

CONCEPTUAL DESIGN OF AN AERODYNAMIC BRAKE FOR HYPERSONIC RECOVERY

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Supersonic combustable ramjet (scramjet) engines have become a prominent field of research in the area of hypersonic technology. Capable of reaching speeds in excess of Mach 10 without the necessity of any moving parts, scramjets may prove to be a viable solution to the problem of dependable hypersonic transport. However, further research into a scramjet's operation is required and therefore provides an impetus for further flight tests. The Hy-V Scramjet Experiment has been established in order to verify scramjet research done at the University of Virginia and elsewhere. Furthermore, a first-ever scramjet recovery is being investigated by the Hy-V researchers at the University. A conceptual design of an aerodynamic brake that may provide a reliable means of recovery at hypersonic flight conditions has been completed. The brake area required to slow the scramjet payload from Mach 5 to Mach 1 was shown to be conducive to a manageable and symmetric 4-brake system. Several brake designs were analyzed using Finite Element Analysis software, and a candidate brake design was decided upon based on its analysis and design feasibility. A solid model was developed illustrating the placement and operation of the aerodynamic brakes and the opening load-reducing dampers.

Nomenclature

a	=	Acceleration
D_{avg}	=	Averaged Drag
g	=	Acceleration Due to Gravity
m	=	Mass of Payload
M	=	Mach Number
ρ_{inf}	=	Free Stream Density
q_{inf}	=	Free Stream Dynamic Pressure
s	=	Height Above Surface of Earth
S	=	Cross Sectional Area
T_a	=	Ambient Temperature
T_m	=	Melting Temperature
T_s	=	Skin Temperature
V	=	Velocity

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I. INTRODUCTION

Supersonic combustion ramjets (scramjets) have become a prominent area of hypersonics research in current times. Capable of sustaining hypersonic ($M > 5$) speeds without the necessity of moving parts, scramjets hold the promise of solving the on-going problem of dependable, long-range hypersonic transport. With respect to space, scramjet engines may provide an alternative and reusable means of reaching space, as a potential replacement of the aging Space Shuttle. Scramjet engines may provide the military with the means to transport soldiers and weapons around the globe within a matter of hours. Further, they may one day enable the commercialization of hypersonic civilian transportation.

Difficulties in modeling supersonic combustion have become a central problem for scramjet development. The necessary tools and models are yet to be refined to the point of adequacy. Though wind tunnel testing has provided much information into the understanding of these processes, verification of these results has been insufficient. The Hy-V Scramjet Experiment aims to provide flight data for a Mach 5 scramjet flight with which data collected from the University of Virginia's hypersonic wind tunnel can be compared, ultimately providing researchers with data to develop better scramjet simulations and modeling tools.

Recently, it was decided that a recovery option be researched in order to attempt a first-ever recovery of a hypersonic scramjet experiment. By successfully recovering the scramjet payload, the researchers would be able to do a post-flight inspection of the engines and payload structure and the onboard equipment would be available in the case of a telemetry failure during flight. The inspection may provide further insight into the impact that the natural environment has upon the scramjet engines and the supporting structure. It is the goal of this research to establish the necessary design requirements for a hypersonic recovery of this payload and to establish a conceptual design for an aerodynamic brake capable of hypersonic deployment.

The following presents a brief overview of the experiment, requirements of a proposed hypersonic recovery option, and a conceptual design for an aerodynamic brake capable of decelerating the Hy-V scramjet payload from a speed of Mach 5 to a speed of Mach 1 by an altitude of 6 km.

II. MISSION OVERVIEW

The goal of this experiment is to provide flight data relating to the operation of a Dual-Mode Scramjet (DMSJ). A DMSJ scramjet has the ability

to transition from subsonic combustion to supersonic combustion, effectively converting operation from a ramjet to a scramjet. This is an area of scramjet research that requires further flight testing in order to verify simulations being produced. Furthermore, it is a very important area of scramjet research because a reliable DMSJ would allow a scramjet to operate without first having to be propelled to hypersonic speeds, thus allowing takeoffs and landings much like regular fixed-wing aircraft.

