The purpose of this investigation is to explore the possibility of using artificial mechanical means for excitation of shear layers with application in swirling jet mixing enhancement. For this purpose, a novel mechanical device for excitation of the helical instabilities of swirling jets is designed, fabricated, and used in these experiments. The device consists of a rotating cylinder with internal lobes of small height to induce small perturbations. The number of lobes and the direction of rotation can be varied to induce helical waves at azimuthal wave numbers of $m = +0, \pm 1, \pm 2, \pm 3,$ and $\pm 4$. The $m = +0$ denotes the plane-wave excitation, $m = \pm 1$ identifies the first helical mode with one lobe, $m = \pm 2$ is the second helical wave with two lobes and so on. The positive and negative signs imply helical perturbation waves that spin in the same or opposite direction to the swirl direction, respectively. Swirl is induced in the airflow by a 45° vane-type swirl generator. Time mean axial velocity and turbulence measurements of the swirling jet, with and without excitation, are measured by hot-wire anemometer. The results are compared with the baseline (plane-wave excitation) at various helical modes. The acquired data is presented in 3D mesh plots and 2D contour plots. It is observed that new device is effective in excitation of the helical instability waves and in mixing enhancement of the swirling jet.

Key Words: Helical Wave, Swirling Jet, Instability, Mechanical Excitation

1. Introduction

Low amplitude acoustic excitation of swirling jets using plane waves has been tried in the past on the swirling jets at low swirl number$^{(1), (2)}$. The non-dimensional swirl number is defined as the angular momentum flux divided by axial momentum flux, times the nozzle exit radius. In these experiments, the jet’s swirl number was 0.35 and the excitation sound pressure level was 126 dB. In spite of the maximum growth of the instability waves at excitation Strouhal number of 0.4, no change in the mixing characteristics of the swirling jet was observed in these experiments. Mixing enhancement by plane wave excitation was only achieved when high amplitude, electro-pneumatic excitation devices (Ling drivers, capable of generating 170 dB SPL in the near field), were used to excite a swirling jet at low swirl numbers of $S = 0.12^{(3)}$.

Theoretical hydrodynamic stability analysis of swirling jets has shown that the helical-instability waves of counter-spin to the swirling jet possess the highest spatial amplification rates$^{(4)}$. Therefore, excitation of swirling jets by helical waves should cause more mixing enhancement of these flows compared to plane waves.

1.1 Flow control for enhanced mixing

Mixing enhancement in swirling jets by using passive and active means has been investigated intensively in recent years. First, on the passive part$^{(5)}$, the initial swirl distribution as a means of manipulating the growth characteristics of centrifugal instabilities has been shown to dominate the streamwise evolution of swirling jets. Second, in the active control front, turbulent swirling jets were excited via plane acoustic waves$^{(6) – (8)}$. At the preferred Strouhal number and larger forcing amplitude, a mixing of a swirling jet (i.e., its rate of spread) was enhanced by using plane acoustic waves. However, linear hydrodynamic stability theory shows that helical disturbances of negative spin exhibit the most effective growth rates. Hence, the augmentation of Taylor-Görtler vortices dominating in the shear layer of a swirling jet is far better achieved by...
non-axisymmetric excitation of negative helicity. This is in contrast to the non-swirling jets which are dominated by Kelvin-Helmholtz instability waves and are more receptive to the plane wave excitation.

Past experimental studies\(^\text{(9)–(11)}\) indicate that excitation can increase turbulence intensity and enhance flow mixing in shear flows resulting in increased spread rates and reduction in jet plume temperature. Jet plume temperature reduction is sought to cut down on the infra-red (IR) signature, to reduce wing surface heating in both over- or under-the-wing engine installations, as well as vertical take-off and landing aircraft to avoid ground erosion and hot gas ingestion.

