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# Downstream boundary effects on the spectral characteristics of a swirling flowfield *

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**Abstract.** The spectral characteristics and the structural response of a swirling flowfield are investigated subject to a non-axisymmetric disturbance and a contraction imposed downstream. Two natural frequencies are noted in different regions of the undisturbed swirling flowfield, one is due to a precessing vortex core and the other to the most amplified downstream azimuthal instability. The downstream contraction usually causes compression of the central recirculation zone into two side-lobes, increases the dominant frequencies and forms a straight central vortex core with a high axial velocity. The dominant downstream instability frequency depends linearly on the inlet Reynolds number and on the mode of the breakdown. For the downstream non-axisymmetric disturbance, such as the passing of the turbine blades, the fundamental frequency is not altered by the disturbance and the oscillation strength of the downstream instability is greatly reduced as the excitation frequency remains unmatched with the dominant downstream natural frequency. Downstream azimuthal instability promotes the breakdown recirculation.

## 1 Introduction

Swirl is used extensively in a modern aircraft combustor to provide flame stabilization and to improve fuel/air mixing. The swirl-induced recirculation is an important phenomenon of combustor research, and has been of major interest to the combustor research community. Syred and Beér (1974), Lilley (1977) and Gupta et al. (1984) documented the experimental and computational achievements. Recently, laser diagnostic techniques have been used extensively in the detailed measurements of the swirling flowfield prevailing in various simulated gas turbine combustors, for example, Heitor and Whitelaw (1986), Altgeld et al. (1983), Jones and Wilhelmi (1989), So et al. (1985), Ahmed and So (1987), Koutmos and McGuirk (1989). Also, considerable efforts have been expended to understand the mechanism that produces the flow reversal and the parameters that govern the occurrence of the flow reversal in the swirling flow. It is now accepted that this phenomenon represents a transition from supercritical to subcritical flows and is generally termed vortex breakdown. In the study of swirling flows, the term vortex breakdown refers to the formation of a central toroidal recirculation zone (CTRZ) in the flow field (Escudier and Keller 1985).

In a gas turbine engine, the turbine is used to convert the kinetic energy, as well as part of the thermal energy of the burnt gas into shaft work. In order to increase the kinetic energy, the heated gas from the combustor is accelerated immediately upstream of the turbine and the effect of the contraction on the swirl recirculation has been investigated by Escudier and Keller (1985), Lilley and Abujelala (1984a) and Lilley and Yoon (1984b). Escudier and Keller (1985) demonstrated that for the subcritical flow, the long inertia waves carry with them the information of the downstream geometry and can propagate upstream against the flow and modify the recirculation characteristics, somewhat similar to acoustic waves in the subsonic flow. However, they did not discuss the spectral properties and turbulence characteristics in the downstream subcritical region.

It has been suggested that, after vortex breakdown has occurred, the central forced vortex region of the flow becomes unstable and starts to precess periodically about the axis of symmetry (Chanaud, 1965). Early reports of this precessing vortex in swirling flow were given by Chanaud (1965), Cassidy and Falvery (1970) and Escudier and Merkli (1979), and visual observations showed flow reversal and a helical precessing vortex. Chanaud (1965) suggested that the precessing vortex derives its energy from the hydrodynamic instability of the flow and Syred and Beér (1974) indicated that its core lies on the boundary of the mean reversed flow zone between the zero axial velocity and the zero streamline. Garg and Leibovich (1979) measured the spectral characteristics of a swirling flowfield and confirmed that the breakdown is unstable to the non-axisymmetric disturbance of the azimuthal mode $|m| = 1$, as predicted by Lessen et al. (1974) using a linearized inviscid stability analysis. However, the role of the precessing vortex on the flow structure and its relationship to a downstream non-axisymmetric instability are still not conclusive. Also, the turbine-blade passage may form an asymmetric blockage and periodic disturbance to

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the combustor swirling flow. In view of the previous results, it may be conjectured that the interaction between the exit non-axisymmetric disturbance and the subcritical precessing vortex may lead to change of the recirculating flow structure.

The purpose of this experimental investigation is to study the response and the spectral characteristics of a swirling flow subject to downstream boundary effects of contraction and a non-axisymmetric disturbance. The effect of the precessing vortex and of the downstream azimuthal instability on the swirling flowfield and their relation to the breakdown structure are also investigated.

