23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

GUIDANCE OF A SUPERSONIC PROJECTILE BY A PLASMA ACTUATOR

P. Gnemmi and C. Rey

French-German Research Institute of Saint-Louis
PO. Box 70034, 68301 Saint-Louis, France
Phone: +33 389 695 187, Fax: +33 389 695 002, email: gnemmi@isl.tm.fr

The generation of a plasma discharge on a projectile surface seems to be a way of producing a pressure imbalance in order to deviate a projectile from its initial trajectory. Thus, some experimental and numerical investigations on the possibilities of guiding a supersonic projectile by using a plasma actuator are presented. The plasma discharge is produced by an embedded voltage generator able to supply an electric discharge between electrodes flush with the conical projectile nose. Experiments carried out in a shock-tube facility under low-altitude conditions prove that it is possible to activate a plasma discharge on a projectile which flies at a Mach number of 6. Transient numerical simulations are performed by using a Navier-Stokes code, in which the plasma discharge is modelled in a very simple way. The validation of the computation is achieved under wind-tunnel conditions at Mach 3. Another computation performed for a projectile flying at the altitude of 1.5 km at the same Mach number clearly shows the flow-field imbalance around the projectile: the drag force is reduced as expected, the lateral force and the pitching moment favourably combine with the aim of steering the projectile.

INTRODUCTION

The change of trajectory of a flying vehicle is made possible by unbalancing the pressures acting on the body surface. This pressure imbalance may be produced by surface deployment or by the use of one or more pyrotechnical mechanisms judiciously distributed along the vehicle. The major drawback when using the surface spreading technique is that it involves large forces for the deployment of surfaces in order to overcome the very high pressures encountered at high-speed 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 an angle of attack must be given to a high-speed vehicle.

Joint studies conducted at ISL and at DREV (Defense Research Establishment of Valcartier, Canada) on the use of projectile fins have been going on for a few years [1-5]. Another study of the use of grid fins on a hypersonic missile has started at ISL in cooperation with EADS-LFK GmbH (Unterschleissheim, Germany) [6]. Other studies, in which ISL, Rheinmetall Landsysteme GmbH (Unterlüss, Germany) and DLR (German Aerospace Center, Köln-Porz, Germany) are involved, deal with the use of lateral jets in order to laterally move supersonic or hypersonic projectiles and missiles [7-11]. All these studies treat the theoretical and experimental aspects of the problem.

The idea of generating electric discharges in order to produce a plasma on the projectile surface originated from the analysis of different solutions for steering a "Guided Supersonic Projectile" flying at a Mach number (*M*) of 3 [12]. The plasma-actuator steering concept consists in unbalancing the flow around the projectile nose by producing one or several plasma discharges near the projectile tip. A patent describing the concept and the first system was registered in February 2002 and was delivered in France in January 2005 and in the USA in February 2006 [13]. The research work is increasingly focused on the use of a plasma for the flow control of aerial vehicles, but few studies are being conducted on the projectile deviation by a plasma discharge. The work described in this paper is quite original (supersonic flow, low atmosphere that means a high-pressure medium) since no application of this type exists at present.

PRINCIPLE OF THE CONCEPT

In the case of a high-speed projectile, a shock wave occurs at its nose tip or ahead of it, depending on the nose geometry. When the projectile flies without any angle of attack, the pressures distributed along its surface balance out one another. For a projectile having a conical nose, the shock wave is attached to the cone tip and is itself of conical shape. The proposed concept consists in producing the imbalance of the flow variables around the projectile nose by generating one or several plasma discharges at the nose tip in order to give an angle of attack to the projectile. The plasma discharge generated over a limited sector modifies the flow structure around the projectile and its boundary layer. The objective consists of the production of plasma discharges so that the imbalance of the aerothermodynamic variables is large enough to cause the deviation of the projectile facing its initial trajectory.

