NUMERICAL INVESTIGATION OF WAVERIDER-DERIVED HYPERSONIC TRANSPORT CONFIGURATIONS

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Abstract

A conceptual design method for generating hypersonic transport (HST) configurations using waveriders is developed. Waveriders generated from osculating cone flowfields are used as the initial platform for the vehicle, and various modifications required for the mission are implemented. The propulsion system assumes a turbojet/ramjet configuration with hydrocarbon fuel; these features are chosen to allow the integration of readily available technologies into the vehicle configurations. The effects of engine surfaces are included in the model, and the upper surface of the HST is modified based on payload and aerodynamic performance considerations. Detailed estimates of the structure weight of the configurations are combined with a method for calculating the total mission fuel requirements. Optimization is implemented into the design method to allow the generation of HST configurations based on desired characteristics; for this purpose, variables describing freestream, geometric, and engine design parameters are varied. The ability of the method to generate realistic HST configurations is investigated by the generation of 250 and 400 seat vehicles; these results indicate the viability of Mach 5 waverider-based HST configurations. Finally, an investigation into the propulsion system model is used to highlight the importance of several assumptions (e.g., combustion efficiency) used in the conceptual design method.

Nomenclature

\[ I_{sp} \] = specific impulse
\[ L \] = lift
\[ m \] = slope
\[ M \] = mach number
\[ \dot{m} \] = mass flow rate
\[ m_{fuel} \] = fuel mass
\[ m_{pay} \] = calculated payload mass
\[ m'_{pay} \] = target payload mass
\[ m_{struct} \] = structure mass
\[ m_{total} \] = total mass at take-off
\[ N \] = number of variables in optimization
\[ p \] = pressure
\[ R \] = cone radius
\[ T \] = thrust
\[ T_0 \] = stagnation temperature
\[ U \] = freestream velocity
\[ V \] = volume
\[ x \] = horizontal distance
\[ \alpha \] = shock wave angle
\[ \eta_c \] = combustion efficiency
\[ \gamma \] = ratio of specific heats
\[ \phi \] = equivalence ratio
\[ \theta \] = rational function parameter; angle

Subscripts

\[ 1-10 \] = station numbers in engine analysis
\[ st \] = stoichiometric conditions
\[ \infty \] = freestream conditions

Introduction

High-Speed Transport Mission

Civil transport aircraft have played an important role in the increasing globalization of modern-day society. Current transport vehicles provide a low-cost and relatively efficient means of moving products and passengers from one part of the globe to another, yet these systems are fixed in a cycle of essentially identical configurations that are still limited to cruise speeds below Mach 1. The most recent attempts at breaking this barrier were introduced in the 1960s (e.g., the Concorde), but high-costs and environmental difficulties have severely limited the impact of supersonic transport (SST) vehicles on the transportation market. Future research into SST design is still underway, but such aircraft must still overcome a variety of obstacles (e.g., sonic boom, cost considerations) before successful operation can ensue.

The Breguet range equation is a simple relation...
that can be used to estimate the cruise performance of a design:

\[
\ln \left( \frac{m_{\text{fuel}} + m_{\text{struct}} + m_{\text{pay}}}{m_{\text{struct}} + m_{\text{pay}}} \right) = \frac{d}{(U_{\infty})(I_{\text{sp}})(L/D)} \quad (1)
\]

A significant portion of the operating cost of a vehicle can be derived from the fuel required for the mission. Therefore, from Eq. (1) it can be observed that for a fixed cruise range, increases in the cruise velocity, the propulsion efficiency \((I_{\text{sp}})\), and the aerodynamic efficiency \((L/D)\) can exponentially decrease the mission fuel requirements.