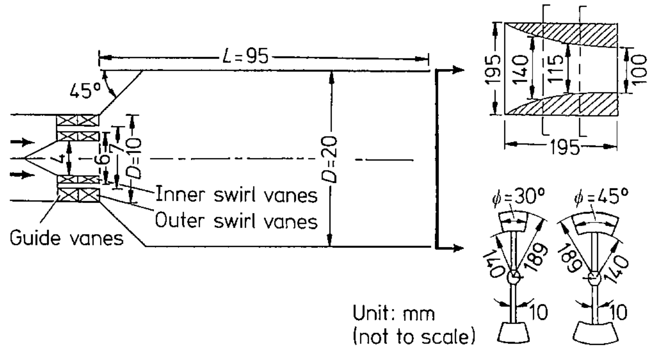


**Fig. 1.** The swirl combustor test facility, the contraction and the non-axisymmetric exciters

## 2 Experiments

The swirl combustor test facility includes a blower, a settling chamber, a plexiglass model combustor, and two sets of vane swirlers to produce co- and counter-swirling flowfields, as shown in Fig. 1. It was used previously by Chao et al. (1987) to study coaxial swirling jet flows. For the downstream boundary effects studied here, the typical ($-45°$, $-45°$) inner and outer co-swirling arrangement was employed and the Reynolds number based on the combustor inlet diameter was fixed at $1.34 \times 10^5$. The combustor inlet velocity $U_i$ was maintained at 20 m/s throughout the experiments. However, effects of the various co- and counter-swirler arrangements and the variation of the Reynolds number on the typical spectral response of the flow were also studied and will be discussed later. The hub of the swirler replaced the fuel injector of a combustor. A separated wake was found behind the center body and this may interact with the central vortex breakdown recirculation to form a two-cell recirculation zone and breakdown recirculation zones, depending upon the swirling strength of the flow, as discussed by Chao (1988) and Escudier and Keller (1985). The settling chamber includes a honeycomb and six fine screens. The contraction section was designed using a fifth-order polynomial profile with an area contraction of 20. The turbulence level at the exit of the settling chamber was found to be 1.2%. A guide vane unit was fixed ahead of the swirlers to straighten the flow and guide it into the swirler vanes. The model combustor is 10 cm in diameter at the inlet, followed by a 45° expansion which ends in a 20 cm-diameter cylinder. The downstream contraction was produced by a smooth convergent nozzle with an area ratio of 0.263. Combination of nozzle segments led to area ratios of 0.717, 0.618, 0.515, 0.348, 0.263 at the combustor exit and the air was discharged into the quiescent surroundings. The asymmetric disturbances were produced by a set of mode exciters as shown in Fig. 1, with the exciter connected to a variable speed motor to generate the disturbances with frequencies up to 6,545 rpm. The frequencies were measured by both a stroboscope and a tachometer.

Axial and azimuthal mean velocity components and the turbulent intensity were measured by a laser Doppler anemometer (TSI-9100-7) and a hot-wire anemometer (TSI IFA-100) and microphone transducers (B & K, 4138) were used to measure the velocity oscillation and the pressure fluctuation for spectral analysis. The laser Doppler anemometer (LDA) comprised a 4 W Argon ion laser with a Bragg cell after the beam splitter to shift the frequency of one beam by 40 MHz, thereby permitting the determination of both the amplitude and the direction of the velocity component. The light beams were expanded to improve the signal quality and intersected at their focal point to form a 88 μm × 1.62 mm ellipsoidal probe volume. The scattered light from the probe volume was collected by the lens through a pin hole and was converted into the electric signal by the photomultiplier and processed by the counter. The data from the counter were processed by a computer which performed the statistical analysis weighted by their residence time. The number of velocity samples ranged form 1,024 to 4,096, depending on the locations and flow conditions. The seeding in the flow required to produce the scattering light intensity was generated from paraffin oil with nominal droplet diameter of 1 μm. The seeding particles were injected into the mainstream in the upstream of the settling chamber. In order to eliminate the error and difficulties encountered in the LDV measurements due to the curvature effect of the combustor wall, sixteen circular windows of 30 mm-diameter and separated by 50 mm were attached to both sides of the combustor wall. They were sealed with thin flat optical glasses to allow accurate intersection of the laser beams and to reduce the noise in the scattered light intensity.

