JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 40, No. 2, March–April 2003

Engineering Notes

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Hypersonic Missile Requirements and Operational Tradeoff Studies

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Introduction

HYPERSONIC velocities provide an attractive responsive option for tactical applications, including the ability to engage and destroy mobile threats rapidly. Missiles under consideration will focus on operational requirements for standoff range in excess of 700 km, cruise speed of Mach 5–8, 100–170-kg payload, and maximum weight of 1225 kg. Missile dimensions and weight have been selected to provide the maximum loadout capability of U.S. military aircraft.[1] Propulsion performance is examined throughout a typical mission corridor, including the initial boost phase, cruise, and terminal phases from air-launched platforms.

Requirements

The operational requirements and performance estimates for a hypersonic airbreathing missile are divided into the three mission phases: launch, cruise, and terminal. The launch phase considers release envelope, requirements for launch, and requirements for boost. The cruise phase considers range vs time and engine models. The terminal phase considers high dynamic pressure at sea level, target acquisition, and flying qualities for guiding to a mobile target.

The threshold range is 740 km, and the objective range (desired) range is 1300 km with a threshold/objective Mach of 5–8, selected for reasonable standoff missions with a maximum missile length of 4.22 m and 1225 kg (2700 lb). By extrapolation from the existing inventory, the hypersonic missile should be able to deliver a threshold/objective payload of 98/172 kg. The cruise profile was chosen to be at constant altitude, with a maximum dynamic pressure of 813 kPa. Guidance systems have not been considered as part of this performance study.

The assumed terminal phase requirements include maximum terminal Mach of 8, maximum dynamic pressure, guidance, and seeker capability. If hypersonic speeds are retained to the end of flight, the missile and guidance suite would have the formidable task of acquiring, targeting, and tracking mobile targets at up to $M = 8$.

Received 18 June 2001; revision received 24 October 2002; accepted for publication 24 October 2002.

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Launch and Boost Phase

The component masses were derived from current subsonic missiles and adjusted for ramjet engine and booster performance.[1] The booster weight and length required for a midaltitude, supersonic boost were included in the missile maximum dimensions. Payload weight was traded between the objective and threshold weights against an increase in fuel capability. The inert mass estimates yield mass fractions of 0.367 for both the threshold and objective requirements. Here, the mass fraction is the ratio of inert mass to total mass, where the inert mass is the total mass minus the payload and propellant.

It was assumed that the missile is released from an aircraft flying at 0.85 M and 8000-m altitude and boosted to ram/scram operation. Effective booster exhaust velocity is assumed constant, as well as the propellant mass flow rate based on the burn duration, that is, fuel grain was not optimized.[2]

The missile altitude and velocity is calculated at burnout assuming a 45-deg climb angle, which was not optimized. Extruded JPN ballistite yielded the needed booster performance for a midaltitude, supersonic boost with the specified mass fractions. With a 25-s burn time, the booster can accelerate the baseline missile to a burnout height of 19 km at Mach 3 to begin operating on an airbreathing cycle. With the mass and density of the extruded JPN ballistite and the constrained diameter of the rocket casing, the length of the booster is found to be 0.84 m. This booster length represents 20% of the missile length. The booster is considered add-on length and is not integrated into the missile ram/scramjet combustor. After midaltitude boost, the missile climbs for an additional 10 s at a 45-deg climb angle to the cruise altitude of 30 km.

Cruise Phase

A quasi-one-dimensional engine model has been used to model the cruise phase combustion flowpath assuming constant pressure combustion using Shapiro's equations[3] (also see Refs. 4 and 5). The heating profile assumes an exponential heating schedule to a set maximum total temperature with constant static pressure; this provides a reasonable match to experimental results.[6] With the temperature profile known, the specific impulse is solved using the idealized ramjet cycle[4] (also see Refs. 7–9), modified to account for supersonic velocities in the combustor when appropriate. Hydrocarbon fuel was chosen as the most practical fuel for an operational missile, though its ability to power scramjets beyond Mach 8 is questionable.

Range Performance

The range performance is calculated assuming that the solid-rocket booster accelerates the missile to a midaltitude, hypersonic velocity, and then the airbreathing engine provides a constant dynamic pressure climb to cruise conditions. The cruise range performance is solved in terms of fuel density and specific energy, with the weight ratio written in terms of the fuel weight fraction and a normalized load.[10] The familiar Breguet form of the range equation is not accurate for a hypersonic missile because of the large change in L/D during the cruise. Instead, the range is calculated with a modified range expression that matches lift to weight.[11] All computations were performed for a ratio of specific heats γ of 1.4 and zero lift drag $C_{D,0}$ of 0.01. The fuel weight fraction was written as a ratio of fuel to total mass, which includes fuel, tanks, engine, and payload. The fuel weight fraction for the objective and threshold requirements was 0.28 and 0.36, respectively.

