Energy Deposition I: Applications to Revolutionize High Speed Flight and Flow Control

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Depositing energy in the air enables revolutionary high-speed flow control abilities that will change how we fly. A number of examples are described here, in order to convey the concept and performance enhancements in a broad range of applications.

I. Introduction

Since its beginning, PM&AM Research has been pioneering a broad range of energy deposition applications to revolutionize how the world flies and controls high speed flow [Ref. 1-10], in particular, how we execute high-speed flight and flow-control, ranging from high subsonic to hypersonic regimes. This conference paper is intended to provide an overview of a number of applications to provide an intuitive feel of the many possibilities opened up by this novel approach. More specifics are described in a separate paper at this conference, including physical mechanisms, their timescales, and their coupling. The basic effect stems from our approach to rapidly expand gas out of regions, through which we want high-speed/high-pressure gas to flow. As a simple analogy (requiring some imagination and license), consider the difference in effectiveness of trying to make a projectile cross through the Red Sea at high speed, either firing the projectile directly through the water from one side to the other, or first “parting” the Red Sea and then firing the same bullet through a path that contains no water (Figure 1).

Figure 1. A schematic cartoon contrasting (a) the ineffectiveness of a bullet trying to propagate through water at high speed, compared to (b) the same bullet propagating effortlessly, after the water has been laterally moved out of its way. In the brute force approach, the bullet’s energy is very quickly transferred to the water (and material deformation). In our approach, the bullet propagates for a much longer distance, interacting with its surroundings through much weaker forces.

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In the first case of firing the bullet directly into the high-density water, even a massive, streamlined, 1000m/s bullet will penetrate less than 1m of the water. In the second case, after first “parting” the water (i.e. creating a path, from which the water has been removed), the same bullet even at 300m/s can easily propagate for very long distances (this heuristic example does not address the drop from gravity, which is addressed later in the paper). It is this concept and geometry that we exploit, in order to achieve revolutionary control over high-speed flow and high-speed vehicles/projectiles. {A notional parametric exploration of the “depth” and distribution of “parting the sea” (independent of a “parting” mechanism) is documented in [Ref. 11-13]}.

II. Impulsive Energy Deposition as a Mechanism to “Part” the Air

The basic idea behind our energy-deposition approach is that we are able to redistribute/sculpt the air’s density by quickly (“impulsively”) depositing energy into it. It is important to note that in order to effectively “part” the air, the energy must be deposited into the air much faster than the gas can expand (e.g. in the form of a short laser- or microwave-pulse, and/or an electric discharge, among other techniques). Any heating that allows the gas to propagate away as it is heated, even if using very high temperatures, will not yield the highly effective results we describe here. The litmus test of a “sudden”/”impulsive” heating process is that it will generate a “snap” or “bang”. It will definitely not be continuous.

Figure 2. Strong electric discharges can be used to deposit energy along arbitrary geometries on a surface, with examples depicted here of (a) a semi-circular path and (b) straight lines.

(To illustrate the following explanation, it is best to first look at Figure 2 and Figure 3 as examples of the expansion being described.) Once the energy has been “effectively instantaneously” (“impulsively”) deposited in a specific region of the air (e.g. along a line or at a point), the surrounding air is driven outward from the heated region by an expanding blast wave. Until the blast wave, resulting from the deposited energy, decays/slow to sonic speed, the surrounding gas is swept outward, leaving behind a region of hot, pressure-equilibrated gas, whose density is much less than the original/ambient density (in some cases, nominally about 1.5% of the ambient density remains behind, with the other 98.5% having been pushed outward). Once the expanding shockwave has slowed to sonic speed, it continues to expand out sonically, no longer pushing gas outward and no longer expanding the low-density region. The low-density region (generated when the blast wave was expanding supersonically) remains behind, pressure-equilibrated with the surrounding ambient pressure (e.g. it survives as a “bubble” of atmospheric-pressure, low-density, hot gas, which does not collapse back onto itself...i.e. it is a region in which “the air has been parted”). The volume of this pressure-equilibrated low-density region is directly proportional to the energy that is deposited in the gas and also inversely proportional to the ambient pressure (e.g. the resulting low-density volume is doubled if the initial atmospheric pressure, before depositing the energy, is halved). An example of this expansion and resultant low-density region along a surface is shown in Figure 3, which provides an end view of a single straight leg of an electric discharge, such as those shown in Figure 2 (b), yielding a schlieren photograph, looking along the path of the electric discharge.
Figure 3. A time sequence of schlieren images which show a blast (supersonic shock) wave pushing open a region of hot, low-density gas (left and center images), as a result of energy being deposited along a surface (as in Figure 1), with the shock wave propagating away at sonic speed after it has reduced in strength to Mach 1 (right image), and can no longer drive/push open the low-density region.

