Characterization of a Counterflow Thrust Vectoring Scheme on a Gas Turbine Engine Exhaust Jet

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Counterflow thrust vectoring is an innovative technique that uses no movable components to redirect a thrust producing jet. This system relies on fixed curved surfaces (named collars), and a secondary stream flowing in opposite direction to the main jet. This paper reports on experimental results of the application of 2-D counterflow thrust vectoring to the exhaust of a gas turbine engine. The characterization of jet response to counterflow is presented for different gap sizes between collars and nozzle. Continuous and proportional control of the jet was demonstrated for vectoring angles up to 25°. Jet attaches to the collar wall for high counterflow levels. The secondary mass flux needed to vector the main jet is less than 6% before attachment, with thrust losses below 8%. Temperature in the vacuum line rises to the point where special caution must be taken when operating electronically controlled valves, which also proved to be affected by pressure losses in the vacuum line. Different frame setups affects the vectoring results, regarding vectoring angles. Regarding the system dynamic response, a slew rate of 160°/s was observed. However, the counterflow thrust vectoring system operates on a very inhospitable environment regarding noise and interference, which degrades the measurement for high sample rates. Based on these results an optimal gap size of 0.625 times the nozzle height was chosen for further studies concerning shear layer mixing enhancement, dynamics and controls.

Nomenclature

\[ \Delta p = \text{relative pressure} \]
\[ \delta_v = \text{vectoring angle} \]
\[ \rho = \text{density} \]
\[ AR = \text{nozzle aspect ratio} \]
\[ c_T = \text{thrust coefficient} \]
\[ F_{gap} = \text{pressure force acting at the gap} \]
\[ F_{X \text{ collar}} = \text{X component of the pressure force acting on the collar} \]
\[ F_{Y \text{ collar}} = \text{Y component of the pressure force acting on the collar} \]
\[ G = \text{gap height} \]

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I. Introduction

THRUST vectoring research was initiated more than thirty years ago. First studies were based on mechanical techniques in which movable vanes, nozzles or plates vectored the jet. The performance of this new flight control concept was tested ten years later in prototype systems such as F-18 HARV, F-16 MATV and X-31. These aircraft have demonstrated the following superior performance characteristics: post-stall flight, reduced take-off and landing distances, overall combat agility and lower radar signature, when compared to conventional aircraft. The results of this research gave rise to the implementation of thrust vectoring to the F-22 Raptor which has pitch vectoring up to 20 degrees produced by movable vanes. However, increase of weight, system complexity, usage of special materials and low response time, typical of mechanical systems, constraint aircraft performance.

The desire for enhanced thrust vectoring performance has motivated researchers to implement simpler systems. In this manner, two different approaches were presented in the 1990’s, based on a fluidic technique. At the NASA Langley Research Center, studies were made injecting a secondary flow in the same direction of the main jet for several nozzle / flow injection configurations. At the FSU/FAMU College of Engineering and the University of Minnesota, fluidic thrust vectoring was achieved using a framework including a secondary flow running in the opposite direction of the main jet, confined by a wall downstream the nozzle exit named collar, as shown in Fig. 1. Comparing results obtained by these two different approaches, counterflow thrust vectoring (CFTV) accomplishes higher vector angles for the same secondary mass flow rates, compared to the secondary injection method. The former has presented maximum values of 8 degrees per each 1% of secondary to primary mass flux ratio, while the later has only presented 4 degrees per each 1% of secondary to primary mass flux ratio of injected air. At the same time, the flow losses seem to be smaller in CFTV. Although large vectoring angles can be attained with a low amount of secondary flow using counterflow thrust vectoring, a catastrophic loss of control can occur for particular suction conditions if the main jet attaches to the collar wall, which is a severe drawback.

Counterflow thrust vectoring has been studied to characterize its performance for different setups and flow conditions in particular when the main jet attaches to the collar. Nevertheless, up to now all research has been conducted with laboratory produced jets which may not effectively represent a real implementation test case. Problems like vibration, noise, high temperatures, jet turbulence, among others are reduced in such cases.