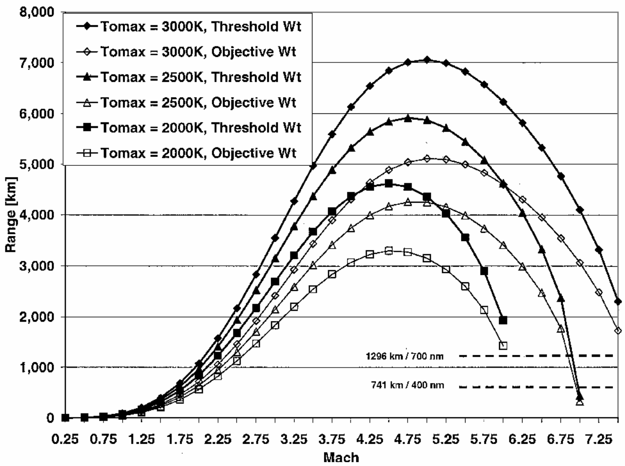

Fig. 1 Threshold vs objective weight missile range analysis.

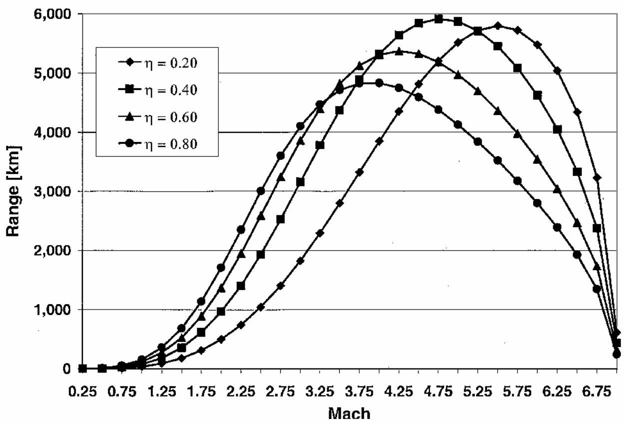

Fig. 2 Volumetric efficiency η threshold range analysis.

Figure 1 compares the range between threshold and objective requirements for different maximum combustor temperatures. With a practical combustor temperature limit, the missile is capable of achieving the objective range of 700 km with both the threshold and objective missile weights. Furthermore, the missile is capable of achieving the objective range with the maximum combustion total temperature of 2000 K, though cruise Mach number will then be limited to 6. The maximum range tradeoff between the threshold and objective weight is over 2000 km for a total temperature of 3000 K and 1300 km for a total temperature of 2000 K. The maximum Mach for the maximum combustion total temperature of 3000 K is 5.0 and Mach 4.5 for 2000 K. The warhead weight is traded for fuel between the objective and threshold versions of the missile. This tradeoff accounts for the increased range.

Figure 2 shows the range analysis at various volumetric efficiencies for a maximum combustion total temperature of 2500 K. The volumetric efficiency is directly related to the reference area and the volume of the missile by $A_{\text{ref}} = \eta V^{2/3}$. Analysis shows ranges of over 2000 km in the low- and midhypersonic regimes. The volumetric efficiencies affect the range for moderate lift coefficients and can produce a comparable increase in maximum range of over 1000 km. However, at the extremes of the range equation and lift coefficients, the lift coefficient has less of an affect on the total range in which weight and dynamic pressure are key factors. In the upper extreme of the range equation, with the Mach increasing, the objective range of 700 km can be achieved for the volumetric efficiency between 0.2 and 0.8.

The initial average density of the missile is 900 kg/m^3, and the postboost average density is 790 kg/m^3. Density will obviously decrease as fuel is consumed. The preimpact density is 500 kg/m^3 for the threshold missile and 570 kg/m^3 for the objective missile. Density is directly related to volumetric efficiency. As the volumetric efficiency increases from 0.2 to 0.4, the range does not increase, but the maximum-range Mach decreases from 5.50 to 4.75 as a result of the increased drag associated with the higher volume. There is an optimal average density for each design.

Terminal Phase

One of the greatest advantages for prosecuting time-critical targets is the response time to engage the mobile target. The time delta from increasing the speed from Mach 5 to 7 is 2.3 min for the threshold range and 4.2 min for the objective range. The greatest impact is if the speed is increased from Mach 5 to 8. The time tradeoff savings is 3.0 min for the threshold range and 5.3 min for the objective range. As the response time decreases to engage the target, the less time the target has to move.

Conclusions

It is feasible to design a hypersonic missile that is capable of being air launched and boosted into a supersonic, midaltitude regime, accelerated to a midhypersonic velocity and cruise at Mach 7, with a range of greater than 700 km, with the capability of destroying time-critical targets. A hydrocarbon-fueled ram/scram combustor would be capable of providing sufficiently high specific impulse to enable operationally realistic cruise ranges at Mach 7+. The analysis indicates that a missile with 1225-kg mass and initial length of 4.22 m is capable of being carried by a variety of aircraft and being boosted into an altitude of 14–19 km at an approximate Mach number of 3.0. This supersonic boost provides conditions for the ram/scramjet engine operation to commence.

The quasi-one-dimensional combustion model, under assumption of constant pressure conditions during combustion, predicts specific impulse values that are adequate to support the missile range requirements. The range equation was uniquely solved using fuel density and specific energy, along with a missile volume and a volumetric efficiency. Results indicate that missile ranges of over 2000 km at Mach 7 and cruise at 30 km are possible if combustor temperatures are in the area of 3000 K, beyond the practical limit of hydrocarbon fuels. However, even at 2000 K temperatures, ranges of up to 1500 km at Mach 6 are possible. Higher Mach numbers come at the cost of range; with 2500 K combustion, the Mach 6 cruise range is approximately six times greater than the Mach 7 cruise range.

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