The simplest example of expanding a low-density “bubble” can be seen when depositing energy at a point in the air (Figure 4), from which the gas expands spherically-symmetrically, in order to open up a low-density sphere (Figure 5).

Figure 4: Energy is deposited in the air, by focusing an intense laser pulse to a point in the air, with sufficient intensity to ionize the gas molecules, effectively instantaneously compared to the fluid response.

Figure 5. Shadowgraph imagery demonstrates the blast wave from a laser “spark”, such as the one shown in Figure 4, driving open a region of low density gas, which stays behind for an extended period of time as a low-density region in the ambient gas.
A similarly simple geometry occurs when energy is deposited along a straight line (Figure 6, Figure 7, and Figure 8). This leads the gas to expand and open up a low-density cylindrical volume (or “tube”), centered around the original line/axis, along which the energy was originally deposited.

Figure 6. Laser filaments create straight ionized channels, along the path of an ultrashort laser pulse.

Figure 7. Laser filaments from ultrashort laser pulses can be used to precisely trigger and guide electric discharges along their (b) straight paths, vs (a) the typically less controllable discharges in spatial and temporal terms [Ref. 14].
The fact that the hot, low-density geometries equilibrate to ambient pressure and remain for long periods of time, compared to the flow dynamics of interest, allows the low-density regions (e.g. spheres and “tubes” in air and half-spheres and half-“tubes” along surfaces, as well as other more complex geometries) to stay “open” sufficiently long to execute the intended flow control.

III. Application: Preferentially Channeling High Pressure Gases for Propulsion and Blast Mitigation [Ref. 10]

One of the simplest ways to envision the benefits of this approach is when looking at a confined blast. The intuition that this affords can be directly applied to other high-speed flow applications (such as high-speed flight and propulsion systems). In particular, we are able to (nearly instantaneously) reduce pressures and direct gases, upon detection of an undesirable pressure build-up and/or shockwave. These problems from the field of blast mitigation are the same concerns that arise in high-speed flight and propulsion systems, so this initial example can be extended to apply the fundamental concepts to a broad range of hypersonic applications. In one particular example of blast-mitigation, when high pressure blast gases are confined between the bottom of a vehicle and the ground, the air is impeded from exiting from under the vehicle by the formation of a shockwave in the ambient gas. The longer the high pressure gas resides under the vehicle, pressing up against its bottom, the greater the integrated impulse presses the vehicle upward. The goal in this application is to vent the high pressure gas from under the vehicle as quickly as possible, thereby relieving the pressure underneath the vehicle and minimizing the integrated impulse transferred to the vehicle. To accomplish this, the high pressure gas can be quickly vented out from under the vehicle, by opening low-density paths along the bottom surface of the vehicle to rapidly direct the gas out from under the vehicle. This can be achieved by incorporating our technology into a ground vehicle, to create low-density paths, along which a nearby blast (e.g. under said vehicle) can quickly escape, thereby strongly reducing the force and time over which the blast gases press on the vehicle, thereby minimizing the total impulse imparted to the vehicle by the blast. Figure 9 shows an example indicating the reduced force and impulse that can result from a blast, when first reducing the air density below the vehicle.

Figure 9. (a) Integrated force and (b) impulse as a function of time, exerted by a blast underneath a test plate, with different initial densities underneath the vehicle (100%, 10%, and 7.5% of ambient density).
To create the high-speed channels, through which the high-pressure gas can more quickly escape from under and around the vehicle, we add conductive paths (similar to those pictured in Figure 2) along the surface of the vehicle (schematically depicted in Figure 10).

![Figure 10. Notional diagram of conductive paths along the surface of a vehicle to quickly channel high pressure gases out of the confined space beneath a land vehicle.](image)

This concept can be used to nearly instantaneously vent high pressure gases in confined volumes, more relevant to high-speed propulsion, such as isolators, combustors, diffusers, exhaust systems… anywhere, in which it is advantageous to quickly mitigate deleterious pressure increases.