The importance of aerodynamic performance can be seen in Fig. 1 by plotting Eq. (1) for \(L/D\) versus Mach number (assuming fixed arbitrary values for the other variables). This figure essentially indicates the \(L/D\) required for a cruise vehicle to successfully meet the specified mission characteristics (e.g., cruise range, fuel limits); the trend towards a higher required \(L/D\) at lower Mach numbers can be seen as an indication that hypersonic configurations have relaxed aerodynamic efficiency requirements when applied to a cruise mission. However, by plotting the \(L/D\) versus Mach number of several real and theoretical aircraft on the same figure, the difficulty in designing hypersonic vehicles with high aerodynamic performance is readily apparent (this trend is sometimes referred to as the “\(L/D\) barrier”). Furthermore, vehicles designed for high hypersonic speeds (e.g., Mach 8 and higher) will face difficulties in propulsion systems, aerodynamic heating, and fuel required for acceleration. Therefore, the low hypersonic regime (e.g., Mach 5) shows potential to provide a good balance of characteristics (e.g., low sonic boom effects due to smaller shock wave angles and higher altitudes, possibility of ramjet/ hydrocarbon propulsion) for application to a high-speed transport mission.

**Waveriders**

As shown in Fig. 1, the maximum \(L/D\) of a design tends to decrease as the Mach number increases. However, a class of vehicles referred to as waveriders have shown the potential to break the “\(L/D\) barrier,” and have been investigated for application to a wide range of missions including Two-Stage-To-Orbit vehicles,\(^4\) aerogravity assist maneuvers,\(^2\) and cruise/accelerator configurations.\(^5\)

A waverider is a supersonic or hypersonic configuration that exhibits the characteristic of an attached shock wave along its entire leading edge. This attached shock wave limits the leakage of the high-pressure lower surface flow into the upper-surface region, thus allowing the potential of a high \(L/D\) relative to conventional designs. Waveriders are typically created using an inverse design process in which the supersonic or hypersonic flowfield around a simple object is used as the generating flowfield for the design. The streamlines behind the shock wave are traced to create the lower surface of the waverider (such that the waverider will be able to recreate the same shock wave shape from its own leading edge); the upper surface configuration is arbitrary, and is commonly created as a surface parallel to the freestream direction. An example of a waverider designed from a wedge generating flowfield is shown in Fig. 2.

**Research Objectives**

The main objective of this research is to investigate the characteristics of waverider-derived hypersonic transport (HST) vehicles designed for Mach 5 cruise. For this purpose, a conceptual design program (“SurferHST”) applicable to HST configurations was developed. The use of waveriders as the basis for an HST is employed not only to provide increased aerodynamic efficiency, but also because of the fact that the inverse design process allows the upper surface to be designed around the mission payload requirements. A turbojet/ramjet engine configuration is considered, along with a hydrocarbon fuel system. Detailed methods for mass and volume sizing are employed, and the use of an optimization process is implemented to force the designs towards desired characteristics (e.g., payload mass, total mass).

In particular, two HST vehicles designed for different payload configurations are investigated to demonstrate the capabilities of the conceptual design method. Additionally, the influences of various parameters in the engine model is also evaluated.

**Conceptual Design Method**

**Introduction**

One of primary segments in a HST mission is the cruise portion; however, a full mission profile is considered in this research (see Fig. 3). The conceptual design method combines a wide variety of computational models, including routines for waverider creation, propulsion system design and analysis, vehicle volume and mass sizing, and aerodynamic performance estimation. Design optimization is also implemented in order to generate realistic designs based on a specified objective function. A flow chart describing the conceptual design method is shown in Fig. 4.

**Waverider Design**

In the present work, the inverse design process is used to create waveriders from a generating flowfield. In past research regarding waveriders, wedge or cone flowfields are often utilized in the design process due to the simple analytical solutions available. Wedge flowfields (solved using oblique shock wave relations) provide a two-dimensional flowfield, which
is a desirable characteristic for engine-integrated vehicles. Conical flowfields, on the other hand, are usually solved by integrating the Taylor-Maccoll equation, and tend to provide designs with better volumetric efficiency (i.e., ratio of volume to surface area) as compared with wedge-derived waveriders. The trade-off, however, is that the flowfield is three-dimensional.