Hot-wire measurements in this complicated swirling flowfield are very difficult and unreliable and, althought the six-orientation method of Jackson and Lilley (1984) provided a useful solution, the uncertainties were large especially in regions of high turbulence so that the hot-wire was used only to measure spectral characteristics. Syred and Beér (1974) and Gouldin et al (1984) used hot wires to measure the oscillatory properties of swirling flowfields by orienting the hot-wire according to the local flow direction and obtained reasonable data. Garg and Leibovich (1979) used the LDV system to measure the spectral characteristics of the vortex breakdown flowfield in a water tunnel facility. Although, several estimations and statistical methods, e.g., Adrian and

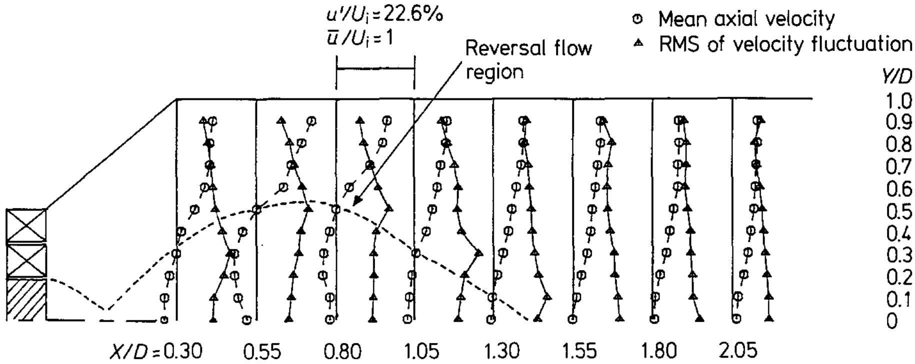


**Fig. 2.** The mean axial velocity component and the rms velocity fluctuation distributions for the unexcited case

Yao (1987), have been reported to estimate the power spectra from the randomly sampled LDV data, the accuracy of spectral analysis with low data rates and high noise situation is questionable. Thus, the hot wire was employed to measure the spectral characteristics with the wire oriented according to the mean flow direction. The microphone transducer was used to measure the pressure fluctuation. The pressure fluctuation data were compared and correlated with the velocity fluctuation to distinguish the periodic characteristics of the precessing motion.

## 3 Results and discussion

In general, three kinds of recirculation zone can be found in the swirling flowfield: the central toroidal recirculation due to vortex breakdown, the separation wake bubble behind the centerbody and the corner recirculation due to combustor wall expansion. As the inlet swirl strength is increased from zero, the breakdown recirculation is found first in the downstream region and then it shifts swiftly upstream to join the separation bubble. A two-cell central recirculation zone may be generated (Chao 1988). In addition to the recirculation behavior, the swirling flow is dynamic so that modes of oscillation of instability vortices are found in the swirling flow (Gouldin et al. 1984). Among them, the precessing vortex caused by the instability of the central forced vortex and the azimuthal instability of the vortex core downstream of the breakdown region (Garg and Leibovich 1979) are most pronounced. Since the wake region downstream of the breakdown flow has been shown theoretically by Lessen et al. (1974) to be most unstable to the non-axisymmetric disturbance with a phase function $kz+m\theta-wt$ when $|m|=1$, where $m$ is the azimuthal wave number, the unanswered question is whether the azimuthal instabilities in some way promote breakdown or are by-products of a primary breakdown (Garg and Leibovich 1979), and may be resolved by artificially exciting the flow non-axisymmetrically and observing the response of the flow. In reality, asymmetric excitation is difficult to generate and, instead, the instability may be suppressed and the breakdown observed. We will discuss this aspect later. To provide an overview of velocity and spectral characteristics of the combustor swirling flowfield, the undisturbed natural frequency distribution was first measured and then, based on the spatial distribution of the natural frequencies and the velocity characteristics of the flow, effects of the downstream contraction and the non-axisymmetric disturbance on the spectral characteristics and flow structure are discussed.

