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SIDE JET INTERACTION WITH SUBSONIC, TRANSONIC AND SUPERSONIC CROSSFLOW: SURFACE PRESSURE DISTRIBUTION

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Abstract: *This paper examines the interaction between a free stream and side jet flow. Experiments were conducted in the VTI T-38 trisonic wind tunnel. The internal side jet system was configured with either sonic or supersonic nozzles, integrated on a generic missile model. Tests were performed at the free stream Mach numbers ranging from subsonic through transonic to supersonic regimes. This interaction generated unique boundary layer profiles and oblique shock wave structures. The resulting tests yielded evaluated pressure distributions and quantified data regarding the interference between the free stream and side jet flows. Such data is essential for analyzing the side jet effects on flow separation, the location of the center of pressure, and the overall maneuverability and stability of missiles.*

Keywords: *trisonic wind tunnel; side jet; pressure distribution; flow interference and separation.*

1. INTRODUCTION

Control of missile systems designed for high agility and maneuverability is increasingly being achieved using side jet control. In contrast to control surfaces that become ineffective at low pressures, side jet control maintains its effectiveness under these conditions. The side jet's effects depend primarily on: the diameter of the side jet nozzle, jet pressure, the Mach number and static pressure of the external flow. In aerodynamic laboratories, various methods and equipment are being developed for wall pressure measurements to investigate the interference of a side jet with cross flow [1-3].

This paper presents results of the pressure distribution measurements on the generic missile model with side jets. Measurements were conducted in the VTI T-38 trisonic blowdown wind tunnel in the subsonic, transonic and supersonic speed range [4]. Tests were conducted with a sonic and supersonic side jet nozzle installed on the generic missile model and for two different values of the side jet mass flow.

2. TEST FACILITY

The VTI T-38 test facility is large scale blowdown wind tunnel. Depending on the Mach number and stagnation pressure, the facility permits run duration from 6 to 60 seconds. The 1.5 m x 1.5 m test section is equipped with a two-degree-of-freedom model support system that permits pitch angles of ±20° and roll angles of 720°. Stagnation pressure can be in range from 1.2 to 15 bar, enabling unit Reynolds numbers, R_e/m, from 5 x 10^6 m^{-1} to 110 x 10^6 m^{-1}. Mach number range in the VTI T-38 wind tunnel test section is 0.2-4.0. Subsonic and supersonic tests are performed in the solid-wall test section, where the Mach number is set by second throat and the variable-geometry nozzle, respectively. For transonic tests, a porous-wall test section is with variable porosity and an ejector-assisted blow-off system is inserted into the wind tunnel circuit for active Mach number control.

2.1 Model description

The generic missile model is developed in VTI, Figure 1. This model is designed for testing primarily in supersonic speed range. The generic missile model consists of an

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ogive nose cone, cylindrical fuselage and four wrap-around fins. Its nominal body dimeter is D = 64 mm. The total length of the cylindrical fuselage, which consists four segments, is 18 D. The ogive nose cone has a length of 3.6 D. The generic missile model is characterized with large slenderness ratio. Ratio of the model length to the model base diameter is close to L/D = 22. Four movable wrap-around fins are installed on the rear fuselage segment and can be individually set to different deflection angles. For the present test campaign, the fins were positioned at 0° deflection. In the initial phase of the testing the model was tested without side jet system and with six-component internal wind tunnel balance [6]. In the measurements with side jet system, aerodynamic forces and moment were measured with five-component flow-through balance. The experimental results obtained in tests with six-component balance were used to determine the optimum position of the five-component balance within the model and maximum Mach number in supersonic testing of the model with side jet system.

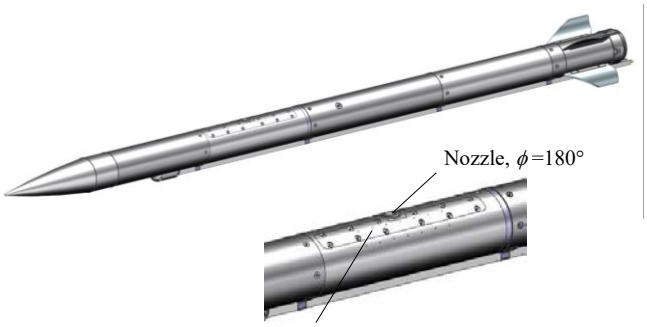


Figure 1. The generic missile model

For investigation of side jet interactions with cross-flow two interchangeable side jet nozzles were designed and manufactured: a sonic (Mach 1) and supersonic (Mach 4) nozzle, both with throat diameter of d = 4 mm. The side jets are positioned at 8.5 D downstream of the model nose and at an azimuth angle of ϕ = 180°. The side jet nozzles are supplied with high-pressure air from an external source through five-component flow-through balance and internal settling chamber that houses the nozzles [7].