The Hy-V Scramjet Experiment is planned to take place in 2009. Utilizing a Terrier-Improved Orion sounding rocket, a scramjet engine payload will be launched from NASA Wallops Island. The experiment will take place after apogee, at an altitude of approximately 27 km. For approximately 30 seconds, dual scramjet engines will burn as the rocket glides at about Mach 5. Pressure and temperature measurements will be taken and radioed to the ground station. One scramjet engine will represent the geometry found in the University of Virginia's hypersonic wind tunnel and the other will represent the geometry found in Virginia Tech's plasma torch wind tunnel.

The experiment's title, "Hy-V" [pronounced "high-five"] is representative of various aspects of the project. The "Hy" represents the hypersonic flow regime at which the scramjet will operate ($M > 5$). The Roman numeral "V" represents the five member universities of the Virginia Space Grant Consortium, and it stands for the Commonwealth of Virginia, where the experiment originated and will take place

III. RECOVERY OPTION REQUIREMENTS

Regardless of what recovery option is chosen, there exists a set of certain requirements that must be met by any design. This research investigated several design requirements for an aerodynamic brake, the results of which are displayed in the following sections.

DECCELERATION

The most fundamental requirement of any recovery option is that it decelerates the payload at a rate adequate for safe recovery. This rate of deceleration is primarily dependent upon payload weight and altitude-velocity constraints. For this mission, the payload's estimated weight is approximately 136 kg. Furthermore, in order to utilize NASA Wallops' standard subsonic parachute, the payload must be traveling subsonically at an altitude of about 6 km. If we assume that the recovery phase will begin at approximately 20 km, we can easily find an estimate for the deceleration required to meet these constraints for a vertical descent.

To begin the calculation of the necessary deceleration, the following fundamental kinematic relation is referenced

$$a \cdot ds = v \cdot dv \quad (1)$$

By integrating from an initial location and velocity, denoted as s_1 and v_1 , to a later location and velocity, s_2 and v_2 , this relation takes the following usable form

$$\int_{s_1}^{s_2} a \, ds = \int_{v_1}^{v_2} v \, dv \quad (2)$$

$$a(s_2 - s_1) = \frac{1}{2}(v_2^2 - v_1^2) \quad (3)$$

By rearranging, the following expression for acceleration, a , is determined as a function of velocity and location (above earth)

$$a = \frac{1}{2} \frac{v_2^2 - v_1^2}{s_2 - s_1} \quad (4)$$

By substituting the known information, the required deceleration is easily determined. It is found that the recovery design must provide a deceleration of approximately 77 m/s in order to slow the payload to a subsonic velocity by an altitude conducive to use of NASA Wallops standard parachute.

DRAG

An estimate for the average drag required to slow the payload can be easily found by noting that for a vertical descent, the only forces acting are in the vertical direction. The forces acting include the average drag force, the payload weight, and the force induced by the net deceleration. Summing forces, a relation for the average drag can be found as given by

$$\Sigma F = m \cdot a \quad (5)$$

$$\Sigma F_y = m \cdot a_{\text{req}} = D_{\text{avg}} - m \cdot g \quad (6)$$

Rearranging, the following expression for the average required drag is found

$$D_{\text{avg}} = m(a_{\text{req}} + g) \quad (7)$$

By substituting the mass of the payload, the acceleration due to gravity, and the required deceleration calculated from the previous section, the average drag becomes approximately 11.8 kN.

REQUIRED AREA

It is known that the drag created by any airfoil in a fluid flow is proportional to the area of the airfoil. This relation holds for the aerodynamic brake once it has been deployed. Therefore, the area required to induce a drag equivalent to the average required drag, as calculated in the previous section, can be estimated relatively easily using standard fluid mechanics.

