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Optimizing Subcritical-Flow Thrust-Vectoring of Converging–Diverging Nozzles

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Engine thrust vectoring (TV) is a potential technology for military and future civil aircraft in which the Technion—Israel Institute of Technology has made significant contributions. This paper provides realistic predictions of steady-state engine performance during steady-state pitch vectoring. The results obtained comprise a required fundamental step for advanced aircraft/TV implementation. This work is a part of the Lockheed Martin yaw–pitch TV F-16/F-100 research study conducted here at the Jet Laboratory. To this end, a unique TV-engine computer algorithm has been developed that expands the conventional steady-state modeling capabilities of on- and off-design as well as the conventional transients (via throttle changes) to create steady-state and dynamic TV–engine simulations at various altitudes and Mach numbers. This paper reviews the steady-state performances and the optimization observations initially obtained. The subcritical flow realm of nozzle performance provides trends aiding in the prediction of thrust benefits beyond the conventional nozzle design of the F100 model are available as the effective nozzle throat area is allowed to contract through vectoring.

Nomenclature

A	= area, m^2
A_8	= nozzle throat area, m^2
A_9	= nozzle exit area, m^2
A_{9e}/A_{8e}	= nozzle area ratio referenced from the effective nozzle areas
A_{9G}/A_{8G}	= nozzle area ratio referenced from the geometric nozzle areas
C_{fg}	= thrust coefficient
h	= altitude, m
M	= Mach
$N1$	= low-pressure spool speed, rpm
PLA	= power lever angle of the throttle, deg
T	= thrust, N
U	= jet exit velocity, m/s
α	= angle of attack, deg or rad
β	= side-slip angle, deg or rad
Δ	= variance from nonvectoring maximum dry thrust performance
δ_y	= geometric yaw thrust vectoring nozzle angle, deg
δ_z	= geometric pitch thrust vectoring nozzle angle, deg
θ	= convergent nozzle angle, deg

Subscripts

e	= effective
g	= geometric
M	= value at maximum dry thrust, i.e., 83-deg *PLA*
x	= body-axis direction
y	= body-axis yaw direction
z	= body-axis pitch direction
1, 2, 3, ...	= thermodynamic engine stations

Introduction

YAW–PITCH–ROLL engine thrust vectoring (TV) is a military and civil aircraft flight-control technology that provides alternative flight control to conventional aerodynamic flight control (CAFC). It is performed through deflecting engine jet(s) away from engine–axis in the pitch, yaw, and roll directions. The engine thus becomes a primary controller of aircraft flight. Hence, the engine influences performance through delay times associated with engine–rotor inertias and other engine-component delay times. Thus, the development of a realistic TV-engine computer simulation, with unique TV-induced engine-response delays as a function of various throttle and TV commands, becomes a key design criterion to TV-aircraft developmental technology.[1]

Active international programs that represent TV-aircraft technology include the X-31, F-22, Su-37, Su30 MKI, MiG-29, JSF, X-36, MCA, F-12, and the additions of various TV nozzle kits and TV software to extant CAFC fighters such as the F-15, F-16, F-18, Su-27, and MiG-29 (MiG-35). These programs involve new software for operating the TV nozzle and TV-based (or modified) airframe. Such software is also needed for advanced learning/training simulators of required systems.

The general TV mathematical methodology, developed by Gal-Or[2–6] and Lichtsinder et al.[7] defines the needed TV-engine force component formulation. It also defines major variables that affect TV-engine responses. To evaluate these responses, one may first review various conventional jet-engine simulation programs that are being used in the public domain. Of these, the program selected to be modified, adopted, and verified for the present work within the Lockheed Martin/Technion Institute of Technology (Technion) program is the well-known NASA DYNGEN program.[8]

Jet-engine TV nozzle designs vary from pitch-only, yaw–pitch, and yaw–pitch–roll TV capabilities for two-dimensional converging–diverging geometrically variable nozzles,[2] to similar axisymmetric geometrically variable converging–diverging types,[9] and from subsonic, fixed-geometry converging nozzles (mainly for future jet transports) to fixed converging–diverging nozzles in rockets and TV missiles. The jet deflection may be executed through the rotation of the nozzle baseframe, prior to the throat (Su-37), at the throat of the nozzle,[2–6,9] or by the addition of various external paddle-type deflectors around the exit of the nozzle,[10] and the X-31 design. Applications vary from near-term fighter aircraft (F-22, F-18, F-16, F-15, JSF, Su-37, MiG-29, and MCA), to future civilian transport jets for enhancing flight safety and aircraft performance. TV can also help to reduce or eliminate the vertical tail, and thus, decrease signatures, fuel consumption, and/or fleet-operating costs.[2]