2.2 Pressure distribution measurements

For measurements of the wall pressure distributions, the model has 34 static pressure taps with a diameter of 0.8 mm. The static pressure taps are arranged in five longitudinal rows around the nozzle exit, Figure 1. The pneumatic tubing from the taps are connected to a Scanivalve MPS4264 miniature digital pressure scanner module, Figure 2. The MPS4264 is a 64-channel scanner with a full-scale range of 1 bar, long-term accuracy of ±0.06 % of full scale, integrated 24-bit analog-to-digital conversion, and maximum scan rate 850 Hz. Reference pressure for all scanner channels is static pressure measured in the tunnel tests section, i.e. pressure of the external flow.

Each scanner channel directly outputs the pressure difference between local surface static pressure and static pressure of the external flow, p-p_∞ , which is used to calculate the pressure coefficient according to next equation:

$$Cp = 2\,(p-p_\infty)/(p_\infty kM^2) \qquad (1)$$

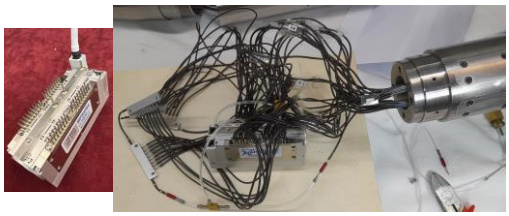


Figure 2. Miniature pressure scanner module

By varying the external source pressure, it was possible to set a predefined side jet pressure ratio p_{ojet}/p_∞. The pressure ratio of the side jet was set to a constant value before the start of cross flow in the wind tunnel test section. The model was traversed in 5° steps in the range -10°≤ α ≤ 10°, or through -12°≤ α ≤ 12° angles during more dynamic and faster sweep regime of measurement. The shock structure is visualized by schlieren technique. The schlieren system for the VTI T-38 wind tunnel is a Toepler parallel beam folded Z-type system.

3. EXPERIMENTAL RESULTS AND DISCUSION

The generic missile model with side jet system in the VTI T-38 wind tunnel test section is shown in Figure 3.



Figure 3. The generic missile model in the VTI T-38 wind tunnel

Experimental results of the side jet interaction with cross flow for Mach numbers M = 0.5, 0.9 and 1.6 are presented. The results refer on sonic nozzle (Mach 1) and the model angle of attack 0°.

The measurements were carried out under test conditions shown in Table 1.

Table 1. Test condidtions

M	M_{jet}	Re	p_o [bar]	p_∞ [bar]	p_{ojet}/p_∞
0.5	1	2.15×10^7	2.0	1.675	18.55
0.9	1	3.06×10^7	2.3	1.360	23.955
1.6	1	3.24×10^7	2.3	0.561	49.72

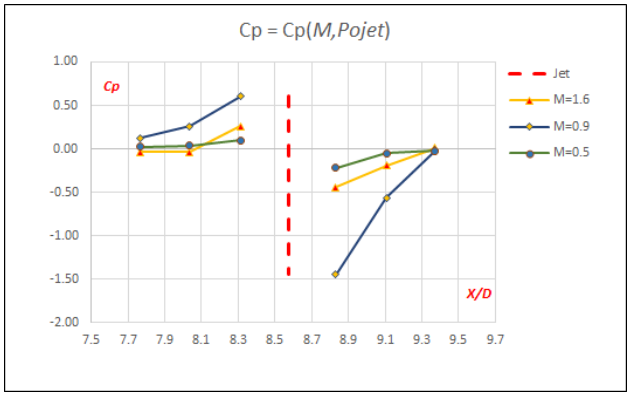


Figure 4. Pressure coefficient distribution: dependence on Mach number and side jet flow characteristics

Pressure distribution across different Mach numbers, shown in figure 4, exhibits close similarity in its overall curve character. Observation reveals that free flow loses velocity (indicated by higher *Cp* values) as it approaches the jet. This interaction between the free flow and the jet effectively acts as a barrier, reducing dynamic pressure and contributing to the overall force generated by the side jet. Consequently, the nozzle produces not only a reactionary force inherent to its design but also a secondary aerodynamic force, acting in the same direction and, though smaller, significantly impacting the overall behaviour.

