To link to this article: DOI: 10.2514/1.59827
URL: http://dx.doi.org/10.2514/1.59827

To cite this version: Binder, Nicolas and Carbonneau, Xavier *Performance of a Thrust Vectoring Solution for UAV.* (2012) Journal of Propulsion and Power, vol. 28 (n° 5). pp. 1125-1129. ISSN 0748-4658

Performance of a Thrust Vectoring Solution for UAV

Nicolas BINDER[1] and Xavier CARBONNEAU[2]
Université de Toulouse;

Institut Supérieur de l'Aéronautique et de l'Espace (ISAE);

10 avenue Edouard Belin,

31400 Toulouse, France

Nomenclature

C_y Lateral force coefficient

CD Distance between engine nozzle and cover-nozzle

EGT Exhaust Gas Temperature

F Thrust

L Cover-nozzle length

N Rotational speed

S Geometric section

SFC Specific Fuel Consumption

V Velocity

R^2 Auto-correlation factor

β Cover-nozzle deviation

Subscript

R Corrected expression with atmospheric conditions

x Projection along engine-axis

y Projection along lateral-axis

P Pitching plane

---

[1] Associate Professor, Département d'Aérodynamique, Energétique et Porpulsion, nicolas.binder@isae.fr, **corresponding author**.
[2] Associate Professor, Département d'Aérodynamique, Energétique et Porpulsion, xavier.carbonneau@isae.fr

Y Yawing plane

I. Introduction

The strategic importance given by UAV/UCAV (Unmanned (Combat) Air Vehicle) for intelligence activities has been demonstrated in military aviation ([1]). Stealth is enhanced by the small size, and maneuverability is no more limited by human presence. In that purpose, the addition of vector thrust systems on UAV/UCAV applications increases their potential. The stealth quality is supported by the prospect of suppressing the vertical tail, as proposed in [2]. Maneuverability is enhanced by the possibility to reach flight configurations impossible for conventional aircrafts with classical control surfaces. The issue has been widely presented and summarized in [3] or more recently in [4], where the requirements in terms of super maneuverability or post-stall behavior have been described. However, for UAV/UCAV application, solutions such as internal thrust vectoring (ITV) are seldom conceived for complexity and mass reasons. External thrust vectoring (ETV) is preferred: post-nozzle exit that deflects the exhaust jet in the yawing and pitching plans and depending on the design, also roll coordinates (for twin-engined applications). A reasonable deviation in yawing and pitching describes a cone of 20^o of half angle (+/-10^o was proposed in [3]). From a physical point of view, the flow deviation can be either generated by fluidic effects (see [5]), or more commonly by mechanical deviation. A comparison between the two solution is proposed in [1] but the latter is preferred for simplicity reasons, since the flow control of fluidic deviation is quite complex to implement (see [6] or more recently in [7]). But the mechanical solution suppose an adequate integration on the aircraft to avoid drag increase during deviation of the device, as studied by [8], or for stealth consideration, as seen in [9]. The present study focuses on the mechanical solution: a simple mobile nozzle, covering the engine nozzle is deviated. A performance analysis for such a simple solution has to be conducted since it is poorly presented in the recent literature, which focuses on ITV, or fluidic solutions. In addition to its simplicity, the cover nozzle also present the advantage to avoid the distortion of the nozzle geometry as described in [10] for IVT applications. This means that the differences of the results compared with the theoretical expectation are only due to the flow pattern. Those kind of discrepancies are the difference between the geometric and the effective vectoring angle, or the flow coefficient, and are presented and modeled in [11] and [12] for IVT solutions. But prior to any evaluation of the performance of the system, the question of the influence of the cover nozzle on the engine behavior must be treated, as was suggested by [13]. Any modification of the outlet configuration of the engine can induce a modification of the pressure field in the engine and displace the operating point to the surge region. The work conducted and here presented is based on an experimental approach, to feed the discussion of the two points mentioned (influence on engine behavior and performance). Since theses effects are geometry-dependent (cover nozzle geometry, distance to the engine nozzle...) different configurations will be studied. The experimental approach is developed, then a short presentation of the experimental device is proposed, leading to the discussion of the results.

