The study of vortex ring/wall interaction for artificial nose improvement

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Abstract

Normal and oblique collisions of a vortex ring with a wall have been studied experimentally and numerically with the aim of analyzing the interaction of vortex structures with the solid boundary and to understand the effect of the impact angle α and the Reynolds number Re on the development of the azimuthal instabilities. The application of such analysis is relevant, for instance, in systems for artificial olfaction (Davide *et al.*, 1994). In fact these devices consist of a box having a sensor array at its bottom wall, devoted to detect the presence of certain substances in the test mixture. The efficiency of the sensor depends on the concentration of the substance that reaches the surface; this requires that the fluid injected in the box organizes into structures that arrive at the wall as much coherent as possible. The vortex ring has been chosen as the advecting structure because its high degree of coherence in the laminar range, allows the mixture to be transported on the sensing surface. During the impingement the vortex ring generates an oppositely-signed vortical layer and the mutual induction between the primary ring and the vorticity induced at the wall is the leading process for the eventual break-down of the structure. The eigenvalues of the velocity gradient tensor have allowed to study the stabilizing effect of impact angle through the topological features of the field. Finally the vortex structure identification allowed to study the vortex dynamics in the vicinity of the wall in order to perform a measure of the stability of the field.

1 Introduction

Strong efforts have been devoted in recent years to the study of the interaction of vortices with surfaces. The interest in this phenomenon is due to the fact that it occurs in countless practical applications.

Our motivating application is an artificial olfaction device in which a finite amount of fluid containing the substance to be detected is injected in a box with the sensors. Usually common substances (coffee, tea or chocolate) are composed of 10 – 50 elementary ingredients while, in contrast, each sensor is capable to detect only one ingredient. This implies that the injected slug of fluid must reach all the sensors in order for the substance to be properly recognized. In the original device this was achieved by promoting the mixing between the injected slug and the ambient fluid even

if this largely decreased the concentration of the substance. Later on, it was recognized by the authors that a more efficient way is to keep the slug confined by the "atmosphere" of a vortex ring and let it to impinge obliquely on the wall. In this way a highly concentrated blob of substance sweeps all the sensors thus reducing the required amount of fluid. Of course during the impact the development of azimuthal instabilities must be prevented since this lead the vortex ring to turbulence and eventually to the mixing of the blob with the ambient fluid. This considerations motivated us to study the dynamics of a vortex ring obliquely impinging on a wall with a particular look at the effect of the impact angle on the azimuthal instabilities.

The study of a simple structure like the vortex ring, in addition, gives a clearer picture of the general vortex dynamics at the wall. The advantage of avoiding a superposed background flow as in turbulence and to manage a simple geometry, makes the vortex ring dynamics one of the most studied subjects in fluid dynamics.

The interaction of a vortex ring with a boundary was studied, through an inviscid theory, since Helmholtz (1858). It resulted that a vortex ring normally approaching a wall spreads radially while shrinking its core. Lim *et al.* (1991) have shown that this is due to the inviscid interactions between the vortex ring and its mirror image. In their experiments it effectively happened (before azimuthal instabilities became important) for the head-on collision of coaxial counter-rotating vortex rings. The interaction with a solid wall was studied, among others, by Walker *et al.* (1985) and Lim (1989) in the normal and oblique cases, respectively. In both works it was observed that the wall vorticity produced by viscous effects, limits the radial spreading of the vortex-ring, detaches from the wall and, for high enough Re , it interacts with the primary vortex.

During this interaction, primary and secondary structure become very entangled and from an instantaneous snapshot of the field it becomes very difficult to distinguish the vortex structures. On the other hand, although vortex dynamics is being studied since a century, a universal definition of a vortex structure is still missing.