**IV. Increased Efficiency, Traveling through the Air at Trans-/Super-/Hyper-sonic Speeds [Ref. 16-18]**

The primary reason that vehicles inefficiently fly through the air at high speeds is that they are effectively accelerating a column of air (from origin to final destination) to a significant portion of the speed of the vehicle. In addition to the resulting large fuel cost, the large amount of energy imparted to the air is associated with additional problems, such as: a strong sonic boom; damagingly strong shockwaves impacting the vehicle behind the nose; and undesirable pressures and heating along leading edges and stagnation lines, due to the frictional forces generated when accelerating the stationary air to match the speed of the vehicle.

When a vehicle instead travels through the low-density “tube” opened up by depositing energy along a long (e.g. laser-filament-guided) line, the drag is dramatically reduced, with a commensurately dramatic savings in total energy consumption. An example of the instantaneously calculated drag curve is shown in Figure 11. In this graph, a small rise from the baseline drag is observed, as the cone passes through the higher density gas at the edge of the “tube”. The drag then decreases dramatically, as the cone flies through the low-density region of the “tube”. As the cone exits the low-density region, and the shock wave begins to re-form, the drag begins to rise up again to the nominal, original/unaltered drag value. In practice, after a vehicle or projectile has propagated through the low-density “tube”, another low-density “tube” can be opened, to allow the vehicle/projectile to enjoy continued drag-reduction. The exact point at which the ensuing “tube” is initiated is a matter of optimization for a given application. The degree to which the drag is consistently allowed to rise, before again reducing it by depositing energy to generate another “tube”, will govern the intensity of the pressure modulation being driven at the same repetition rate of the energy-deposition, which will be roughly equal to the vehicle speed divided by the effective tube length (adjusted to accommodate how far the vehicle/projectile actually travels before depositing energy again).
This modulation will lead to an additional source of airplane noise, and can be tuned by adjusting the “tube” length, in order to avoid vehicle resonances and nuisance frequencies. Each successive “tube” also presents an opportunity to slightly re-direct the “tube’s” orientation, to steer the vehicle (this will be further addressed below).

Figure 11. The drag on a cone is significantly reduced when the cone travels through a low-density tube generated by depositing energy upstream, along the cone’s stagnation line. The letters below the graph, correspond to the times marked by the vertical lines beside them, which correspond to the similarly labeled frames in Figure 14.

The most important exploration was to determine the drag-reduction and energy saved when implementing this technique, as well as to perform cursory parametric studies to assess the dependence on different parameters, such as Mach number, cone angle, and “tube” diameter compared to the cone base. These parameters are depicted in Figure 12, with the understanding that Mach number is referenced to the nominal, unaltered flow. Once energy is deposited upstream, the conventional definition and concept of a uniform Mach number no longer applies. This results, because the speed of sound inside the “tube” is many times higher than that outside the tube in the nominal unaltered free stream. By conventional definition, the Mach number inside of the “tube” is significantly lower than that outside of the “tube”. In fact, in many cases, the flow inside of the tube is subsonic, compared to supersonic/hypersonic flow outside of the tube, allowing for dramatically different flow-fields than those observed when flying through uniform air, which has not been modulated by depositing energy. Some of these dynamics are described here, and can only be achieved by depositing energy into the flow.

Figure 12. The parameters varied for the study results shown in Figure 13 include: four Mach numbers $\rightarrow$ M=2,4,6,8; three cone half-angles $\rightarrow$ 15°, 30°, 45°; and four low-density “tube” diameters $\rightarrow$ 25%, 50%, 75%, and 100% of the cone’s base diameter.

The results in terms of maximum drag reduction and energy savings (return on invested energy) for the various cases shown in Figure 12 are described in greater detail in [Ref. 16-18], and are summarized here in Figure 13, including drag-reduction of up to 96% and 65-fold return on invested energy in the total energy balance (i.e. for every Watt or Joule deposited into the air ahead of a cone to open the low-density “tube” along the cone’s stagnation line, 65 times this “invested” energy was saved in the propulsive power or energy that was otherwise required to counter the much stronger drag experienced when not depositing energy ahead of the cone).
Figure 13. Drag-reduction and return on invested energy is plotted for 15/30/45-degree cones propagating at Mach 2,4,6,8, through tubes with diameters of 25%, 50%, 75%, and 100% of the base diameter of the cone. In some cases, nearly all of the drag is removed, and in all cases, the energy required to open the “tubes” is less than the energy saved in drag-reduction, showing up to 65-fold return on the energy deposited ahead of the cone).

