Table 2 Variation of S_L and S_M with $\dot{Q}$

$\dot{Q}$, kW/m	$\bar{Q}_{NR}$	$z/h = 0$	$z/h = 0.1$	$z/h = 0.2$	$z/h = 0.3$
			S_L		
0.0	0.0000	——	——	——	——
4.0	0.0038	1.86	18.0	19.1	16.6
20.0	0.0192	0.163	7.18	14.0	11.1
40.0	0.0384	0.063	5.67	7.40	7.18
60.0	0.0576	0.00205	4.46	4.55	5.51
			S_M		
0.0	0.0000	——	——	——	——
4.0	0.0038	0.993	12.0	10.8	9.16
20.0	0.0192	0.0903	3.46	8.03	6.00
40.0	0.0384	0.0375	2.43	3.83	3.69
60.0	0.0576	0.0123	1.95	2.33	2.80

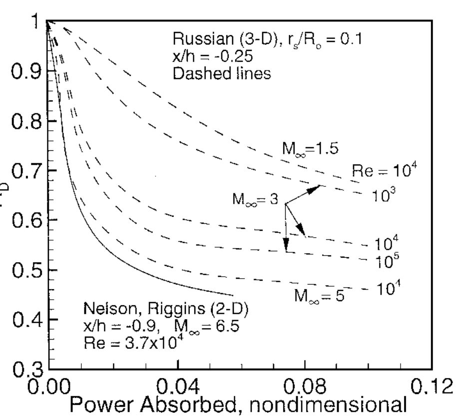

Fig. 4 Comparison of current and Russian R_D profiles for energy absorbed along centerline (upstream of body at $z/h = 0$).

where Q_q is the energy deposition rate (watt per kilogram), U_∞ is the freestream velocity (meter per second), ρ_∞ is the freestream density (kilogram per cubic meter), V_q is the cylindrical volume in which the energy is absorbed (cubic meter), and R_0 is the radius of the spherical body (meter). The corresponding nondimensional power ratio in the current two-dimensional research is

$$\bar{Q}_{NR} = \dot{Q}/0.5\rho_\infty V_\infty^3 h \tag{6}$$

where values of $\bar{Q}_{NR}$ are given in Tables 1 and 2.

Figure 4 shows a plot of R_D vs either $\bar{Q}_s$ or $\bar{Q}_{NR}$. The Russian data are shown as dashed lines. There are several differences between the flow conditions and geometry of the Russian and current calculations: 1) Russian is three dimensional, current is two dimensional; 2) Russian for $M_\infty = 1.5$, 3, and 5 and three Reynolds numbers, 10^3, 10^4, and 10^5, current for $M_\infty = 6.5$ and $Re = 3.7 \times 10^4$; and 3) Russian and current absorption spot size and position are different. In spite of these differences, the current calculations of R_D have the same trends and magnitude of the previous Russian work. The three-dimensional results allow for pressure reliving and, hence, have slightly less drag reduction, compared to the two-dimensional results.

Conclusions

This Note presents a parametric study of the effect of energy deposition rate at a point upstream of a hypersonic blunt body on the blunt-body flowfield. It is shown the wave drag is reduced up to 50%, depending on the location of the deposition point. When the deposition point is moved off the stagnation streamline, the energy deposition also produces a lift force and a pitching moment. Trends and magnitudes of the current results are in agreement with recently available Russian results. The modifications in the flowfield created by upstream power deposition may lead to effective ways to stabilize and control hypersonic vehicles.