The drag induced by any aerodynamic brake is given by the following

$$D = q_{\text{inf}} \cdot S \cdot C_d \quad (8)$$

where S is brake area, C_d is the coefficient of drag, and the dynamic pressure, q_{inf} , is

$$q_{\text{inf}} = \frac{1}{2} \rho_{\text{inf}} V_{\text{inf}}^2 \quad (9)$$

For the purposes of this research, the aerodynamic brake can be modeled as a flat surface with a uniform profile subjected to a hypersonic flow. Thus, Newtonian Flow Theory may be used to approximate the coefficient of drag for the brake, as governed by the following relation

$$C_d = 2 \cdot \sin^3 \alpha \quad (10)$$

It is clear that the coefficient of drag reaches a maximum as the angle, α , becomes 90° . Therefore, the C_d to be used for the brake is 2. Furthermore, by analyzing the predicted trajectories of the payload as depicted in section II, the coefficient of drag for the payload was estimated to be 1.28.

Since both the velocity and atmospheric density vary as a function of altitude, there exists no simple expression for the drag on the brake and payload. However, it is assumed that the dynamic pressure may be averaged over the range of brake operation to yield an appropriate estimate. Using this method, the average dynamic pressure becomes 66.31 kPa. Furthermore, the drag expressed as a function of brake area can be written as the following

$$D_{\text{avg}} = q_{\text{avg}}(S_p \cdot C_{d,p} + S_{\text{brake}} \cdot C_{d,\text{brake}}) \quad (11)$$

where S_p and $C_{d,p}$ refer to the area and drag coefficient of the payload bay, respectively. Solving for S_{brake} yields

$$S_{\text{brake}} = \frac{1}{C_{d,\text{brake}}} \left(\frac{D_{\text{avg}}}{q_{\text{avg}}} - S_p \cdot C_{d,p} \right) \quad (12)$$

By substituting in the known information, the brake area required to slow the payload from a speed of Mach 5 at an altitude of 20 km to a speed of Mach 1 at an altitude of 6 km becomes 0.05276 m^2 .

TEMPERATURE

The drag experienced by the recovery system while traveling at hypersonic speeds will induce temperatures much more extreme than ambient ones. The order of the temperatures experienced by the brake can be approximated by calculating the peak skin temperature of the recovery module. According to Ashby and others, the maximum skin temperature can be approximated according to

$$T_s = T_a(1 + 0.2M^2) \quad (13)$$

Using a Mach number of 5 and ambient temperature of 216.65 K (at 20 km), the temperature experienced by the brake will be on the order of 1300 K. Therefore, the brake's maximum service temperature may not be less than this value.

In addition to service temperature, the effects of creep and oxidation must be taken into account. It is common to approximate the temperature at which creep becomes a problem as $0.5T_m$. Therefore, it would be most beneficial to use a material whose melting temperature was at least 2600 K. Additionally, the material must have superb oxidation resistance due to the extremely high temperatures and oxygen-rich environment the brake will experience.

IV. CONCEPTUAL DESIGN

Using the basic design requirements, as determined in the previous section, a conceptual design for an aerodynamic brake was developed. This design is shown below in Figure I.

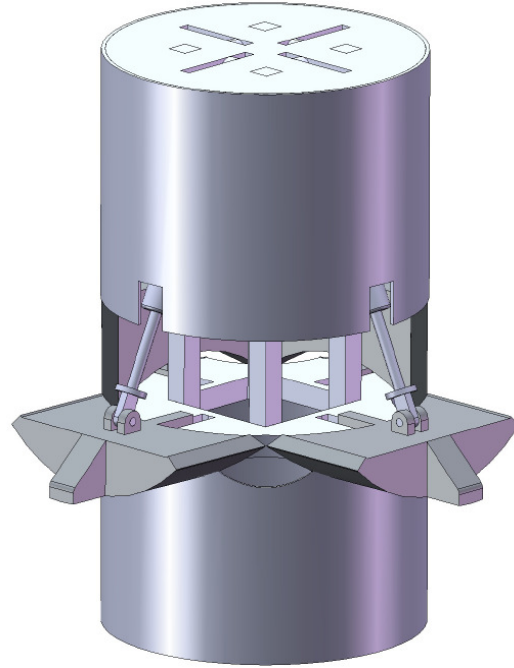


Figure I. *Solid Model of Conceptual Design*

The design is illustrated here in order to give the reader a basis for understanding the design rationale and information presented in the following section.

