PASSIVE CONTROL OF MIXING IN A COAXIAL JET

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Abstract

An experimental investigation regarding interacting shear layers in a coaxial jet geometry has been performed. The present paper confirms experimentally the theoretical result by Talamelli and Gavarini (2006), who proposed that the wake behind the separation wall between the two stream of a coaxial jet creates the condition for an absolute instability. This instability, by means of the induced vortex shedding, may provide a continuous forcing mechanism for the control of the flow field. The potential of this passive mechanism as an easy, effective and practical way to control the near-field of interacting shear layers has been demonstrated.

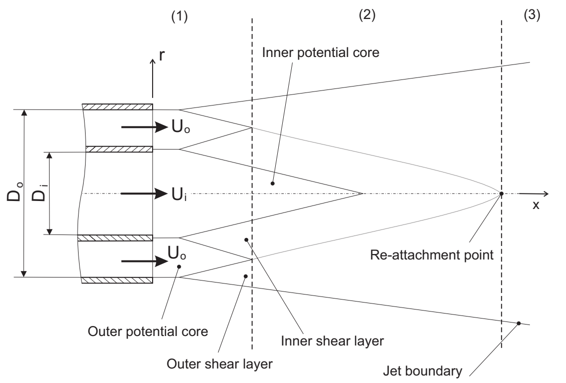

Figure 1: Sketch of the flow field of a coaxial jet configuration and its main parameters. (1) Initial merging zone, (2) Intermediate zone, (3) Fully merged zone.

1 Introduction

Flow control in transitional and turbulent flows has become more practical since the recognition of organised motions attributed to coherent structures embedded in the incoherent turbulent background. Through these coherent structures, which comprise a considerable fraction of the total turbulent energy, ways have been opened to manipulate the dynamics of the flow (cf. Fiedler (1987)). A variety of passive and active flow control mechanisms have been tested and applied within the last decades, principally in single jets and other canonical flows.

In the case of coaxial jets, however, flow control studies have been primarily investigated regarding their receptivity to active flow control strategies, as for instance done by Kiwata et al. (2001) or Angele et al. (2006). Passive control strategies, on the other hand, have mainly been disregarded, despite their promising results in other flow cases. One reason for this imbalance might be the fact that a full characterisation of the apparently simple geometry of coaxial jets, depicted in figure 1, is governed by a multitude of parameters, as listed by Buresti et al. (1994).

The prevailing model for more than a decade, put forward by Ko and Kwan (1976), was that coaxial jets could be considered as a simple combination of single jets, where the two shear layers originating from the nozzles develop independently from each other. This simple view was challenged when Dahm et al. (1992) in their flow visualisation study evinced the existence of different topological flow regimes for different velocity ratios, $r_u = U_o/U_i$ (here U_i and U_o denote the maximum absolute velocity of the inner and outer streams at the nozzle exits, respectively) as well as absolute velocities. Furthermore the same authors as well as Wicker and Eaton (1994) found that the vortical motion for $r_u > 1$ is dominated by the vortices emerging in the outer shear layer. They showed that the evolution of the inner shear layers vortices is dictated by the outer vortices motion and hence trapped in the spaces left free between two consecutive outer layer vortices; this is the so-called 'locking phenomenon'. Consequently the vortex passage frequency of the inner shear layer will differ from the one predicted by stability analysis for a single axisymmetric shear layer as shown by Dahm et al. (1992) and da Silva et al. (2003) by means of flow visualisations and direct numerical simulations, respectively. This finding has led to an increased focus on the control of the outer shear layers vortices as evident for instance from Angele et al. (2006) or Balarac et al. (2007).

One of the parameters, emphasised by Buresti et al. (1994), playing an important role in the evolution of transitional coaxial jets, is the thickness of the (duct) wall, t, separating the two streams from each other. It was shown by the same authors that two trains of alternating vortices are shed from both sides of the inner wall with a well-defined frequency, which scales with the wall thickness and the average velocity of the two streams. In fact both the geometry of the inner wall thickness and the velocity ratio were found to be crucial in determining whether the behaviour in the near-field of coaxial jets could be considered as wake-like or shear-layer-like.