The purpose of the present study is the implementation of CFTV in a small scale gas turbine engine and characterization of CFTV performance. This characterization was performed for different setups, namely gap sizes, and with the presence/absence of the lower collar, to optimize the final configuration. Results obtained will serve as a starting point to more detailed fluid dynamics studies of the vectored jet, and to implement an automatic feedback control system.
II. Experimental Setup and Methods

Experiments were conducted in a setup that was projected, developed and implemented in the Aeronautical Laboratory at the Portuguese Air Force Academy in Sintra, Portugal. This section presents a description of the main components of the experimental setup, as well as the methods used to obtain the vectoring angle, $\delta_v$.

A. Engine

Engine choice was made based on size, reliability and simple maintenance needs. Indoor operation required a small scale engine, whereas testing for a wide range of vectoring angles required both stable operation for over 30 minutes and simple maintenance actions, so to allow in site maintenance avoiding sending the engine to the manufacturer.

Following these criteria, the JG100 by ArtesJet was chosen. This engine is normally used for flying remote controlled aircraft, has a maximum rotating speed of 120,000 rotations per minute (RPM) and a maximum rated thrust force of 98N. The rotating components are a single stage centrifugal compressor and a single stage axial turbine wheel. The engine burns a mixture of jet fuel with 5% jet oil in an annular combustion chamber fed by 12 injectors. A Full Authority Digital Engine Control (FADEC) monitors engine throttle, RPM and temperature, ensuring a stable engine regime. Service time is 25 hours between maintenance procedures.

Before the vectoring tests, conditions at the nozzle exit plane were monitored using a pitot and shielded thermocouple probe for different RPM values, providing data that allowed choosing the best RPM to operate the engine. It was observed that Mach number and mass flux both increase with RPM, while temperature is high for low and high values of RPM, presenting a minimum at 80,000RPM. The minimum temperature point was chosen, as low operating temperatures increase the engine's service life. For 80,000RPM, the Mach number at the nozzle exit is $M=0.4$, axial velocity is $U=250m/s$ and the stagnation temperature is $T_0=959K$. It was also observed that the jet exits the nozzle with top hat shaped Mach number profiles, in both the minor and the major axis central planes.

B. Nozzle

The choice of the nozzle aspect ratio followed the trend in modern aviation aircraft, where low aspect ratio rectangular nozzles are progressively substituting axisymmetric ones. A rectangular nozzle with an aspect ratio AR=2 was designed to fit the engine. The dimensions chosen for the exit were width $W=56$ mm and height $H=28$ mm. These provide the highest possible area within the engine's original circular nozzle area, keeping the aspect ratio of 2. The nozzle, shown in Fig.2, has a smooth, 112mm long transition from round to rectangular, followed by a 49mm long uniform section.

C. Collars

A two-collar assembly was chosen to allow, if needed, for a symmetric setup. Figure 3 shows a general view of the setup. The side plates were made of high temperature Vycor® glass to gain optical access to the counter flowing layer. All the parts were screwed and sealed with high temperature cement to avoid pressure losses.

The collars used in this research were 30º circular arcs with a radius of curvature $R=70$ mm, thus having a length $L=140$ mm. The choice for circular arcs followed the previous research in order to obtain comparable data.

The dimensions of the collars were chosen to allow the study of both unattached and attached regimes, based on an attachment model as presented in Ref. 6.

D. Pressure and Temperature Measurements

Pressure was measured at the gap and in different points along the vacuum line using Validyne variable reluctance pressure transducers model DP15, and high gain carrier demodulator model CD19A. The demodulator provides excitation for the transducers and also carries and
demodulates the output signal. The DP15 pressure transducer was calibrated using a Meri.Cal II pressure calibrator. The calibrator reads both voltage and absolute pressure with an accuracy of ±0.025% of the full scale (39 psia), thus providing the necessary data to obtain the transducer calibration curve. The CD19A carrier demodulator provides a 0-10 VDC output signal.

A pitot and shielded thermocouple probe was used to measure mean total pressure and temperature for different engine RPM values. The pitot was connected to a Validyne pressure transducer as well. A type J thermocouple was used with a thermal compensated digital display by Omega. The display produces a 2-10VDC linear output voltage.

A digital baro/thermometer by Luft was used to measure the local ambient conditions. These were performed daily before each test.