The osculating cone method\(^7\) is a third technique that has seen increased use recently; it is a essentially a “strip method” in which a cone flow solution is scaled locally over strips (i.e., osculating planes) of a specified shock profile curve (SPC) to create a non-axisymmetric three-dimensional shock wave. The curvature of the shock wave determines the local cone radius and position (since the cone solution is applied in a plane normal to the shock curvature). A curvature of zero implies that the cone is infinitely large; in this case the flow conditions correspond to the region immediately after the cone shock wave – equivalent to the flow behind a two-dimensional oblique shock wave. Because only a single cone flow solution is required, the computational cost is minimal. Furthermore, control over the shape of the shock wave is possible to an extent; this is implemented by dividing the SPC into “wedge” and “cone” sections as shown in Fig. 5. This allows a two-dimensional flow region near the center of the waverider (where the engine in an HST would be located), whereas the region near the edges of the generating flowfield shock wave can be curved to allow increased volumetric efficiency. Finally, the SPC (both size/location of the cone/wedge flow regions, and the cone half angle) can be included in an optimization process to allow further expansion of the possible design space.

The shape of the waverider in a given generating flowfield is described by its lower surface base curve (LBC). The lower surface of the waverider is created by starting from the LBC and tracing the streamlines in the generating flowfield upstream until the shock wave is intersected (this indicates the leading edge of the waverider). In this research, a fourth-order Runge-Kutta algorithm is used for this purpose. The shape of the shock wave is determined by the isolator (stations 2 to 3), which is designed using a series of vertical struts; the isolator is present to contain the normal shock train used to slow the engine flow to subsonic speeds before entry into the combustor (stations 3 to 4). The struts continue a small amount into the combustor section to provide locations for fuel injection; the rest of the combustor is then designed assuming area expansion at a constant angle (thermal choking is used to allow the flow to expand back to supersonic speeds). At the combustor exit, the flow enters the nozzle region (stations 4 to 10). Although ramjets typically use physical area choking to slow the flow to subsonic speeds for combustion (versus the use of a normal shock train) and expand it back to supersonic velocity afterwards (versus thermal choking), the configuration applied in this research consists of flat surfaces and a simplified physical structure, making it easier to deal with the high temperatures and pressures involved in slowing a hypersonic flow to subsonic velocities. Furthermore, the use of a normal shock train eliminates the need for a variable geometry throat (assuming the isolator can contain the shock train), which provides a less-complex design applicable to a wide-variety of operating conditions.

**Quasi-1D Engine Model**

The isolator and combustor sections of the ramjet engine are modeled using a quasi-one-dimensional analysis similar to that described in Ref. 9 and 10. Combustion is simulated as an increase in the stagnation temperature of the flow in the combustor up to a specified maximum; this temperature release profile is described using a rational function:

\[
\frac{T_2(x)}{T_{2,0}} = 1 + \left( \frac{T_{2,0} - 1}{\frac{\partial \tau}{1 + (\theta - 1)\tau}} \right),
\]

where \(x\) is the horizontal distance from the start of the combustor, and \(\theta = 40-50\) for subsonic ramjet combustion.\(^10\) The main equation describing the quasi-one-dimensional flow through the combustor includes area variation, friction, and mass injection, and can be written as:
For a vehicle operating at hypersonic flow conditions, a highly integrated propulsion system is required for efficient operation. Waverider configurations are characterized by a high-pressure lower surface; this can be used as the first component in the integration of the engine system into a HST design. In the present work, an arbitrary number of two-dimensional inlet ramps are used to provide additional interior compression to the engine. Assuming these ramps exhibit some variable geometry, they can be used to allow efficient operation at lower Mach numbers, and also as a means to control flow access to the turbojet engine modules. The current design method assumes that the inlet ramp shocks coalesce at the cowl lip, which is then reflected to terminate at the shock cancellation point as described in Fig. 6.

In the current design method, the engine width is specified to be constant; the isolator, combustor, and nozzle lengths are also specified constants (the cowl angle is a parameter in the engine design). The isolator/combustor sections are divided into an arbitrary number of engine modules, which allows the engine length to be kept at reasonable levels. In the present work, the nozzle is modeled as a straight planar ramp; this has the potential to provide advantages regarding structural construction and cooling system configuration (based on the simple geometry), but does not necessarily represent an optimal design. The angle of the ramp, however, is used to provide some control over the performance of the nozzle. Finally, it should be noted that for simplicity, the cowl bottom and side surfaces are modeled with zero thickness – in reality, finite thickness will likely cause shock/expansion interactions with the lower surface flowfield of the waverider, which is currently not considered.