In a recent study Talamelli and Gavarini (2006) formulated a theoretical background for this experimental finding. They showed, by means of linear stability analysis, that the alternate vortex shedding behind the inner wall can be related to the presence of an absolute instability, which exists for a specific range of velocity ratios and for a finite thickness of the wall separating the two streams. The authors proposed that this absolute instability may provide a continuous forcing mechanism for the destabilisation of the whole flow field even if the instability is of limited spatial extend. It is important to point out that this mechanism does not require any external energy input, being considered passive, and therefore is attractive for practical applications.

The aforementioned ideas have been experimentally realised in this paper and it has been shown that the vortex shedding behind a thick separating wall can be facilitated as an easily applicable and effective passive control mechanism. The vortex shedding was also found to dominate an observed 'whistler phenomenon' present at some of the measured absolute velocities. It emphasises thereby how an absolute instability, can be used as a passive mechanism to control its dynamics. The trapping of the inner shear layers vortices into the free spaces of the Kelvin-Helmholtz instability of the external shear layer, known as the 'locking phenomenon', has in the present study been shown to be indeed reversible. We observed that the vortex shedding behind the thick separating wall dictates the passage frequency of the external shear layers vortices and thereby controls the inner and outer shear layers evolution globally.

The remainder of the paper is organised as follows: Section 2 describes the coaxial jet facility as well as the measurement technique used. Results of the passive control mechanism and their discussion are given in section 3. An outlook towards the effect on the mixing is presented in section 4 and followed by conclusions in section 5.

2 Experimental procedure

The experiments were carried out in the *Coaxial Air Tunnel* (CAT) facility in the laboratory of the *Second Faculty of Engineering* at the *University of Bologna* in Forlí. The facility is composed of two independent centrifugal blowers equipped with three-phase motors. Two pre-settling chambers are placed downstream the blowers to reduce the disturbances from the blowers. Flow conditioning is performed by means of three screens and a honeycomb in the inner pipe as well as five screens and a honeycomb on the outer circuit. The inner and outer contraction ratios are 11:1 and 16.5:1, respectively, whereas the inner and outer coaxial nozzles, of exit diameter $D_i = 50$ mm and $D_o = 100$ mm, end with two straight pipes of 100 mm length.

In the present experiment, two types of separation walls between the two streams have been used. The first one has a thickness of $t = 5$ mm and ends in a rectangular geometry, whereas the second one ends with a sharp trailing edge making the wall thickness negligible ($t \approx 0$ mm) with respect to the sum of the side boundary layers thicknesses. The aforementioned separating walls will in the following be denoted as thick and sharp, respectively. The temperature difference inside the pre-settling chambers of the inner or outer jet has been introduced by means of a heat gun and electrical resistors placed at the inlets of the outer settling chamber, respectively. The amount was kept small in such a way that the temperature can be considered as a passive scalar and is still large enough to ensure a high temperature resolution. A series of experiments have been performed with the inner or outer jet heated in order to study the passive scalar mixing between the two coaxial streams and the annular stream and its surrounding ambient, respectively. Nevertheless, in the present paper, the focus lies on the control of the flow dynamics, and hence the passive scalar quantities will only be presented where necessary as a supplementary indication, due to its higher sensitivity to intermittent and sudden events.

For the present investigation a variety of hot- and cold-wire probes were used. The characterisation of the boundary layers, upstream the orifice exit and in the vicinity of it, were performed by self-made long and slender boundary layer probes consisting of 2.54 micron Platinum wires with a length-to-diameter ratio of 400 in order to avoid any blockage effects within the nozzle and reduce near wall effects. All other measurements were performed with a *DANTEC* 55P61 X-wire probe in combination with a self-made cold-wire probe comprising an 1.27 micron Platinum wire with a length-to-diameter ratio of 600. The axial and radial velocity as well as the temperature are acquired simultaneously and enable therefore the instantaneous temperature compensation of the velocity readings.

Most of the measurements have been obtained using one point statistics. The measurement set related to the triggering investigation, on the other hand, has been conducted in the cross stream direction and simultaneously behind the inner and outer wall in order to obtain conditional measurements able to highlight the dynamics of the interacting shear layers.

