Application of Vortex Generators in Flow Control of the Inlet

CHEN XIAO, FANG LIANG-WEI
Aero-engine Department
Nanping Aeronautical Institute
Nanjing, The People's Republic of China

ABSTRACT

This paper introduces the features of using co-rotating vortex generators for controlling boundary layer and flow field in the inlet without flow separation. The principles of the arrangements of the blades and selection of constructional parameters of the generators that are applied to create the transverse flow between the high and low pressure regions and to reduce the secondary flow losses are analysed. The experimental results show that when the appropriate parameters of the co-rotating vortex generators are chosen for the inlet subsonic diffuser with apparent high and low pressure regions, not only the nonuniformity of the flow field is greatly improved but also the dynamic performance of the flow at exit is slightly improved.

NOMENCLATURE

C
chord of vortex generators

DC
60
total pressure distortion coefficient at exit of the inlet

DC
60
= P
Tav
- P
Tmin 60
q
Tav

F
area

h
height of duct at the station where vortex generators are installed

L
distance from the location of the severe bend in vertical direction to the reference point in the front section of the inlet

l
distance from vortex generators to the reference point in the front section of the inlet

n
number of vortex generators

P
H
total pressure at entrance of the inlet

P
PSD
power spectrum density

P
Tav
average total pressure at exit of the inlet

P
Tmin 60
minimum value of the mean total pressure over any 60° sector of the exit section

q
Tav
mean dynamic head at exit of the inlet

S
spacing of vortex generators

Tu
radial average turbulence level at exit of the inlet,

Tu
= (5
i
ΔP
rms
i
)/60
Tav
sectional average turbulence level at exit of the inlet

Tu
60
maximum value of the mean turbulence level over any 60° sector of the exit section,

Tu
60
= ΔP
rms
60/q
Tav

W
width of duct at the station where vortex generators are installed

X
axial distance

ΔP
rms
angle of attack of the vortex generators

ΔP
rms
60
maximum RMS value of the mean total pressure fluctuation over any 60° sector of the exit section

T
boundary layer thickness

θ
circumferential angle

σ
total pressure recovery coefficient of the inlet,

σ
= P
Tav
/PH

ρ
mass flow ratio

Subscripts

1
outerside

2
top-bottom side

INTRODUCTION

Due to the overall arrangement of the aircraft and structural weight limitations the internal passage of the inlet is usually designed with large diffusion angles and curvature. This brings about flow separation in the diffuser. The flow losses due to the secondary flow caused by the inertia of the turning of the flow are greatly increased and the pressure distribution at the exit of diffuser is seriously nonuniform. The controlling technique of the flow is extensively used in preventing or delaying the separation and improving the flow nonuniformity. The flow control devices are divided into two kinds, one is called the "active"
control which has an obvious effect on improving the performance of the diffuser. It is to bleed or blow the low energy flow in the boundary layer to prevent flow separation caused by the interaction between the terminal shock in the supersonic flow and the boundary layer. Another is called the "passive" control. It is to mix the high-energy air with the low-energy boundary layer by the trailing vortices of various types of vortex generators, so that the additional energy is transferred from the main flow to avoid or reduce the flow separation. The blade vortex generators is one of the "passive" type. Late in the forties, the generators by Taylor (1) was used to delay the separation of the flow on the wing surface to increase the critical Mach number and to prevent the boundary layer separation in the diffuser for increasing the diffuser efficiency. At present they are still used as the main way to prevent and reduce the separation and to improve the flow field nonuniformity at the diffuser exit (2,3,4).

As the vortex generators cause losses by themselves, suitable arrangement and constructional parameters should be selected to prevent flow separation and to improve the total pressure distribution at the diffuser exit.

(5), (6) present respectively the experimental results using vortex generators of different constructional parameters in two-dimensional and axisymmetric diffusers.

This experimental investigation is made for determining suitable constructional parameters of vortex generators to improve the performance of the inlet, especially to decrease total pressure distortion and also for determining the effect of these parameters on the steady performance by a series of the experiments without flow separation in the diffuser. It is shown that the dynamic performance at exit is slightly improved as the vortex generators are installed.