### *3.1 Natural frequencies of the swirling flowfield*

It is known (Garg and Leibovich 1979) that the swirling flow structure and its spectral characteristics are complicated functions of Reynolds number and swirl number. Here we present only the typical cases of coswirl ($-45°$, $-45°$) and counter-swirl ($-45°$, $+45°$) at a Reynolds number of $1.34\times10^5$. The mean axial velocity component and the rms of velocity fluctuations are shown in Fig. 2 where the dashed line is the locus of the zero axial velocity component which indicates the reversed flow region and the breakdown recirculation is clearly seen in the central region of $X/D=0.3\sim1.4$. In addition, an elongated separation wake bubble can be identified in the head end region against the centerbody and, together, these two recirculations form a bottle-neck of the reversed flow region. Obviously, these two types of recirculations interact with each other at $X/D=0.3$ and the breakdown recirculation stabilized itself against the separation bubble. A "tail" with insignificant reversed velocity is found behind the breakdown. The axial velocity is observed to change from a jet-like distribution in the upstream region of the breakdown recirculation to a wake-like distribution downstream the breakdown. The wake-like distribution is gradually smeared out as the flow moves downstream and an near-flat distribution is reached at the exit $X/D=4.05$. The tangential velocity distribution (not shown) develops into Rankin vortex for $X/D=1.05$, corresponding to the region immediately downstream of the breakdown recirculation zone.

High velocity fluctuation, Fig. 2, is found in the breakdown recirculation region, $X/D=0.3\sim1.05$, and gradually decays in the downstream wake region. The profiles of the fluctuation are consistent with the measured mean velocity, especially the axial component, with local peak value arising

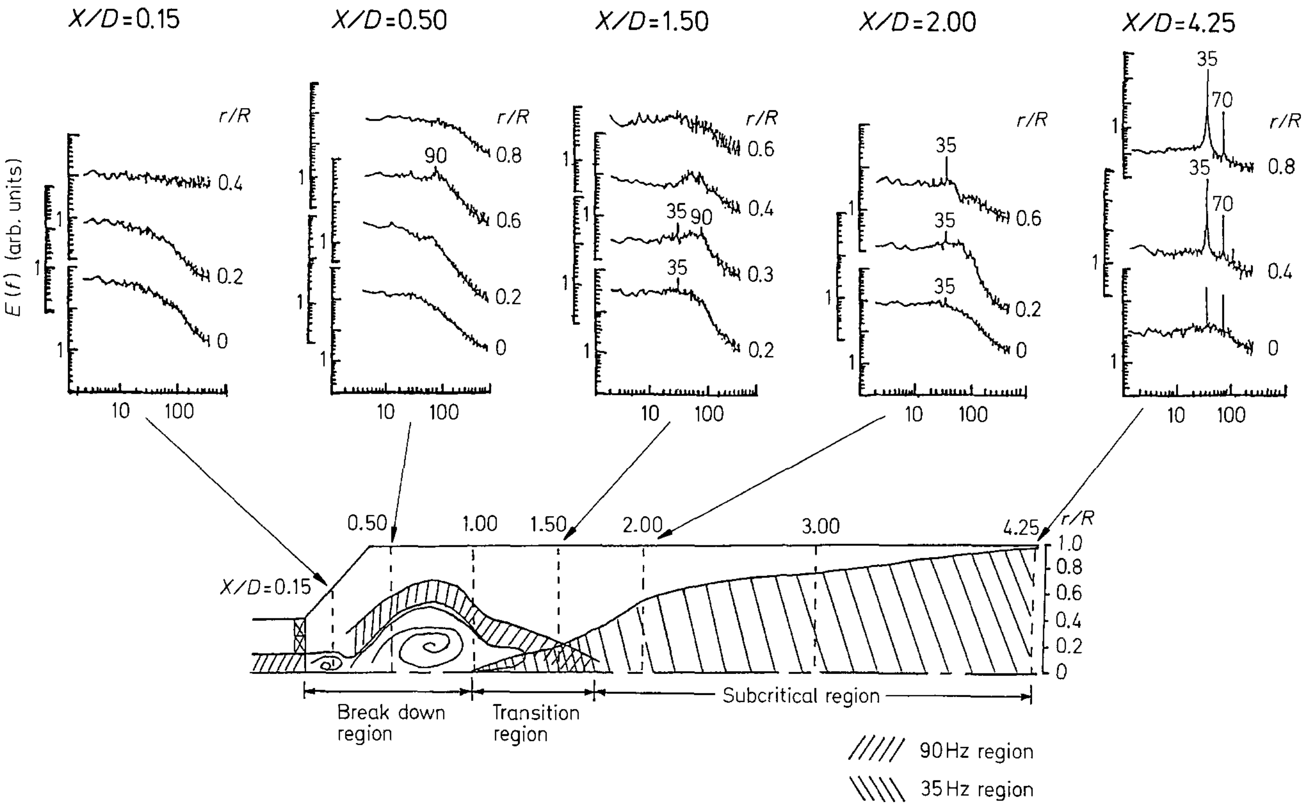


**Fig. 3.** The distribution of the dominant frequencies and the typical power spectra at typical axial and radial locations in the combustor swirling flowfield