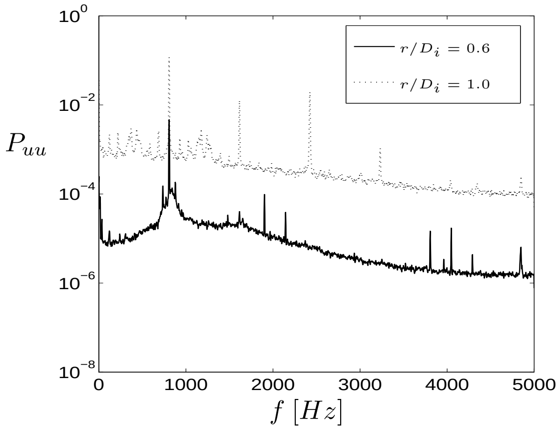

Figure 2: Power-spectral density function of the streamwise velocity component measured behind the inner (r/D_i = 0.6) and outer (r/D_i = 1.0) wall at $U_o = 20$ m/s and $x/D_i = 0.26$ for the sharp wall.

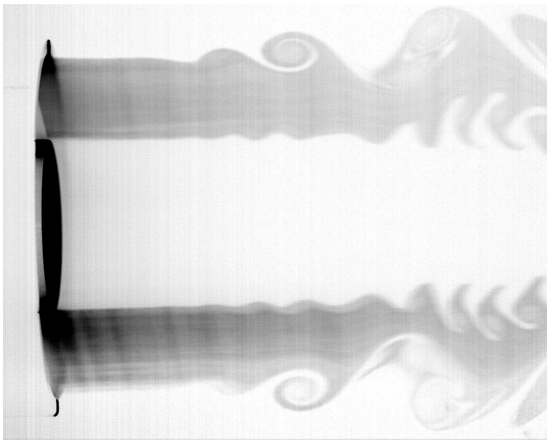

Figure 3: Smoke flow visualisation at $U_o = 4$ m/s and $r_u = 1$ for the sharp wall.

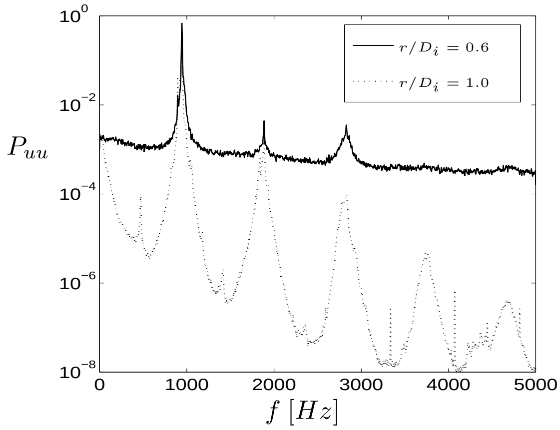

Figure 4: Power-spectral density function of the streamwise velocity component measured behind the inner (r/D_i = 0.6) and outer (r/D_i = 1.0) wall at $U_o = 20$ m/s and $x/D_i = 0.26$ for the thick wall.

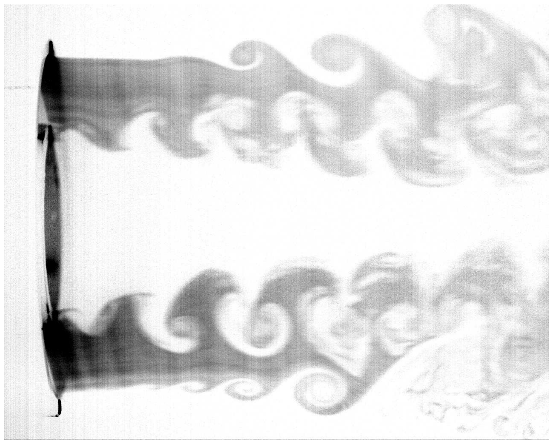

Figure 5: Smoke flow visualisation at $U_o = 4$ m/s and $r_u = 1$ for the thick wall.

3 Results and Discussion

In the following results from the sharp and thick wall cases are presented to highlight the effect of the absence and presence of the vortex shedding mechanism in the wake of the inner separating wall. The results shown here are all for the case of equal velocities in the inner and annular jet, i.e. $r_u = 1$. This velocity ratio was selected, because it lies within the velocity ratio for which an absolute instability behind a thick wall has been shown to exist (cf. Talamelli and Gavarini (2006)).