Acknowledgments

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Ablative Laser Propulsion: An Old Concept Revisited

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Introduction

THE concept of laser propulsion (LP) is not very new. The idea was introduced in 1972 by Kantrowitz,[1] passed through a decade of active research in the mid-1970s and mid-1980s, and culminated in the first field demonstrations led by Mead and Myrabo in the mid-1990s.[2–4] The intrigue of the concept is that a vehicle driven by LP needs no engine or fuel in the traditional sense, a major advantage over any rocket, with a promise of a reduction in payload costs down to $100/kg (compared to $10,000+ for a modern rocket).[4]

The decade of intensive research in LP was limited to powerful lasers available at the time: mostly CO_2 or sometimes hydrogen fluoride–deuterium fluoride (HF-DF). To some extent, the concept was formally divided along two branches defined by the type of laser irradiation: continuous wave (CW) or repetitively pulsed (RP).[3] Research in the steady-state regime (CW) concentrated on describing laser-supported combustion waves (LSC) at low fluences and laser-supported detonation waves (LSD) at higher fluences.[2,3] All momentum transfer in the CW regime occurred through the gaseous or plasma state so that the choice of fluids as propellants for CW propulsion was predetermined.

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The exploration of RP-powered craft with solid targets also employed a fluid (plasma) dynamics description.[5–7] Energy transfer to the target was practically entirely through an opaque laser-induced plasma, developing within fractions of microseconds of exposure. When the target was placed in air, then the plasma originated through an air breakdown, occurring at an essentially reduced threshold because of a supply of free electrons from the target surface.[8,9] Airborne plasma absorbed an initial portion of laser irradiation via inverse bremstrahhlung and reflected the rest as soon as its frequency exceeded that of the light. In addition to breakdown in air or in vacuum, the laser energy was decoupled from direct absorption by the target via LSD waves, originating from the ablated portion of the target.[10,11] In terms of energy utilization, because the laser pulse duration was much longer than the time needed for plasma formation, RP excitation was identical to CW; energy transfer was practically independent of target material. Strong experimental evidence confirmed that the LSD wave was the major agent of laser/target energy transfer, and although participation of direct absorption was not entirely ruled out, its part was reasonably assumed to be of minor importance.[10] During this intensive research on laser/target energy transfer, ablation was ignored compared to the LSD phenomena.

Perhaps ablative laser propulsion's (ALP) time has come: the trend in the modern photonics toward the development of short-pulsed high-power lasers and the first free-electron lasers (FEL) has already lowered pulse times from microseconds to picoseconds. Significant ejection of matter starts at ~ 100 ps after arrival of the laser pulse.[12] Therefore, 100 ps can be taken as a rough estimate of the time interval preceding formation of a dense laser-induced plasma. State-of-the-art laser technology has already progressed to the point that plasma formation occurs long after the cessation of the laser pulse so that there is no interaction. It is reasonable to expect that, starting from picosecond timescales and clearly for subpicosecond laser pulses when plasma cannot obstruct light absorption, direct ejection of matter from the target will turn into the dominant source for propulsion. At this point ALP becomes an option that cannot be ignored.

Discussion

ALP can be conceptually defined as a sequence of events. Absorption of the laser pulse energy by a solid target is followed by a supersonic ejection of highly ionized matter from the target surface (i.e., ablation). Because of conservation of momentum, ablation imparts an impulse to the target in the direction opposite the jet. The target is propelled.

The absorption of laser energy by any state of matter is governed by an inverse bremstrahhlung, which requires the presence of initial free electrons for developing a cascade breakdown with further plasma generation.[13] Whereas a solid propellant usually possesses enough free electrons, a fluid propellant (which, by the time it is exposed to the laser irradiation, is in a gaseous state) first must be ionized. Multiphoton ionization of gases will require much higher irradiances for initialization of the plasma. For example, using a CO_2 laser, an isolated nitrogen atom must absorb about 120 photons to release a single free electron, which raises the threshold irradiance to about 10^{12} W/cm^2 (Ref. 13), and it can be achieved by a gradual purification of the gas.[14] This is a real problem; for example, breakdown was not achieved in hydrogen and nitrogen gases with FEL irradiation at 10.6 μm, 10-ps pulses, and an irradiance $\sim 10^{11}$ W/cm^2 (Ref. 15).