While engine/aircraft responses to steady-state deflections of jet streams have been studied extensively,[2–6,7,9–16] dynamic engine TV effects and delays, otherwise not in the open literature, have only

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been recently addressed by the Technion.[1] Because of the nature of the jet engine,[2–6] the inertia of engine rotating spools strongly affect the benefits of TV-induced poststall maneuverability and airline safety. Hence, the integration of a dynamic TV-engine model with a full TV-aircraft model is required. Such a simplified model was first attempted by General Electric[17] for the F-18/F-404 HARV TV program, and further study is required.

The primary aim of this work is to use realistic F-16/F-100 inlet, compressor, turbine, and combustor data,[18,19] to provide initial steady-state engine performance results in response to pitch TV commands, and thus provide trends showing the fundamental differences in engine-thrust performance and increase the understanding of benefits attainable from TV implementation during engine operation. This is believed to be a fundamental step for future implementation of advanced TV in F-15 and F-16 aircraft, and for a more global application of TV in future civil and military aircraft.

TV effects under steady-state engine operating conditions at $M = 0$, $h = 0$, and $\alpha = \beta = 0$ was studied for the following two nozzle configurations:

1) Converging–diverging geometrically variable nozzle (no afterburner), also referenced as A_{9e}/A_{8e}.

2) Converging fixed geometry nozzle, also referenced as A_{9G}/A_{8G}, with trends similar to transport-type converging-nozzle jet engines.

Beyond the scope of this work, the results provide sufficient tabular data to estimate transient TV-induced ram–thrust and TV-engine gyroscopic effects in aircraft simulations as well as the possibility to integrate engine/airframe simulations and provide greater insight of aircraft behavior and control.

Algorithmic Engine and TV Model

The DYNGEN algorithm was altered to include the capability of accepting actual performance maps for the rotating components and the inlet to facilitate a realistic model of the F-100 engine. The conventional nozzle schedule,[18] controlled by the nozzle throat area A_8, was included along with the nozzle area ratio A_9/A_8 schedule. Full verification of the engine model is given in Ref. 1.

The fundamental changes in the algorithm include the map-type specifications, i.e., the algorithm now accepts pressure ratio as well as enthalpy turbine maps, open-loop acceleration requests without the required specification of final speed, temperature, or time, as well as the calculation procedure for a nonideal fixed-area mixer. A full explanation of the code is given in Ref. 1.

The addition of TV to the algorithm is unique with its own special algorithmic requirements. The yaw–pitch TV model was obtained through the addition of experimental nozzle metrics[19] of a two-dimensional converging–diverging geometrically variable nozzle (2D–CD) to the verified F-100 model. The geometric-effective nozzle area relation is taken to be

$$A_e = A_G \cos\delta_z \cos\delta_y \tag{1}$$

in accordance with Gal-Or's control rules 1 and 2 (Ref. 3), where δ_z is the geometric pitch-vectoring angle and δ_y is the geometric yaw-vectoring angle. The relation between the effective and geometric vectoring angles is proprietary to the Technion and unique for each nozzle. Yet, it is assumed to be suitable for TV nozzles in general in the present study.

Adapting the model of Berrier and Re,[14] for the flow coefficient of a convergent–divergent nozzle and adjusting it for TV, the effective flow coefficient is written in this work as

$$C_{D8} = [1.0 - 0.5(1.0 - \cos\theta)]\cos\delta_z \cos\delta_y \tag{2}$$

where θ is the convergent nozzle angle. It is thus adjusted for thrust vectoring in reference to the nozzle effective throat area A_{8e}, which varies from the geometric throat area as illustrated in Fig. 1. This will include any effective area variations that may occur in configuration 2, at constant A_{8G} as well. Experimental results show that the thrust coefficient varies by less than 5% below the nozzle choking point,[19] which is sufficiently small that it may roughly be assumed to be constant and still reveal nozzle performance trends for optimization purposes. Thus, it is maintained constant at $C_{fg} = 0.981$.