1.2 Plane wave excitation

The first experiment of the controlled excitation of a cold turbulent swirling jet was done by Farokhi et al.\(^\text{(6),(12),(16)}\) and Taghavi\(^\text{(14)}\). The experiments were carried out for flow with swirl number of 0.35 and Mach number of 0.26. The time-mean axial velocity distribution did not have a “top-hat” radial profile at the nozzle exit. The excitation level of plane acoustic waves was held constant at 124 dB at various Strouhal numbers ranging from 0.326 to 0.903. The results showed that even if the axial velocity distribution at the nozzle exit did not have a “top-hat” profile, the instability waves were amplified rapidly in the streamwise direction, reaching a maximum in amplitude and then decaying further downstream. Excitation at a Strouhal number of 0.4 exhibited the largest growth. Therefore the “preferred” Strouhal number was found to be 0.4, based on the nozzle exit diameter, mass averaged axial velocity and excitation frequency. Furthermore, it was observed that the instability waves peaked closer to the nozzle exit and their maximum amplitudes were only about 50% of their counterparts in non-swirling jets having the same mass flux, Mach number, and Reynolds number. At this forcing level the mean velocity components of swirling jets did not experience any change. In addition, Farokhi, et al.\(^\text{(16)}\) further investigated the effect of large-scale organized motion. This is similar to the behavior of excited non-swirling jets. He found that:

(a) Kelvin-Helmholtz instability waves of helical (both \(m = +1\) and \(m = -1\)) and axisymmetric (\(m = +0\)) modes are found to exist in the shear layer around the periphery of a swirling jet.

(b) The growth rate of the helical \(m = -1\) mode is relatively higher than the axisymmetric mode growth rate.

(c) In general, the total growth of the instability waves is smaller in swirling jets compared to the non-swirling condition.

Generation of pure and controllable helical waves\(^\text{(18)}\) to excite these natural, fast-growing instability waves has always been a challenge. In some attempts, an array of loud speakers have been placed surrounding the jet\(^\text{(19),(20)}\). The complexity of such arrangement, among other problems, has prevented realistic and practical application of this important physical phenomenon to date.

Motivated by the above arguments, the following research activities are carried out (\(Re = 5.7 \times 10^4\)):
(a) A unique facility is designed and built to incorporate a novel, robust mechanical excitation device that is capable of generating helical waves, mechanically rather than acoustically which has traditionally been done. It facilitates future hardware design for practical applications.

(b) The above facility is used to excite the natural instabilities (Kelvin-Helmholtz) of a swirling jet at different modes \(m = \pm 0, m = \pm 1, m = \pm 2, m = \pm 3,\) and \(m = \pm 4,\) where \(m\) is the azimuthal wave number.

(c) The effect of growth of natural helical instability waves of different modes on mixing enhancement of a swirling jet is experimentally demonstrated.

2. Experimental Set-up

The experimental set-up is shown in Fig. 1. It consists of a blower, flow conditioners, adaptor, vane-type swirl generator, nozzle, and the excitation device. The blower supplies air flow at the mean velocity of 24.38 m/s.

2.1 Subsonic nozzle

Subsonic Nozzle I is located between the blower and the swirl generator. This nozzle is made of solid acrylic plastic for flow visualization purposes with an inside radius of \(r = 65.53\) mm for the inlet and \(r = 44.45\) mm for the exit of the nozzle. There are eight tiny orifices (approx. 0.50 mm Dia.) to accept devices which measure the properties of passing flows on the outer surface of this nozzle. Due to the inside cross section area being narrowed and smooth, the flow is accelerated in \(x\)-direction without swirl. Subsonic Nozzle II connects the swirl generator to the excitation device. This nozzle is also made of solid acrylic plastic with a constant inside radius of \(r = 88.90\) mm.

2.2 Swirl generator

A schematic of swirl generator is shown in Figs. 2 and 3. An axisymmetric core surrounded by eight fixed plastic vanes is used to generate swirl. The vanes’ angle are adjustable to change the degree of make it easier to observe the inside motion of fluid (using smoke or dye) through out the subsonic nozzle I and II. The vane angle can be adjusted between zero degrees (no swirl) and 75°. The swirl angle of 45° was used in these experiments.