TEST MODEL, APPARATUS AND INSTRUMENTATION

The model of fuselage side inlet and the test apparatus are shown in Fig. 1. The geometrical shape of the inlet passage is shown in Fig. 2. The passage is gradually transformed from the approximate square (700×764mm) at the entrance to round profile (of diameter 824mm) at the exit. The area distribution along the axis is shown in Fig. 3. The inner lip is made of a single circular arc and is of thinner profile. The scale of the model is 1:7 and is made of hard wood composed of right and left parts to facilitate assembling and regulating and for making oil flow prints. Since the passage I and II are of different shapes their models are different. The exit of the model passage is connected to the measuring sector to measure the inlet flow field. "Cross" type total pressure rake (Fig. 4)
in the measuring sector. The total pressure measurement is made by rotating the above rake at 15° a time. 144 total pressure values are obtained. Four holes from which the average static pressure is taken are drilled 90° apart along the circumference at the total pressure measuring plane. The velocity distribution at position where vortex generators are installed is measured by the total pressure rake consisting of 21 total pressure probes of 1.2mm diameter. The static pressure distributions are obtained from a row of longitudinal taps (of diameter 0.8mm) at the top and bottom wall. The Reynolds number based upon the entrance characteristic dimension is greater than 10^6. The exit Mach number is in the range of 0.65~0.38.

Five 75KW vacuum pumps are used to suck the ambient air into the inlet to simulate the ground conditions. The air mass flow is controlled by a by-pass valve.

The digital pressure transducer equipped with a scanner is used to measure the pressure, the data are recorded by a digital printer. The error of the measurement is 0.2%. The total pressure fluctuations at the inlet exit are measured by a high frequency response transducer (EPA-120-50). Via an amplifier the output signals from the transducer are recorded on FM tape recorder and are processed subsequently by a power spectrnum analyzer for power density spectrum analysis. The RMS values of the total pressure fluctuation signals from a low-pass filter with cut-off frequency of 1600 HZ are measured by a RMS meter. In order to analyse the flow quality at the inlet lip and in the duct, flow patterns are obtained by oil print with red oil and carbon black on the surface of the model.

FLOW FEATURES OF THE TEST INLET

The flow features of the test inlet are as follows:
1. Severe flow separation at the inner lip, especially serious reversal flow at inner lip of outside and at corner (Fig. 5) is found.

2. Due to the inertia of the turning of the flow in the vertical and horizontal direction in the diffuser passage and the lip separation, the secondary flow is resulted. In passage I, near the outside at the point of greatest curvature in the rear of passage the secondary flow is severer than that in passage II (Fig.6).

   a. Lip separation, flow friction, secondary flow and turbulent mixing loss of the nonuniform flow cause the total pressure losses at the inlet exit. The total pressure distortion at the inlet exit is mainly caused by the lip separation and the bending of the duct in vertical and horizontal direction. Thus the main feature of the flow field at the inlet exit is that the high pressure region is formed at the inner side (left side) while the low pressure region at the outer side (right side).

SELECTION OF THE VORTEX GENERATORS TYPE

The blade vortex generators are a set of small blades installed on the wall of the duct. The blade profile is a half NACA 0012 airfoil. The blades are set at an angle with the flow direction. When the flow passes through the blades, behind the blades trailing vortex which flows downstream along the flow direction will be induced. If the core of the trailing vortex maintains a proper distance away from the wall within quite a distance downstream, the induced velocity of the trailing vortex near the boundary layer edge is able to urge the main flow to mix with the low energy flow. The vortex generators are divided into two kinds according to their configuration, the co-rotating vortex generators and counter-rotating vortex generators.

The vorticity and effective range of the vortex depend on the generator height h, chord c, spacing between two adjacent blades S and angle of attack α etc. As long as the reasonable construction parameters are chosen, both kinds of generators are capable of preventing or delaying the flow separation. While these two kinds of generators have different features due to their different blade arrangement. There are differences in the capability to urge the main flow to mix with the low energy flow, in the range of effectiveness and in the losses of blades drag. Their advantages and shortages will not be described here, but it is noted that the main characteristic of the co-rotating vortex generators (Fig. 7) is the ability to control the traversing flow in the duct. As shown in Fig. 8, because the trailing vortices are of the same direction
of rotation, the induce action of the vortex cores causes the air flow toward left and that above the vortex cores flows toward the right. This characteristic is used to control the flow in the duct of obvious high and low pressure regions and to improve the total pressure distribution. The traversing flow can also be used in reducing the losses of the secondary flow. As there is no separation in the inlet diffuser and the high and low pressure regions are observed at the exit, it is reasonable to select the co-rotating vortex generators.

RESULTS AND DISCUSSION

According to the flow features of the tested inlet and the requirement of performance, not to eliminate the flow separation, the co-rotating generators are so chosen that the total pressure distortion coefficient $DC_{60}$ should be greatly decreased without decreasing the total pressure recovery $\sigma$. Consequently the arrangement of vortex generators in the duct and the selection of the constructional parameters have the following features.