Whenever the light is focused in the vicinity of, or on, a solid surface,[4] a significant reduction in the air-breakdown threshold must be expected. The same phenomenon apparently imposes an immense limitation on realizing LP in airbreathing craft. Formation of air breakdown on the surface of a reflective shroud sets an extremely strict (if not prohibitive) requirement on the quality of reflective surfaces. High-quality mirrors can reflect pulsed laser light of high fluences ($\sim 10^3$ J/cm^2) but can hardly withstand any contact with $\sim 10^4$ K hot plasma, perhaps complicated by deposition of nonreflecting particulates. A possible solution could be in turning this problem into an advantage: focus the beam onto a solid propellant and employ ALP.

In general, because of the presence of free electrons, breakdown thresholds for solids are low, 10^6–10^7 W/cm^2 (Ref. 13), a factor of 10^3–10^5 lower than for gases.[14,15] For space propulsion, where the operational distance for LP is limited by diffraction of the laser beam, the reduction in threshold irradiance of about a factor of 10^4 allows an increase in the distance for acceleration up to 100 times, or if the distance is not so crucial, it will allow the use of a much less powerful laser.

Low breakdown thresholds of solid propellants are critical not only for space propulsion but also for launches from the Earth. For ground-based LP launching, breakdown in air along the beam path will be a highly undesirable event, attenuating the laser beam. This seems to be an immense impediment to LP in general and to airbreathing mode craft in particular because the requirement of GW laser power is essential in lifting heavy payloads. This problem was pointed out by Kantrowitz in his original paper from 1972,[1] and a reduction of energy coupling caused by air breakdown has been observed.[10,11] The natural air-breakdown threshold is 3×10^9 W/cm^2 (Ref. 16) and can actually be even lower for dusty air. To avoid the undesirable plasma formation along the beam path, an ideal propellant must have a breakdown threshold as low as possible and a reasonable breakdown threshold difference between the propellant and the atmosphere.

When a short light pulse is focused on the surface, supersonic ejection of matter is strictly a directional process. At microscopic scales it is much like propulsion by a collimated ion beam. Maxima in energy and mass flow occur normal to the surface and can be described with a simple cosine function[17,18]:

$$E(\theta) = E_0 \cos^n(\theta) \tag{1}$$

where θ is the angle of ejection with respect to the surface normal, E stands for energy or density of ejected atoms, and n varies with ablation conditions from unity[17] to 4.0–8.0 (Ref. 18). An important practical consequence of Eq. (1) is that ALP does not require a combustion chamber. The impulse is applied directly to the solid body of the propellant and, therefore, directly to the vehicle itself. Fluid propellants (primarily liquefied gases) cannot be used without combustion chambers and sophisticated sealing and injection systems. Also, plasma generated in the fluid propellant expands in all directions with almost spherical symmetry.[19] Ultimately, these features will negatively affect specific impulse and reduce the practicality of laser propulsion over ordinary chemical propulsion.

Formation of narrow, directed plasma jets is an important advantage of ALP, but there is actually more physics involved. The kinetic energy of a supersonic plasma jet is directly proportional to the degree of ionization of the species composing it. The kinetic energy of an ion under a potential difference ϕ is $me\phi$, where e is

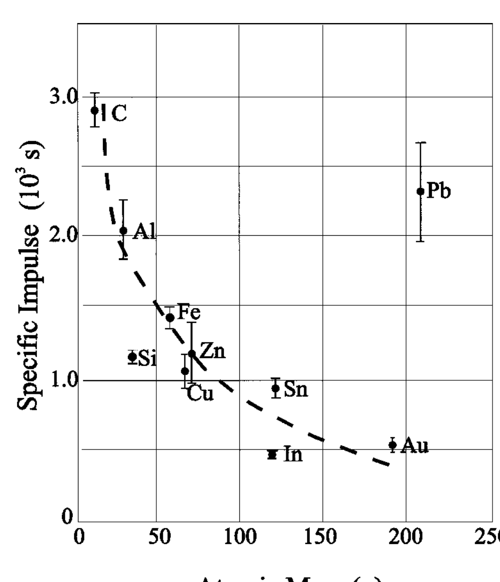

Fig. 1 Specific impulse vs atomic mass obtained using elemental targets ablated by 0.1-ps pulses from a Ti:sapphire laser: – – –, numerical fit of the data.