Some interesting trends are observed in the results, with the most basic observation being that opening larger tubes increases the drag-reduction for all of the Mach numbers and cone angles. A more nuanced and interesting observation is that the energy-effectiveness (i.e. 
\[
\frac{(\text{propulsive energy saved}) - (\text{invested energy})}{(\text{invested energy})}
\]

appears to have two regimes. This energy-effectiveness describes how much energy is saved out of the propulsion system for each unit of energy deposited ahead of the vehicle to open up a low-density “tube”. One regime occurs at higher Mach numbers with narrower cones, in which the bow shocks tend toward oblique/attached. In this regime, the energy-effectiveness increases with Mach number and the most efficient “tube diameter” transitions in a clear and understandable fashion from smaller to larger diameters, with increasing Mach number. Removing the gas along the stagnation line always provides the greatest benefit, whereas the benefit of removing gas further out from the stagnation line is a function of the vehicle speed, with increasing benefit being gained at higher Mach numbers. In the lower Mach number regime, where the bow shocks tend to normal stand-off shocks, a strong rise is observed in efficiency for small diameter “tubes”, which can effectively serve to “puncture” the bow shock, allowing the high pressure gas behind the normal shock to be relieved, since the flow within the “tube” can now be subsonic (in the high-speed-of-sound “tube”) and no longer confined by the cone’s bow shock (Figure 14).

Although efficiency studies can help identify the energy one can deposit to achieve optimal performance, it is also worth noting that the effects scale, and that the amount of energy one deposits in a specific platform can also be determined, based on what the platform/vehicle system considerations can accommodate. Even if a smaller diameter “tube” is opened than the optimum, it will nonetheless yield better vehicle/projectile performance, in terms of increased range and speed, lower fuel consumption, and decreased emissions and noise/sonic boom (with some other benefits noted below). It is particularly favorable, that significant benefit can be obtained when depositing energy, even much smaller than the optimal amount. The actual amount of energy-deposition capacity and power that is incorporated into a system, can be determined by the amount of room that can be accommodated for it, in terms of available size, weight, and power, and how much of these same parameters are improved after incorporating the technology. This flexible iterative process affords the luxury of incorporating the technology into any system that can benefit from it. In addition, given that the energy required to open a given volume of low-
density gas scales with the ambient pressure, a given amount of energy deposited in the air will open increasingly larger volumes at the lower pressures encountered at increasing altitudes. This effect also works well in a scenario, in which a given range of energy pulses will open increasingly large “tube” diameters as a vehicle/projectile climbs in altitude. Instead of increasing the “tube” diameter, the increased low-density volume at higher altitudes can be used to increase the tube-length, or to distribute the greater volume across an increase in both length and diameter. An increase in “tube” length lends itself to increased speeds, and as seen in Figure 13, larger “tube” diameters can help maximize efficiency at higher Mach numbers.

V. Sonic Boom Mitigation and Base Repressurization [Ref. 16-18]

Representative density-contour frames from the dramatically modified flow dynamics, resulting from flying through a low-density “tube” are shown in Figure 14. The letters A, B, C, D correspond to the times marked on the drag-curve in Figure 11 (with D representing when the cone has traveled the original extent of the “tube”, not accounting for the tube’s deformation/extrusion, resulting from its interaction with the cone).

![Figure 14](image)

**Figure 14.** Density profiles, taken at times corresponding to the times marked in Figure 11, showing the flow modification as a cone flies through a low-density “tube”. The sequence from A to D demonstrates a strong reduction in bow shock (with its associated wave drag and sonic boom), as well as a strong re-pressurization of the base, indicating the removal of base-drag and increase in propulsive effectiveness of exhaust products at the base.

Contrasting the differences evolving from the nearly unperturbed density distribution in frame A, and the ensuing dynamics, we note several points:

- in regular flight, there is a strong bow-shock and associated sonic boom, whereas flying through the low-density “tube” strongly mitigates both the bow-shock and its associated sonic boom;
- in regular flight, the gas accelerated laterally and forward by the cone, leaves behind a low-pressure/low-density region at the cone’s base, whereas when the gas is moved laterally from in front of the cone, by depositing energy to form a low-density “tube”, the gas accumulated at the perimeter of the “tube” is recirculated behind the cone, and serves to re-pressurize the base;
- this repressurized base mitigates base drag;
- the significantly higher gas density at the base can also provide a level of confinement of the propulsion products, which can strongly enhance the propulsive effectiveness of the exhaust system, and increase its
effective impulse many-fold...this results from the recirculated atmospheric gas backstopping the propulsion products to exploit their high pressure for longer times, versus having the high-pressure products simply exhaust unconfined into the otherwise low-density, low-pressure base region.