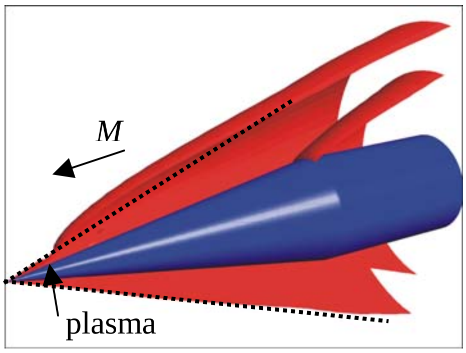


Figure 1. Surfaces of constant pressure in the flow field of a supersonic projectile having a plasma discharge

Theoretical investigations were undertaken in order to illustrate the feasibility of such a system prior to experimental investigations. Numerous numerical computations performed for an ideal gas show that the shock wave attached to the conical nose tip of the projectile is distorted by a discharge simply modelled. Figure 1 presents the result of the numerical computation of a supersonic projectile having a conical nose, flying from right to left, to which a plasma discharge is applied near the nose tip during a certain length of time. The figure shows the projectile forebody in blue and the halves of two surfaces in red. These surfaces represent a constant pressure in the flow field which is chosen to highlight its main structure. The attached shock wave is perfectly visible at the tip of the conical nose as well as the Prandtl-Meyer expansion wave at the junction of the conical nose and of the cylindrical part of the forebody. On the side of the conical nose where the plasma discharge is activated, the geometry of the shock wave is clearly distorted due to the action of the plasma discharge. On the contrary, on the opposite side, the geometry of the shock wave remains undistorted.

The absence of mobile parts and the repetitive action of discharges are the main advantages of this technique. In fact, the control of the projectile can be achieved by repetitive discharges activated on demand depending on the required trajectory.

EXPERIMETAL SET-UP AND INSTRUMENTATION

A lot of experiments are conducted in the 0.2 m × 0.2 m supersonic wind tunnel of ISL at $M = 3$. This facility operates in the blow-down mode with a blow duration of typically 50 s. The model-related Reynolds number based on the body diameter is 10^6; the static free-stream pressure is $P_\infty = 0.1906 \times 10^5$ Pa. The projectile model is mounted on a shaft assembly along the tunnel centre line.

Other experiments are carried out in a shock tunnel, in which the atmospheric flight conditions can be duplicated, ranging from ground level up to more than 30 km of altitude. The gas is expanded and accelerated inside the nozzle in such a way that the desired flight conditions are present at the nozzle exit during 3 to 4 ms. The body is fixed inside the test chamber at the front of the nozzle and the airflow is accelerated to the desired pressure, temperature and flight velocity.

The experimental study is conducted for a 50-mm caliber projectile (D) without any angle of attack. Figure 2 shows the sketch of the projectile geometry. Electrodes forming a plasma actuator are embedded in the conical nose, they are located near the tip of the projectile model. A plasma

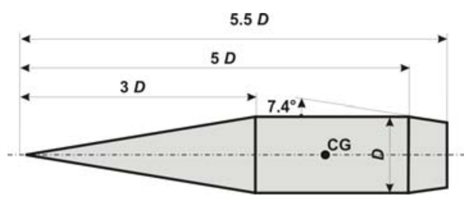


Figure 2. Projectile geometry

discharge is generated between these electrodes. The electrodes flush with the conical surface are arranged according to the longitudinal axis of the model, allowing the production of a quasi-linear discharge. The distance between the electrodes ranges from 3.5 to 9.5 mm.

The plasma discharge is produced by using of a voltage generator embedded in the projectile and able to supply an electric discharge between the electrodes. Measurements of the voltage and current during the plasma discharge are recorded. The plasma discharge is produced at the projectile nose tip when the flow is quasi-steady around the model. A differential interferometer system (DI) is used in order to visualize the flow field structure by a CCD camera. The DI is working as a flow visualization technique [14] based on the density-gradient field in order to gather information on a interferogram showing the flow pattern around the model. The DI apparatus is adjusted in such a way that the density-gradient direction is vertical.

NUMERICAL SIMULATION

Numerical simulations of the interaction of the plasma discharge with the projectile cross-flow were conducted by means of the CFX-10[*] code [15]. The fluid solver is based on the Reynolds-Averaged Navier-Stokes equations and provides solutions for the compressible, transient, turbulent single-phase fluid flow. For the computations presented here, the *SST* two-equation model of turbulence [16] was used to provide a link between the turbulent transport of momentum and energy and the mean flow variables and fluid properties. The computation was conducted using a first-order discretization scheme in space and a second-order one in time.