in the location where inflection in the mean velocity occurs. The local peaks found between $X/D$ of 0.55 and 1.3 are near the zero axial velocity contour. We believe that these local peak velocity fluctuations are closely related to the generation of the precessing vortex, as has been pointed out by Syred and Beér (1974) that this vortex lies on the boundary of the mean reversed flow zone between the zero velocity and zero stream line. Thus, high velocity fluctuations measured in the vicinity of a precessing vortex comprise a combination of turbulent fluctuations and those which stem from the movement of the precessing vortex across the measuring volume. Fig. 2 can serve as a convenient base to map the characteristic frequency distribution in the following results.

The power spectra at different axial and radial locations were measured and results of the frequency characteristics and the peak frequency distributions of Fig. 3 are plotted against the mean recirculation profile. No dominant frequency was found in the recirculation, except for a layer near the zero axial velocity contour, and in the region near the combustor inlet. There are two dominant frequencies in the flowfield and the regions of distribution of dominant frequencies are also shown in Fig. 3. A peak at 90 Hz extends along the zero axial velocity contour of the recirculation zone toward the transition region and is the precession frequency which contributes to a large three-dimensional instability also, is responsible for the peak values of the rms of velocity fluctuations measured around the zero velocity contour. Since the location of the precessing vortex, the position of the local peak velocity fluctuation and the inflection point across the zero axial velocity contour are identical, it may be concluded that the precessing vortex is due in part to the hydrodynamic instability of the velocity inflection found near the zero axial velocity contour, rather than to the instability of the central forced vortex, as suggested by Chanaud (1965). A lower frequency at 35 Hz becomes obvious and extends from the immediate wake of the breakdown to become the dominant oscillation in the downstream region. This frequency was also found by Garg and Leibovich (1979) and is believed to be related to the most amplified downstream azimuthal $|m|=1$ instability. In Garg and Leibovich's (1979) experiment, they used a downstream contraction so that the amplitude of the azimuthal instability was smaller and existed only farther downstream. The 35 Hz peak oscillation and its harmonic can clearly be observed all over the region near the exit. Peak frequencies at 90 Hz, and 35 Hz co-exist in the transition region extending from $X/D$ of 1.0 to $X/D$ of 2.0. For the counter-swirl case ($-45°$, $+45°$), the dominant frequencies are 78, and 26 Hz and regions of peak frequencies distribution are almost identical to those of the co-swirl case. The reason for the lower peak frequencies for the counter-swirl case may be explained by the relation (Gupta et al. 1984) $W = f\, R_p$ where $W$ is the tangential ve-

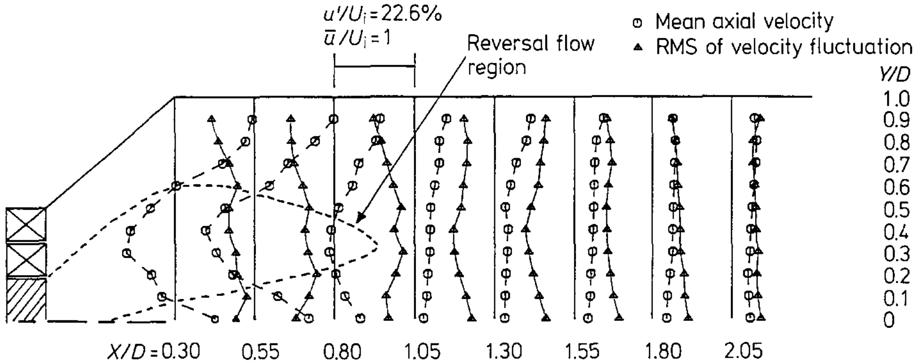


**Fig. 4.** The mean axial velocity component and the rms of velocity fluctuation distributions for the contraction case with an area ratio $A_R = 0.515$

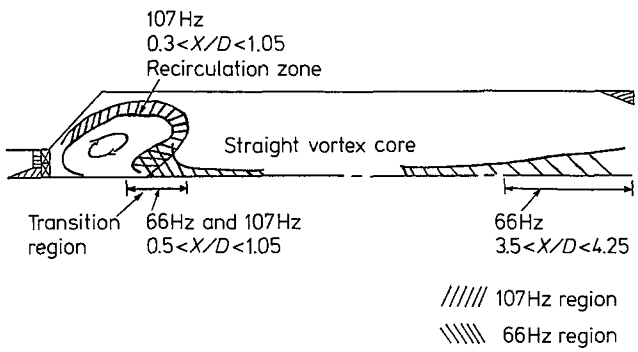


**Fig. 5.** The effect of the downstream contraction on the distribution of the spectral characteristics of the swirling flowfield

locity, $f$, the frequency and $R_p$, the radius measured from the central axis to the location of the precessing vortex. Counter-swirl gives lower tangential velocity due to the interaction of the counter swirling jets so that the frequencies are lower.