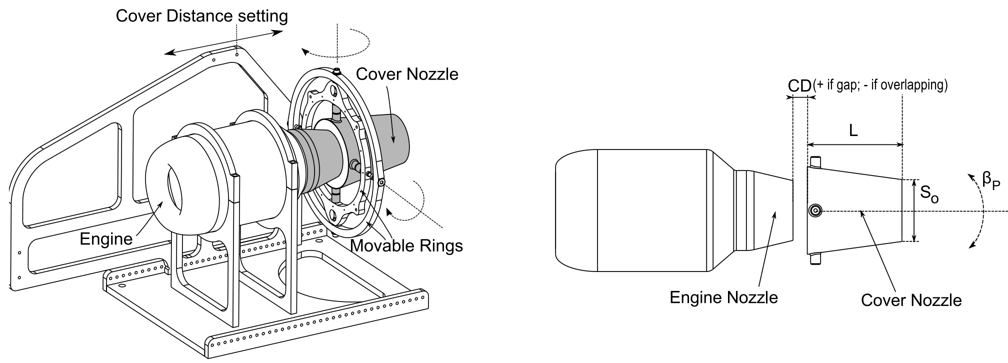
II. Experimental approach

Two objectives are defined for this work:

1. determine the influence of the cover nozzle on the engine operating line;

2. analyze the performance of the vectoring system compared with classical control surfaces.

The experimental approach is based on a parametric study of the geometric configuration of the cover-nozzle; the geometry of the engine is fixed. Two families of parameters can be identified: the parameters defining the geometry of the cover-nozzle, and the parameter defining the position of the cover-nozzle. In the first family, the use of simple shapes for the cover-nozzle (cone-shaped or cylinder-shaped) reduces the number of parameters to explore; namely the inlet and outlet cross-sections, and the length of the cover-nozzle. The second family contains the distance between the outlet section of the engine and the inlet section of the cover-nozzle (called cover distance, or CD; the distance is counted negative for overlapping configurations), and its angular deviation in the yawing and pitching planes (β_Y and β_P). Those parameters are non-dimensionalized. The cross-sections will be reduced by the outlet section of the engine nozzle; the cover distance, and the cover-nozzle length by the outlet diameter of the engine nozzle. The parameters are illustrated in figure 1, the ranges given in table 1. Time scale comparison between travel in the cover nozzle ($\approx 0.1ms$)



(a) Illustration of the experimental device. (b) Parameters of the study.

Fig. 1 Experimental setting.

Table 1 Non-dimensional parameters of the study (lengths are relative to the engine outlet diameter value, sections to the engine-nozzle outlet cross-section value).

Parameter	Symbol	Variation range
Inlet section	S_i	fixed at 2
Outlet section	S_o	$[1; 2]$
Length	L	$[0.73; 2]$
Cover distance	CD	$[-0.1; 0.6]$
Yawing deviation	β_Y	$[-12^o; 12^o]$
Pitching deviation	β_P	$[-12^o; 12^o]$

and cover nozzle displacement ($\approx 0.5s$) suggests a quasi-static phenomenon (also demonstrated in [14]). Thus for different parametric configurations of the cover-nozzle, some stabilized operating points of the small turbojet are measured. Three initial titanium cover-nozzles were designed, and successively cut to modify the length and the outlet cross-section (see figure 2). For each of these configurations both CD and β were modified. The identification of the influence of the cover-nozzle on the engine behavior is obtained through thermodynamic cycle measurements. The performance of the vectoring system is evaluated with thrust composition measurements.