The numerical study was made for a 20-mm caliber projectile without any angle of attack. The location of the electrodes is identical to that defined by the experiments. The studied configuration having a symmetry plane, the numerical study was thus performed for half the computational domain. The computation focused only on the flow around the body, so that the projectile wake was not meshed.

A block-structured non-orthogonal grid was created to discretize the domain. The mesh is

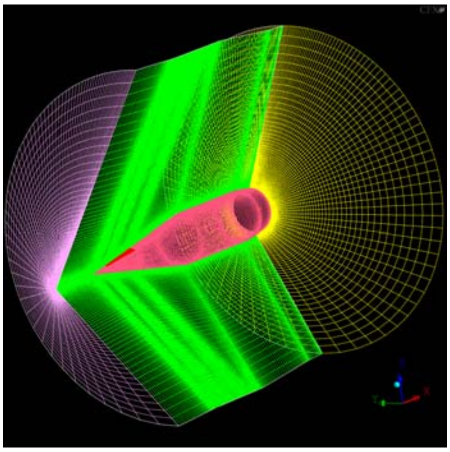


Figure 3. Mesh of the symmetry plane and of the projectile surface

[*] CFX-10™ is a trademark of ANSYS CFX Ltd.

composed of a block having 230 x 90 nodes in the longitudinal and radial directions. 70 nodes are distributed along the projectile circumference and are located closer to one another on the side of the plasma discharge. The complete mesh of the half-volume has 1,449,000 nodes (Figure 3).

The optimum performance of turbulence models is achieved by the proper resolution of the boundary layer and the correct spacing of the first point near the wall. The distance between a node located on the projectile surface and the first node located in the flow is 1.2 µm. Therefore, the mesh is built in such a way that the y^+ values are lower than 2, allowing the use of the near-wall treatment.

The interferogram pictures obtained from the experiments allow the adjustment of the boundary conditions of the numerical simulation in which the plasma discharge was modelled very simply. The plasma discharge was considered to be continuous. The computation was made for a perfect gas. The discharge was modelled by considering that a very small region of the projectile surface produces a temperature rise and a mass-flow-rate increase during a certain length of time. The major difficulty consists in quantifying the boundary conditions to be applied to the plasma-discharge generation. A previous study concerning the adjustment of the boundary conditions was used to fix the ones set for the computation [17]. The adjustment consisted in performing a numerical simulation with specific boundary conditions and in comparing the distortion of the computed shock wave attached to the nose tip with the experimental distortion. The adjustment is considered correct when the theoretical and experimental distortion traces of the shock wave can be superposed on one another.

RESULTS

A lot of experiments were carried out for different electrode distances, capacitors and supplying voltages. The study focused only on the first 60 millimeters of the conical nose in order to be comparable to the numerical simulation results. Thus, the experimental and computational configurations were perfectly identical.

Wind-Tunnel Facility, $M = 3$

The interferogram pictures were recorded using a PCO SENSICAM camera and the exposure time was 0.2 µs. A series of pictures was taken for a configuration in which the energy (E) stored in the capacitor was 12 J.

The plasma discharge was produced under wind-tunnel conditions at $M = 3$ without any angle of attack. The electrode distance was 3.5 mm. Figure 4 shows pictures taken before the plasma discharge ($t = 0$) and for 3 instants after the beginning of the plasma discharge until its extinguishing near 250 µs. The visualizations show that the generation of a plasma discharge produces a perturbation between the projectile surface and the shock wave attached to the conical projectile tip. The perturbation is maintained during a certain length of time and is strong enough to distort the attached shock wave. The perturbation is stronger on the upper side than on the lower side of the projectile tip producing an imbalance in the flow field, as expected.