an electron charge and m is the charge state of an ion. Therefore, better propellants must have lower ionization potentials, allowing maximum m. The gain in specific impulse I_{sp} will be proportional to $m^{1/2}$. From this point of view, the proposed use of onboard hydrogen as a second stage, after exhaustion of the airbreathing mode,[4] will hardly have any advantage over any other similar propellant. On the contrary, solid propellants with low ionization potentials, such as lead or perhaps vanadium, may provide a high I_{sp}.

Figure 1 shows the dependence of specific impulse on the atomic mass of a target, irradiated by 0.1-ps-long pulses from a Ti:sapphire laser/regenerative amplifier system. The data were deduced from time-of-flight measurements of ion velocity and yield vs angle to the target surface and are described in detail elsewhere.[17]

Absolute values of I_{sp} are approaching 3×10^3 s, and, excluding lead, I_{sp} is roughly inversely proportional to the square root of mass (i.e., I_{sp} is strongly material dependent). For the majority of ablated elements, the kinetic energy E_K of individual ions varied within a relatively narrow range of ~20–50 eV. When kinetic energy is roughly constant, the speed is inversely proportional to the square root of mass and so is the specific impulse. Lead ions exhibited very high mean $E_K = 571$ eV. This effect, at least partly, can be caused by multiple ionization.[17]

Conclusion

To conclude this brief Note, it seems that ALP based on picosecond or subpicosecond pulses can be a reasonable alternative to existing LP concepts. The approach simplifies the construction of LP-driven vehicles and can resolve other limitations endangering the progress of LP using LSC/LSD wave mediated momentum transfer. Preliminary data indicate that ALP will have its own place in future space transportation applications.

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Criterion to Determine the Number of Modes in a Frequency Band

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Introduction

IN the time domain, selecting the model order, or the number of modes in a frequency band, is a key first step toward the goal of estimating the modal parameters of a vibrating system. Several information theoretic criteria have been proposed for this model-order selection task. Akaike has provided two criteria. His first criterion is the final prediction error (FPE)[1] criterion and selects the order so that the average error variance for a one-step prediction is minimized. Akaike also suggested another selection criterion using a maximum likelihood approach to derive a criterion termed the Akaike information criterion (AIC).[2] The AIC determines the model order by minimizing an information theoretic function. FPE and AIC are asymptotically equivalent but do not yield consistent estimates of the model order; the result is a tendency to overestimate the order as the data record length increases.[3] In response to this, another effective criterion, the minimum description length (MDL) criterion, is proposed by Schwarz[4] and Rissanen.[5] This criterion uses a penalty function, which provides consistent estimation of the model order. All of these methods are applicable only to scalar processes, and a generalization to multivariate processes remains to be established.

In this Note, using a combination of an overdetermined instrumental variable scheme[6] and the multivariate MDL criterion, we propose a new method for autoregressive (AR) order determination of a vector-autoregressive moving average or VARMA(p, q) process. To determine p, the order of the multivariate AR part, an overdetermined instrumental variable product moment matrix is defined. Once p has been estimated, the number of modes in a frequency band is derived. In a mechanical structure the number n of modes in a frequency band is related to the order p of the AR part and to the number of sensors m by the relation $p = 2n/m$.

The applicability of the proposed procedure to typical engineering problems is the determination of the model order from accelerometer output only, which is the first step in the estimation of modal parameters. The second step is the identification of these modal parameters using the eigensystem realization algorithm[7] or AR coefficients[8,9] of a VARMA model. The proposed method is experimentally applied to acceleration signals. But this method is easily generalized to other systems that use displacement or velocities and more generally an observation data vector, which has a VARMA representation.

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