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Plasma Actuation for the Control of a Supersonic Projectile

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The generation of a plasma discharge on a projectile surface seems to be a way of producing a pressure imbalance to divert a projectile from its initial trajectory. Thus, some experiments dealing with the steering of a supersonic projectile by using a plasma actuator are presented. The plasma discharge is produced by an embedded low-voltage generator capable of delivering an electric discharge between the electrodes flush with the projectile surface. A first series of experiments carried out under wind-tunnel conditions at a Mach number of 3 allows the detailed study of the perturbation evolution along the projectile surface, the disturbance being generated by the plasma discharge. A second series of experiments in the wind tunnel at the same Mach number demonstrates that a plasma discharge generates the angular deviation of a fin-stabilized projectile: 243 J of stored energy delivered in 2.5 ms at the cone–cylinder junction of the projectile induces an angle of attack of 2 deg after the plasma-discharge generation. Other experiments conducted in a shock-tube facility under low-altitude conditions prove that it is possible to activate a plasma discharge on a projectile flying at a Mach number of 6.

I. Introduction

THE change in the trajectory of a flying vehicle is made possible by unbalancing the pressures exerted on the body surface. This pressure imbalance can be produced by the deployment of control surfaces [1–9] or by the use of one or more pyrotechnical mechanisms judiciously distributed along the vehicle [10–15]. In the case of supersonic projectiles, the major drawback to the use of the surface-spreading technique is that large forces are involved for the deployment of surfaces to overcome the very high pressures encountered at high velocities. Thus, the use of pyrotechnical mechanisms is more appropriate for high-speed vehicles, but the fact that the pyrotechnical mechanism works only once and produces everything or nothing is a main drawback when a controlled angle of attack must be given.

The idea of generating electric discharges producing a plasma on the projectile surface comes from the analysis of different solutions for steering a guided supersonic projectile (GSP) flying at a Mach number (M) ranging from 3 to 4 [16]. The GSP is a short-range guided antiaerial projectile launched by a 40 mm gun and designed to increase its precision when faced with increasingly agile aerial vehicles flying up to a few kilometers of altitude. The underlying idea consists of giving the GSP a maneuvering capacity, allowing it to compensate for the trajectory prediction error. The plasma-actuator steering concept consists of unbalancing the flow around the projectile nose by producing one or several plasma discharges near the projectile nose. A patent describing the concept and a first high-voltage system was registered in February 2002 and was issued in France in January 2005 and in the United States in February 2006 [17]. A new low-voltage device was designed to avoid the high-voltage apparatus drawbacks and a patent was also registered in September 2005, was issued in France in December 2007, and was published in the United States in August 2007 [18].

Flow control around aerial vehicles using plasma has been part of the fluid dynamics flow control community for more than a decade. The most recent state of the art concerning a type of plasma actuator is given in [19]. That plasma actuator that is being used widely is based on a dielectric barrier discharge mechanism that has desirable features for use in air at atmospheric pressures. It has been employed in a wide range of applications that include drag reduction at supersonic speeds [20–22], steering vehicles at supersonic speeds [23], exciting boundary-layer instabilities at supersonic speeds [24–27], lift increase on a wing section [28–31], low-pressure turbine-blade separation control [32–37], turbine tip-clearance flow control [38,39], bluff-body flow control [40–42], turbulent boundary-layer control [43,44], unsteady vortex generation and control [45,46], and airfoil-leading-edge separation control [47–50].

Analysis of the previous publications shows that few studies are being conducted on supersonic projectile steering by the use of a plasma discharge. Therefore, the work described in this paper is original; indeed, a plasma-discharge production on the surface of a supersonic projectile flying in the low atmosphere has not been applied up until now for the control of projectiles in terms of a trajectory change.

Section II of the present paper deals with the principle of the concept for controlling a supersonic projectile by a plasma discharge. Section III describes in detail two plasma-discharge actuators. Section IV presents the experimental setups and the instrumentation used for the experiments. Section V shows the experimental results obtained in the wind-tunnel facility at Mach 3 and in the shock-tube facility at Mach 6. Section VI concludes the paper and proposes future investigations.

II. Principle of the Concept

In the case of a high-speed vehicle, a shock wave occurs at its nose tip or ahead of it, depending on the nose geometry. When the vehicle flies without any angle of attack, the pressures distributed on its surface balance one another out and the shock wave has symmetries depending on the vehicle geometry. For example, for a supersonic projectile forebody with a conical nose, the shock wave is attached to the cone tip and has itself a conical shape. The proposed concept consists of obtaining the asymmetry of the flow variables around the projectile nose by generating one or several plasma discharges at the nose tip to give an angle of attack to the projectile. Indeed, a single plasma discharge can produce an initial angle of attack followed by a damping motion, whereas a set of plasma discharges or a longer plasma discharge with constant power can produce a constant angle of attack.

Some theoretical investigations illustrate the feasibility of such a system [51]. Figure 1 presents the qualitative result of a numerical computation of the projectile forebody, flying from right to left near

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