VI. Phased Implementation of propulsion and energy deposition, to optimize the dynamics

Given the multitude of beneficial dynamics, designing a system to maximize the benefit from each effect will clearly result in the most effective system possible. This concept can be flexibly applied to any number of applications/embodiments, in order to improve efficiency and leverage/synchronize symbiotic effects/benefits of the various steps/processes. This may entail the optimization of a number of possible parameters, including length scales, ignition, air-fuel ratio, timing, repetition rates, chemical processes, electrical discharges, laser pulses, microwave pulses, electron beams, valving/throttling, among others. Some notional examples, among many possibilities are:

- **Laser-launching:** In laser-launch applications, one embodiment entails one or more ground-based lasers as the propulsion source, firing at the back-end of a launch vehicle, that refocuses the propulsive laser-light via a rearward facing optic to heat and expand gas or ablation products out the back end of the launch vehicle. Designing the laser system and launch vehicle to:
  - allow some laser energy to be deposited ahead of the vehicle to open a low-density “tube” and reduce drag;
  - size and throttle the vehicle body and internal paths to allow sufficient propellant air to be heated by the driving laser-pulse(s);
  - size the vehicle body to ensure that the modulated gas ahead of the vehicle flows around to establish a high-density back stop, against which the propellant gas can more effectively push;
  - deliver driving laser pulses to allow the vehicle to fully exploit the low-density “tube” and propulsive push, before the ensuing laser pulse repeats the process.

- **PDE/Chemical lasing/Pulsed Power:** This type of system calls for the same types of phasing/timing optimization considerations as listed above. In this case, however, the driving energy is a series of pulsed chemical detonations that take place inside of the vehicle. The timing of this detonation can be controlled via properly-timed valving and ignition, and the detonation may actually be able to drive the processes required to deposit the upstream energy.

- **Industrial and Transportation Applications:** In these cases, similar timing and system optimization as in the above applications can be applied to achieve the desired level of phasing, with additional potential considerations of different propulsion, such as electric propulsion, as well as magnetic levitation. Each element can be timed, not only to ensure optimal fluid flow, but also to ensure that the least amount of energy is used in the on-board systems, such as the propulsion and levitation systems, as well as any additional systems, unique to a given approach, which can be sized and timed for optimal implementation.

VII. Direction and Phasing of Beams to Scale up Energy Deposition and Facilitate Control

As stated earlier, electric discharge is one possible technique capable of realizing flexible geometries that can be used to not only generate the dramatic benefits, but also control and phase the aerodynamics to ultimately exact powerful and efficient control on the vehicle. If electric discharge is to be used, a conductive path must be created to allow a current to flow. The ability to “paint” a conductive path using a laser pulse (Figure 6) and guide/initiate an electric discharge (Figure 7) was demonstrated in a separate paper [Ref.10,16]. Filamenting lasers are able to form such ionized paths with sufficient accuracy and length to flexibly trace out any number of desired patterns.
Figure 15. An electrically conductive path 108 can be painted and directed in the air to allow the electric discharge required to control/modify the vehicle’s shockwave(s).

An example is shown in Figure 15, in which a conductive path (108a,b) is created to connect electrodes 106 and 107, intersecting at point P₁. A second example in Figure 16 and Figure 17 depicts more detail of the actual discharge device. In this example, a laser pulse 111 is directed to three separate electrically-isolated lens/electrode assemblies 102 (Figure 17).

The adjustable (122) optical elements 121 focus the different pulses through their respective metal cones 123 to ensure that filamentation begins as close as possible to the tips of the metal cones. This will ensure the best electrical connection possible. The metal cones are electrodes connected to the appropriate poles of a capacitor bank. Upon creation of the ionized path, the capacitors will discharge their energy along said path. As a result, the electrical energy that was stored in the capacitors will be deposited into the air along the conductive pathways in the form of ohmic heating.