To identify large-scale vortical regions that are dynamically significant it is necessary an objective definition of a vortex. Some conditional-sampling techniques have been suggested for coherent structure eduction both in experiments and numerical simulations (e.g. Kim 1987, Hussain 1993) but all the attempts revealed not to be objective. In the past, for example, a vortex has been considered to be a tube whose surfaces consists of vortex lines (Lamb, 1945) but the existence of a vortex tube does not imply the existence of a vortex. Recently Lugt (1980) defined a vortex as a multitude of a material particles rotating around a common center. Chong, Perry & Cantwell (1990) on the other hand defined a vortex as a region of complex eigenvalues of the velocity gradient tensor $\nabla \mathbf{u}$. Hunt, Wray & Moin (1988) identify a vortex as a region containing both positive second invariant of $\nabla \mathbf{u}$ and low pressure. In the present work all these methods have been considered and the intermediate pressure Hessian eigenvalue proposed by Jeong & Hussain (1995) has shown to be the most accurate to extract the vortical structures developing with the ring/wall collision.

2 Experimental and Numerical Methods

An experimental set-up was designed in order to analyze the vortex ring dynamics during the impingement on a wall. A vortex ring is produced each time a fluid mass is impulsively pushed through a circular nozzle. In the present case a piston moving in a cylinder ejected a quantity of colored fluid. The piston motion was controlled by a cam moved by an AC electrical engine whose angular velocity could be adjusted by an inverter (Manna, 1995). The experiments were carried out in a $50 \times 50 \times 70$ cm water tank.

Figure 1: Perspective view of the normal collision. $Re = 600$. $T=40$.
Left: Experimental Visualization. Right: Numerical Simulation

In the present study only perspective visualizations are shown because it is sufficient the qualitative contribute of experiments. The experimental visualization were used as a guideline for the numerical simulation which provided detailed quantitative information on the dynamics of the collision. The numerical code is essentially that described in Verzicco & Orlandi (1994) here it suffices to mention that it is a second order finite-difference code which solves the Navier-Stokes equations in Cartesian coordinates. Several simulations were run for different impact angles ranging from 0° to 38.5° . The computational domain was a rectangular box of dimension $L_x L_y L_z$ equal to $8R$, $4R$ and $8R$ respectively being R the ring radius. Periodic boundary conditions were applied in the x and z horizontal directions while the lower wall ($y = 0$) was no-slip and the upper ($y = L_y$) free-slip. The discretization was uniform in x and z with 129 grid points and it was non-uniform in y with the grid points (also 129) clustered close to the no-slip wall. The initial condition consist of a Gaussian vortex-ring with core-toroidal radius ratio $a/R = 0.4131$ initially at a distance $d = 1.5R$ from the no-slip wall.

3 Interaction Phenomenology

The dynamics of the normal collision of a vortex ring with a wall has already been the subject of several papers (Walker *et al.* 1985, Orlandi & Verzicco, 1993) therefore it will only be shortly summarized here in order to stress the differences with the oblique collision. The dynamics of the collision strongly depends on the Reynolds number; for low Re (< 350) the wall vorticity stops the radial spreading of the primary ring but it is too weak to generate secondary vortex. For higher Reynolds numbers, in contrast, the boundary layer separates, rolls-up and generates a secondary vortex ring.

The dynamics of this event can be summarized as follows: when a vortex ring approaches a solid wall (in an otherwise stagnant fluid), it induces a radial flow that, on account of the no-slip condition, produces a boundary layer of oppositely-signed vorticity. At the same time the ring, by the effect of the image vortex, increases its toroidal radius while further decreases its distance from the wall. The radial spreading of the ring is accompanied by the shrinking of its core to preserve its volume with an increase of the vorticity owing to stretching.

As described in Verzicco & Orlandi (1994) the radial flow generates an adverse pressure gradient responsible for the boundary layer separation.

Figure 2: Perspective view of the oblique collision of the vortex. $Re = 600$. $\alpha = 19^\circ$. $T=40$.

Left: Experimental Visualization. Right: Numerical Simulation

For $Re_v \geq 440$ within the primary and secondary rings azimuthal instabilities appear as reported by Cerra & Smith (1983) and confirmed by the present visualization. In Figure 1 the azimuthal instabilities of the vortex ring are shown. The complex interaction between the wavy rings brings to the breakdown of the vortices.

From the numerical simulation it is seen that the vorticity of the secondary ring is reduced because of compression while it is subject to an increased strain being the sum of the self-induced strain and that induced by the primary. The secondary ring is then strongly deformed and becomes wavy.