The Arrangement of Vortex Generators in The Diffuser

The total pressure recovery coefficient $\sigma$ distribution (shown in Fig. 9) at the inlet exit shows that its higher total pressure distortion is caused by the existence of the outside low pressure region and the great total pressure difference between that region and the inside high pressure region. When the vortex generators are installed on top and bottom surface of the duct (Fig. 10), convection is formed between the inner and outer side and so the total pressure of the outer side low pressure region is increased. With the vortex generators so installed in passage II, the total pressure distribution at the exit is decreased. Fig. 11 and Fig. 12 show respectively the $\sigma$ distribution at the exit of duct II with vortex generators installed and the variation of total pressure distortion $DC_{60}$ with mass flow ratio $\psi$ both with and without the...
vortex generators installed. The average total pressure recovery coefficient \( \sigma \) at the exit remains unchanged with vortex generators installed.

As shown earlier, secondary flow is found in the heavy bend region along the vertical direction in passage I. With vortex generators appropriately installed on the outer surface of the duct which has already been installed with four blades on upper and lower sides, it illustrates that the secondary flow losses are reduced with the three blades installed.

Selection of The Height of Vortex Generators

The height \( h \) of the vortex generators is an important contructional parameter, and is one of the factors which directly affects the effect of vortex. Generally the height of the vortex generators must be slightly higher than the thickness \( \delta \) of the local boundary layer in order to mix the high energy main flow with the low energy flow in the boundary layer. (1) recommends that \( h \) equals about 1.2 times the height of local boundary layer thickness \( \delta \). However, the turbulent boundary layer is fully developed at the station with generators, so the generator's height cannot be selected by means of the \( \delta \). In this paper \( h/w \) (or \( h/H \)) is selected as the dimensionless parameter of the blades height. To create traverse flow greater value of \( h/w \) (or \( h/H \)) is used here. The greater the value of \( h/w \) is, the greater the induced velocity of vortex created in the high pressure region of the main flow will be. Thereof the \( DC_{60} \) will greatly be decreased. But if the value of \( h/w \) is too great the \( \sigma \) will be decreased due to the increase of the frictional losses of the blades. As shown in Table 1 the values of \( DC_{60} \) decrease as the values of \( h/w \), \( h/H \) increase. Moreover \( \sigma \) has not changed its value much in the ranges of \( h/w \) and \( h/H \) selected, yet possesses an optimal value. Although the value of \( \sigma \) has begun to decrease as the values of \( h/w \) and \( h/H \) are about 0.1 (w-H-100 mm), yet such values of \( h/w \) and \( h/H \) are suitable from the view point of \( DC_{60} \) and \( \sigma \) (the engine required \( DC_{60}=0.25 \)).

Selection of Axial Location of Vortex Generators

The vortex generators must be installed at certain location before sharp bend of duct to reduce effectively the losses of the secondary flow. \( 1/L \) is defined as the parameter of axial location. Table 2 shows that the inlet performances vary with the axial location for the same constructional parameters of generators. The value of \( \sigma \) is the greatest when the vortex generators are installed slightly ahead of the starting point of the curve of streamline on the outer side surface \( 1/L=0.72 \) as shown in Fig. 14, and the \( DC_{60} \) is the smallest when they are installed in the front part of the duct \( 1/L=0.31 \). This is due to that the total pressure nonuniformity caused by the lip separation and

<table>
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<th>( 1/L )</th>
<th>( DC_{60} )</th>
<th>( \sigma )</th>
<th>( \psi )</th>
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<tr>
<td>0.31</td>
<td>0.31</td>
<td>0.893</td>
<td>0.897</td>
</tr>
<tr>
<td>0.72</td>
<td>0.16</td>
<td>0.897</td>
<td>0.894</td>
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<tr>
<td>0.13</td>
<td>0.22</td>
<td>0.896</td>
<td>0.892</td>
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Table 2 Effect of Axial Locations of Vortex Generators Performance
first bend of duct can be improved earlier by installing the vortex generators in the front of the duct, while the vorticity of that vortex is continuously weakened in the flow, it is less effective as to reduce the secondary flow losses at severe bend of duct behind, thus $\theta$ is lower.