The current engine model makes the assumption of a calorically-perfect gas – in other words, the ratio of constant heats is specified as a constant throughout the engine calculations. For highly energetic flows, this assumption can lead to a significant overestimation in the propulsion forces. Therefore, as described in Ref. 10, a compromise between model complexity and accuracy is implemented by assuming different constant ratios of specific heats for the major engine sections. Freestream conditions were assumed to be at $\gamma = 1.4$; the inlet ramp, isolator, and combustor were assumed to be at $\gamma = 1.36$, and the nozzle flow was assumed to be at $\gamma = 1.24$ due to the larger number of molecular degrees of freedom present in the exhaust flow.

**Fuel Considerations**

One of the important decisions for a first-generation HST will be the type of fuel used for the mission. Hydrogen (H$_2$) offers the advantages of
high mass-specific energy content and minimal environmental impact. However, the low density and difficult storage/handling requirements of a cryogenic fuel create challenges regarding packaging and implementation into a HST vehicle. A variety of hydrocarbon fuels, on the other hand, can provide a much higher volume-specific energy content, and eliminate the need for compressed or highly-insulated storage systems. For a first-generation HST, the storage and infrastructure advantages of hydrocarbon fuels may have a significant impact on the economic viability of such a vehicle; therefore the present work focuses on hydrocarbon-fueled designs (H₂ may warrant further consideration for use in a second- or later-generation HST vehicle).

For operation at low hypersonic speeds, the hydrocarbon fuel Methylcyclohexane (MCH) shows promise; its properties include: \( \Delta h_k = 43700 \text{ kJ/kg}, f_v = 0.068 \), and a STP density of 770 kg/m³. Unlike cryogenic fuels such as H₂ or methane, MCH can be stored at standard temperatures and pressures, which allows the possibility of fuel storage in smaller arbitrary volumes (e.g., sections in the wing). Additionally, MCH is an endothermic fuel, providing a relatively large cooling capability through the use of catalytic dehydrogenation;¹⁴ this can be important considering the high temperatures experienced by the engine and nozzle surfaces.

In SurferHST, the fuel volume is calculated assuming storage at STP conditions in the wing regions of the HST. The total tank volume is calculated by multiplying the fuel volume by a specified factor (e.g., tank volume equal to 1.4 times the fuel volume); this is used to provide a means to allow for tank insulation, structural supports, and arbitrary tank divisions into the design method. Additionally, the tank volume is required to fit within a specified fraction (e.g., 0.6) of the total wing volume, which takes into account that not all of the wing is available for fuel storage based on structural supports, control systems, and other components.

**Payload Configuration and Upper Surface Modification**

The main factor determining the size of the HST payload is the number of passengers. Using the conceptual design approach described in Ref. 15, the payload is divided into rectangular passenger and cargo compartments. The seating layout of the passenger compartment is used to determine its size – for example, a seating arrangement 15-seats wide (12 actual seats, with three seat-width aisles) is shown in Fig. 8. The height and width of the passenger compartment are design parameters, and the specification of the seating width/pitch allows the volume of the passenger compartment to be calculated. Using empirical relations, the size and number of lavatories, and the lavatory/galley volume is calculated. The cargo compartment volume (located behind the passenger compartment) is also determined assuming a specified volume per passenger. The current design method assumes a single-class economy style seating arrangement (for simplicity); this method can be easily modified to allow more detailed multi-class passenger configurations.

In order for the payload to be integrated into the HST design, the upper surface of the waverider is modified based on the size of the payload – this has no effect on the lower surface flow region and leading edge shape, and is therefore a major advantage in using waveriders and the inverse design process in the generation of HST configurations. The payload volume is offset horizontally a specified distance from the nose of the HST, and is located such that a minimum vertical offset of the bottom of the payload from the HST lower surface and engine region (defined as a straight surface from the start of the inlet ramps to the end of the nozzle) is maintained.

The upper surface is expanded such that a minimum vertical offset is maintained between the HST upper surface and the top of the payload. Cubic splines are used to provide a smooth blend between the nose and the start of the payload, and between the end of the payload and the end of the nozzle of the HST.