The collar used in the first part of this study had 24 pressure taps. Pressure scanners model 9016 by Pressure Systems were used to measure collar pressure simultaneously in all locations. Each scanner has 16 pressure ports and each port has its own 10 psig pressure transducer. Accuracy and measurement resolution are ±0.05% and ±0.03% of the full scale. These scanners communicate with Labview by an Ethernet connection using a TCP/IP protocol.

Mean pressure transducers such as those described above give an incomplete picture of high frequency signals, so a XCE-093 Kulite transducer was used to characterize the dynamics of the CFTV system. This transducer was mounted in a different collar to measure the gap pressure. Next to the Kulite pressure transducer was placed pressure tap connected to a Validyne pressure transducer, in order to compare values. The range used for the current experiments was 10 psig. The main reasons for its choice were the following: maximum operating temperature of 274º C, natural frequency of 200 KHz, 0.5% of full scale accuracy and diameter of 0.095 in.

E. Vacuum Line

The vacuum line was designed to allow mass flux readings in both directions, because even though in most cases there is counter flow in the line, in some cases there will be co flow. Since true mass flow meters are unidirectional, a two-branch line was used. Check valves in each branch ensured that there was flow going only one way at a time and that no flow went through a meter in the wrong direction. The vacuum line is made of 35mm inner diameter stainless steel pipes. The choice of steel was made due to the anticipation of an increase in temperature in case attachment occurred. The flow meters and check valves can also operate at high temperatures for this reason.

In this setup two thermal dispersion gas mass flow meters model MasterTouch™ by Eldridge Products, Inc. were used. The full scale is 0.016 kg/s and the accuracy is 5% of the full scale. The main criteria for the choice of this particular model were: minimum pressure loss in the vacuum line and high temperature operation.

The setup could operate either manually or electronically controlled valves. For the latter case, it was also possible to remove the flow meters, to obtain a shorter configuration, for dynamic studies. The former were used for the study of gap influence and the latter for the dynamic characterization of the system.

A liquid ring vacuum pump by SIEMEN&HINSCH mbH was used to provide the necessary suction for the secondary flow. The pump’s rotating speed is 1450 RPM and it provides a maximum air flux of 248m³/h. The maximum suction pressure is 900 mbar below atmospheric pressure.

F. Electronically Controlled Valves

This study uses for the first time electronically controlled valves in a CFTV system. Up to now, CFTV research was based on manually controlled valves. However, this study is the basis for the implementation of the feedback control design on CFTV system so a complete automated system is needed.

The valve requirements were based on previous work, which have shown that the dynamics of the system could go up to 200⁰/s and that the maximum secondary mass flow rate would be less than 5% of the primary one.
Thus, the valves would have to be very fast, not restrict the system dynamics, and be large enough to allow high flow rates and consequently high thrust vector angles. At the same time, the valves would have to withstand temperatures that though high, were expected to be less than 150º C. Other important features were linearity, hysteresis, repeatability and leakage.

The choice was the Tecknocraft 203 313 proportional flow control valve which has the following specifications: frequency response greater than 250 Hz, time delay less than 35 ms and proportional command signal from 2 to 10 volts. However, the maximum mass flow rate was much less than the 5% of primary jet (maximum predicted value for the secondary mass flow rate) and the maximum temperature allowable was only 130º C. Thus, it was therefore decided to use three valves in parallel and place them as far as possible from the engine, in the secondary flow line, allowing for heat dissipation.

G. Data Acquisition System

All pressure, temperature and mass flux data was acquired to a National Instruments system through Labview. The main component of the system is a PXI 1011 chassis. This is the component that communicates with the PC through a NI-6071-E data acquisition board. This board has a sampling rate of $1.25 \times 10^6$ samples/second and a 12 bit resolution Analog to Digital Converter. Instruments communicate with this board through a BNC 2110 connector block.

This system also provided the electric signal to activate the solenoid valves, used for automatic thrust vectoring operation.

H. Methods Used to Obtain the Vectoring Angle

The angle by which the main jet is deflected from its original position is the main parameter used to measure how the jet responds to counterflow. It can be visualized using different optical techniques. In this case the high temperature made Schlieren visualization very appealing for basic visualization purposes, as it is easy to implement, and provides real time images of the jet as suction is increased. This technique was used for a first confirmation of jet deflection and later on, to confirm jet attachment.