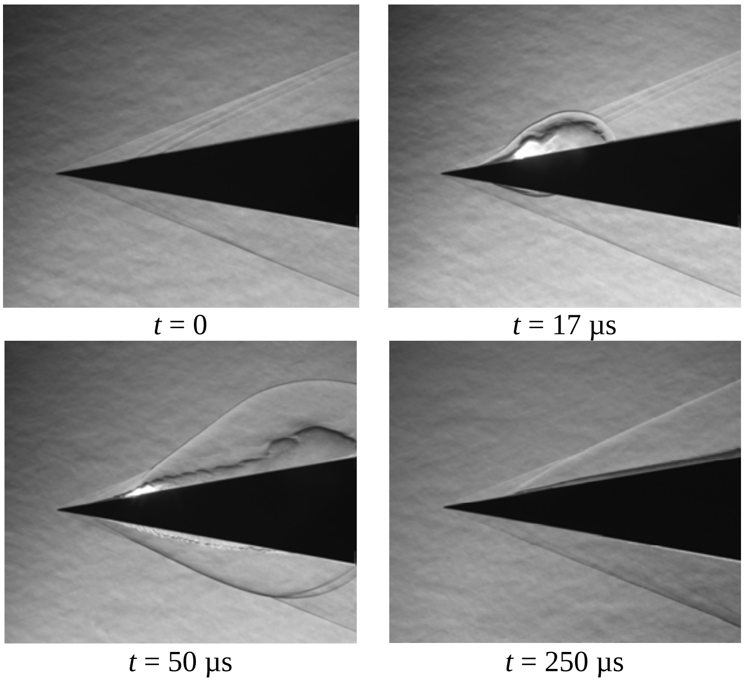
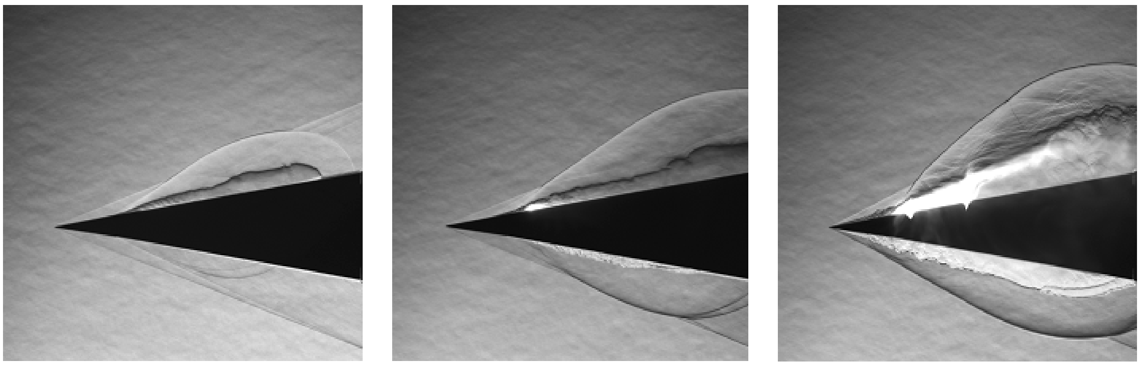


Figure 4. Plasma-discharge visualizations at *M* = 3, *E* = 12 J, time evolution

The influence of the energy is clearly examined by using capacitors able to supply 7, 12 and 50 J. Figure 5 shows interferograms taken 50 µs after the beginning of the plasma discharge: the higher the supplied energy, the larger the perturbation. This result must be analyzed very carefully: the fact that the perturbation is larger when the higher energy is used, does not mean that the pressure imbalance on the projectile surface is stronger.



7 J 12 J 50 J

Figure 5. Plasma-discharge visualizations at *M* = 3, *t* = 50 µs, energy influence

Numerical Simulation Validation: Wind-Tunnel Conditions, *M* = 3

Transient numerical simulations are carried out by using CFX-10, in which the plasma discharge is modelled in a very simple way. Figure 6 presents the interferogram and the computed density field disturbed by the plasma discharge under wind-tunnel conditions at *M* = 3. The qualitative comparison between the pictures shows the similarity between the visualized and the computed flow structures. The computations allow the quantification of the aerodynamic loads induced by the modelled plasma discharge.

