Studies on Thrust Vector Control using Secondary Injection Sonic and Supersonic Jets


Abstract—Numerical studies have been carried out using a validated two-dimensional steady RNG k-epsilon turbulence model with standard wall functions for the design optimization of a thrust vector control system for aerospace applications. In the present paper we focus on two critical elements of the thrust vector control system with non-reacting gas. The first one pertains to the location of the secondary injection nozzle and the second one refers to the desired flow features of the secondary jet. Parametric analytical studies have been carried out with various secondary jet pressures at different divergent locations. We concluded that fixing the supersonic secondary jet nozzle at a distance around 20 % of the total nozzle length away from the exit boundary could facilitate better thrust vectoring for the supersonic aerospace vehicles with a marginal decrease in acceleration compared to the sonic secondary jet. We also concluded that supersonic secondary jet will be more powerful than the sonic secondary jet with the same mass flow rate and jet pressure for an efficient and lucrative thrust vectoring.

Keywords— Fluidic thrust vectoring, rocket steering, secondary jet, TVC in spacecraft.

I. INTRODUCTION

THRUST Vector Control (TVC) or Thrust Vectoring is a technology that deflects the mean flow of an engine jet from the centerline in order to transfer some force to the aimed axis. By that imbalance, a momentum is created and used to control the change of attitude of the aircraft. Among other things, thrust vectoring greatly improves maneuverability, even at high angles of attack or low speeds where conventional aerodynamic control surfaces lose all effectiveness. Thrust Vector Control is currently achieved by complex arrays of mechanical actuators capable of modifying the geometry of the nozzle and thus deflects the flow. This variable geometry greatly increases weight and maintenance to the engine, and therefore limits the benefits from vectoring the thrust. Fluidic Thrust Vector Control is a technology aiming at the above listed benefits by the use of fluidic means, implying less complexity and faster dynamic responses. Different concepts have been developed in the last decade to redirect the thrust without mechanical actuators.

The concept of TVC by secondary fluid injection into the exhaust stream dates back to 1949 and can be credited to A. E. Wetherbee, Jr [1]. Application of liquid injection thrust vector control (LITVC) to production vehicles began in the early 1960s. Both inert (water) and reactive fluids (such as hydrazine or nitrogen tetroxide) have been used. Although side injection of reactive liquids is still used on some of the older vehicles, it requires a pressurized propellant tank and a feed system. A high-density injection liquid is preferred because its tank will be relatively small and its pressurization will require less mass. Because other schemes have better performance, liquid injection TVC will probably not be selected for new applications. Hot gas injection TVC of solid rocket propellant or liquid propellant combustion products is inherently attractive from a performance and packaging viewpoint. In liquid propellant engines it is feasible to tap or withdraw gas from the thrust chamber at a location where there is an intentional fuel-rich mixture ratio; the gas temperature would then be low enough (about 1100°C) so that uncooled metal hardware can be used for hot gas injection TVC valves and piping. The total side force resulting from secondary injection of a fluid into the main stream of the supersonic nozzle can be expressed as two force components: (1) the force associated with the momentum of the injectant; and (2) the pressure unbalance acting over areas of the internal nozzle wall. The second term results from the unbalanced wall pressures within the nozzle caused by shock formation, boundary layer separation, difference between injectant and undisturbed nozzle stream pressures, and primary-secondary combustion reactions (for chemically active injectants). The strength of the shock pattern and the pressure unbalance created between opposite walls in the nozzle is dependent on many variables, including the properties of the injectant and whether it is liquid or gas. These are succinctly reported in the open literature [1]-[15].

Fluid injection induces a bow shock in the supersonic stream followed by a deflection of the flow and high pressure on the downstream side of the shock. This produces necessary
vectoring in the desired direction. Literature review reveals that the maximum vector deflection angle occurs at mass flow rate ratios ($m_{inj}/m_{nozzle}$) in the range of 0.05 - 0.08. The deflection angles can be as high as $7^\circ$ with liquid injection and up to $12^\circ$ with hot gas injection.

With the advent of computational fluid dynamics (CFD) and available computer power, several numerical studies have been reported on the TVC of aerospace launch vehicles using different techniques [14] - [15]. Even though all these studies have been helpful in interpreting many fundamental processes on thrust vectoring, the understanding of an efficient and lucrative TVC system using secondary injection TVC has been elusive. This calls for a reexamination of all the available information before embarking on the formulation of a new TVC system with sonic and/or supersonic secondary injection. In the present paper we focus on two critical elements of the thrust vector control system with non-reacting gases both primary and secondary. The first one pertains to the location of the secondary injection nozzle and the second one refers to the desired flow features of the secondary jet.

II. NUMERICAL METHOD OF SOLUTION

Numerical simulations have been carried out with the help of a two-dimensional steady RNG k-epsilon turbulence model with standard wall functions. Ideal gas is considered for analysis. The model uses a control-volume based technique to convert the governing equations to algebraic equations. The viscosity is computed based on Sutherland formula. A typical grid system in the computational domain is selected after a detailed grid refinement exercises. The grids are clustered near the solid walls using suitable stretching functions. The nozzle geometric variables and material properties are known a priori. Initial wall temperature, inlet total pressure and temperature are specified. At the solid walls a no slip boundary condition is imposed. The code has successfully validated with the help of benchmark solutions. Figure 1 shows the physical models of the primary nozzle and the locations of the jet nozzles ($L_1$-$L_4$), both sonic and supersonic. Nozzle flow features have been examined with sonic and supersonic secondary jet nozzles at various locations between the nozzle exit and the throat with different jet pressures.