The wing region of the HST is likewise expanded in a similar manner. Non-dimensional horizontal offsets from the leading edge and trailing edge of the wing are used to specify control points for the wing surface expansion; at each location the wing height is set to be equal to a specified wing thickness (e.g., 2 m) or to the height of the leading edge for that section, whichever is less. The region from the leading edge to the first control point and from the second control point to the trailing edge is created using cubic splines; the region between the two control points is formed using a straight line. In this manner, the upper surface of the wing region expands the flow from freestream conditions, offering an increase in the aerodynamic efficiency of the HST.

The trailing edge thickness of the HST is also a design parameter than can be specified. The vertical spacing between the nozzle and upper surface for the body region, and between the lower surface and upper surface for the wing region, are set independently to a finite thickness (e.g., 1 m and 0.2 m, respectively).

**Vehicle Sizing**

The total mass at take-off of a transport aircraft can be divided into three major categories: fuel mass, structure mass, and payload mass. The take-off weight of a vehicle is frequently used as an indication of the total life cycle cost of the aircraft;¹⁶ thus an accurate estimation of the three values can be a large factor in determining the overall economic viability.
of a design.

For a cruise vehicle, it is typically desired to match the lift and weight at cruise conditions. Therefore, in SurferHST the lift of the vehicle at cruise conditions is used to calculate the vehicle mass at the start of cruise (centrifugal force, which can reduce by 5% or more the effective weight of a high-speed vehicle, is included). Next, using the empirical and historical relations described in Ref. 15, the fuel required for engine start, taxi, take-off, climb and acceleration, loiter, descent and landing, and taxi-back can be estimated. The fuel required for cruise is calculated by multiplying the fuel mass flow rate by the engine size and time required for the cruise segment of the mission. The fuel flow rate is calculated from the fuel/air ratio, which is obtained assuming an idealized combustion process:

\[
f = \frac{(T_{\text{in}}/T_{\text{ch}}) - 1}{(\eta - \Delta h_{\text{i}}/c_{\text{T_{\text{ch}}}})} \quad (5)
\]

For the results presented in this report, the combustion efficiency was set equal to 1. Typically, limits on the maximum stagnation temperature \((T_{\text{in}})\) in the engine require that lean operation occur; i.e., the equivalence ratio \((\phi = f/f_{\text{stoich}})\) is usually less than 1 at cruise conditions. By utilizing these methods, the total fuel required from mission start to finish can be estimated.

The structure weight is calculated in SurferHST using the HASA method. The HST is divided into wing/body sections, such that the center part of the vehicle up to the engine width is considered the body, whereas the remainder is specified as the wing region. The individual weights of various structural components (e.g., thermal protection system, landing gear, thrust structure, engines, fuel tanks, subsystems) are then calculated. This model uses empirical and historical methods, and was shown to accurately predict the structure weight to within 10% when applied to several past HST designs.

Finally, the payload mass is determined from the take-off mass, fuel mass, and structure mass:

\[
m_{\text{pay}} = m_{\text{total}} - (m_{\text{fuel}} + m_{\text{struct}}) \quad (6)
\]

**Aerodynamic Performance Estimation**

The aerodynamic performance of an idealized waverider can be estimated by applying the generating flowfield properties to the lower surface, and the freestream conditions to the upper surface (base drag is ignored by assuming the base to be at freestream pressure). The inviscid performance is calculated by integrating the pressure distribution over the waverider surfaces, and the viscous effects are estimated by applying the reference temperature method. Although a variety of reference temperature models exist, White’s method for turbulent flow has shown relatively good accuracy when compared with experimental results for flat plate flow with a turbulent boundary layer.

For an HST created using the conceptual design process described above, the idealized waverider shape is modified substantially by the inclusion of a propulsion system (e.g., inlet ramps, cowl, nozzle), and by the modification of the upper surface of the waverider (based on payload and fuel volume considerations). The nozzle flow is calculated from the combustor exit conditions using expansion wave theory based on the nozzle angle. The engine inlet ramps, cowl surfaces, and the HST upper surface properties are obtained using either oblique-shock relations or expansion wave theory depending on the local normal for each surface element. Friction estimations are again included using the reference temperature method.