Signals from the hot-wire anemometer and the microphone transducer at the downstream azimuthal instability region were displayed simultaneously on the oscilloscope. The velocity and the pressure were seen to oscillate at the same frequency and nearly in phase, as observed by Syred and Beér (1974). The strong correlation of the velocity and pressure fluctuations at a dominant frequency confirms that the azimuthal oscillation is the dominant periodic phenomenon in the downstream region.

### *3.2 Spectral characteristics of the swirling flowfield with downstream contraction*

It was shown by Escudier and Keller (1985) that effect of the downstream contraction could propagate upstream and modify the breakdown for the subcritical downstream flow. The axial velocity and rms of velocity fluctuation profiles of Fig. 4 were obtained with a downstream contraction at a ratio of $A_R = 0.515$ and reversed flow region is seen to be compressed into two side lobes leaving a vortex core in the central region. The centerbody separation bubble is not clear in the present case. The vortex core is a strongly jet-like straight core with a high positive axial velocity component in the central region. The downstream contraction should cause an increase in upstream pressure and a stronger adverse pressure gradient in the combustor which favors the breakdown and strengthens the recirculation. Also, it causes acceleration in the vicinity of the exit and the jet-like, high axial velocity core. The velocity fluctuation distributions in Fig. 4 also show local peaks which follow the zero axial velocity contour and suggest that the precession prevails around the recirculation, even in the concave cavity near the central region between the two lobes. The peak frequency distributions in the combustor with a downstream contraction of area ratio of 0.515 is ploted against the mean recirculation profile in Fig. 5 which shows that as the cross section of the combustor outlet is reduced by the contraction the dominant frequencies are increased to 107 Hz and 66 Hz for the precessing vortex and the downstream azimuthal instability respectively. The radius of influence of the downstream azimuthal instability is greatly decreased and confined to the central straight vortex core and around the combustor exit. Precession is also found in a layer close to the zero axial velocity contour extending from $X/D = 0.3$ to 1.05 and in the central region between $X/D = 0.5 \sim 1.05$ where the breakdown and the straight vortex core co-exist, with dominant frequencies of 107 Hz and 66 Hz. This region is termed the transition region.

The downstream azimuthal instability frequency is shown as a function of the downstream area ratio in Fig. 6 for two typical cases of co-swirl ($-45°$, $-45°$) and counter-swirl ($-45°$, $+45°$). As the area ratio of the contraction is further increased, the dominant frequencies increase and the spatial distributions of the azimuthal instability decrease. The structure of the downstream azimuthal instability would be destroyed if the contraction ratio were to be increased to a critical value slightly higher than 0.515 for both cases and would develop into a core with highly positive axial and tangential velocities throughout the downstream region. Thus, it is obvious that periodic oscillations of the precessing vortex and the downstream azimuthal instability are the spectral characteristics of the confined swirling flow. For various cases of combinations of the inner and outer