2.3 Excitation device

The excitation device consists of a smooth rotating cylinder, having 95.3 mm diameter, with internal lobes as shown in Figs. 4 and 5. The cylinder can be rotated in either direction by a V-belt which was connected to a reversible-electrical motor. The motor’s speed can be maintained to within ±1.6% of the desired RPM. The cylinder’s rotational speed used in these experiments was 800rpm. The spinning disturbances were induced on the
swirling jet by internal contoured lobes located on the inside surface of the rotating cylinder (Figs. 6 and 7). These lobes consist of cylindrical-wooden rods, having a 4.24 mm diameter, and running the entire length of the cylinder. The cross-sectional area of the each lobe is about 0.2% of the inside cross-sectional area of the cylinder. A thin sheet of plastic is wrapped around the inner surface of the tube and over the wooden rods to provide a smooth transition. The upstream ends of the lobes are contoured flush with the inner-surface of the circular nozzle exit to provide a smooth transition and therefore prevent the flow separation at this location. Identical rotating cylinders with zero (no lobe; baseline configuration), one, two, three, and four lobes were used in these experiments, simulating nine helical-instability modes; i.e., \( m = +0, \pm 1, \pm 2, \pm 3, \text{ and } \pm 4 \).

2.4 Test conditions

The test conditions are as follows:

- **Swirl Number:** 0.8
  The ratio of maximum mean tangential-to-axial velocity at the nozzle exit is 0.88.
- **Vane Angle of Swirl Generator:** 45°
- **Swirl Direction:** Clockwise (as shown in Fig. 5)
- **RPM (tube):** \( \pm 800 \)
  + : Co-rotational (spin) to the swirling jet
  - : Counter-rotational to the swirling jet
- **Flow Speed (at the exit of the subsonic nozzle I):** 24.38 m/sec
- **Helical Mode:**
  + 0: No lobe (disturbance) case with co-spin to swirl, plane-wave
  \( \pm 1 \): One lobe cases (Co-& Counter-spin to swirl)
  \( \pm 2 \): Two lobe cases
  \( \pm 3 \): Three lobe cases
  \( \pm 4 \): Four lobe cases
- **Ambient Temperature:** 20°C

3. Results

The effect of excitation on the growth of the natural helical instability waves and the resulting mixing enhancement are investigated by the mean and fluctuating (turbulent) velocity measurements using a hot-wire anemometer. A definition sketch is shown in Fig. 8. A single-probe hot-wire anemometer is used to measure the axial time mean velocity and the fluctuating turbulent quantities of the excited swirling jet. Comparison of the axial mass flow rates and velocity profiles between jets at various excitation modes provides an indication of the jet entrainment and mixing.
Plotting is executed in two ways (i.e., three dimensional mesh plots and two dimensional contour plots). Contour plots show the same velocity (or turbulence intensity) distribution by using closed lines in an equivalent level. In addition, three dimensional mesh plots enable us to observe those distributions instantly by a cubic effect. The detail velocity profile of vortex core is presented in radial distribution plots.

### 3.1 Error analysis

The error analysis has been carried out for axial velocity and axial turbulence intensity measurements because these are the only quantitative measurements made. For this analysis, the inner and outer radii of the cylinders (or nozzles) are known to be accurate within ±0.127 mm (i.e., tolerance).

The presented percentage errors in the following sections are acquired by the iteration of measurement under the same condition. For instance, RPM of the blower was measured by the stroboscope 10 times under the exact same controller condition. After the calculation of mean value of the acquired data, the absolute value of maximum deviation is divided by the mean value and multiplied by 100 to be expressed in percentage. The same iteration concept is applied to the electric motor, the hot-wire anemometer, and traverse table settings.

First of all, the RPMs of the motor and the blower may cause the same kind of error. Even though the motor RPM is measured every two minutes to maintain ±800 rpm, there is a ±1.625% error. In case of the blower, the error is within ±1.375%.

Next, ±1.675% is from the hot-wire system. These measurements are performed 10 times at the point of \((x/D, y/D, z/D) = (3, 1.5, 1.5)\) (* refer to the Fig. 8 for “D” definition).

Last, the maximum possible error in the measurement can occur when the investigator was setting the origin point of the traverse table coordinate. It has been estimated that the settings are accurate to ±1.82%.

Therefore, the total percentage error in the measurements is ±3.261% (square root of the squared of possible errors). In the velocity plots presented in this chapter, the error is represented by error bars on selected data points in order to demonstrate the error range. Error bars, however, are not placed on all the data points in order to avoid the clutter in the plots.