In the case of the sharp wall, the power-spectral density of the fluctuating streamwise velocity component in the inner and outer shear layer as well as an snapshot of a smoke visualisation shown in figure 2 and 3, respectively, depict the expected flow scenario. The Kelvin-Helmholtz instability emerging between the annular stream and the ambient is clearly highlighted in the visualisation as well as spectral content of the flow. The coinciding peak frequencies are a manifestation of the so-called 'whistler phenomenon', i.e. the jet produces a loud pure-tone sound (cf. Hasan and Hussain (1982)), to which we will come back later on.

For the thick wall, on the other hand, both the smoke visualisation as well as spectral content of the flow, have strong imprints of the vortex shedding behind the inner wall, which changes the flow scenario drastically, as evident from figures 4 and 5. Whereas the energy in the outer shear layer was mainly buried in the incoherent background turbulence in the absence of the vortex shedding (cf. figure 2), it is highly concentrated in its fundamental peak and harmonics in the presence of the vortex shedding.

The vortex shedding, starting right behind the inner wall and hence upstream the first emergence of the Kelvin-Helmholtz instability, traps the outer shear layers vortices into the free spaces left between the ones of the inner shear layer. This increases the coherency between the two shear layers and can further

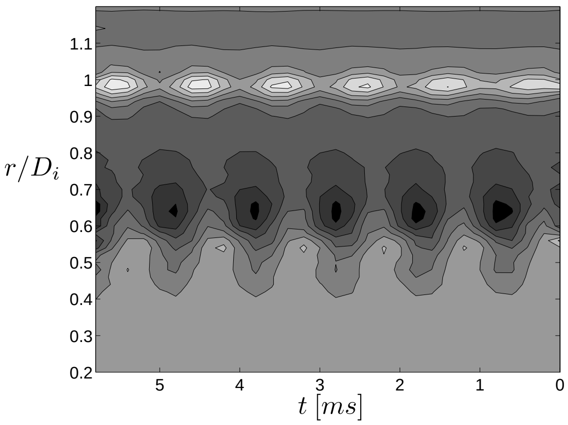

Figure 6: Pseudo-flow visualisation by means of conditional sampling technique of the radial velocity component at U_o = 20 m/s and r_u = 1 for the thick wall. Colormap from white to black corresponding to inflow and outflow conditions, respectively.

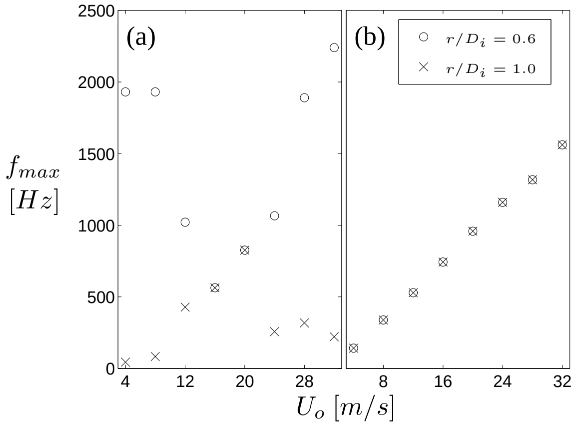

Figure 7: Fundamental frequency as function of the outer jet velocity behind the inner and outer wall at r_u = 1 and x/D_i = 0.26 for the sharp (a) and thick (b) wall.

be evinced through figure 6, where a pseudo-flow visualisation has been plotted through a conditional sampling technique. An X-wire probe was thereby triggered by the vortex shedding behind the inner separating wall detected by a single hot-wire probe which was placed at the same downstream location, $x/D_i = 0.26$. The clear fundamental spectral peak of the vortex shedding phenomenon and the pronounced fundamental and its harmonics in the outer shear layer in figure 4 anticipate a clear cyclical path of the streamwise and radial velocity component as found in the conditionally sampled pseudo-flow visualisation. Although the instantaneous smoke visualisation image has been taken at a much lower velocity (due to the difficulty to obtain expressive images at higher velocities), compared to the presented spectral measurements and pseudo-flow visualisation, its spatial character complements the quantitative time evolution of the two point hot-wire measurements. The recent finding of Balarac and Métais (2005), who showed that the vortices of the outer shear layer develop with a Strouhal number corresponding to the value predicted by linear stability analysis for the Kelvin-Helmholtz instability, is therefore not generally true, particularly in the presence of an absolute instability, which dominates the motion of the organised structures.