Figure 16. A more detailed schematic of a laser pulse split through multiple electrically-isolated focusing/discharge devices.
Figure 17. A yet further detailed schematic, showing the optical path/elements to focus the laser pulse through the conical-shell electrode (123).

In the event that sufficient energy cannot be deposited along a single path to achieve the desired flow control, several energy discharge devices can be arrayed/phased to achieve any number of objectives (Figure 18 and Figure 19).

Figure 18. A schematic example of how an array of discharge devices can be used to augment the energy deposition and create a much larger core by phasing a number of smaller discharges.

An array of energy discharge devices is illustrated in Figure 18. An array of energy emitting mechanisms or elements 106a, 106b, 106c is arranged on a body 101. The body 101 includes a central element 106a surrounded by an inner annular array of elements 106b and an outer annular array of elements 106c. The total array of elements 106 can be used to increase the effectiveness and magnitude of the energy deposition by firing the individual elements 106 or groups of elements 106 in succession. This can be achieved by using the array of elements 106 to continue to push the fluid 105 cylindrically outward, after the fluid has expanded outward from the central heated
core, generated by the central element 106a. In this example, when electrical discharge is implemented, it follows ionized paths 108 that complete separate conducting circuits between elements 106b and 106a. The next set of conductive paths and discharges could then be between 106c and 106a (or 106b).

In operation, as illustrated in Figure 18 (top), the central element 106a and one or more elements 106b of the inner array would be fired to create a central heated core 160a. This heated core would expand outward, possibly bounded by a cylindrical shock wave, which would weaken with the expansion. To add energy to the weakened cylindrical expansion, elements 106b could be fired, as illustrated in Figure 18 (bottom). Upon further expansion, elements 106c of the outer array would then also be fired to maintain a strong continued expansion of the heated core 160b.

Figure 19. A schematic example of how an array of discharge devices can be used to augment the energy deposition and “sweep” the flow in a desired direction by phasing a number of smaller discharges.

A schematic representation of a similar application, involving a linear array of energy discharge devices 102, is illustrated in Figure 19. The energy discharge devices 102 are mounted on a vehicle 101 to push incoming fluid 105 outward along the wing 150, in a wavelike motion, by firing sequentially from the innermost energy discharge device 102a to the outermost energy discharge device 102f furthest from the centerline of the vehicle 101.

The energy discharge devices 102 would typically be electrically isolated, as with the connecting charging units and switches. Additionally, neighboring energy discharge devices can be fired effectively simultaneously to create an electrically conducting path 108, as previously discussed with regard to Figure 16 and Figure 17. The energy discharge devices 102 can also be fired successively in pairs to use the electric discharges to sweep the fluid 105 outward toward the tips of the wing 150. This method of sweeping fluid toward the wingtips also directs the fluid over and under the wing 150. Environmental sensors can also be included to monitor performance and be coupled to the energy discharge devices to modify the different parameters of the energy deposition.

VIII. Steering/control - stronger at higher speeds; Reduce Pressure&Temperature [Ref. 19]

In addition to drag-reduction, there are a number of associated benefits that accompany use of the described energy-deposition technique.
To explore the control forces and moments associated with this technique, the Cobalt CFD solver was used to perform 3-D simulations, in which low-density cores were generated to impinge on the vehicle over a continuous range of off-axis positions. The offset in core position is depicted as upward in Figure 20. In these runs, the core’s initial position was co-axial with the vehicle, and was then slowly moved upward (remaining parallel to the cone axis with no angle of attack). This allowed quasi-steady state assessment of the effects of the core, when offset by an amount ranging from co-axial (no offset) to an offset of roughly one half of the base diameter. This is schematically depicted in Figure 20. We performed this series in order to explore the full range of responses, resulting from cores aligned with the direction of flight.

Figure 20. In the 3-D runs, the initial core position is axi-symmetric with the vehicle (a), yielding maximum drag-reduction and no lateral force or torque. The core is then gradually shifted upward as the run progresses, allowing a quasi-steady state value of control forces and torques to be monitored over this entire range of core positions. We characterized up to a shift of roughly 1/2 of the base radius (b).

Figure 21. A frame of a test run using a standard cone to investigate the effects on heating, drag, and control forces when creating a hot low-density core ahead of a hypersonic vehicle’s shock wave. (Top – density; Bottom left – pressure; Bottom right – temperature; Bottom right – drag, forces, and moments.)