### 3.2 Mean flow results

Detailed time-mean-axial-velocity measurements were made in the jet, on a plane perpendicular to the centerline at 3 nozzle diameters downstream from the nozzle exit. The effects of excitation on the time-mean-axial-velocity distribution of this swirling jet, excited at positive and negative helical modes, are plotted selectively in Figs. 9 and 10. For the velocity contour Figs. 11–13, the outer-contour lines start at 0.61 m/sec and they all have the same contour interval of 0.61 m/sec. The case of \(m = +0\) (meaning the co-rotational excitation with no lobes) was used as the baseline for these experiments.

### 3.3 Effect of excitation on shear layer

As shown in Figs. 12 and 13, the effect on shear layer near the mean characteristic boundary is generally intensi-
Fig. 11 Contour of mean axial velocity $u$ at $x/D = 3$ ($m = +0$) Contour interval at 0.61 m/s

Fig. 12 Contours of mean axial velocity $u$ at $x/D = 3$ for various positive helical excitation modes (contour interval at 0.61 m/s)

Fig. 13 Contours of mean axial velocity $u$ at $x/D = 3$ for various negative helical excitation modes (contour interval at 0.61 m/s)

Fig. 14 Comparison of radial profiles of the mean axial velocity $u$ (m/sec) at $x/D = 3$ for various negative helical excitation modes ($y/D = 0$)

3.4 Effect of excitation on the vortex core and maximum velocity

The radial contour plots are arranged together in Figs. 14 through 15 for the purpose of easy comparison of the radial velocity distributions. Even though the lobes are small and attached to the inner surface of the rotating cylinder, there are significant effects on the velocity profile at the center part as well as the shear layer. As shown in Figs. 14 and 15, the positive helicities ($m = +1$ to $m = +4$) affect mainly the shear layer, and there is no noticeable effect on the vortex core. It is, however, revealed that negative helicities ($m = -1$ to $m = -4$) reduce the depth of the double hump profile which is formed due to the wake effect of the central cone of the vortex generator and also swirling characteristics of the flow. The maximum velocity of $m = -3$ case is up by 8.7% compared to $m = -2$ case, and the center velocity is up by 4.1%. Especially in case of $m = -2$, the maximum velocity is reduced by 16.2% of
the $m = +0$ case, and the center velocity is increased by 20.5% simultaneously. The width of the velocity profile at $u = 1.52$ m/sec is augmented by 19% caused by $m = -2$ excitation compared to $m = +0$ case. In addition, Fig. 14 shows increased velocities at the range of $z/D = -2$ to $-1$ and $z/D = 1$ to 2. The second negative case shows the maximum increased percentage of 400% at $z/D = 1.2$. This indicates that the more effective entrainment of the ambient flows and the mixing enhancement can be produced under $m = -2$ condition. The mass flow calculations confirm the same results in chapter 3.7 $m = -3$ and $m = -4$ excitation cases also have significant effect on vortex core but again their effect on mixing is not as pronounced as $m = -2$ case.

3.5 Axial fluctuation velocity measurements

The concept of turbulence intensity led by Osborne Reynolds in 1895 resulted in writing the continuity and momentum equations in terms of mean and time-averaged turbulent variables.

Time mean $u$ of a turbulent function $u(x,y,z,t)$ is defined by

$$\bar{u} = \frac{1}{T} \int_0^T u dt$$

where $T$ is an averaging period.

The mean square of a fluctuation is a measure of the intensity of the turbulence.

$$\bar{u}^2 = \frac{1}{T} \int_0^T u'^2 dt$$

where $u' = u - \bar{u}$.

The results of turbulence intensity ($\sqrt{\frac{u^2}{\bar{u}}} \times 100$) measurements for the axisymmetric swirling jets at $x/D = 3$ are plotted in Figs. 16 through 18. All the numbers used in Figs. 16 through 18 are non-dimensional, and the $z$- and $y$-axis are also normalized by $D$.

3.6 Effect of excitation on turbulence intensity

The comparison between Figs. 16–18 (outer contourline = 10, and contour interval = 10) shows that the counter-spin (negative helicity) excitations are more effective in augmentation of the turbulence intensity than the co-spin (positive helicity) ones. Negative helicity cases show the several significant effects on turbulence intensity.

First, the intensity at the center of $m = +0$ case is decreased by 40% (50 to 30) when the negative helical modes are applied.