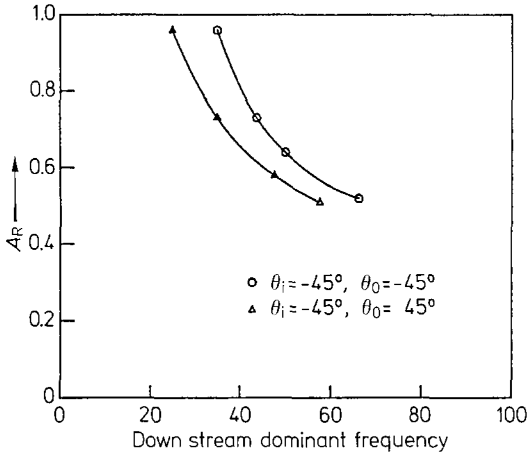


**Fig. 6.** The downstream dominant frequency as a function of the contraction area ratio

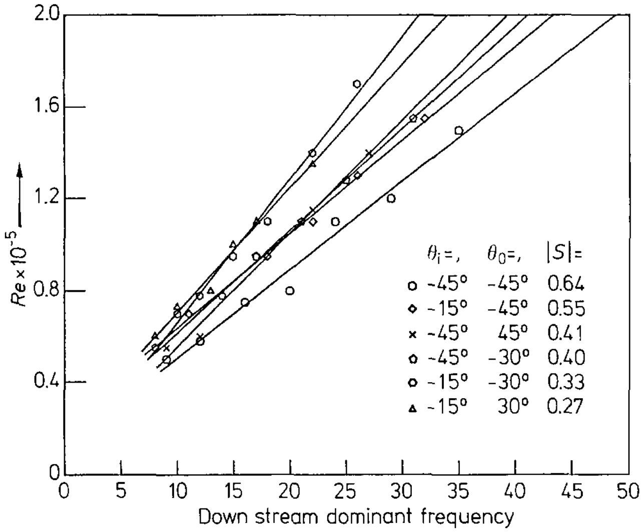


**Fig. 7.** The downstream dominant frequency as a function of the Reynolds number and the swirl strength

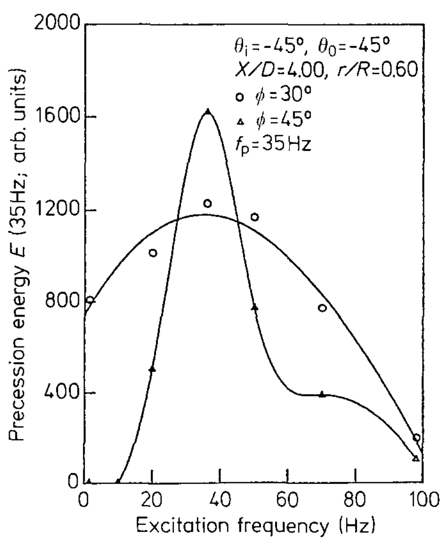


**Fig. 8.** The response of the downstream dominant frequency to the non-axisymmetric excitation

swirl strength and the Reynolds number studied here, the spectral characteristics were found sensitive to both the inlet Reynolds number and swirl strength.

Figure 7 represents the relationship of the downstream azimuthal instability frequency with Reynolds number and the double vane swirler arrangements. For a fixed inlet swirl strength, the downstream azimuthal instability frequency increases linearly with the Reynolds number and curves separate into three groups according to the inlet swirl strength. For each group, the curves almost collapse into one, implying that the frequency is not a strong function of the inlet swirl strength. Examination of the swirl breakdown type, as defined by Faler and Leibovich (1977) shows the striking correspondence of these three groups to the three breakdown modes. For the co- and counter-swirl cases of $(-15°, \pm 30°)$, the swirl strength was weak and no breakdown was observed: these belong to the double helix mode. It is generally accepted for the confined swirling flow that, when the inlet swirl strength $S$ is larger than 0.6, the flow is categorized as the strong swirl flow and a bubble type breakdown of central toroidal recirculation can be found near the centerline (Beér and Chigier 1983). The co-swirl $(-45°, -45°)$ case belongs to the bubble breakdown mode and for swirl strengths between these two modes, a spiral breakdown can be expected. Thus, the three cases of $(-15°, -45°)$, $(-45°, +45°)$, $(-45°, -30°)$ belong to the spiral breakdown mode and the downstream azimuthal instability frequency depends strongly on the mode of the vortex breakdown and is a very weak function of the swirl strength.

### *3.3 The effect of the downstream asymmetric disturbance*

The most amplified instability in the downstream wake region of the vortex breakdown has been shown to be the downstream azimuthal $|m| = 1$ mode. Artficial asymmetric excitation was applied at the exit of the combustor to suppress the downstream instability to determine the relation of the downstream instability with the breakdown. The asymmetric excitation was produced by exciters made up of sectors with arc angles of 30° and 45° rotating at various frequencies at the exit. The downstream dominant frequency was unaltered at 35 Hz and 26 Hz for the co- and counter-swirl cases respectively. But the response strength of the downstream oscillation to the excitation at various frequencies was different, as shown in Fig. 8. The response strength peaks at an excitation frequency corresponding to the undisturbed instability frequency and decreases rapidly as the excitation frequency departs from the instability frequency. Note that the magnitude drops from 1,600 to nearly zero for the 45° arc angle case as the frequency differs from with the undisturbed instability frequency. In view of this striking effect of the excitation on the strength of the downstream oscillation, the extreme condition of the exciter at zero frequency was chosen to reveal the structural response of the swirling flow to the asymmetric excitation. Thus, the relation