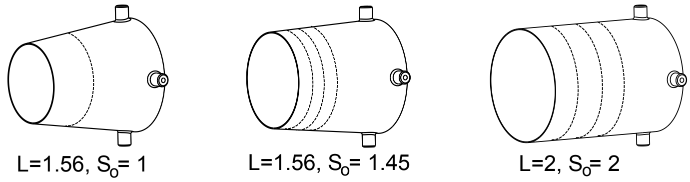


Fig. 2 Geometric configurations for the cover-nozzle.

III. Experimental resources

Some thrust vectoring is performed on an AMT Titan engine. The Titan is a 40 daN thrust engine (single-spool axial flow turbojet, characteristics in Table 2). The engine is set in a specific frame (illustration in figure 1(a)) divided in two parts. A fixed one dedicated to the engine, and a mobile one holding the cover-nozzle. A setting between these two parts allows modifying the cover distance (CD). Two electrical actuators act on the rings holding the cover-nozzle, and pilot its orientation. Two linear potentiometers give the indication of the actual deviation. Global instrumentation, among which the air mass-flow (inlet duct measurement), fuel consumption, rotational speed and outlet temperature gives the operating point of the engine. Local instrumentation is implemented on the engine system (pressure and temperature measurements in the intermediate sections). The whole device is set on a six-axis balance. Simultaneous recording is performed (NI Fieldpoint & Labview) and post-treated to extract the mean information. The repeatability ability has been evaluated during preliminary tests. It is in the range of 1% of engine characteristics at maximum speed.

IV. Results

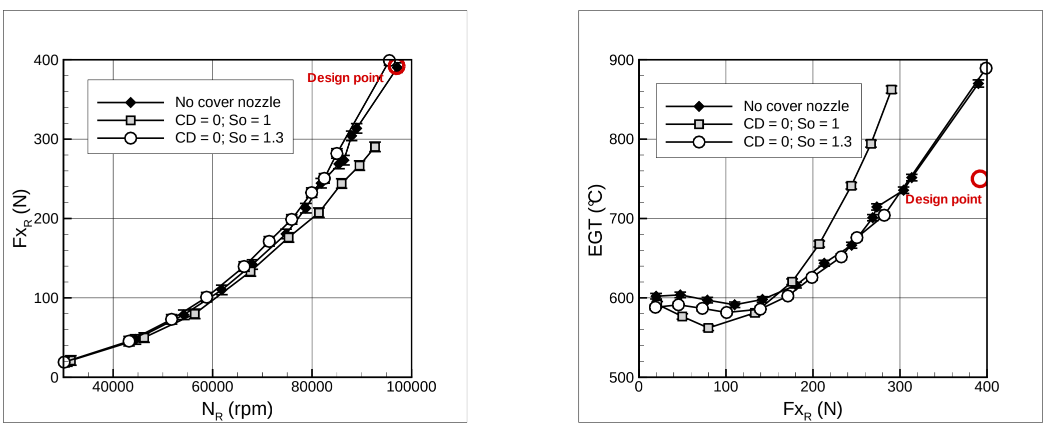
Influence of the cover-nozzle on the engine

For every configuration of the cover nozzle (variations of CD, L, S_0, and β) the cycle is compared with the reference case, i.e. without cover-nozzle. Amongst all of the configurations tested, the only case worth being reported is one of the smallest outlet section cover nozzle ($S_0 = 1$). As presented on figure 3 a loss of thrust at given rotational speed is observed (15% of the thrust is missing @ 92 000 rpm), and the level of temperature in the engine is increased ($+130^o$ for EGT). An increase of the SFC (13% @ 92 000 rpm) was also measured, coupled with an higher compressor pressure-

Table 2 Specifications given by AMT for the Titan engine.

Engine Diameter (mm)	147
Engine outlet Diameter (mm)	73
Weight (kg)	3.35
Thrust (daN)	39.2 @ 95 000 rpm
Max. speed (rpm)	97 000
Pressure ratio	3.8
Air mass-flow (g/s)	660
Outlet Temp.(^{o}C)	750
SFC (kg/h.daN)	1.71

ratio (3.5 instead of 3.2 for the same axial thrust). The compressor operating point approaches the surge region. The bad behavior of the engine in that configuration was also reported during the conducting of the tests for every value of CD or β (brutal ignition, critical EGT and operating fluctuation) forbidding to reach the maximum rotational speed. No other nozzle configuration presented such difficulties, even for the second smallest nozzle (see figure 3 for $S_0 = 1.3$) whatever the other parameters (CD, L or β). A critical value of the outlet section must then exists in the



(a) Evolution of the axial thrust.