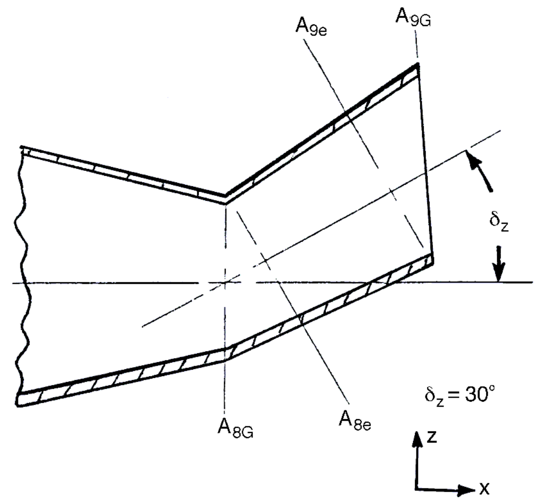

Fig. 1 Basic two-dimensional schematic diagram of yaw–pitch TV nozzle in this work.

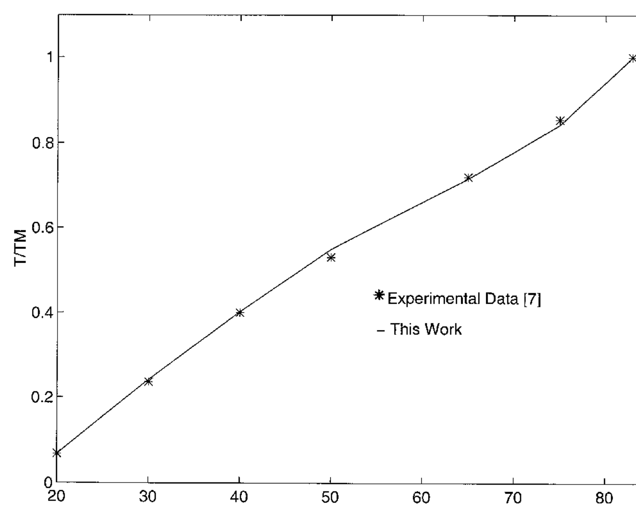

Fig. 2 Installed F-100 simulation total TV thrust results for variable A_{9e}/A_{8e} nozzle compared with experimental nonvectoring data.

Figure 1 demonstrates the basic two-dimensional geometry of the TV-nozzle model in this work, as well as the labeling and location of significant nozzle area and angles.

While this investigation remains in the pitch direction only, this TV model and investigation, based on a yaw–pitch 2D–CD nozzle, provides a reliable general description of axisymmetric nozzle performance capabilities through converting the pitch coordinate z into the radial cylindrical coordinate r.

Total Net Thrust Evaluation

Configuration 1

In proceeding into the TV-performance domain, one must first stress the fact that this vectoring configuration reduces the effective throat area unless the nozzle is geometrically variable. Namely, as one deflects the jet at a constant throttle setting, the engine nozzle control opens the throat and accordingly varies the nozzle area ratio A_{9G}/A_{8G}. In other words, as the jet is deflected in this control configuration under steady-state conditions, A_{9e}/A_{8e} remains constant.

For these operating conditions, the total net thrust (not axial net thrust) remains constant across the vectoring range for a given *PLA* value. In other words, in this nozzle configuration, TV-jet deflection has no effect on steady-state engine performances. This result is verified in Fig. 2 in a comparison with experimental data of the

F-100 steady-state performance without TV for the same throttle region.[16]

Thus, configuration 1 demonstrates the ability of implementing TV without disrupting the airflow of the jet. The importance of this result is more evident while implementing TV in the critical flow range at maximum dry thrust and during the ignition of the afterburner (not pursued in this study). Configuration 1 provides a standard for the performance capability requirements of military and other supersonic aircraft with TV converging–diverging geometrically variable nozzles.

Configuration 2

This configuration characterizes subsonic nozzles such as those available on the A-4, various military trainers, etc., and on turbofan transport engines. Namely, we consider here both fan-air TV and core-air TV as a general principle. Specific evaluations of these civil TV-nozzle configurations lie outside the scope of this work. What is established, however (see Fig. 3), are the fundamental changes in the total net thrust expected for such configurations.

To understand the meaning of Fig. 3, one should first note that TV at lower *PLA* values for nozzles of this type causes higher velocities at the nozzle exit (because of the decreased effective nozzle area caused by TV in configuration 2). Hence, Fig. 3 shows that as one increases jet deflection, total net thrust increases below *PLA* ≈ 81 deg (the 81–83 deg *PLA* region is dealt with in more detail later).