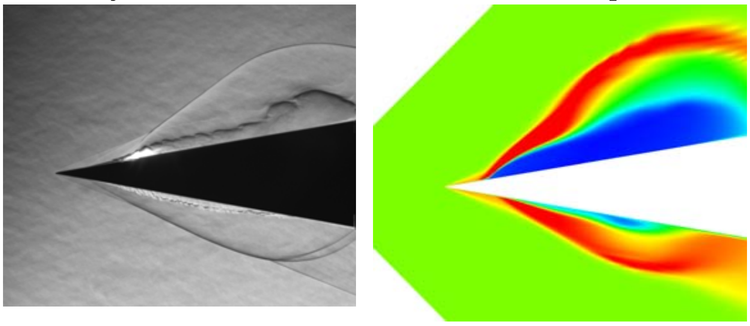


Figure 6. Visualized and computed flow structures, wind-tunnel conditions at *M* = 3, *t* = 50 μs

Numerical Simulation: Projectile at the Altitude of 1.5 km, *M* = 3

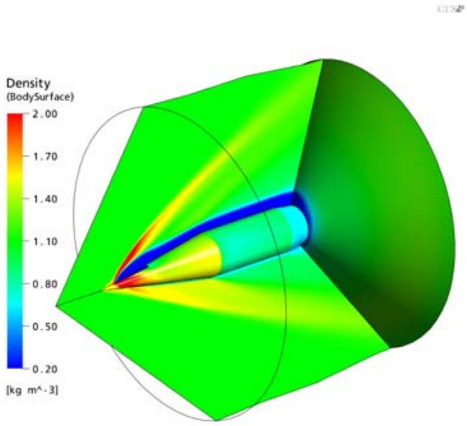


Figure 7. Computed density fields for the projectile flying at 1.5 km of altitude at *M* = 3

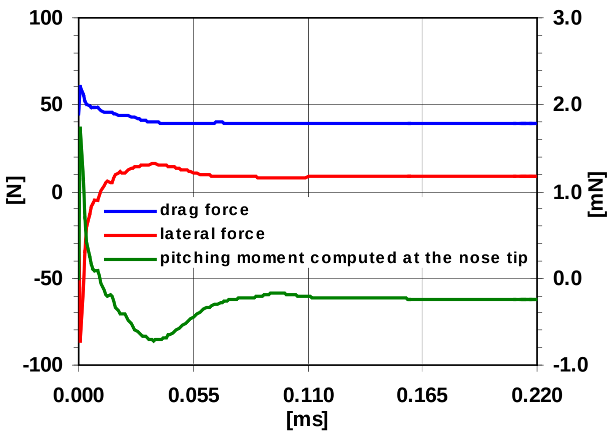


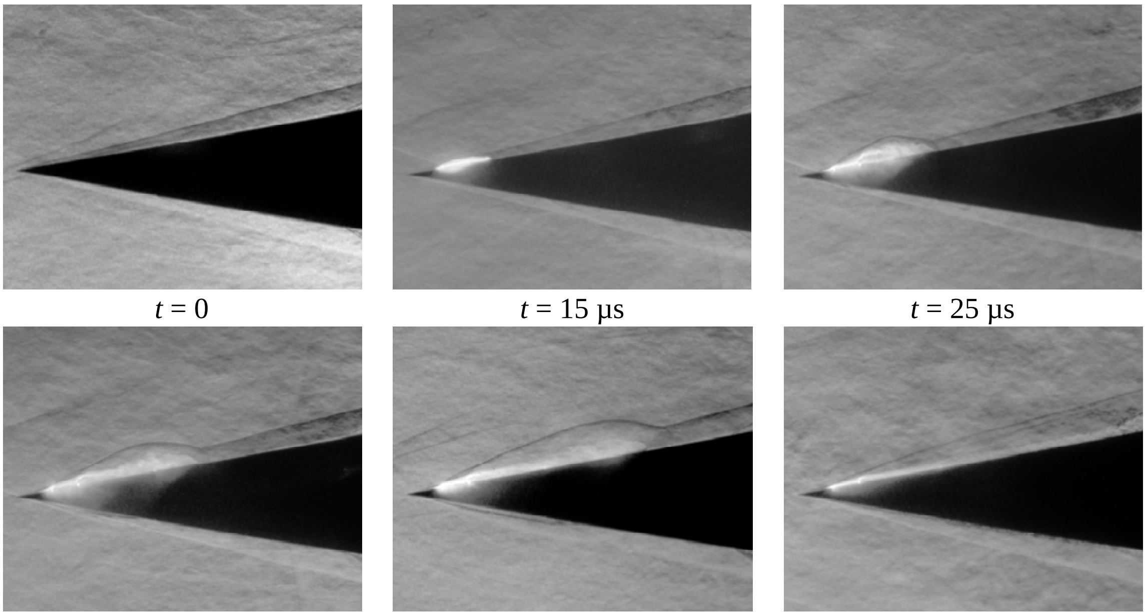
Figure 8. Computed resulting loads on the projectile flying at 1.5 km of altitude at *M* = 3