(b) Evolution of the exhaust temperature.

Fig. 3 Influence of the cover-nozzle on the engine operating line.

range: $1 < S_{0-Crit} < 1.3$, but could not be exactly identified because of critical functioning.

Performance of the vectoring system

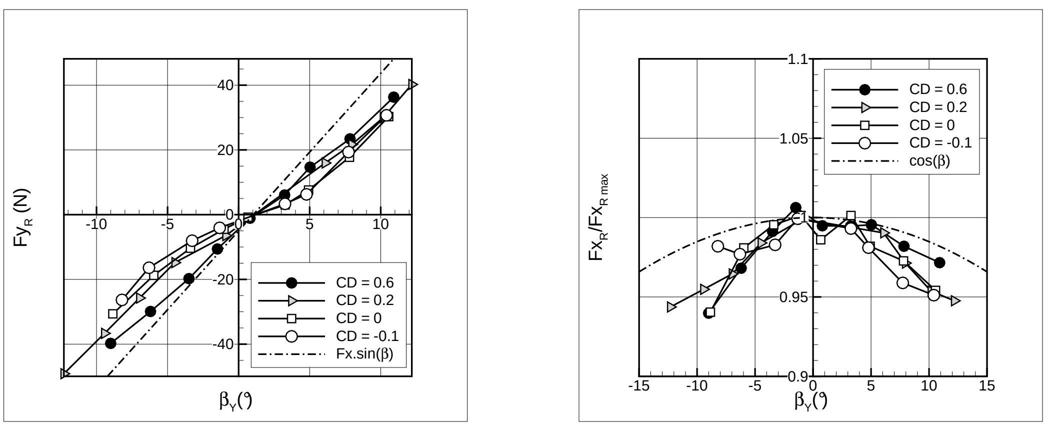
Actually, the vectoring system is a dual-purpose device:

1. since it is supposed to replace the rudder, it must insure the directional stability;

2. the super-maneuverability expected while using a thrust vectoring system must be substantial.

The first objective is eased by the good performance for small values of the angle of deviation: the directional stability will be insured by a dynamic regulation producing rapid movement of the cover-nozzle. For the second objective, the maximum lateral force obtained must be as high as possible. On figure 4 the maximum of lateral force measured is in the range of what can is expected of a classical control surface solution ($C_y = 1$ on a rudder of 0.01 m^2 at 80 m/s gives $F_y = 40N$). Another important result is that no significant difference has been observed in the results between yawing and pitching deviations, whatever the cover-nozzle configuration.

The theoretical projections of the thrust on the axial and lateral axis are presented on both fig-



(a) Evolution of the lateral thrust.

(b) Evolution of the axial thrust.

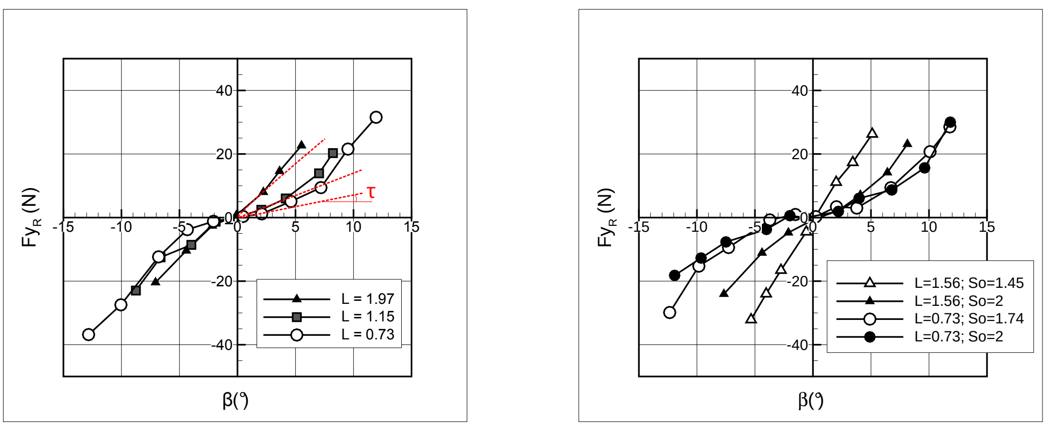
Fig. 4 Influence of deviation of the cover-nozzle at $S_0 = 1.3$ **and** $L = 1$**.**