**Design Optimization and Constraints**

Using the above conceptual design method, the initial design and analysis of a waverider-derived HST can be performed. However, this technique does not guarantee that the thrust is equal to drag at cruise conditions, or that the calculated payload mass will meet mission requirements. Additionally, a low take-off mass is desired in order to minimize the total costs associated with the construction and operation of an actual HST vehicle. For these reasons, an optimization process is implemented in which the objective function:

\[
F_{\text{obj}} = \left(\frac{T}{D}\right)^{a} \left(\frac{m_{\text{pay}}}{m'_{\text{pay}}}\right)^{b} \\left(\frac{1}{m_{\text{total}}}\right)
\]

if \( T < D, \quad a = 1 \quad \text{if} \quad m_{\text{pay}} < m'_{\text{pay}}, \quad b = 1 \)

if \( T > D, \quad a = -1 \quad \text{if} \quad m_{\text{pay}} > m'_{\text{pay}}, \quad b = -1 \)

is minimized. The first factor is used to match thrust to drag at cruise conditions, the second term is used to match the calculated payload with the specified target for the mission, and the third term represents a method for reducing the total weight of the optimized HST.

The optimization algorithm used is the Nelder-Mead downhill simplex method. In this technique, 1) \( N+1 \) configurations are initially generated, 2) a new configuration is generated based on the best \( N \) configurations, and 3) the new configuration replaces the worst. Steps 2 and 3 are repeated until the difference between the best and worst designs reaches a specified tolerance. In the current version of SurferHST, \( N = 21 \) parameters are set variable during the optimization process; these parameters are summarized in Table 1 (the use of side constraints is also indicated for each variable).
**HST Configuration Examples**

**Mission Payload Results**

In order to evaluate the ability of SurferHST to generate realistic conceptual HST designs, two configurations were created. For both designs, the payload configuration consisted of an economy-class passenger compartment layout as shown in Fig. 8. The HST-250-C100 configuration (where “C100” refers to a combustion efficiency equal to 100%) was optimized for a 250 passenger mission (target payload mass of 30,000 kg), whereas the HST-400-C100 configuration was optimized for a 400 passenger mission (target payload mass of 50,000 kg). The initial conditions used to start the optimization process for both designs included: $M_e = 5$, altitude = 30 km, and $T_{i0} = 2300$ K. The mission parameters included cruise range $d = 11,000$ km, and a 30 min. loiter at subsonic speeds. For both designs, the engine width was fixed at 10 m, the payload width set to 9 m, and the number of engine modules (6) and isolator, combustor, and nozzle lengths (8 m, 6 m, and 10 m, respectively) were also specified.

Plan view and three-dimensional views are shown in Fig. 9 and 10, respectively, for the 250 and 400 seat configurations. A comparison of many important design characteristics is summarized in Table 2. Key parameters such as the shock wave angle $\beta$ and vehicle length show relatively large differences; these are the results of the mission requirements specified for each design optimization. In particular, it can also be seen that the payload length is a dominant factor in the design results. Optimization constraints are implemented such that the end of the payload is required to be located ahead of the start of the nozzle – looking at the two configurations, it is apparent that, unlike the HST-250-C100 configuration, the vehicle length of the HST-400-C100 design is near the minimum required to fit the payload. Therefore, the longer length of the payload can be seen to be restricting the possible design space available to the optimization process. From these results, it can be inferred that a wider (and shorter) passenger configuration might yield more optimal results for large-payload missions.

The structure mass of both configurations was calculated using HASA. A breakdown of the individual structure component masses is shown in Fig. 11. From these results, it can be seen that for both configurations the wing structure and turbojet engines (used for low-speed operation) are the heaviest components present. The model also resulted in landing gear systems with large mass; this indicates that further investigation into the design of such components is required for future refinement of the HST configurations presented.

**Aerodynamic Performance**

The “no engine” waverider configurations (with no engine surfaces, but including the modified upper surface) used for the HST-250-C100 and HST-400-C100 configurations are shown in Fig. 12. Slight differences in the generating flowfield shape are visible. From Table 2, it can be seen that an $L/D$ of 5.05 and 6.25 are realized for each waverider. Compared to a potential $L/D$ of 9 or more for a Mach 5 waverider (according to Fig. 1), this demonstrates that the aerodynamic performance of a design is not necessarily the most important factor in regards to the generation of a design that meets the mission requirements (e.g., assuming lift equal to weight at cruise conditions, a high lift vehicle will be heavier and therefore less optimal from a cost standpoint).