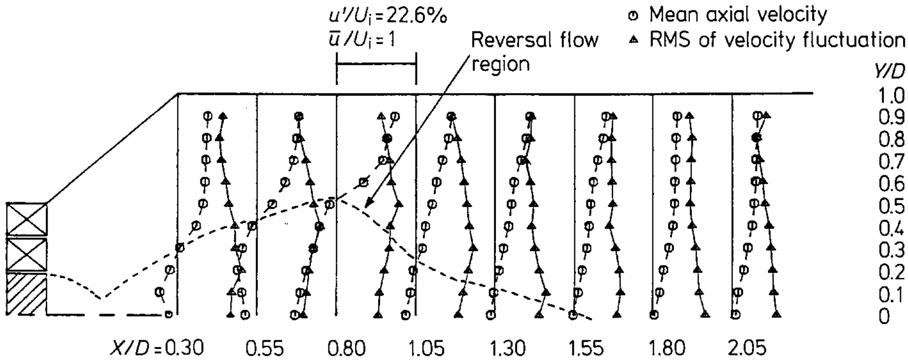


**Fig. 9.** The mean axial velocity component and the rms of velocity fluctuation distributions for the non-axisymmetric excitation case

of the breakdown recirculation to the downstream instability may be delineated.

In Fig. 9, the recirculation structure is clearly changed from that of the non-excitation case of Fig. 2 so that the breakdown recirculation has become smaller and shifted slightly downstream. The cross sectional areas at $X/D$ of 0.3 and 0.55 of the reversed flow region become smaller and the maximum reversed velocity is now at $X/D$ of 0.8. However, the overall recirculation zone still consists of separate regions of the breakdown recirculation and the separation bubble, which is similar to that of the unexcited case. The axial velocity near the center line in the downstream region remains small, in contrast to that of the unexcited case where the central low speed behind the breakdown gradually decayed into a more uniform distribution beyond $X/D$ of 2.8. This response of the flow recirculation structure indicates that the asymmetric disturbance would relax the breakdown recirculation to that with a lower swirl strength, that is, suppressing the downstream instability by asymmetric disturbance would degenerate the breakdown structure. Thus, the subcritical nature of the downstream region can transport the asymmetric disturbance upstream to modify the breakdown structure and the downstream region is sensitive to the disturbance. Also, in contrast to the contraction which compresses the recirculation and pushes it upstream, the asymmetric disturbance relaxes the breakdown. So now the azimuthal instabilities are not just by-products of a primary breakdown and in some way promote the vortex breakdown. The peaks of velocity fluctuations in Fig. 9 still closely follow the zero axial velocity line.

## 4 Conclusion

There are two dominant natural frequencies that of the precessing vortex observed along the zero axial velocity of the recirculation zone and the periodic oscillation of the most amplified downstream azimuthal instability in the subcritical region. A transition region exists in the immediate wake region of the breakdown recirculation where both frequencies coexist. High values of the rms of velocity fluctuations are in a layer surrounding the zero axial velocity contour which characterizes the precessing vortex as a large three-dimensional, time-dependent hydrodynamic instability caused by the inflection of the axial velocity distribution near the zero velocity contour. Contraction usually causes compression of the recirculation zone into two lobes and a vortex core with high axial velocity in the center of the combustor. Contraction also increases the dominant frequencies and the spatial distribution of the dominant downstream instability frequency is confined in a small central core and near the exit of the combustor. The downstream instability frequency increases with the contraction ratio and contraction destroys the azimuthal oscillation leaving a straight central vortex core as the contraction is increased beyond a critical value of 0.515. The downstream azimuthal instability frequency depends linearly on the inlet Reynolds number, also strongly on the mode of the vortex breakdown and very weakly on the swirl strength within the same mode. For asymmetric disturbances, the dominant frequencies are not altered and the disturbance propagates upstream and modifies the recirculation structure. Oscillation strength of the downstream instability is greatly reduced as the excitation frequency differs from dominant natural frequency. The downstream asymmetric disturbance causes suppression of the azimuthal instability which further relaxes the breakdown. Thus, the downstream azimuthal instability promotes the breakdown recirculation.


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