BRAKE DESIGN AND LAYOUT

The most feasible way to distribute the drag forces and to maintain stability was to create an aerodynamic decelerator consisting of four brakes, symmetric about the center of the body. By distributing the required area, as calculated in the previous section, it is found that each brake therefore must be at least 0.01319 m^2 . In order to meet the required area constraint while minimizing the distance of the outside brake edge from the body, the width of each brake was determined to be the length of a side of the largest square to fit inside the body of the payload (diameter of 0.279 m). Thus, the brakes must be approximately 19.7 cm long and 6.7 cm wide, as illustrated in the following diagram

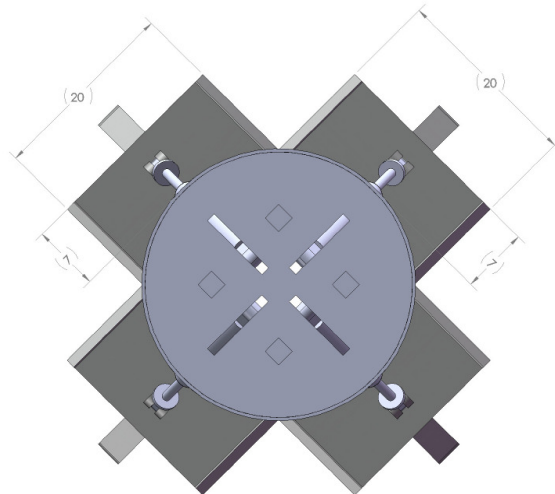


Figure II. *Brake Layout*

In designing the brakes, it was determined that shaping the exterior such that the underside of the brake is curved with the same radius as that of the payload body would allow for minimal drag while not deployed. In fact, this would allow the brakes to be effectively invisible to the flow over the payload. However, once deployed, it is desired that the brake surface be flat and perpendicular to the flow, since Newtonian Flow Theory suggests that this configuration would provide the largest drag coefficient. Combining these attributes, the brakes were designed as the following figure illustrates

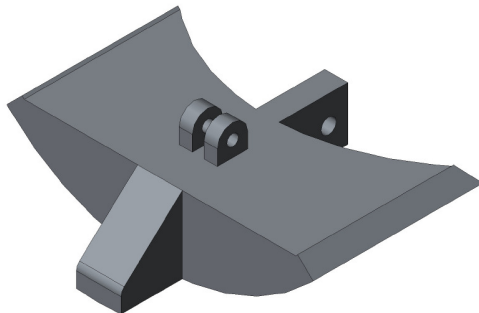


Figure III. *Candidate Brake Design*

As can be seen in Figure III, the brake consists of the curved exterior and the flat interior, which will be the primary decelerating surface. The extrusion at the top of the brake will prevent hot air from entering the body at the damper holes while the brakes are not deployed, as illustrated in Figure I. The single, centered hinge extrusion will be the primary hinge-to-body connecting device. However, it has been reasoned that dual hinge extrusions would provide for a much more stable deployment of the brake. Thus, the next iteration of the design process will incorporate this idea.

DAMPER DESIGN AND LAYOUT

In order to prevent catastrophically-high opening loads on the brakes, it was decided that hydraulic dampers would be used in order to slow the brakes' deployment. Designing and fabricating dampers for the recovery module is not a smart or economic idea when such a myriad of dampers are readily available and affordable. Therefore, a set of constraints was determined using the approximated brake loadings and space constraints, and a damper that fulfilled these requirements was located in a well-known engineering parts catalog.