In the oblique case, by observing the flow visualization of Figure 2 it is immediately evident that the dynamics of the collision shows different features. In particular, the region of the ring closest to the wall becomes thinner owing to stretching while it is visible a wavy structure generated by the accumulation of the secondary vorticity in the farthest region. In the first zone the vorticity intensifies and the wall vorticity produced at small scale, rapidly diffuses and annihilates primary vorticity because of cross-diffusion. The numerical simulations (see figure 2) allowed to measure and explain the main phenomena. A vorticity gradient is created along the ring axis and this is responsible for a convective motion in the farthest zone resulting in new structures production. Maxima in vorticity and minima in pressure are related by the divergence of the momentum transport equation:

$$\nabla^2 p = \omega^2 - \sigma^2, \quad \omega^2 = \Omega_{ik}\Omega_{ki}, \quad \sigma^2 = S_{ik}S_{ki} \quad (1)$$

where S_{ik} is the rate of strain tensor and Ω_{ik} is the rate of rotation tensor. The Laplacian of the pressure is positive yielding a pressure minimum if vorticity overcomes the strain. In the region closest to the wall, after the initial increase, the vorticity annihilates and the strain-rate dominates. In contrast, in the region far from the wall the vorticity overcomes the strain-rate. This implies the pressure to be high in the former region and low in the latter, creating a pressure gradient along the core of the ring that drives the fluid towards the region of the ring far from the wall. This motion leads the secondary vorticity ejection. The azimuthal perturbations, finally, are seen not to be amplified as in the normal case. This is experimentally evident by looking at the amplitude of the wave in the secondary ring that during the impact are firstly created close to the wall and then compressed away. This results in an extension of the secondary structure in the zone close to the wall that smoothes out the instabilities.

The study of a vortex-ring impinging on a wall can be useful to the optimization of an odor sensor. In the actual case a $5\text{ cm} \times 5\text{ cm} \times 2\text{ cm}$ sensor has been studied where a gas at the rate of $100 \div 500\text{ ml/min}$ was injected through a duct of $d = 0.15\text{ cm}$ in diameter. This corresponds in air ($\nu_{\text{air}} = .15\text{ cm}^2/\text{s}$) to $Re_v = 100 \div 500$ that is in the laminar range. The bottom surface is covered by a matrix of sensors (3 mm^2) each of them is specialized in some gases. The test gas injected in

a mixture of ambient gas must reach the sensing surface with the maximum concentration in order to have high probability that a sufficient mass can be adsorbed to make the sensor react in short time and proportionally to its concentration. The analysis of the isolated vortex–ring impinging on a wall is well suited for test–gases impulsively injected with a frequency lower than the overall time scale of the interaction. The vortex dynamics at the wall in the oblique collision helps the increase in the concentration at the wall of the incoming test–mixture (figure 3). This happens because the layer of the ambient fluid that was on the wall is spanned away by the ring owing to particles migration toward the lower pressure region, while the core region of the mixture is pushed on the sensing surface. Increasing α gives further improvement to the concentration because of a longer distance traveled by the oblique vortex ring shearing on the wall and longer time in which diffusion from the core ring to periphery part plays a positive role in increasing the concentration at the wall. The concentration peak, in the oblique collision increases up to 6 times in comparison with the normal impact reaching a maximum in the range $50^\circ \leq \alpha \leq 60^\circ$ (Mammetti, 1999). For higher angles the structure travels almost parallel to the wall and does not interact in the optimal way.

4 Topological Analysis

The Eulerian velocity field in the physical space is linked to the dynamical systems in the phase space, through the equation of motion of the fluid particles (Cantwell, 1981):

$$\dot{\mathbf{x}} = \mathbf{u}(\mathbf{x}, t), \quad (2)$$

where $\mathbf{x} \in X \subset \mathcal{R}^3$ is a vector representing the position in the real three-dimensional space X , $t \in I \subset \mathcal{R}$ is the evolving parameter time, $\mathbf{u} : (X \times I) \rightarrow V \subset \mathcal{R}^3$ is the velocity field depending on position and time, the notation $\dot{\mathbf{x}} = d\mathbf{x}/dt$ indicates the time-derivative. At a certain time $t = t_0$ the velocity field is fixed and the corresponding dynamical system is said to be autonomous. Around a certain point $\mathbf{x}_0$, the Taylor expansion of the non-linear velocity field yields:

$$\dot{\mathbf{x}} = \mathbf{u}(\mathbf{x}_0, t_0) + \mathbf{A}\mathbf{y} + o(|\mathbf{y}|^2), \quad (3)$$

where $\mathbf{y} = \mathbf{x} - \mathbf{x}_0$ is the vector joining the reference point $\mathbf{x}_0$ with its neighbor $\mathbf{x}$, $o(|\mathbf{y}|^2)$ represents the lower order terms in the limit $|\mathbf{y}| \rightarrow 0$, $\mathbf{A} = \nabla \mathbf{u}$ is the velocity gradient tensor. Being $\dot{\mathbf{x}}_0 = \mathbf{u}(\mathbf{x}_0, t_0)$ we can rewrite (3) neglecting the higher-order terms in the following way:

$$\dot{\mathbf{y}} = \mathbf{A}\mathbf{y}, \quad (4)$$

it corresponds to the linearization around the point $\mathbf{x}_0$ of the original non-linear dynamical system (2) and physically it corresponds to the velocity field seen in a reference frame centered at the position $\mathbf{x}_0$ moving with the velocity $\mathbf{u}(\mathbf{x}_0, t_0)$. Equation (4) is a linear differential problem in $\mathcal{R}^3$ with constant coefficients, therefore we can try to find the solution in the class of functions: $\mathbf{y}(t) = \mathbf{v}e^{st}$ that leads to solve $(\mathbf{A} - s\mathbf{I})\mathbf{v} = 0$ where $\mathbf{v}$ are the eigenvectors and s the eigenvalues of the matrix $\mathbf{A}$ and $\mathbf{I}$ is the identity matrix. The latter is a homogeneous system and for its solution, we have to enforce $\det(\mathbf{A} - s\mathbf{I}) = 0$ from which we get the characteristic equation:

$$s^3 + Ps^2 + Qs + R = 0, \quad (5)$$

where P , Q and R are the invariants of the matrix $\mathbf{A}$. In fluid dynamics of incompressible flows it results $P = 0$ and all the elements of $\mathbf{A}$ are real numbers hence the eigenvalues can be only of

Figure 3: Iso-levels of the concentration near the wall. $Re_v = 1000$. $T=40$.

Left: Normal collision. Right: Oblique collision

two types: three real or one real–two complex conjugate (Chong *et al.*, 1990). From the condition of two coincident roots the discriminant quantity rises as:

$$D = \left(\frac{R}{2}\right)^2 + \left(\frac{Q}{3}\right)^3 \quad (6)$$

By means of D we can distinguish between the following cases:

$D = 0$ two real coincident solutions–one real solution

$D > 0$ one real–two complex conjugate solutions: focus type topology

$D < 0$ three real solutions: node/saddle/saddle topology.

In summary the condition $D > 0$ can be a good candidate for the extraction of a vortical structure because it links the swirling motion expected in the structure with the topology of the foci of the dynamical system representing the linearized velocity field. The focus type topology represents a vortex in the physical space because spiral trajectories insure some swirling motion to be performed. Therefore the condition to extract a vortical structure in the topological approach will be: $D > 0$. The analysis of the invariants of strain tensor S_{ij} and the rate of rotation tensor Ω_{ij} leads to a relation between the second invariants stating that:

$$Q = Q_S + Q_\Omega \quad (7)$$

where:

$$Q_S = -\frac{1}{2}S_{ij}S_{ji} = -\frac{1}{4\nu}\epsilon$$

where ϵ corresponds to the local dissipation, instead

$$Q_\Omega = -\frac{1}{2}\Omega_{ij}\Omega_{ji} = \frac{1}{4}\omega_k\omega_k$$

is equal to the enstrophy density. From (6) is clear that a sufficient condition for $D > 0$ is: $Q > 0$. This is physically explained by looking at (7): $Q > 0$ occurs when Q_Ω prevails on Q_S and this happens in zones characterized by rotational motion. On the contrary $Q < 0$ states that pure strain is prevalent and this typically happens in zones where $D < 0$ characterized by saddle points. The condition proposed by Hunt *et al.* (1988) $Q > 0$ is, then, another condition to extract the vortical structure, being even more restrictive with respect to $D > 0$ (see figure 5).