For example, at 50-deg *PLA*, where the experimental data shows that about 55% thrust is achieved without vectoring ($\delta_z = 0$), at $\delta_z = 30$ deg, ~62% thrust is achieved, providing an increase of ~8% in the total net thrust. Table 1 provides a numerical comparison of the thrust benefits at various throttle settings for configuration 2 (fixed nozzle, A_{9G}/A_{8G}) in more detail.

To delve into the upper *PLA* region of Fig. 3, it should be reemphasized that TV in configuration 2 reduces the effective nozzle area A_{8e} through maintaining constant geometric nozzle areas, A_{8G} and A_{9G} Thus, at 100% maximum dry thrust, each of the vectoring positions evaluated here reaches a different performance level as a function of the effective nozzle throat area A_{8e}, i.e., at maximum dry thrust and $\delta_z = 30$ deg, $T/TM = 98.5\%$ and not 100%. This becomes more apparent in the closeup of Fig. 4.

Table 1 Configuration 2 change in percent thrust vs the *PLA* position for various vectoring angles

	$\Delta\%T$, deg		
PLA, deg	δ_z = 10	δ_z = 20	δ_z = 30
20	0.11	0.47	1.57
30	0.37	1.49	4.84
40	0.74	2.90	7.18
50	0.71	2.77	6.68
65	0.68	2.63	6.12
75	0.68	2.65	5.92
83	−0.15	−0.62	−1.47

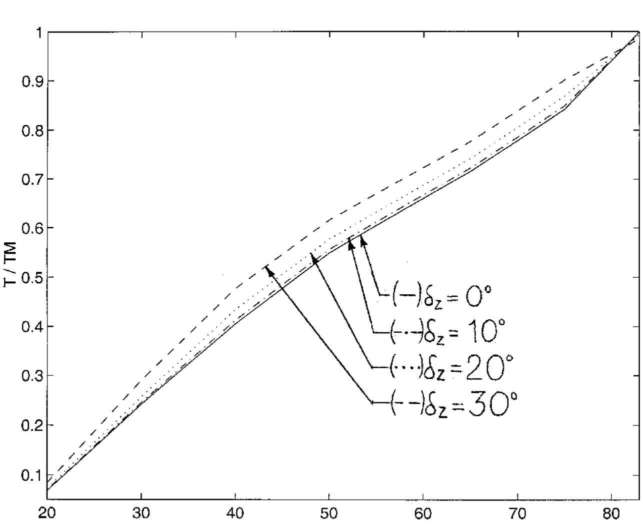

Fig. 3 Installed engine simulation total thrust results for a fixed geometry A_{9G}/A_{8G} nozzle at various vectoring positions (δ_z = 0, 10, 20, and 30 deg).

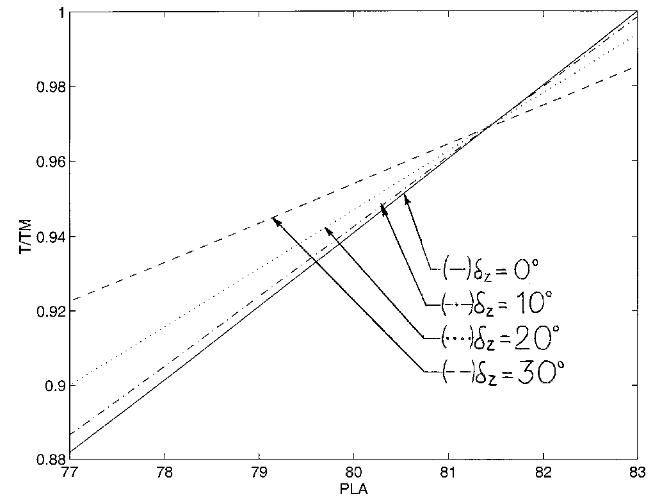

Fig. 4 Total thrust results for a fixed geometry A_{9G}/A_{8G} nozzle at various vectoring positions (δ_z = 0, 10, 20, and 30 deg) focused near the choking region.

Analytically, this means that each line representing a different vectoring position is a different path for achieving the critical flow in the nozzle and is a function of the effective nozzle areas. What proves to be beneficial over the *PLA* range is the closing of A_{8e} as a function of vectoring [see Eq. (1)] in the upper *PLA* range, this also proves to slightly lower thrust with increasing δ_z close to the critical nozzle point of *PLA* = 83 deg.