ure 4(a) and figure 4(b) and compared with the results. For the lateral force, it is almost linear because the angles of deviation are rather small. The linear behavior of the lateral force is indeed convenient for handling qualities implementation. But the actual lateral force is not a strict projection of the thrust in the lateral direction. This has been presented in the literature ([10], [11] or [12]) by the use of CFD: a discrepancy exists between the effective angle of the flow compared with the deflection angle. Here, the lateral force created is lower than expected, mainly with the configuration having a small cover-distance value. The linear behavior is even lost for the low cover-distance configuration. The plot of the axial thrust equally presents a difference between the expected projection (figure 4(b)) and the results. An additional loss of axial thrust in the range of 5% is to be expected when pivoting the cover-nozzle.

As stated above a linear response of the lateral force is appreciated. The results show that this linearity can be lost, mainly for configurations for which the cover-nozzle is short (figure 5). Two indicators are needed to track this "linearity performance". The usual auto-correlation coefficient R^2 in the range [0;1], and the gradient of lateral force near zero deviation (τ).

$$\tau = \left.\frac{\partial F_{y_R}}{\partial \beta}\right|_{\beta=0}$$

A perfectly linear response with a high gradient meets the performance requirements mentioned at the beginning of this section. High values are expected for both of the indicators to define an "efficient" configuration. The figures 4(a) and 5 show that the cover distance has a lesser influence



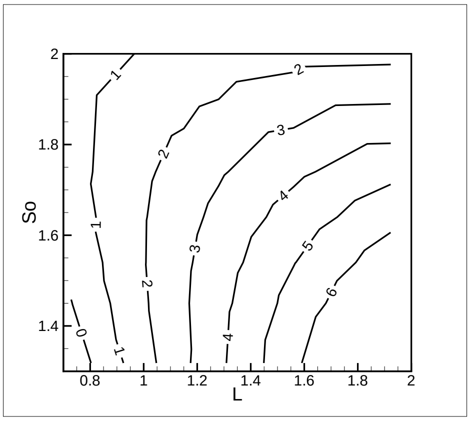
(a) Influence of the length of the cover-nozzle, for $S_o = 2$ and $CD = 0.2$.

(b) Influence of outlet section of the cover-nozzle, for $CD = 0$.

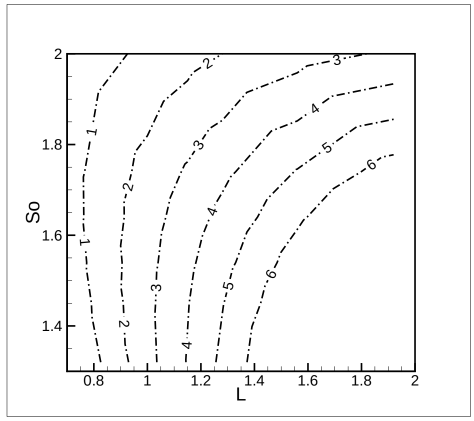
Fig. 5 Evolution of the lateral thrust for different configurations of the cover-nozzle.

on τ than the length of the nozzle or the outlet section value, since the loss of linearity is more evident than on figure 4(a). On figure 5(a) the influence of the length is checked, for a given outlet section. Short nozzles present a very bad performance for small angles of deviation, and a poor linearity. It is also the case if the outlet section is important (figure 5(b)) even if this degradation is lessened by the length of the nozzle.