The chosen damper had to be able to withstand the force of tension exerted by the vertical-downward force of drag on the brake. Further, the tension in the damper is directly proportional to the angle the damper makes with the face of the brake, thus placing a constraint on the damper's placement.

A hydraulic damper rated at supporting a tensile load of 3.25 kN and having an available stroke of 10 cm was chosen as the candidate damper. At an extended length of 32 cm, this damper will allow an angle of no smaller than 65 degrees with respect to the flat plate. Thus, the tensile load will not exceed the rated 3.25 kN, while still allowing a fluid deployment of the brake. The dampers' size and placement are illustrated below in Figure IV, where the top skin has been taken off the module

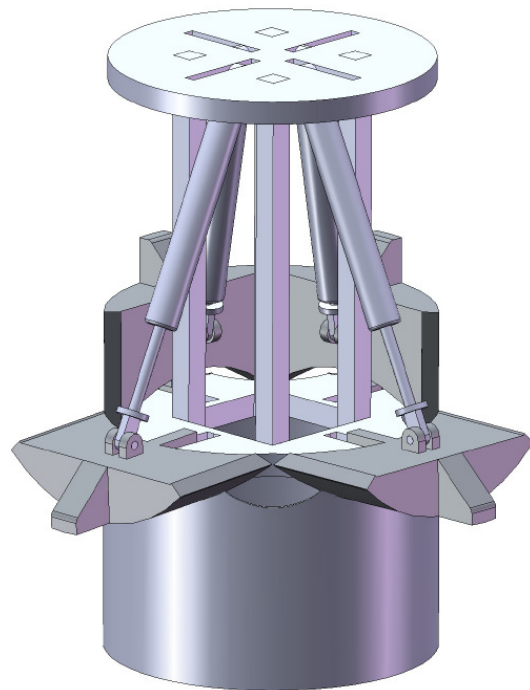


Figure IV. *Solid Model with Top Skin Removed*

Thus, it is clear that these dampers will operate within the space constraints, and their load rating is sufficient for the loads induced by the drag force acting on the brakes.

MATERIAL SELECTION

In selecting a material for the brakes, the Cambridge Engineering Selector software package was used. This software package contains a database of all engineering materials and properties and enables the user to place limits on properties and material indices. By determining the appropriate material indices and property limits, one can use the program to find the optimum material for an application.

To begin the material selection, limits on melting temperature, oxidation properties, and maximum service temperature were set in the software program. By limiting the available materials to only those with $T_m > 2600$ K, great oxidation properties, and maximum service temperature, $T_{service} > 1300$ K, the number of viable materials dropped considerably. With this small group of materials, application of material indices allowed for further narrowing of viable materials.

For the purposes of material selection, the brake was approximated as a flat plate in loading. The material that allows the least deflection and greatest strength, while minimizing mass, is desired. Therefore, the thickness of the brake was designated a free variable, and the equations for stiffness and bending and shear were used in conjunction with the following equation for mass

$$m = \rho A t \quad (14)$$

where ρ is the material density, A the area, and t the thickness. By solving for the thickness in the stiffness and strength equations, the following two material indices arise

$$M_1 = \frac{E^3}{\rho} \quad M_2 = \frac{\sigma_y}{\rho} \quad (15)$$

By plotting M_1 on the y-axis and M_2 on the x-axis, a line with slope of -1 can be plotted and moved upward and to the right to find the stiffest and strongest materials, as can be seen in Figure 5 below. Additionally, the brake cannot be allowed to fracture during deployment due to crack propagation. Therefore, it must be able to withstand some level of cracking. The following material index can be maximized in order to minimize the brakes susceptibility to failure by crack propagation