Though image processing is possible to estimate $\delta v$ from Schlieren images, an automated process was necessary due to the high number of test cases that arise from multiple suction/gap size combinations. A control volume analysis was used to automatically obtain $\delta v$ from the pressure readings at the gap and throughout the collar.

1. Schlieren Visualization System

The Schlieren setup follows a z-type arrangement as described in Ref. 10. The light source is a high intensity lamp. The illuminating beam optics form a homogeneous round beam that illuminates the first parabolic mirror, by means of an achromatic lens with diameter and focal length of 50mm and a 1.5 $\times$ 5 mm rectangular slit. Light passes through the test section when traveling from the first to the second mirror. Both mirrors are parabolic with a focal length of 2032 mm and a diameter of 203.2 mm. The second mirror then reflects the image to be acquired by the camera. This analyzing beam is fitted with a knife edge for image contrast adjustment and an achromatic lens of 50mm both in diameter and focal length for focusing. For long exposure photos a circular neutral density type filter is used. The distance between mirrors was 4 times their focal length and the offset angles were 10 degrees. All elements were mounted on Newport rails. The rails were fixed to the laboratory floor and were equipped with shock absorbers. The optical elements were manufactured by Edmund Optics, Ltd. The camera is equipped with a Sony ICX085AL sensor. The spatial resolution is 1300(H) $\times$ 1030(V) with a pixel size of 6.7$\times$6.7 mm. Acquisition can go up to 40 frames/second. Data transfer to the PC is done using IEEE1394-1995 FireWire™ protocol thus transferring data at rates up to 400MB/s.

2. Control Volume Analysis

The 2D control volume (CV) chosen for this study was the same as in Ref. 7 and is depicted in Fig. 3. It is useful to use the same control volume as in previous studies, to obtain comparable data.

The following assumptions were made in order to allow carrying the momentum balances in the x and y axis. A detailed explanation can be found in Ref. 11.

1) Constant momentum exiting the CV through the nozzle for all suction conditions.
2) Atmospheric pressure in all boundaries except in the gap and the collar wall.

![Figure 5. Control volume used to estimate the vectoring angle.](image)
3) Linear variation of pressure from the nozzle lip to the collar wall at the gap.
4) Absence of viscous drag.
5) No transverse pressure variations. This is indeed the assumption that allows the use of a 2D control volume.

In the nozzle exit, the top hat profiles observed previously corroborate this assumption.

A steady state flow is considered. From the assumptions presented above, it follows that the only forces being exerted in the control volume are pressure forces at the gap $F_{\text{gap}}$ and in the collar wall $F_{X_{\text{collar}}}$ and $F_{Y_{\text{collar}}}$. Therefore, momentum balances in the x and y axis are given by Eqs. (1), where the subscripts $p$ and $s$ refer to the primary flow (engine jet) and to the secondary flow (from suction).

\[
\begin{align*}
F_{\text{gap}} + F_{X_{\text{collar}}} + R_X - \dot{m}_p U_p - \dot{m}_s U_s &= 0 \\
F_{Y_{\text{collar}}} + R_Y &= 0 
\end{align*}
\]

Equations (1) provide the means of computing the vertical and horizontal reaction forces $R_X$ and $R_Y$, which are used to estimate the vectoring angle, $\delta_v$:

\[
\delta_v = \tan^{-1}\left(\frac{R_Y}{R_X}\right)
\]

III. Results and Discussion

The characterization of CFTV performance is presented in for static and dynamic response. For the static response a parametric study for gap size is presented, followed by an analysis of other factors such as lower collar, type of valves and vacuum line configuration. The dynamic response is analyzed to obtain the slew rate and system delay.

A. Gap Size

The influence of gap size on CFTV performance was well established in Ref. 5, among others. Gap height changes the area available for the secondary flow, which is also the space available for the jet to deflect before impinging on the collar wall, thus affecting all secondary flow parameters. For this reason, smaller gaps lead to smaller amounts of counterflow necessary to achieve the same value of $\delta_v$, but will also favor jet attachment. Therefore, parametric studies on gap size have the purpose of finding a trade-off between secondary flow requirements, which should be kept low, and a wide regime of continuous proportional control before attachment occurs.