A generalization of the results is presented in figure 6 and in figure 7. The two indicators present

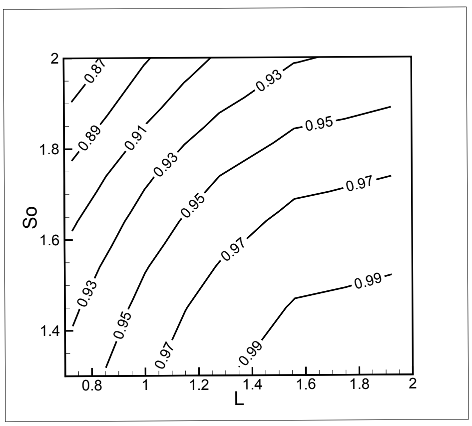


(a) Value of τ for $CD = -0.1$.

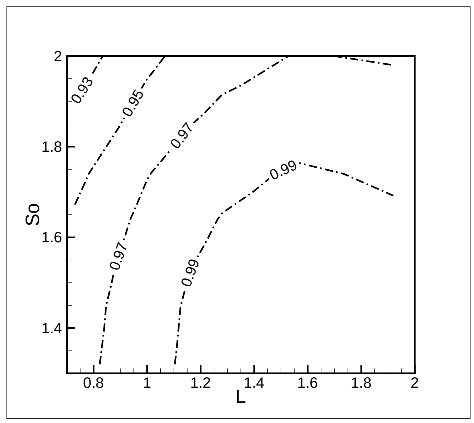


(b) Value of τ for $CD = 0.2$.

Fig. 6 Interpolation of the value of τ in a S_0-to-L map.



(a) Value of R^2 for $CD = -0.1$.



(b) Value of R^2 for $CD = 0.2$.

Fig. 7 Interpolation of the value of the inter-correlation factor R^2 in a S_0-to-L map.

the same trend of variation. The most interesting configurations are found when S_0 is minimum, L and CD maximum, defining trends of recommendation for design. This can rise problems because the use of long cover-nozzles tends to increase the general length of the aircraft. Moreover, it is not possible to decrease the outlet-section “at will”, because the functioning of the engine can be endangered as stated above. Better than considering the length of the nozzle and the cover distance, those two parameters could be merged into the effective position of the outlet section. The figure 6 tends to support this assessment. Anyway, from a practical point of view if a directional stability is difficult some linearity in the creation of the lateral force can be recovered by placing the cover nozzle farther after the engine.

V. Conclusion

An experimental study of a thrust vectoring system fit for UAV/UCAV applications has been conducted. The influence of the cover-nozzle configuration on both the engine behavior and the vectoring performance has been checked. The most relevant conclusions of this work can be summarized as follow:

1. the cover-nozzle does not influence the engine functioning provided that its outlet section is high enough, compared with the engine exhaust-nozzle one. The critical value is estimated in the range $1 < S_{0-Crit} < 1.3$;

2. a linear relation between the lateral force created and the deviation angle of the cover-nozzle is observed when increasing the distance between the outlet on the engine and the outlet section of the cover-nozzle. This distance can be increased by changing either the cover nozzle length, or the cover distance.

For the first one of these conclusions, additional experiment need to be conducted to refine the critical range (including transient phases, impact on life-time, influence of architecture). Anyway, no other parameter has such an influence on the engine behavior than this outlet section. It means that the designer is free to interfere at will on the other parameters (L, CD...) to create the required variation of lateral force against deviation without danger for the engine. A linear variation with a slope as high as possible seems to match the requirements of a thrust vectoring system, but other configurations can be envisaged to meet uncommon specifications.

Some additional work is also needed on this vectoring system. In extreme deviation situation, both ejection of the exhaust gas or suction of the external flow can occur at the interface between the two nozzles. The consequences on the performances and the safety of integration need to be checked.