Another computation was conducted for the same projectile flying at the altitude of 1.5 km at an *M* = 3 without any angle of attack. Figure 7 presents the imbalance of the density field around the projectile and on the projectile surface after 220 μs of computation. The plasma discharge produces a reduction of the drag force, a lateral force and a pitching moment calculated at the nose tip (Figure 8). Despite the low amplitudes of the lateral force and the pitching moment, they favourably combine to steer the projectile. Nevertheless, the system can be interesting in case the loads are low, because a slight controlled dissymmetry of the flow field due to a discharge near the nose tip can destabilize the projectile when it flies near its stability limit. A second plasma discharge would stabilize the projectile again on the corrected trajectory.

Shock-Tube Facility: Projectile at Altitudes of 5 and 15 km, *M* = 4.5 and 6

More experiments were carried out in the shock-tunnel facility in order to prove the feasibility of activating a plasma discharge at the tip of a supersonic projectile flying in real conditions. Plasma discharges were performed on the same model at $M = 4.5$ and $M = 6$, at altitudes of 5 and 15 km, respectively. Series of interferograms were taken with a PCO HSFC PRO camera, the exposure time being 0.1 µs.

Figure 9 shows pictures taken before the plasma discharge ($t = 0$) and for 5 instants after the beginning of the plasma discharge. The energy stored in the capacitor was 50 J. The electrode distance was 9.5 mm. The visualizations prove again that the generation of a plasma discharge produces a perturbation between the projectile surface and the shock wave attached to the conical projectile tip. Due to the short exposure time, small structures are visible in addition to the main structures of the flow.



$t = 0$ $t = 15$ µs $t = 25$ µs

$t = 35$ µs $t = 50$ µs $t = 100$ µs

Figure 9. Plasma-discharge visualizations at *M* = 6, 15 km of altitude, *E* = 50 J, time evolution

CONCLUSION

A plasma-actuator device embedded in a projectile model has been developed in order to produce a plasma discharge at the tip of a projectile. The ISL wind-tunnel facility was used for studying the interaction of a plasma discharge generated at the tip of a conical projectile with a cross-flow at a Mach number of 3. The flow-field visualizations obtained by using a CCD camera located behind a differential interferometer have allowed the validation of a numerical simulation in which the plasma discharge is modelled in a very simple way, what seems to be sufficient for a first approach.

The shock tube used as a wind tunnel is a facility well adapted to the experimental study of the steering of a supersonic projectile flying in the conditions of the low atmosphere. The flow-field visualizations prove that a plasma discharge can be produced at the tip of a projectile flying at altitudes of 5 and 15 km, and at Mach numbers of 4.5 and 6, respectively, which is not trivial at all.

The studies will continue in wind-tunnel and shock-tube facilities and free-flight tests are planned for next year. Such a type of plasma actuator can be embedded anywhere on the projectile surface or in other parts of it, especially in fins, canards, etc. This concept can also be applied to other subsonic, supersonic or hypersonic flying vehicles such as missiles, UAVs, MAVs, waveriders, etc. However, an optimization phase is necessary for each application and this is long-term work. This is due to the fact that the resulting aerodynamic forces and moments are a function of the Mach number, angle of attack, actuator number, delivered energy and voltage, actuator location, electrode distance, etc.

ACKNOWLEDGMENTS

The authors thank the Aerothermodynamics and Shock Tube Department and the Aerodynamics and Wind-Tunnel Department staff for their efficiency. They thank A. George and N. Faderl for the devotion which they showed when conducting the experiments.