Figure 21 depicts density, pressure and temperature on the body surface. The moments and forces are listed as coefficients on the same graph. The two moments are calculated as examples of different centers of mass that yield stable flight for different payloads/missions. We also demonstrated that otherwise unstable vehicles (center of mass aft of the center of pressure) are stabilized when flying through the low density cores. This is because the higher density gas at the outer edges of the base shifts the center of pressure significantly to the rear of the vehicle and behind the center of mass. This benefit of stabilizing otherwise unstable designs can result in far greater flexibility in ensuring stable hypersonic vehicles, removing conventional constraints on the location of the center of mass. The other benefits of this technology further reduce the design constraints by allowing much broader performance envelopes, using much lower-cost materials, as well as a significant reduction in fineness requirements of the body, as well as significant weight reductions due to reduced thermal protection system (TPS) requirements, easier inlet (re-)starting and greatly reduced control/actuator hardware.

The analytical upper bound estimates and computed lower bounds on a generic cone yielded control forces from several G to many tens of G, depending on the altitude and Mach number. These upper and lower bounds provide helpful limits in assessing the utility of this technique in different applications. For a launch vehicle with a 1m base,
we estimate that a deposited power of 480kW can produce a useful effect over the entire range of Mach 6-20. This power allows: 1/5 diameter cores to be opened ahead of the hypersonic vehicle at 15km; 1/2 diameter cores to be opened at 30km; and full-diameter cores to be opened at 45km altitude. If only 10% of this power is available, then we can open “tubes” roughly 1/3 of the cited diameters, and still obtain tremendous benefits in terms of efficiency, control, and greatly facilitated designs.

One of the current limiting factors in hypersonic vehicles is mitigation of the thermal effects of sustained hypersonic flight. In addition to reducing drag and enabling vehicle-control, our approach reduces the temperature on the vehicle surface, as well as the resulting heating. This allows significant reduction in TPS weights and specialty materials required at leading edges. It also allows for greatly improved vehicle performance before encountering material limitations. Opening small diameter “tubes” ahead of a vehicle demonstrate great benefit, and help guide a vehicle, similar to how a pre-drilled hole can help guide a large nail. Despite this, it is instructive to think in terms of the extreme case of opening a “tube” that can fit an entire vehicle. This makes it intuitive to see the vehicle as locked into the “tube” similar to a luge sled in the Olympics. If the vehicle begins to bump into a “tube” wall, it will experience very strong forces pushing the vehicle back to center. This works in the vertical direction, as well as all the others, and the vehicle will find a position, in which its weight is balanced by the upward resistive force. As a result, the entire body can serve as a lifting surface, uniformly distributing the associated forces and temperatures. Similarly, the entire body can serve as a control surface, in that the same phenomenon that balances gravity will consistently exert restoring forces to constrain the vehicle within the tube. On the one hand, this makes control very attractive, since it entails simply directing the “tube” (which can be as easy as directing the initiating/guiding laser pulses) in the desired direction, and the fluid forces will ensure that the vehicle follows, distributing the control forces across the entire body, as appropriate. This suggests that further weight and volume requirements can be traded to help accommodate the hardware required for our approach, by obviating heavy hypersonic actuator/control-surface systems. In certain cases, each flap has a sizable associated volume and can weigh roughly 20kg. These actuators can require gas bottles or power from the vehicle, which have additional weight, volume demands, and risk, the elimination of which can be used to offset the requirements for the energy-deposition system.

IX. Incremental adoption and ground applications

As described above, the best approach to fully take advantage of the technology described in this paper is to design a vehicle completely around the fluid dynamics, allowing full exploitation of the many benefits they afford, including drag-reduction, flight-stabilization, reduced design constraints, enhanced lift/control/inlets/propulsion, and dramatic gains in speed, performance, range, payload, and fuel-efficiency. This being said, there are a large number of ways, in which this technology can incrementally “buy its way” onto existing platforms, by enabling incremental gains in performance that can’t otherwise be achieved in otherwise optimized systems. Some examples of this include: depositing energy along a surface to mitigate the drag of unavoidable protrusions (e.g. vertical tail-sections, joints, rivets, wipers, seams, etc), as well as depositing energy at or ahead of leading edges. In addition to the performance gains these can afford, they can also enable otherwise unachievable capabilities. One set of applications includes the ability to puncture a tube from the side of the vehicle through an oblique shockwave, as sketched in Figure 22, to facilitate passage of projectiles/sub-vehicles, as well as optical imaging and communication [Ref. 2, 4].