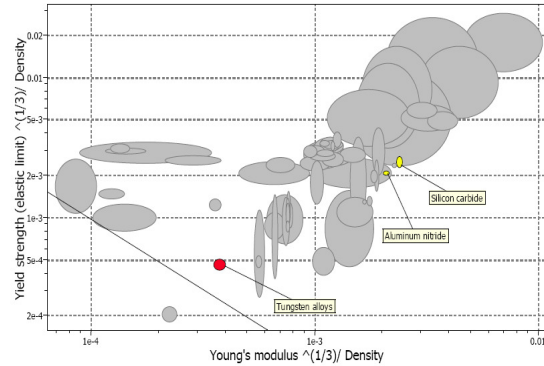


Figure V. Material Indices Plotted

$$M_3 = \frac{K_{Ic}^2}{\sigma_y^2} \quad (16)$$

By applying this index to the already-narrowed-down materials, it is clear that Tungsten alloys become the optimum material for the aerodynamic brake. The density of Tungsten alloys is somewhat high, resulting in each brake weighing approximately 2.72 kg. However, its mechanical, thermal, and oxidation properties are ideal. Further research into material selection will be necessary, as it is clear that weight is a major constraining factor for this design. Therefore, focus may be shifted to carbon/carbon composites or high performance ceramics in the future.

V. BRAKE ANALYSIS

The current candidate brake design is the best fit, qualitatively, for the application, but it must also be the best quantitatively. By utilizing the Finite Element Analysis (FEA) package, COSMOS, available as part of the Solidworks student edition software, structural analysis was conducted for the chosen brake in order to prove that the brake design was suitable for its application.

The brake was restrained at its hinge and damper attachment locations and at the rear curved surface of the brake (invisible in the following figure). A distributed load of 2.95 kN was then applied to the flat face of the brake in the direction of air flow in order to simulate the drag force. An FEA simulation was run using 12710 nodes, producing the von Mises stress distribution shown below in Figure VI

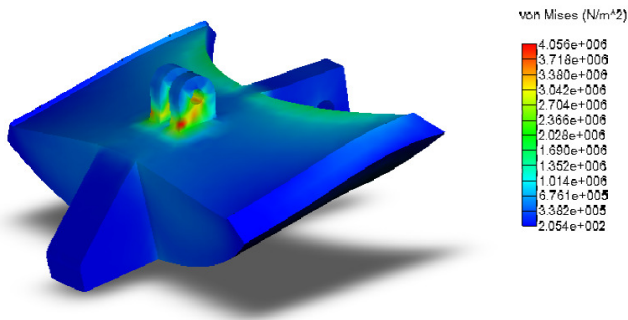


Figure VI. *FEA Stress Analysis of Brake*

A maximum stress of approximately 4.056 MPa was calculated and is represented as the red color in the figure. This makes sense qualitatively that the highest stress would occur at the indicated locations, due to the changing geometry and high stress concentrations at those locations. This maximum stress is far under the accepted Tungsten. However, it should be noted that even though the maximum stress is far under the yield stress, any decrease in experienced stress would be beneficial. There exists no definite calculation of the expected error of the FEA analysis using COSMOS. Therefore, the stress analysis results may only be taken at face value until a thorough FEA analysis is done using more nodes or more sophisticated software.

VI. FUTURE WORK

Since the payload design is yet to be finalized, changes to the aerodynamic brake system may be required to compensate for any changes made to payload, including weight, sizing, etc. This research will stay up to date with the payload design and modify the aerodynamic brake design as required. Once a payload design is finalized, detailed design work will progress.

The first Hy-V flight experiment is scheduled for the summer of 2009. However, due to the vast amount of work to be done on the aerodynamic brake recovery system, its first test flight will not occur until a later Hy-V flight. Much design work remains to be completed on the aerodynamic brake system, and it is the goal of this research to facilitate the progress of further design work. The research presented here outlined the rationale, design, and analysis of a conceptual design for the aerodynamic brake and sets forth the claim that it is a viable recovery option. Furthermore, it is the ultimate goal of this research to establish the basis for the work that must take place in order to produce a prototype, worthy of flight testing, by the launch date of the second Hy-V flight experiment.

Acknowledgments

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