For example, under the current conditions ($M = 0$, $h = 0$, and $\alpha = \beta = 0$), the vectoring thrust to nonvectoring thrust ratio is simply reduced to the exit velocity ratio at the critical point of *PLA* = 83 deg and is written

$$T_0/T_M = 1.0 \tag{3}$$

for $\delta_z = 0$. The ratios for each nonzero vectoring position of configuration 2 in this work are then

$$T_{10}/T_M = 0.9985, \qquad T_{20}/T_M = 0.9938, \qquad T_{30}/T_M = 0.9853$$

for $\delta_z = 10$, 20, and 30 deg, respectively, showing the thrust reduction through the velocity as a function of effective nozzle area reduction for increasing δ_z.

This establishes that steady-state engine performance varies with the vectoring angle for fixed area nozzles at and below this nozzle critical condition. It is assumed in this work that TV of a steady-state engine does not alter the low-pressure spool speed, i.e., $dN1/dt = 0$. A more sensitive model would allow for this variation such that $N1$ would increase with a decreasing A_{8e} below ~81-deg *PLA*, consequently increasing the thrust. Hence, the thrust benefits of configuration 2 in this work are somewhat conservative. The thrust increase attained when $\delta_z > 0$ over the nonvectoring performance is only a function of the A_{8e} reduction by TV.

It is demonstrated by this simulation for fixed area nozzles that as the *PLA* increases up to choking (83 deg) each vectoring position provides a different point of choking (see Fig. 4) as function of the exit velocity reduction expressed in Eq. (3).

Thrust Components

Figure 5 is applicable to configuration 1 situations. Its purpose is to focus attention on the forward (body-axial) thrust reduction with TV in A_{9e}/A_{8e} configurations.

As TV is implemented, deflecting the total thrust away from the body-axis, the body-axis thrust was found to reduce, consequently

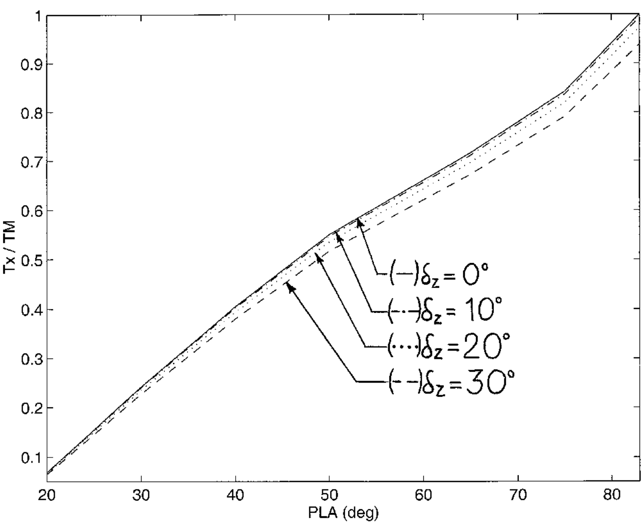

Fig. 5 Installed engine simulation body-axis thrust results for variable A_{9e}/A_{8e} nozzle configuration.

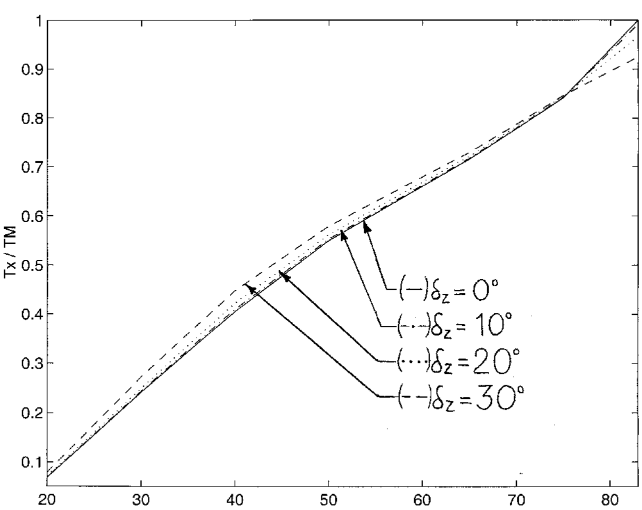

Fig. 6 Installed engine simulation body-axis thrust results.

reducing the flight speed of the aircraft in actual maneuvering situations.