The powered aerodynamic performance of each configuration is also shown in Table 2. In this case, the effects of the engine and nozzle surfaces are included, which results in a substantially higher $L/D$ (versus the “no engine” performance). A breakdown of the lift and drag coefficients are shown in Fig. 13 and 14 for the two designs; it can be seen that the HST lower surface and nozzle are the dominant factors in producing lift for each design (over 95% of the net lift for each configuration is generated by these surfaces). Likewise, the nozzle surface for each design also generates a large thrust force, more than offsetting the drag resulting from integration of the engine system into each design. In fact, it can be observed that for both configurations, the thrust produced by the nozzle is larger than the momentum thrust of the engine (the “engine” term in Fig. 13 and 14).

**Influence of Propulsion System Assumptions**

An important factor influencing the final optimized designs was the use of Eq. (5) to calculate the fuel/air ratio of the engine. This equation assumes ideal combustion of the reactants; in reality this will not be the case due to inefficiencies in fuel injection, mixing, and combustion. Therefore, the HST-250-C80 configuration was generated using the same initial design parameters as HST-250-C100; the only difference is that the combustion efficiency $\eta$ was set to 0.8 (corresponding to 80% combustion efficiency). As can be seen by Fig. 15, the two designs appear quite different in shape. The mass breakdown (see Table 3) indicates the substantial increase in fuel required to complete the mission. This forced the final HST-250-C80 design to a take-off mass of 502,278 kg, which is more than 60% heavier than the HST-250-C100 configuration. This increased mass would translate into significantly higher production and operation costs; therefore it can be observed that efficient combustion is a requirement for realistic hypersonic cruise vehicles.
Conclusions and Future Work

In this research, the viability of a Mach 5 HST vehicle was investigated by the development of a conceptual design program including detailed models for engine analysis, aerodynamic performance estimation, mass and volume sizing, and payload configuration. Taking the generated examples as first-order conceptual results, it can be inferred that a waverider-derived HST optimized for cruise in the low hypersonic regime shows potential for future development.

The importance of the combustion efficiency of a hypersonic vehicle was also demonstrated; small reductions in the efficiency can reduce the design space to a point where economically viable configurations are not possible. As was shown by these results, further refinement of the engine model might yield an increased accuracy of the conceptual design method.

Further investigation into the development of several other models might also warrant consideration. For example, the empirical/historical relations used to estimate the fuel required for the non-cruise portions of the mission could be replaced with a more detailed trajectory-analysis model. Use of computational fluid dynamics for the estimation of the aerodynamic performance would increase the resolution of the final results. The addition of control/stability considerations (e.g., vertical horizontal stabilizers, static stability) might also provide further insight into the viability of final designs. Finally, future versions of SurferHST will include a more detailed nozzle design/analysis routine (e.g., method of characteristics design and analysis), and incorporation of the effects of leading edge bluntness and aerodynamic heating are also planned.

References

### Table 1  Optimization parameters and constraints

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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mission Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>payload x offset</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>wing x1 LE offset</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>wing x2 LE offset</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>wing thickness</td>
<td>Yes</td>
<td>Yes</td>
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</table>