Acknowledgments

The authors would like to express their gratitude to the French Ministry of Defense (Délégation Générale de l'Armement) for the financial support of this study.

References

[1] Ghal-Or, B., "Fundamental Concepts of Vectored Propulsion," *Journal of Propulsion*, Vol. 6, No. 6, 1990, pp. 747, 757.

[2] Friehmelt, H., "Thrust vectoring and tailless aircraft design - Review and outlook," *AIAA Atmospheric Flight Mechanics Conference, San Diego, CA*, AIAA-1996-3412, 1996.

[3] Hienz, E., Vedova, R., "Requirements, Definition and preliminary Design for an Axisymetric Vectoring Nozzle, to Enhance Aircraft Manoeuvrability," *AIAA/SAE/ASME 20th Joint Propulsion Conference, Cincinnati*, 1984.

[4] Jimenez, A., "Thrust Vectoring for Advance Fighter Aircraft, Propulsion Package Development," *37th AIAA/SAE/ASME Joint Propulsion Conference & Exhibit, Salt Lake City*, 2001.

[5] Wing, D. J., Giuliano, V.J., "Fluidic Thrust vectoring of an axisymetric exhaust nozzle at static conditions," *ASME Fluids Engineering Division Summer Meeting*, FEDSM97-3228, 1997.

[6] Sparrks, R., Michie, S., Gill, K., Crowther, W.J., and Wood, N.J., "Development of an Integrated Circulation Control / Fluidic Thrust Vectoring Flight Test Demonstrator" *1st International Conference on Innovation and Integration in Aerospace Sciences,Queen?s University Belfast, Northern Ireland, UK*, CEIAT 2005-0086, 2005.

[7] Forliti, D., Echavarria Diaz-Guardamino, I., "Exploring Mechanisms of Fluidic Thrust Vectoring Using a Transverse Jet and Suction," AIAA Journal, 0001-1452 vol.47 no.10 (2329-2337), doi: 10.2514/1.39063, 2009.

[8] Capone, F., Smereczniak, P., Spetnagel, D., and Thayer, E., "Comparative Investigation of Multiplane Thrust Vectoring Nozzles," *AIAA/SAE/ASME 28th Joint Propulsion Conference and Exhibit, Nashville*, 1992.

[9] Giuliano, V.J., Flugstad, T.H., Semmes, R., and Wing, D.J. "Static Investigation and Computationnal Fluid Dynamics Analysis of Flowpath Cross-Section and Trailing-Edge Shape Variation in Two Multiaxis Thrust Vectoring Nozzle Concepts," *AIAA/SAE/ASME 30th Joint Propulsion Conference, Indianapolis*, 1994.

[10] Wilson E.A., Adler D., Bar-Yoseph P ., "Geometric evaluation of thrust-vectoring nozzles for aerodynamic performance predictions ," International Journal of Turbo & Jet-Engines, Volume 20, Pages 275-287, 2003

[11] Wilson E.A., Adler D., Bar-Yoseph P ., "Thrust-vectoring nozzle performance modeling," Journal of Propulsion & Power, Volume 19, Pages 39-47, DOI: 10.2514/2.6100, 2003

[12] Ma H.M., Fan S.Q., Chen H.P., "A real-time performance model for thrust vectoring nozzle & appli-

cation in aero-engine simulation, " International Journal of Turbo & Jet-Engines, Volume 22, Pages 21-29, 2005.

[13] McLafferty, G.H., and Peterson, J.L., "Results of tests of a rectangular vectoring/reversing nozzle on an F100 engine," *AIAA/SAE/ASME 19th Joint Propulsion Conference and Exhibit, Nashville*, 1983.

[14] Ma H.M., Fan S.Q., Chen H.P., "Numerical Study of Unsteady Flow in Thrust Vectoring Nozzle, " International Journal of Turbo & Jet-Engines, Volume 22, Pages 31-40, 2005.