![Fig.1 Physical models of the primary nozzles with sonic and supersonic secondary jet nozzles](image)

(a) TVC with sonic jet  (b) TVC with supersonic jet

Fig.2 Grid systems in the computational domain (Corresponding to secondary jet nozzle location $L_2$ in Fig.1.)

III. RESULTS AND DISCUSSION

Thrust vectoring is the ability of an aircraft, rocket, or other vehicle to manipulate the direction of the thrust from its engine(s) or motor in order to control the attitude or angular velocity of the vehicle. Aerospace vehicles that fly outside the atmosphere, aerodynamic control surfaces are ineffective, so thrust vectoring is the primary means of attitude control. In this paper the forces produced by the exiting exhaust gases are manipulated from the axial direction to produce a side or vertical force by injecting a secondary jet with different jet pressures from various divergent locations of the primary nozzle to examining the best location and the desirable secondary jet characteristics for devising an efficient TVC system. Note that after injecting the secondary jet to the primary flow the resulting force vector will have an axial component in line with the body that propels the aircraft forward and a radial or side force that will result in a turn angle of the body. We have selected both sonic and supersonic jet nozzles for the secondary injection at four different divergent locations of the primary nozzle (see Fig. 1(a-b)).
Fig. 3 Various contours of the primary nozzle showing the shock free divergent region for the model validation.

(a) Mach number contour before vectoring

(b) Static pressure contour before vectoring

Low  High

Fig. 4 Contours before vectoring with secondary sonic nozzle geometry.

(a) Mach number contour after vectoring

(b) Static pressure contour after vectoring

Low  High

Fig. 6 Contours after vectoring with secondary sonic nozzle geometry.

(a) Mach number contour after vectoring

(b) Static pressure contour after vectoring

Low  High

Fig. 7 Contours after vectoring with secondary supersonic nozzle geometry.

(a) Mach number contour after vectoring

(b) Static pressure contour after vectoring

Low  High
In cases (Fig. 8,10 and Fig. 9,11) ratio of the primary to the secondary mass flow is kept constant. Secondary jet pressure is varied from 2 MPa to 10 MPa to facilitating different primary to secondary mass flow rate ratios for the design optimization of TVC system. As a first step primary nozzle flow features are examined without having any secondary jet nozzle geometry for model validation (see Fig. 3). Figures 4-7 show very clearly the variations of contours before and after vectoring with sonic and supersonic secondary jets with 10 MPa jet pressures. Shock waves are evident in both cases near the secondary jets. It is very interesting to note that such shock waves will be helpful for thrust vectoring. Figures 8-11 show the nozzle exit radial velocity profile corroborating the various qualities of vectoring produced with different secondary jets locations and with different jet pressures but with the same primary to the secondary mass flow rate ratio. For examining the influence of location of secondary injection jet nozzle we have carried out parametric studies with the same primary to the secondary mass flow rate ratio \( \frac{m_p}{m_s} \). Later we have varied \( \frac{m_p}{m_s} \) and conducted parametric studies a few cases are reported in Figures 8-11. Note that Case-1 corresponds to the baseline case without secondary jet and Case-2 corresponds to location \( L_1 \), Case-3 corresponds to location \( L_2 \), Case-4 corresponds to location \( L_3 \) and Case-5 corresponds to location \( L_4 \), which are shown in Fig.1(a-b). Figure 12(a-c) shows clearly the variations of flow features after vectoring with supersonic secondary jets with 10 MPa injection jet pressures. Shock waves are evident in each case. Note that the secondary jets influence over a segment of the nozzle drastically alters the pressure distribution on the nozzle surface in an unsymmetrical way about the nozzle axis. This produces the necessary moments to the vehicle (pitch, yaw and certain extent to roll also). We have observed from these studies that the magnitude of vectoring increases as the location of the secondary injection port is at \( L_2 \), which is near to the nozzle exit. We have also observed that with the secondary injection, the axial thrust level also increases to certain extent because of the enhanced mass flow. But at higher injection rates the shock affect the bulk of the flow, thus bringing down the axial thrust values and marginally decreases the vehicle acceleration. Note that at higher injection rates, the interaction with the opposite walls tends to lower the side force also.

All these studies lead to say that in addition to the primary to the secondary flow rate, the jet pressure, location and characteristics of jet are important for the quantitative estimation of thrust vectoring for aerospace applications.
away from the exit boundary could facilitate better thrust vectoring for supersonic aerospace vehicles with a marginal decrease in acceleration compared to the sonic secondary jet for the case on hand. In the case of aerospace with sonic secondary jet TVC system vehicle acceleration is found decreased on the order of 0.56%. We also concluded that supersonic secondary jet will be more powerful than the sonic secondary jet with the same mass flow rate and jet pressure for an efficient and lucrative thrust vectoring.

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REFERENCES


IV. CONCLUDING REMARKS

We concluded that fixing the supersonic secondary jet nozzle at a distance around 20 % of the total nozzle length from these parametric studies we have conjectured that the supersonic secondary jet nozzle fixed at a location around 20 % of the nozzle length away from the nozzle exit with a secondary jet pressure of 10 MPa will facilitate better thrust vectoring with the chosen primary nozzle. Nevertheless, we have observed that while using supersonic secondary jet the vehicle acceleration is found marginally decreased while comparing a case with sonic secondary jet with the same primary to secondary mass flow rate. We have observed that in the case of TVC with sonic secondary jet average exit velocity is significantly decreased compared to the supersonic secondary jet with same in flow conditions. Therefore designer should select the secondary jet location and characteristics judiciously after detailed analyses with all the operating ranges of the aerospace vehicles.