Experiments were conducted at this stage without the lower collar and using manually controlled valves. Test cases were G/H = 0.25, 0.325, 0.5, 0.625 and 0.75. For each gap, tests started with the vacuum pump off, relief valve closed and control valve open. This allowed the jet to entrain freely in the presence of the collar, resulting in coflow. The second data point was taken with the control valve closed. This restrained jet entrainment, and imposed a null secondary flow. Further data points were measured with the vacuum pump on and gradual opening of the control valve, leading to increased amounts of suction.

Figure 6. Normalized gap pressure versus vectoring angle, all gap sizes.
1. Jet Response to Counterflow

The variation of $\delta \tilde{v}$ with the level of suction applied is plotted in Figure 6. The level of suction is quantified by a normalized gap pressure, computed using Eq. (3).

$$\bar{p} = \frac{\Delta p_{\text{gap}} L}{\rho U^2_H}$$ (3)

Figure 6 shows that continuous and proportional control of the engine’s jet is possible for all the gaps tested up to $25^\circ$. For higher amounts of suction, as $\bar{p}$ increases, jet response shows some saturation, as $\delta \tilde{v}$ no longer increases with $\bar{p}$. This can be an indication of jet attachment, which can be confirmed observing collar pressure distribution or Schlieren images. As expected, higher gaps present higher values of $\delta \tilde{v}$ before saturation. Therefore, if the criterion for gap choice is only a large linear regime, higher gaps sizes must be considered. Figure 6 also shows the effect of the presence of the collar on jet entrainment, when no suction is applied. Table 1 presents the vectoring angle for the free entrainment condition for all the gaps tested. As the gap decreases, the jet becomes more vectored towards the collar. This is caused by the asymmetry in the setup, as the lower collar was not present. For this reason, the upper shear layer is restricted by the presence of the collar, while no such effect exists on the lower shear layer. The jet vectors towards the collar wall as pressure decreases, as a result of the air that is entrained into the jet being replaced.

<table>
<thead>
<tr>
<th>G/H</th>
<th>0.25</th>
<th>0.375</th>
<th>0.5</th>
<th>0.625</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \tilde{v}$ [°]</td>
<td>11.9</td>
<td>10.9</td>
<td>7.9</td>
<td>5.3</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 1. Vectoring angles for the free entrainment condition.

Figure 8. Jet response in the linear regime.

Present data for all gap heights
Van der Veer (1995) 0.2< G/h< 1.0
Strykowski et all (1996) G/h= 0.65
Strykowski et all (1996) G/h= 0.58
To confirm jet attachment for higher suction levels, long exposure Schlieren images were taken. Shown in Fig. 7 are two images for G/H=0.625 corresponding to $\bar{p} = 0.37$ and 0.97. For the latter case attachment is confirmed by the presence of a shear layer developing from the collar exit.

For the linear regime, data is compared with previous studies. Results in Fig. 8 show that data collapses reasonably well, taking experimental uncertainties, that change with the experimental setup, into account. Therefore, it seems that a real engine jet responds to counterflow as well as any other type of jet.

2. Collar Pressure Distribution

Figure 9 shows the collar pressure distribution for two gaps, G/H=0.5 and G/H=0.625. It is clearly visible that as suction increases pressure becomes lower throughout the entire collar. However, for high values of $\bar{p}$, there is a local pressure maximum that can even reach over atmospheric values. This is an indication of attachment, as pressure is expected to rise to stagnation values as the jet impinges on the collar wall. Therefore, these results confirm those in Fig. 4. For smaller gaps, the attachment location moves further upstream, a result of less space available for the jet to deflect.

3. Secondary Flow

Characterization of the secondary flow is of primary importance when it comes to real aircraft implementation. One of the main advantages of CFTV over other fluidic techniques is low secondary mass flux requirements.

Secondary to primary mass flux ratio is plotted against $\delta_v$ in Fig. 10. For every gap, the free entrainment condition shows coflow, which increases for smaller gaps, again a result of collar constraints imposed on jet entrainment.