The use of topological approach is not only a method to educe a vortical structure but it can lead to a deeper insight into the tendencies that a physical system shows in amplifying or damping perturbations. The two invariants Q and R and the quantities derived from them hold the main features of the physical phenomenon. The velocity gradient tensor and its invariants are calculated at each point in the flow; these are objective measurements because the derivatives insure the coordinate independence. Plots of the joint probability density functions (PDF) of the invariants

Figure 4: Iso-levels of the joint PDF exponentially spaced in (R, Q) -plane. $Re_v = 1000$. $T=40$. Left: $\alpha = 0^\circ$. Right: $\alpha = 38.5^\circ$

for the entire flow can reveal global trends in the geometry of the velocity field (Cheng and Cantwell, 1996). Large scale motions are associated with relatively low gradients while small scale motions are associated with high gradients. Thus different length scale in the physical flow naturally tend to be sorted into different regions in the invariants space, and thus may be examined separately. The smallest scales in the flow, having high gradients, will tend to lie far from the origin in (R, Q) -plane that corresponds to big eigenvalues. If Q is negative the local strain dominates the enstrophy density, while the relative importance of rotation tensor overcomes the strain tensor in agreement with (7). Figure 4 corresponds to the distribution of the joint probability on the (R, Q) -plane for two cases: normal ($\alpha = 0^\circ$) and oblique impact ($\alpha = 38.5^\circ$) after the collision. The PDF has been calculated among the points of the field where enstrophy overcomes the 1% of the maximum enstrophy value in order to neglect from the statistics all the dynamically passive points. As α decreases the activity in the smallest scales increases. This is shown by the wider area on the (R, Q) -plane covered by the events in the normal collision in comparison with the oblique impact. The points farthest from the origin, particularly in the fourth quadrant, witness to the instability tendencies of the high gradient regions. This is an indirect proof of the tendency to amplify the azimuthal perturbation for decreasing α .

5 Structure Identification

The investigation of the vortex dynamics can be improved firstly by educing vortical structures. An *ad hoc* criterion must fulfill the following three main requirements (Hussain, 1993):

- the core of a vortex must have a net vorticity (i.e. non zero circulation): this means that potential flow regions are excluded from the definition; the presence of vorticity different from zero is a necessary but not sufficient condition;
- the existence of a vortex must be represented by a scalar quantity to simplify the representation by a surface plot;
- the identification of a vortex should be a Galilean invariant (a scalar quantity satisfies such a condition).

In the last section the positive *second invariant* $Q > 0$, and the positive *discriminant* $D > 0$ have been introduced as two criteria to educe vortical regions. They fulfill the three above requirements and can be used for structure identification.

Figure 5: Left: Discriminant $D = 0$. Right: Second invariant $Q = 0$. $Re_v = 1000$ $\alpha = 19.25^\circ$. $T=40$

In contrast the *minima in the pressure* criterion for vortex identification (Lugt, 1980) based on the relation (1) fails particularly for highly viscous and unsteady flows. In addition the length scale of pressure may be greatly different from that of the vortical structure. Then it is not possible to have a clear demarcation of weaker, yet significant, vortices especially if these are located closely to stronger vortices (Jeong & Hussain, 1995).

The use of *pathlines and streamlines* to identify a vortex has also been considered (Lugt, 1980). However, they are not appropriate because they are not Galilean invariant measures. Moreover the detection criterion must reflect the instantaneous field rather than some mean value. The *vorticity magnitude* is probably the most widely used quantity to identify and represent vortices both from experiments and numerical simulations. But, for instance, this criterion identifies the presence of a vortex everytime a velocity gradient (a shear flow) is encountered for one velocity component. Therefore a wall-bounded flow will always exhibit vortices that are not effectively present. Nevertheless, isovorticity surfaces will continue to be employed as indicators of the presence of vortices easily obtained from velocity fields.