Second, the maximum turbulence intensity for $m = +0$ case is 120, but several contour areas of 140 or 150 are shown in Fig. 18. This result reveals that swirling jet is more unstable in shear layer when the negative helicity excitations are applied.

Finally, the intensified fluctuating velocities that are shown in negative excitations imply the effective entrain-
Fig. 18 Contours of mean axial turbulence intensity at $x/D = 3$ for various negative helical excitation modes (contour interval = 10)

Fig. 19 Ratio of mass flow rates at $x/D = 3$ and various helical modes

ment effects between the swirling jet and the ambient flow around the mean characteristic boundary.

Generally, the negative helical excitations are the more effective way of the shear layer control than positive ones.

3.7 Mass flow results

In the calculation of mass flow rate, all the data acquired from the present experiments were integrated down to 10% of respective maximum velocities. This radial location determines the mean characteristic boundary on the jet.

The mass flow ratios are plotted at various helical excitation modes in Fig. 19. Mass flow ratio is defined as the ratio of the excited and baseline ($m = +0$) mass-flow rates. From this figure it is clear that the counter-spin excitation generally results in more mixing enhancement compared to the co-spin cases. The maximum mixing enhancement for both positive and negative helical excitation modes were measured for the case of $m = \pm 2$. For $m = -2$, the mass flow ratio was increased by about 18% compared to the $m = +0$ (baseline) case. The mixing enhancement decreased as the excitation helical-mode number was increased to $m = \pm 3$, and was completely diminished at mode numbers of $m = \pm 4$. This 18% difference proves that the mechanical excitation is an effective way to increase the mass flow rate and the mixing of swirling flows. Furthermore, choosing the proper helical mode is an important factor to maximize the effect of excitation. As a result, the preferable helicity mode of this investigation (as measured at $x/D = 3$) is regarded as $m = -2$ case, and the effects, however, are decreased when $m = -3$, and $m = -4$ are applied compared to $m = -2$. To avoid the reverse effect (less effective than plane wave excitation as shown in $m = -4$ case), finding a preferred helical mode that can produce a maximum mixing effect should be considered.

3.8 Comparisons with analytical stability analysis

In this section, the experimental results are compared with analytical results of Wu, C(21). In this investigation, the third helical mode in the direction of shear layer rotation (i.e., $m = +3$) was the least amplified instability wave, while the third helical mode against the direction of shear layer rotation (i.e., $m = -3$) was the most amplified one, among the seven modes (i.e., $m = \pm 0, \pm 1, \pm 2, \pm 3$) investigated. The present investigation however, turns out several different results. For the fast dispersion around the shear layer, $m = +3$ excitation is the most effective method, and $m = -3$ mode is the most effective when applied to diminish wake effect at the vortex core. Especially, $m = -2$ excitation shows a remarkable effect on the outer flow entrainment and mixing enhancement as well as fortifying turbulence intensity. Even though the results of this investigation doesn’t exactly agree with the Wu’s, the general fact that negative helical modes are more effective than the should be realized that Wu’s theoretical results were based on the stability analysis of swirling jets with top-hat initial axial velocity distributions. In our case, the axial profiles were double-humped and far away from top-hat approximation.

4. Conclusion

A novel mechanical device for helical-wave excitation of swirling jets was designed, built, and tested. The
device was effective in exciting a swirling jet at the swirl number of 0.8.

It was shown that the response of the swirling jet to helical-mode excitation was not only dependent on the helical-wave mode number, but also strongly on its sign; meaning the spin direction of the excitation device with respect to the swirling jet. Excitation at both positive and negative helicities affected the time-mean velocity distributions in the vortex core and the shear layer areas. But changes were more pronounced for the counter-spin \( m = -1 \) to \( m = -4 \) compared to co-spin \( m = +1 \) to \( m = +4 \) cases.

Excitation at negative helicities resulted in more mixing enhancement compared to positive cases. For both positive and negative helical modes (co-spin and counter-spin cases), mixing enhancement was maximized at \( m = \pm 2 \). The mixing enhancement benefits were reduced as wave number was increased to \( m = \pm 3 \) and diminished at \( m = \pm 4 \). These observations are in general agreement with the results of stability analysis.

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