To understand the presence of coflow, it is best to consider the CFTV setup as two pumps working against each other. On the one hand, the main jet entrains air from its surroundings, thus acting as an ejector pump, pulling air from the vacuum line (coflow). On the other hand, the vacuum pump is pulling air into the vacuum line (counterflow). The relative strength between these two pumping actions is going to determine which type of secondary flow is present.

Once the vacuum pump is on and the control valve is opened counterflow is established, and $\delta_v$ increases with counterflow up to a maximum value. Further increase in counterflow levels does not influence $\delta_v$. This is another indication of jet attachment.

A very interesting feature in Fig. 10 is the existence of a region of quasi-constant counterflow levels for increasing values of $\delta_v$. It is better observed in the higher gaps, as the $\delta_v$ range is wider, but that does not imply that it does not exist for the lower gaps. An explanation for this effect is as follows: as $\delta_v$ increases with lower gap pressures, thus increasing secondary flow velocity, the main flow chokes the secondary one, by decreasing the area
available between jet and collar. It seems that these two effects balance each other resulting in a nearly constant mass flux ratio.

Secondary flow requirements are higher for higher gaps, as expected. Nevertheless, even for the highest gaps, continuous control of the jet requires less than 6% of counterflow. Though higher gaps provide a large linear regime, the accompanying higher secondary mass flux becomes prohibitive, for practical applications. For the present case a gap of $G/H=0.625$ represents the optimal solution as less than 4% of counterflow is required in the linear regime.

Secondary flow temperature, $T_{line}$ was also monitored, to verify if the electronically actuated valves could be used. Figure 11 shows that temperature increases dramatically with counterflow, and values much higher than the anticipated 150ºC were observed. This data is very important to limit the higher values of suction that can be applied when automatic valves are used.

Based on secondary and primary mass fluxes and temperatures, mass and energy balances provide the amount of air originating in the main jet that goes into the vacuum line, $\dot{m}_2$. Figure 12 shows that the secondary flow can contain up to 35% of primary jet gases, regardless of gap height. This is also an important factor to consider when installing automatic valves, as the exhaust gases have fuel particles that can be harmful.

4. Thrust Losses

It is important to quantify how the thrust vectoring process affects the thrust produced by the engine. For that purpose, a thrust coefficient $c_T$ was computed. It represents the ratio between the thrust force produced and the total momentum available to generate thrust as detailed in Eq. (4).

\[
c_T = \frac{\sqrt{R_v^2 + R_r^2}}{m_p U_p + \dot{m}_2 U_r}
\]

(4)

B. Other Factors Affecting CFTV Static Performance

1. Electronically controlled valves

The results presented in Figs. 14 and 15 clearly show that the configuration with electronically controlled valves shortens the linear range of this mapping. This is caused by the pressure drop inside the valves and by the maximum mass flow rate obtained with this configuration.

In terms of the mass flow rate, the difference is more noticeable for the higher thrust vector angles. For example, consider the case in which $\delta_v \approx 15^\circ$ for both configurations; the mass flow rate for the manually
controlled valves is more than 1.5 times the one obtained with the electronically controlled valves. At the same time, the coflow is severely affected because the electronically controlled valves do not have the same performance for the flow in the opposite direction.

Another significant aspect of the behavior of these valves is the pressure drop between the input and the output. To distinguish a pressure drop in the vacuum line from the one arising from the valves, the pressure is measured for both configurations in a similar position along the vacuum line. For the electronically controlled valves, this measurement is obviously made in the vacuum pump side near the valves. The results for this specific electronic valve configuration show that the pressure drop inside the valves goes from 26 KPa when the two valves are completely open, up to 35 KPa, when the two valves are completely closed.

Another problem introduced by the electronically controlled valves was some nonlinearity in the static mapping from the command signal to $\delta_v$. Furthermore, this nonlinearity is not the only one introduced by the electronically controlled valves. Examining the performance of these valves when they are opening and closing, as seen in Fig. 16, some hysteresis is also noticed. This fact will emphatically affect the automation of CFTV system.

2. Influence of the Lower Collar and Lower Coflow

As presented in Table 1, results show a large thrust vector angle even when no suction was applied. The asymmetry of the CFTV frame configuration without the lower collar gives rise to this finding. However, this setup was used as a worst case situation in which the jet is nearest to the collar and consequently attachment occurs faster.