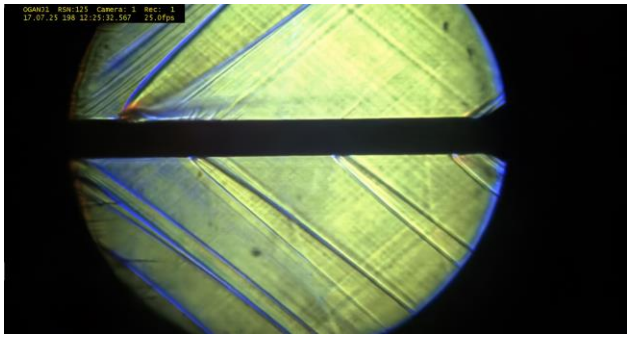


Figure 5. Schlieren system visualisation of shock waves generated by free stream and side jet interaction.

Schlieren system visualization provides a detailed view of the array of aerodynamic effects generated by the interaction. Visualization based on density differences provides an implicit view of changes in fluid properties – specifically, the shear layer, Figure 5. Rapid expansion of gas into the free stream field acts as a blunt obstacle against the free stream, resulting in the formation of a bow shock in front of the visible barrel shock. A small separation region is observed near the bow shock zone.

Shear layer vortices and more turbulent flow develop downstream and gradually recirculate into the main flow. Expansion of the side jet generated a Mach disc, along side the expected bowshock.

A heatmap overlay further revealed asymmetry in the pressure distribution, Figure 6. Subsequent analysis indicated that this asymmetry was a consequence of material discrepancies, which subsequently disrupted the already turbulent flow near the nozzle. In other words, the observed pressure asymmetry was primarily a result of the model's physical construction and had no direct relationship to the interaction of the side jet.

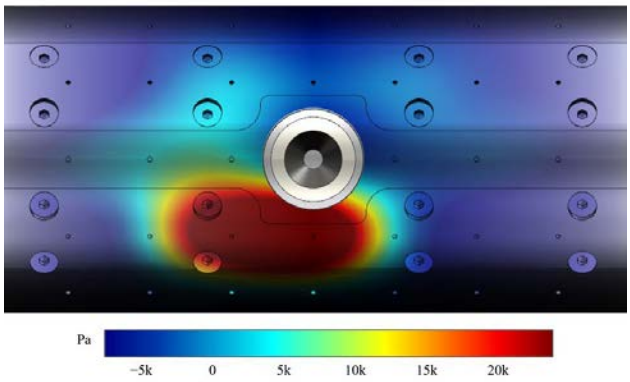


Figure 6. Pressure distribution over area near nozzle for supersonic crossflow (external flow *M*=1.6, side jet flow M=1)

With this data, it was possible to confidently deduce that the overall pressure distribution, under similar conditions, remained within a range of no more than 10 kPa.

Furthermore, Figure 6. provides in quantity and quality more broad view of general interaction between free stream and side jet. The stagnation zone can clearly be observed in front of the nozzle, along with zone of recirculation further downstream.

4. CONCLUSION

Effective control of aerodynamic bodies utilizing side propulsion systems depends not solely on the impulse generated by the reactive force, but also on a comprehensive understanding of the aerodynamic effects produced under these conditions.

The resulting bowshock, Mach disk, intensified turbulence, and flow separation further complicate the necessary control strategies.

Tests conducted under transonic conditions demonstrated that transonic flight generates the greatest aerodynamic contribution to the overall force, along with significant flow separation.

During these tests, it was clearly demonstrated that pressure distribution and flow separation, when considering the interaction between the freestream and the side jet, should not be dismissed. Indeed, careful consideration of flow separation is crucial in real flight conditions.

Acknowledgements

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Nomenclature

C_p	– Pressure coefficient
D	– Model diameter
d	– Throat diameter
L	– Model length
M	– Mach number
p	– Local surface pressure
p_∞	– Static pressure of the external flow
p_{ojet}	– Jet stagnation pressure
R_e	– Reynolds number
k	– Specific heat ratio for air
α	– Angle of attack