Jeong & Hussain (1995) proposed a vortex core to be identified by the *second largest eigenvalue* λ_2 of the tensor $(S_{ik}S_{kj} + \Omega_{ik}\Omega_{kj})$. This definition takes into account in some way the intuitive notion of the minimum pressure to define a vortex. In fact, by operating the gradient of the Navier-Stokes equations, one can obtain a direct relation between the second derivative of the pressure and $(S_{ik}S_{kj} + \Omega_{ik}\Omega_{kj})$. The presence of a pressure minimum can, then be detected by the condition for which the second largest eigenvalue, λ_2 , of this tensor must be negative. Therefore a vortex consists of a region with two negative eigenvalues of the previous tensor. The definitions $D > 0$, $Q > 0$ and $\lambda_2 < 0$ satisfy the three necessary requirements. In 2D flows the three schemes lead to the same results, as Jeong & Hussain (1995) showed whereas in axisymmetric flows all of them requires the derivative of the square azimuthal velocity to be positive ($\partial v_\theta^2 / \partial r > 0$): this excludes the potential part of the velocity distribution with decreasing azimuthal velocity. However, in 3D Jeong & Hussain (1995) showed that the use of the scheme $D > 0$ overestimates the extension of the vortices and obscures their details (see figure 5); the $Q > 0$ scheme also shows disconnections of the vortices and sometimes holes in their axis. The use of the $\lambda_2 < 0$ scheme has not revealed such limitations.

In the present work all these different methods have been tested in the extraction of the structures developed by a vortex ring impinging on a wall in order to distinguish between primary and secondary vorticity. In particular the objective presence of the structures had to be clear even in the first stages of their formation where the inner vorticity in the induced structures is too small to be detected by classical methods. In the successive stages especially in the oblique collision case it

Figure 6: Left: Vorticity magnitude $\omega = .5\omega_{\max}$. Right: Intermediate eigenvalue $\lambda_2 = 0$.
 $Re_v = 1000$ $\alpha = 19.25^\circ$. $T=28$.

should occur a break-down of the weaker structure and this phenomenon had to be studied even when the vortex structures were too close each other or too distorted. Figures 5 and 6 correspond to the first stage of the oblique collision. It is noticeable the coincidence of the condition $Q = 0$, and $\lambda_2 = 0$ while $D = 0$ overestimates the shape of the structure. The unarbitrary condition $\lambda_2 = 0$ is capable of distinguishing the different structures, giving them a very well defined shape, without misleading emphasis on the wall layers detected by the vorticity magnitude criterion, where no vortical structures exist. At this stage the secondary ring has already been lifted by the primary in the region closest to the wall while progressively detaches the wall toward the farthest zone. A tertiary ring is still being formed and it has just got the sufficient circulation to detach from the wall.

The iso-levels of vorticity magnitude hide substantially the main information because the points on the wall are not belonging to the actual vortical structure and in a automatic implementation they surely damage the attempt of the axis extraction. Secondly the important detail of the tertiary ring is not possible to be isolated with an arbitrary threshold on the vorticity magnitude because of the low level of vorticity, the same for the weakest part of the secondary.

The identification of the vortex displacement is only partially achieved by $\lambda_2 < 0$ criterion because, like in experimental visualizations, it is still qualitative. Anyway the objectivity of the identification ensure to properly locate the vortex structure in the field. The exact configuration of the structure is known only by the measure of its location. This is achieved by the axis extraction. This technique allows a vortical elongated structure to be reduced to a vortex filament coinciding with its axis.

The technique is based on a “guess and check” method: the first step is an attempt to find the center of one section of the structure. The maximum local vorticity is chosen as a criterion to locate the center. In the first guessed center, O , the unit eigenvector, $\mathbf{v}_1(O)$, corresponding to the first eigenvalue λ_1 of the pressure Hessian tensor, determines the local axis direction and consequently the normal plane Π . The intersection between the plane and the structure is a closed area S_O in Π where we check only points having a swirl motion (Kida, 1997) with respect to the local axis direction. Among these points, the highest in vorticity magnitude is chosen as the center. The new guessed center is on the direction of the local axis and the routine starts again. The routine stops when the structure close on itself, when it reaches a boundary, or when the continuity in