Several other researchers have used a configuration in which lower coflow was permitted. This was done by opening the lower cavity in the CFTV frame. In this scenario, when no suction was applied the thrust vector angle was lower than the one in the configuration referred to above. Nevertheless, the minimum angle obtained for this configuration was not zero.

Another configuration is also presented in this study, in which lower coflow is not allowed. This case represents the situation when full pitch vectoring is implemented, so both cavities will be connected to electronically controlled valves. Taking into account that these valves will also be connected to vacuum lines, a simple scheme does not allow coflow.

The differences between the three configurations are shown in Fig. 17. Although the range for all cases is very similar (8 degrees), initial $\delta_v$ are completely different.

3. Influence of the Piping Configuration

The final concern is related to the dynamics of the CFTV. In the present apparatus, the electronically controlled valves are placed relatively far from the CFTV frame. This was initially done to allow the placement of measuring equipment between frame and valves. Nevertheless, during the experiments some lag was noticed from the time that a signal was applied to the valves to the time the gap pressure changed. In light of this, a configuration with a shorter distance between the valves and the frame was tested to reduce this problem.
The most relevant result of these experiments is presented in Fig. 18, which is related to the temperature in the vacuum line. The shorter configuration referred to herein the one described above in which mass flow meters were not used. In this configuration, the lag problem was considered a secondary concern because a new problem arose. The valves could not be used for all command signals because at higher values, which correspond to higher δv, the temperature inside the vacuum line reached the limit of the valve specifications, as shown in Fig. 11.

C. Dynamic Response

The use of Kulite pressure transducer to measure the gap pressure in a high sample rate was very challenging. During the first tests, several difficulties were found related to grounding and electromagnetic interference. The radio system used to command the engine, the vacuum pump and the engine, interfered with the Kulite pressure transducer performance, as shown in Fig. 19. In this case, either slight changes in a short period of time or no changes at all were being made in the flow conditions; however, measurements have shows very fast transitions.

After several changes were made inside the lab, the problem was confined to the engine startup system and the radio control system/engine fuel pump. The former was mainly related to the spark plug because every time it was activated a significant jump was noticed in the Kulite pressure transducer signal. The latter was triggered either by electromagnetic interference or by a change in the fuel pump regime.

Despite all the difficulties found in obtaining a clean and reliable high frequency pressure signal, an experiment with a very controlled environment was made in which the engine radio control signal was not changed and other interference with the Kulite pressure transducer was restricted. Usually, the engine regime changes during the experiments. To compensate for these changes, the radio control was used such that the regime remained essentially constant during the entire experiment. In this particular experiment, no significant change in the engine regime was noticed so the radio control signal was not changed and consequently no noticeable interference with the Kulite pressure transducer was noticed; but this barely happened in other experiments. Thus, an accurate measurement of the CFTV dynamics was made. To obtain the high frequency dynamics a 5 ms sampling time was used during these experiments. The dynamics of the CFTV system as seen by the Kulite are presented in Fig. 20, when a step input corresponding to a variation of 8 degrees was applied to the electronically controlled valves.

The results have shown a CFTV slew rate of 160º/s and a 0.035s delay for both experiments when opening and closing the valves. The latter value is caused by the valves, which have a time delay given by the company specifications of exactly 35 ms. Hence, the additional hardware apparently does not introduce noticeable delay in the CFTV dynamics. The former value is in the interval of 140-200º/s presented in Ref. 5, which confirms the fast response of this system. Further details about the system dynamics can be found in Ref. 12.
IV. Conclusions

The present study has demonstrated for the first time the ability to vector the thrust producing jet of a gas turbine engine for angles up to 25°. However, to keep counterflow levels within reasonable limits for practical applications, a gap of \( G/H = 0.625 \) is chosen. Another reason to keep counterflow levels low is the increase of vacuum line temperature, which affects the performance of the automatically controlled valves.

The dynamics of the system has demonstrated the huge potential of these type of systems to improve aircraft maneuverability, as the slew rate is 160°/s. This value confirms the results presented in Ref. 2.

Acknowledgments

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