improved performance at sea level or low altitudes. (Annular nozzles with high expansion area ratios can be used for a single-stage sea level to vacuum vehicle mission.)
3. **Space:** The relatively stagnant region in the center of the nozzle can possibly be used for installation of gas generators, turbo pumps, tanks, auxiliary equipment, and turbine gas discharges.
4. **Combustion:** A segmented combustion chamber design approach can be used, easing development effort (individual segments can be built and tested during the early phases) and improving combustion stability.

DISADVANTAGES:

1. **Cooling:** Relatively high cooling requirements, because of higher heat fluxes and greater surface areas to be cooled.
2. **Weight:** Heavier structural construction in some applications.
3. **Manufacturing:** The aerospike is more complex and difficult to manufacture than the bell nozzle. As a result, it is more costly.
4. **Flight inexperience:** No aerospike engine has ever flown in a rocket application



[From Rocketdyne, 1999] References

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