We have seen that the existence of the ‘whistler phenomenon’ dominates the results around 20 m/s, which is evident from spectral analysis and was also audible during the course of the experiments. This caused a jump in the turbulence intensity around the existence of the ‘whistler phenomenon’ within the outer shear layer and made any comparison between the sharp and thick wall cases in terms of mixing impossible. Nevertheless it is important to point out, as evident from figure 7, where the fundamental peak frequency as a function of the absolute velocity for both wall cases is shown, that no trend or relationship is observable for the sharp wall case (a) between the vortices in the inner and outer shear layer. Contrary, the strong controllability of the evolution of the vortices in both shear layers is evident from the linear relationship in the thick wall (b) case. This is even true for the case where a pure-tone sound was audible, hence the absolute instability, by means of the induced vortex shedding behind the inner wall, dictates the evolution of the vortices in both shear layers and hence the whole flow field.

The overlapping at 16 and 20 m/s for the sharp wall in figure 7 is a consequence of the whistler. However, there is no controllability of the fundamental peak, in the sharp wall case, whereas the thick wall presents a means to predetermine the evolution of the vortices in the inner and thereby outer shear layer, just by knowing the separating wall thickness, t, and the absolute velocity, U_o, or the average velocity for the case of unequal velocities within the range of the presence of an absolute instability.

4 Outlook

The aforementioned paragraphs and figures have demonstrated that an absolute instability in form of the vortex shedding phenomenon behind a thick separating wall between the two streams of a coaxial jet provide a continuous forcing mechanism for the control of the whole flow field and dominates all other disturbances in the flow.

The possibility to control the flow field by the presented passive mechanism has been shown in the present paper. What is left open is, what effect it has on the mixing, spreading and entrainment and hence turbulence itself. These questions could not be answered by linear stability analysis and are therefore left out for computational simulations or experimental investigation.

As an outline for further investigations the cross stream probability density distribution of the axial velocity fluctuations are given in figure 8. The contour plot indicates that the presence of the thick wall implies an increased turbulence activity in the inner mixing region. Contrary, a turbulence suppression and an increase in the organisation of the vortices, due to the continuous forcing (as described by Zaman and Hussain (1981) in simple jets or by Dahm et al. (1992) in coaxial jets), can be observed in the outer shear layer. It should be kept in mind, however, that these conclusions are biased due to the presence of the 'whistler phenomenon'. The bimodal probability density distribution within the outer shear layer shown in the insert (at $r/D_i = 0.93$), is caused by the occurrence of two dominant states of streamwise velocities apart from the mean value supporting the increased organisation of the vortices.

Due to the simultaneous acquisition of two velocity components and the temperature the possibility arises to investigate the distribution of fluctuations of the streamwise velocity and temperature at the same time by means of joint probability density functions (jpdf). The jpdfs of the axial velocity and temperature fluctuations, $p(u, \vartheta)$, normalised with their own root mean square (rms) values for the sharp and thick wall downstream the inner and outer wall are shown in figure 9. Shaded areas and black curves denote linearly and logarithmically spaced isodensity loci, respectively, in order to separately visualise the state of mixing and the entrainment, respectively. Hereby the inner jet was slightly heated above the ambient as well as the outer jet as can be anticipated from the entrainment of colder and warmer air downstream the inner and outer separating wall, respectively, for the thick (b) wall case. As evident from the shaded areas, i.e. their local concentration opposed to the much further reaching black curves, the newly entrained air is still highly segregated from the downstream convected stream, and this especially in terms of the passive scalar quantity. In the case of the sharp wall the outer shear layer seems to mix the newly entrained air better than for the case of the thick wall, confirming what have been extracted from figure 8.

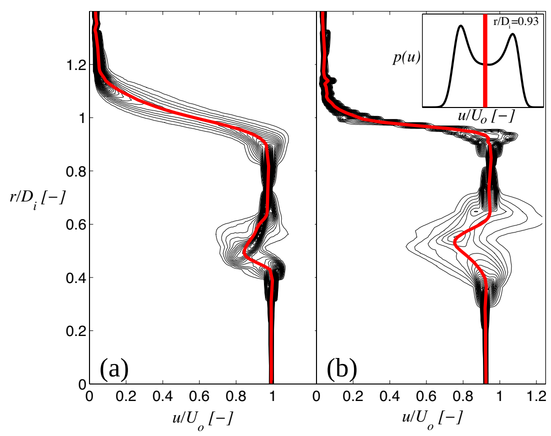

Figure 8: Contour plots of the probability density function of the instantaneous streamwise velocity, $p(u, r)$, at x/D_i = 0.5 for U_o = 20 m/s. Thick line represents the mean velocity, U/U_o. (a) sharp wall (b) thick wall. The bimodal probability density function in the outer shear layer is shown in the enclosure.