### Table 2  HST configuration results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HST-250-C100</th>
<th>HST-400-C100</th>
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</thead>
<tbody>
<tr>
<td>$\beta$, deg</td>
<td>14.8</td>
<td>15.7</td>
</tr>
<tr>
<td>$M_\infty$</td>
<td>4.98</td>
<td>5.01</td>
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<tr>
<td>altitude, km</td>
<td>31070</td>
<td>31480</td>
</tr>
<tr>
<td>length, m</td>
<td>64.8</td>
<td>74.5</td>
</tr>
<tr>
<td>$A_{\text{engine}}, m^2$</td>
<td>17.2</td>
<td>34.2</td>
</tr>
<tr>
<td>$\theta_{\text{nozzle}}, \text{deg}$</td>
<td>18.0</td>
<td>18.1</td>
</tr>
<tr>
<td>$\theta_{\text{cowl}}, \text{deg}$</td>
<td>3.4</td>
<td>3.6</td>
</tr>
<tr>
<td>$\phi$, $\text{deg}$</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>$T_0$, K</td>
<td>2252</td>
<td>2316</td>
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<tr>
<td>$L/D$ (No Engine)</td>
<td>5.05</td>
<td>6.25</td>
</tr>
<tr>
<td>$C_L$ (No Engine)</td>
<td>0.047</td>
<td>0.073</td>
</tr>
<tr>
<td>$C_D$ (No Engine)</td>
<td>0.009</td>
<td>0.012</td>
</tr>
<tr>
<td>$L/D$ (Powered)$^a$</td>
<td>30.70</td>
<td>27.72</td>
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<tr>
<td>$C_L$ (Powered)$^a$</td>
<td>0.058</td>
<td>0.075</td>
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<tr>
<td>$C_D$ (Powered)$^a$</td>
<td>0.002</td>
<td>0.003</td>
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<td>$I_\text{sp}$, s</td>
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<td>130496</td>
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<td>$T_0$, K</td>
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<td>566</td>
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<tr>
<td>$\phi$</td>
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<td>0.37</td>
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<td>$m_{\text{total}}$, kg</td>
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<td>$m_{\text{payload}}$, kg</td>
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<td>50000</td>
</tr>
<tr>
<td>$m_{\text{structure}}$, kg</td>
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</tr>
<tr>
<td>$m_{\text{fuel}}$, kg</td>
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<td>344468</td>
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<tr>
<td>fuel volume, m$^3$</td>
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<td>445</td>
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<tr>
<td>$V_{\text{cool}}/V_{\text{eng}}$</td>
<td>0.25</td>
<td>0.31</td>
</tr>
<tr>
<td>$V_{\text{cool}}/V_{\text{body}}$</td>
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<td>0.36</td>
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<tr>
<td>passengers</td>
<td>250</td>
<td>400</td>
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<tr>
<td>lavatories</td>
<td>6</td>
<td>10</td>
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<td>passenger volume, m$^3$</td>
<td>256</td>
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<tr>
<td>cargo volume, m$^3$</td>
<td>110</td>
<td>176</td>
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<tr>
<td>lavatory/galley volume, m$^3$</td>
<td>22</td>
<td>35</td>
</tr>
</tbody>
</table>

$^a$ Includes ramp, cowl, and nozzle forces

### Table 3  Combustion efficiency results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HST-250-C100</th>
<th>HST-250-C80</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\text{cool}}$, kg</td>
<td>304879</td>
<td>502278</td>
</tr>
<tr>
<td>$m_{\text{payload}}$, kg</td>
<td>30000</td>
<td>30000</td>
</tr>
<tr>
<td>$m_{\text{structure}}$, kg</td>
<td>99798</td>
<td>138258</td>
</tr>
<tr>
<td>$m_{\text{fuel}}$, kg</td>
<td>175081</td>
<td>334019</td>
</tr>
<tr>
<td>$I_\text{sp}$, s</td>
<td>591</td>
<td>468</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.35</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Fig. 1 L/D trends versus Mach number.

Fig. 2 Waverider construction from wedge flowfield.

Fig. 3 Hypersonic transport mission trajectory.

Fig. 4 Flowchart of conceptual design method.

Fig. 5 Waverider shape design parameters.

Fig. 6 Engine stations and strut layout.

Fig. 7 Example of quasi-one-dimensional engine flow simulation.

Fig. 8 Passenger compartment layout.
Fig. 9  HST-250-C100 configuration.

Fig. 10  HST-400-C100 configuration.

Fig. 11  Breakdown of structure component masses.

Fig. 12  Generating flowfields for a) HST-250-C100 and b) HST-400-C100 configurations.

Fig. 13  Breakdown of normal forces acting on HST configurations.

Fig. 14  Breakdown of axial forces acting on HST configurations.

Fig. 15  Comparison of 250-passenger HST configurations optimized with combustion efficiency set to a) 100% and b) 80%.