Figure 6 is a general guide for what is to be expected in future vectored transport jets. This is a configuration 2, fixed-area nozzle study and it shows the opposite effects of TV in comparison with the military-type geometrically variable nozzles. As the total thrust is deflected away from the body axis, a thrust decrease is naturally expected, as occurred earlier, yet, the thrust increases, most noticeably at high deflection angles above $\delta_z = 20$ deg. This demonstrates that TV in configuration 2 not only provides the total thrust increase and expected TV benefits, but provides a noticeable increase in the body-axis thrust at $\delta_z = 30$ deg, up until $PLA \approx 65$ deg, which may prove useful in emergency situations of transport aircraft involving the loss of one or more engines. As a note of caution, this may cause the fan to surge toward the stall region if the airflow rate of $N1$ is allowed to increase (suggesting a separation of the effective-nozzle-throat-area/$N1$ relation through maintaining speed control by the geometric-nozzle-throat-area/$N1$ relation). The issue demonstrated here is the increase of thrust at *PLA* less than 83 deg, the designed choking point, through maintaining the engine on the design path and reducing the effective nozzle throat area, thus bringing the flow closer to choking before the actual *PLA* design point of 83 deg. It is noted that in the region of 65 deg $< PLA <$ 73 deg, the body-axis thrust does not vary greatly from the total nonvectoring thrust. After

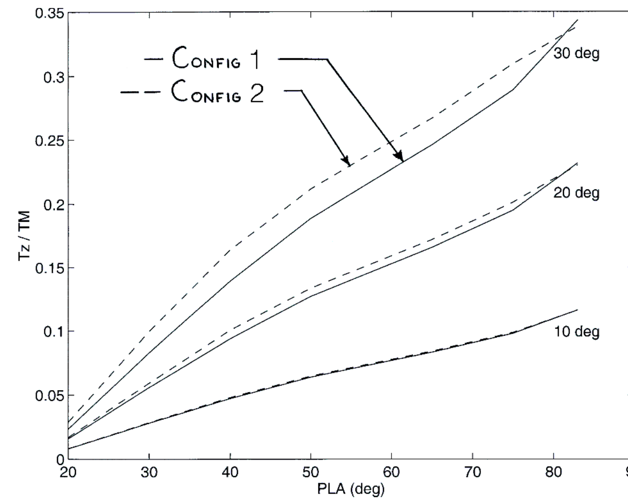

Fig. 7 Installed engine simulations pitch component thrust results.

this, a sharp deviation occurs somewhat sooner than demonstrated in Fig. 4, only as a function of cos δ_z.

Figure 7 demonstrates the difference in pitch force available by TV in fighter aircraft vs transport jets or subsonic attack aircraft. No significant performance differences between the two configurations is visible at $\delta_z = 10$ deg, whereas at $\delta_z = 30$ deg, a thrust increase of configuration 2 over configuration 1 is demonstrated and behaves as that discussed in Fig. 3, differing only as a function of sin δ_z.

In comparison of the overall performance of configurations 1 and 2, it is evident that the A_{9G}/A_{8G} fixed-area nozzle control of configuration 2 achieves greater benefits from TV until the nozzle choking point is approached. After this, a A_{9e}/A_{8e} nozzle area control of configuration 1 is better suited to meet the needs of the supersonic flow.

Conclusions

In this work, a new and realistic computer program has been developed and verified for estimating thrust-vectored engine responses to conventional engine operation as well as TV during engine steady-state and transient operations. The initial steady-state performances have been evaluated and provide nozzle-control optimization trends that are applicable not only to current military aircraft but to future converging–nozzle civil aircraft as well.

For a variable geometry nozzle designed to maintain nonvectoring engine performances, steady-state engine behavior for the F-100 engine has been modeled and shown to provide no TV-induced engine performance variations while providing TV-flight control benefits.

A fixed geometry nozzle has shown the somewhat surprising results of increased thrust values during TV of civil transport and subsonic military aircraft, not only in the total thrust provided, but in the body-axial thrust and pitch directions as well. It has been demonstrated as the low-pressure spool speed is scheduled with the geometric nozzle throat area, greater thrust benefits are provided through the reduction of the effective nozzle throat area, this is a result not achieved with the variable nozzle throat area. This conclusion remains valid for all *PLA* positions between idle and maximum dry thrust.

To improve future TV modeling, this work may be introduced into TV-airframe performance simulations that also evaluate the effects of engine and TV-induced delay times during air combat or recoveries from emergency situations.

The present work can be expanded to include its verification vis-à-vis larger transport-type engines as well as smaller turbofan and turbojet engines, provided realistic turbine, compressor, and TV metrics are available as inputs.

The present work can also be expanded to include more realistic effects of inlet airflow distortions caused by high sideslip and high-angles-of-attack maneuvers characteristic of the emerging new TV-aircraft technology.

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