![Figure 22](image-url)

Figure 22. A low-density tube can also be created from the side of a vehicle through an oblique shockwave to facilitate imaging and release of sub-vehicles without slowing the primary vehicle [Ref. 2, 4].
Puncturing the main vehicle’s shock wave in this fashion can be of particular interest in certain hypersonic flight applications, since it enables creation of a path, through which images can be more clearly recorded, and through which secondary bodies can be launched from the primary vehicle without the strong interaction they would otherwise experience with the unpunctured shock wave.

Additional examples of high-speed flow control and facilitation of supersonic/hypersonic propagation/travel include propulsion and internal flow applications, in particular starting supersonic inlets and mitigating engine/augmentor noise, including screech and other resonances [Ref.10]. These involve surface discharges, which we achieve using a variety of electrode types, either with or without lasers, depending on the specific details. We are also applying energy-deposition along surfaces and/or in the open air to ground-based applications to improve wind tunnel performance, industrial/manufacturing processes, and transportation.

X. Remotely modifying surface flows, drag, and lift [Ref. 9]

For the above flight applications, our primary concern is to enable dramatic gains in capabilities and efficiency. In ground-based industrial/manufacturing/transportation applications, the constraints on size, weight, and power can be more relaxed. A desire to control uncooperative vehicles from a distance has also led us to deposit energy on remote platforms. For this application, the fluid dynamics resulting from depositing energy remain the same. However, instead of carefully engineering one’s own platform to most efficiently deposit energy into the flow, while reducing the size/weight/power demands, the primary task now becomes delivering the energy to the remote platform, in order to control its dynamics. In this case, instead of depositing energy via efficient electric discharges, we wind up using less efficient laser (and/or microwave) energy to quickly/impulsively deposit energy at or near the remote platform’s surface. The cost of this energy (in terms of its generation-efficiency) is much higher than simply using an on-board electric discharge as the primary energy deposition source. However, in return, one obtains the ability to remotely deliver this energy over large distances, in order to exert significant control over remote projectiles/vehicles by locally modifying the drag and lift on them. Figure 23 shows schlieren images of laser energy being deposited on a remote surface in both quiescent and flowing air. In our wind tunnel tests, we were able to measure a sizable effect on both lift and drag on an air foil, associated with our ability to interrupt the surface flow and boundary layer.

Energy Deposition on a Surface in Quiescent Air

Energy Deposition on a Surface in Flowing Air

Figure 23. Top row (left to right) – A shock wave opens up a low-density “half-sphere” on a surface in quiescent air, resulting from energy that was impulsively deposited using a laser pulse at a distance; Bottom row (left to right) – The same laser pulse is used to impulsively deposit energy and create a shock wave that opens up a similar low-density “half-sphere”, which is shown being convected by air flowing along the same surface.
XI. Conclusion

Quickly/impulsively depositing energy into the flow, faster than the fluid can mechanically respond, can be accomplished using any number of mechanisms, including lasers, electric discharges, microwaves, electron beams, etc. This energy can be deposited in a variety of useful geometries to significantly modulate/sculpt the density of the fluid and achieve tremendous control. This control results from the strong difference in forces experienced when a body interacts with the ambient fluid density vs. with the regions of dramatically-reduced density. Common geometries are combinations of spherical and cylindrical low-density regions ("tubes") generated off-body, and "half-spherical" and "half-cylindrical" low-density regions generated along surfaces. These geometries enable dramatic increases in speed, efficiency, control, and overall performance, resulting directly from the strong reduction in drag, heating, pressures, and shock waves when traveling through very low-density fluid (vs. ambient density). The most advantageous exploitation of our revolutionary approach will be to design a system around the beneficial dynamics, by tailoring: inlets; timing; and propulsion, to maximize the effects over the full range of desired operation. Less extensive efforts can also be pursued, by incorporating these benefits in a way that "buys" the technology’s way onto existing or near-term platforms, and/or to enable specific capabilities. Such efforts can include: point-wise mitigation of strong shocks/drag/heating/pressure; internal flow-control of high-speed propulsion units; inlet (re-)starting at lower Mach numbers; among many others. A number of applications are not detailed here, including: ground testing; manufacturing; ground transportation; and puncturing the shock wave generated by a supersonic/hypersonic platform to facilitate passage of optical signals and sub-vehicles.

References