REFERENCES

[1] C. Berner, A. Dupuis, Wind Tunnel Tests of a Grid Finned Projectile Configuration, *39th Aerospace Sciences Meeting & Exhibit,* Reno/NV, USA, January 08-11, 2001

[2] A. Dupuis, C. Berner, Aerodynamic Aspects of a Grid Finned Projectile at Subsonic and Supersonic Velocities, *19th International Symposium on Ballistics*, Interlaken, Switzerland, May 7-11, 2001

[3] C. Berner, A. Dupuis, Wind Tunnel Tests of a Long-Range Artillery Shell Concept, *AIAA Atmospheric Flight Mechanics Conference and Exhibit,* Monterey/CA, USA, August 5-8, 2002

[4] C. Berner, V. Fleck, A. Dupuis, Experimental and Computational Analysis for a Long-Range Spinning Artillery Shell with Lifting Surfaces, *20th International Symposium on Ballistics*, Orlando/FL, USA, September 23-27, 2002

[5] A. Dupuis, C. Berner, V. Fleck, Aerodynamic Characteristics of a Long-Range Spinning Artillery Shell. Part 1: From Aeroballistic Range Free-Flight Tests, *21st International Symposium on Ballistics*, Adelaide, Australia, April 19-23, 2004

[6] J. Srulijes, F. Seiler, P. Hennig, P. Gleich, Visualisierung der Umströmung von Lenkflügeln im Stoßrohr-Windkanal bei realen atmosphärischen Strömungsbedingungen, ISL report RV 229/2004, 2004

[7] P. Gnemmi, F. Seiler, Interaction of a Lateral Jet with the Projectile External Flow, *Atmospheric Flight Mechanics Conference & Exhibit*, Denver/CO, USA, August 14-17, 2000

[8] H.J. Schäfer, E. Augenstein, H. Esch, H. Emunds, Experimental Investigation of Transverse Jet Interaction on a Missile Body Using Laser Velocimetry and Flow Visualization, *19th International Congress on Instrumentation in Aerospace Simulation Facilities*, Cleveland/OH, USA, August 27-30, 2001

[9] F. Seiler, P. Gnemmi, H. Ende, M. Schwenzer, R. Meuer R., Jet Interaction at Supersonic Cross-Flow Conditions, *Shock Waves*, Vol. 13, No. 1, July 2003, pp. 13-23

[10] P. Gnemmi, H.J. Schäfer, Experimental and Numerical Investigations of a Transverse Jet Interaction on a Missile Body, *43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno/NV, USA, January 10-13, 2005

[11] M. Havermann, F. Seiler, H. Ende, A. George, Untersuchungen im Stossrohr-Windkanal zur Steuerung eines Hochgeschwindigkeits-Flugkörpers mit Seitenstrahlen, ISL report RV 232/2004, 2004

[12] P. Wey, C. Berner, E. Sommer, V. Fleck, H. Moulard, Theoretical Design for a Guided Supersonic Projectile, *22nd International Symposium on Ballistics*, Vancouver, BC, Canada , 2005

[13] P. Gnemmi, M. Samirant, R. Charon, ISL, Saint-Louis, France, French Patent Application for "Pilotage d'un projectile par décharge plasma," Patent No. 02 12906 registered on 17 Oct. 2002, delivered on 7 Jan. 2005. USA Patent Application for "Projectile Steering by Plasma Discharge," Patent No. US 7,002,126 B2 registered on 17 Oct. 2003, delivered on 21 Feb. 2006

[14] G. Smeets, Interferometry, ISL Report CO 214/90, May 1990

[15] ANSYS Canada Ltd., "CFX-TASCflow Computational Fluid Dynamics Software, Version 2.12,", Waterloo, Ontario, Canada, 2003

[16] F.R. Menter, Two-Equation Eddy-Viscosity Turbulence Models for Engineering Application, *AIAA Journal*, Vol. 32, No. 8, 1994, pp. 1598-1605

[17] P. Gnemmi, R. Charon, J.P. Dupéroux, A. George, Feasibility Study for Steering a Supersonic Projectile by a Plasma Actuator, under revision for *AIAA Journal* publication