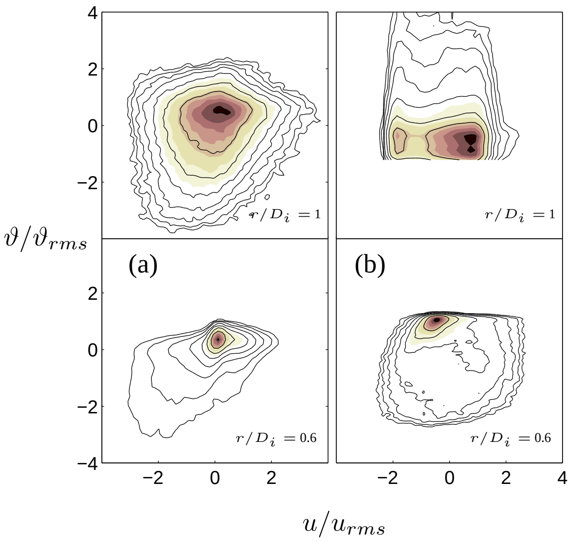

Figure 9: Joint probability density distributions of the axial velocity and temperature fluctuations normalised with their own rms values at U_o = 20 m/s and x/D_i = 0.26 for the sharp (a) and thick (b) wall downstream the inner, r/D_i = 0.6, and outer, r/D_i = 1, wall. Black lines and shaded areas denote logarithmically and linearly spaced isodensity loci, respectively.

We restrain ourselves at this point from general conclusions regarding the effect of this passive mechanism on the mixing, due to the multitude of flow regions in transitional coaxial jets (cf. figure 1). Also the existence of the 'whistler phenomenon' makes it impossible to make any general conclusion for the absolute velocity where the majority of measurements were taken, viz. 20 m/s. Simple axial evolutions of the mean or turbulence intensities of the streamwise velocity, but also the passive scalar (temperature) quantities, are known to be insufficient in describing the state of mixing in transitional free shear flows as for instance shown by Liepman and Gharib (1992). Further investigations are hence needed in the absence of the 'whistler phenomenon', to make statements regarding the spreading and mixing efficiency of this passive mechanism. The outlined (j)pdf analyses, figures 8 and 9, seem most appropriate to account for the organised vortices, which—in the near-field region—comprise a considerable fraction of the total turbulent kinetic energy. Their contribution on the mixing would have been smeared out by classical analyses, i.e. axial decay of first and second order statistics.

5 Conclusions

In summary we have presented results from an experimental investigation confirming the theoretical study by Talamelli and Gavarini (2006), where it was suggested that the self-exciting temporally growing wake instability behind an inner thick wall in coaxial jets, may provide a continuous forcing mechanism for the passive control of the whole flow field. The present paper has hence shown, that despite the current trend to utilise mainly active flow control strategies in coaxial jet flows, there are basic flow features, like the vortex shedding behind a thick wall, which—if correctly recognised—can be facilitated to control the flow field without external energy supply. It was furthermore shown that the 'locking phenomenon', which commonly is restricted to the dominance of the outer shear layers vortices over the inner ones, is reversible and therefore open doors to apply flow control strategies on the inner nozzle wall. The present paper underlines the potential of this passive mechanism as an easy, effective and practical way to control the near-field of interacting shear layers and pinpoints the way for further mixing analyses.

Preliminary mixing studies by means of probability density distributions have been performed to investigate the effect of this mechanism on the mixing, however, due to the multitude of flow regions as well as the existence of the 'whistler phenomenon', which was found at some of the measured absolute velocities, caution is advisable when making general statements. Nevertheless we showed that the absolute instability, by means of the induced vortex shedding, controls the evolution of the vortices and hence the whole flow field, despite the strong 'whistler phenomenon', which otherwise would dominate the spectral content of the flow.

Acknowledgments

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