Figure 7: Vortex axis extraction $Re_v = 1000$ $\alpha = 19.25^\circ$. $T=28$.

the vorticity vector is lost. A parameter to evaluate the regularity of the structure is necessary to discern among several new sections found on the plane Π . On the base of previous accepted centers a continuity in the geometrical displacement, on the vorticity magnitude and direction is expected. If the tolerance threshold is overcome a new structure begins but at the end of the process all the structures detected undergo a check if two of them are pieces of a single bigger structure. Finally a set of structures synthesize the whole velocity field with the coordinate of the center on the axis for each structure and the vorticity component in the center. In Figure 7 it is shown the vortex filament corresponding to the center locus of the primary ring, secondary and tertiary ring corresponding to the same field of Figure 6. The extraction technique has been tested on a vortex structure whose axis was known and the resulting axis displacement has been compared with the exact location of the structure (Mammetti, 1999). This technique is used in the next section in order to perform the stability analysis.

6 Stability Analysis

In the section 4 we have shown an indirect proof of the intrinsic ring instability in the normal impact by the joint PDF in the (Q, R) -plane. A direct measure of the instability needs firstly to define deviations from a reference configuration. Widnall *et al.* (1973) studied the stability of a free vortex ring assigning an initial sinusoidal displacement in the radial and axial direction to the undisturbed circular configuration. The conditions under which a perturbation in a certain mode n is amplified are taken as the conditions for the instability of the ring. In the present problem where the structures after the impact lose their original circular form, a reference configuration can not be easily defined.

The structure identification and axis extraction has allowed the study of the evolution of the vortical structures by tracking their axes $\mathbf{s}_i(\theta)$, θ being a coordinate along the axes. The reciprocal interactions among the structures can be evaluated from the evolution of the vortex filament configuration. Figure 8 shows typical profiles for the vorticity magnitude $\omega(\theta)$ and the vertical axis displacement $z(\theta)$ during the oblique impact of the primary ring. The θ coordinate along the axis is such that the impinging section always corresponds to $\theta = -\frac{\pi}{2}$. It can be noted the vorticity increase in the closest part to the wall owing to stretching, and a corresponding decrease in the opposite section. In the present case the ring was initially perturbed by a sinusoidal displacement

Figure 8: Vorticity and vertical displacement along the axis. $Re_v = 1000$ $\alpha = 19.25^\circ$. $T=28$.
Left: $\omega(\theta)$. Right: $z(\theta)$.

of amplitude 2% the toroidal radius in $n = 5$ mode in order to study the evolution of the azimuthal perturbation.

In the sake of shortness, we can not provide the reader with the complete time sequence of the axis deformation like that in Figure 8 for $T = 28$. However the process can be summarized in the following: as the ring impinges on the wall some waviness develops uniformly along the ring axis at the imposed azimuthal wavenumber n . Later on, because of the symmetrical convective motion, driving fluid from the region closest to the wall toward the farthest one, the n wavelengths are compressed in an increasingly smaller portion of the ring (see figures 2 and 8). This implies

Figure 9: Square amplitude of the fifth Fourier modes of $z(\theta)$. $Re_v = 1000$.
Left: $E_5(T)$ From top to bottom: $\alpha = 0$ (∇), $\alpha = 9.625$ ($\circ$), $\alpha = 19.25$ ($\triangle$), $\alpha = 38.5$ ($\diamond$).
Right: $E_5(\alpha)$ in $T = 40$

that the azimuthal wavenumber of the perturbation increases and the viscosity can damp the disturbances at a faster rate. Of course the larger α , the more intense is the convective motion and the faster is the damping of the perturbation. This is shown in Figure 9 where the time evolution of the $n = 5$ mode for different impact angles is shown. The final conclusion is then that the oblique impact stabilize the ring because of the smoothing effect of the convective motion in its core. Hence an obliquely oriented vortex ring impinging the sensing surface is suggested in order to improve the artificial nose efficiency. In this way a bigger percentage of the test gas is transported on the sensors, higher concentrated gas volume are pushed and touch the sensors, wider area of the sensing surface is spanned by the test gas and for longer time.

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