Selection of Spacing, Angle of Attack and Chord Length

The dimensionless constructional parameter $S/h$ denotes the spacing of generators. Due to the limitation of the inlet model height and width, the number of the blades is very small even if the smaller value of $S/h$ is selected. Besides, in order to cause stronger convection between high pressure and low pressure regions, the number of the blades should not be too small. Only two values of $S_1/h_1$ (2.3 and 3.2) on the top and bottom surface are selected for comparison, the $S_2/h_2$ (of value 2.8) on the outer surface and other constructional parameters are of the same value. When the mass flow ratio $\varphi$ is equal to 0.826, the performance data vary from $\varphi=0.899$, $D_{C60}=0.158$ with $S_1/h_1=2.3$ (four blades) to $\varphi=0.996$, $D_{C60}=0.178$ with $S_2/h_2=3.2$ (three blades). This shows that the value of $S/h$ should be smaller in order to create the convection between high pressure and low pressure regions.

The angle of attack is generally chosen in the range of $14^\circ$~$16^\circ$. The experiments show that the value of $D_{C60}$ is decreased by increasing $\alpha$ on the top and bottom surface, nevertheless $\sigma$ is also decreased.

Larger chord of $C$ ($h/C=0.5$) is used to increase the vorticity. The vorticity of blades of low aspect ratio is not sensitive to the variation of angle of attack.

Comparison of the Performance of The Inlets with and without Vortex Generators

The Comparison of Static Performance. For passage I with vortex generators selected $\sigma$ increases from 0.984 to 0.995 in take-off condition and $D_{C60}$ decreases from 0.38 to 0.21. For passage II with vortex generators selected $D_{C60}$ decreases from 0.52 to 0.20 and the \( \sigma \) remains constant.

Comparison of Dynamic Performance. In order to investigate whether trailing vortices are still existing at the exit of the diffuser (or that periodic pressure fluctuations are occurring at the exit) and whether the magnitudes of the total pressure fluctuations at the exit are affected by the generators, it is necessary to measure the fluctuations of total pressure at the exit and to analyze the associated dynamic parameters. The RMS values of the total pressure fluctuations are measured at 16 circumferential stations at an interval of 22.5° with 6 radial locations at each station at the exit section of passage I with the EPA-125-50 high frequency response pressure transducer made in America. The signals of the total pressure fluctuations at 4 typical locations (as shown in Fig. 4 at A) are with power spectrum density analysis. In Fig. 15 is shown the radial average turbulence level $Tu$ at the exit varying with the circumferential location with and without vortex generators. It is seen from Fig. 15 that the magnitudes of maximum $Tu$ and their positions are not changed. Table 3 shows the

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>$Tu$</th>
<th>$Tu_{c60}$</th>
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</thead>
<tbody>
<tr>
<td>NO VORTEX GENERATORS</td>
<td>1.94%</td>
<td>12.7%</td>
</tr>
<tr>
<td>WITH VORTEX GENERATORS</td>
<td>1.87%</td>
<td>11.5%</td>
</tr>
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</table>

In Fig. 16, the power spectrum density of total pressure fluctuations at four typical locations in passage I is shown.
average turbulence levels $Tu$ of exit section and the maximum average turbulence levels $Tu_{c60}$ at the exit.

We can see from the table that the $Tu$ and $Tu_{c60}$ are slightly decreased with vortex generators used. From the curves of power spectrum density at the four typical locations as shown in Fig. 16, the periodic functions are not found whether there are vortex generators or not. So it can be seen that periodic disturbance does not occur at the diffuser exit as vortex generators are installed.

CONCLUSIONS

By installing the co-rotating vortex generators the nonuniformity of the flow field at the exit can be greatly reduced and the total pressure recovery coefficient remains constant when there is no separation, but there are apparent high and low pressure regions, in the inlet subsonic diffuser. The secondary flow losses in mild curved duct tested can be reduced and the total pressure recovery coefficient can be increased by using the co-rotating vortex generators.

When the co-rotating vortex generators are used to create transverse flow between the high and low pressure regions so as to obtain more even total pressure distribution and reduce the secondary flow losses, the governing principles of the arrangements of the blades and selection of constructional parameters $h/W$, $1/L$ and $s/h$ are different from that for the conventional vortex generators used to prevent the boundary layer separation. The value of the parameters $h/W$ (or $h/H$) = 0.10, $1/L=0.72$, $s/h=2.5-2.8$, $h/c=0.5$ and $\alpha =15^\circ$ chosen in this experiment is suitable.

The results of the analysis of the parameters of total pressure fluctuation at the exit show that there is no periodic disturbance signal of total pressure and the turbulence parameters $Tu$ and $Tu_{c60}$ of total pressure fluctuation are slightly decreased when the co-rotating vortex generators are installed at some suitable location of the diffuser.

REFERENCES