Propagation of Sound through a Turbulent Vortex

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We report an experimental study of sound propagation in the bulk of a homogeneous flow made of a single intense vortex in air. By using an adaptive-coherent average technique, the mean amplitude and phase of the distorted wave fronts are reconstructed. A large phase shift is observed on the wave fronts on either side of the "shadow" region behind the vortex. The shape of the averaged amplitude, as a function of space coordinates, shows that *caustics* are also formed in the acoustic field. In a nonstationary flow, these effects make it possible to monitor the vortex strength and position. [S0031-9007(98)06866-5]

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A number of theoretical and experimental works have been done on the subjects of sound propagation through vortices and scattering of sound by vortices and turbulence, aiming to gain a better understanding of the interaction of sound waves with vorticity and turbulence. In addition to the interest that these subjects have in themselves, this knowledge may subsequently be applied to the study of turbulent and vortical flows using sound waves.

When a sound wave propagates through a vortex, one expects a change in the direction of propagation and modifications in the phases and amplitudes of the wave fronts on each side of the vortex. The variation in the direction and the phase shift between the fronts propagated at opposite sides of the vortex has been calculated in the limit of geometrical acoustics (vanishingly small wavelength compared to the vortex size) by Lindsay [1] and Landau *et al.* [2]. In this limit, Klimov has also expressed the generation of caustic surfaces in the case of Hill's spherical vortices [3]. Experimentally, differences in the times of arrival of acoustic pulses propagating through each side of a vortex have been measured on wing tip vortices in air [4]. The shape of wave fronts has been obtained in visualizations of surface waves propagating through "bathtub" vortices [5] and with arrays of transducers on pulses propagating through stretched vortices in a water tank [6]. In the case of bulk waves in water, the effects of density variations cannot be ruled out since strong pressure drops are known to occur in the core of intense concentrated vortices [7] and may result in filling the vortex cores with air bubbles. In surface waves, the deformation of the free surface induced by the vortex introduces changes in the path length of the waves that lead to phase shifts and focusing effects not related to vorticity. In the study reported here, an intense vortex is produced in the gap of two corotating disks in air, so that the flow is homogeneous [8,9]. A continuous harmonic wave is sent onto the vortex and monitored behind it; its phase and amplitude are resolved with high accuracy using an adaptive-coherent averaging technique [9]. A large phase shift from one side of the vortex to the other is observed and related to the vortex characteristics. Because of the precision of the experimental technique, we also report the formation of caustics: The sound waves are focused in the side in which the phase is delayed, with a corresponding defocusing at the opposite side, in which the phase is advanced.

We now describe the experimental setup. The vortex is produced in the gap between two coaxial disks of diameter $D = 20$, 30 cm apart, rotating in the counterclockwise direction at $\Omega = 27$ Hz. The disks are fitted with a set of blades and covered with thin disks having a 5 cm diameter hole in their center—see Fig. 1. This arrangement improves the vortex intensity and stability: A strongly recirculating flow occurs in which air is ejected at the periphery of the disks and drawn through the holes in their centers. As the incoming air contains a substantial amount of angular momentum, the stretching provided by the disks develops a strong vortex near their common axis [10]. It is found that this vortex performs a slow precession motion around the rotation axis of the disks; its core describes an almost circular trajectory whose radius is approximately 2.5 cm.

A capacitive Sell-type transducer [11] (16 cm $\times$ 16 cm) is used to send an ultrasonic wave onto the vortex. The sound frequency is $\nu_0 = 34$ kHz, so that the corresponding wavelength, $\lambda \sim 1$ cm, is of the same order as the diameter $d \sim 4$ cm of the vortex core—note that the hypotheses of geometrical acoustics are not met here. The emitter is placed at a distance of 100 cm from the rotation axis of the disks. Even though the wave fronts produced in this way are not flat, the distortion produced on them by the vortex can be observed by comparing the ones obtained in air at rest with those obtained in the presence of the vortex. The sound detector is a miniature B&K microphone (model 4138) placed 30 cm behind the vortex, its position being adjustable on a line

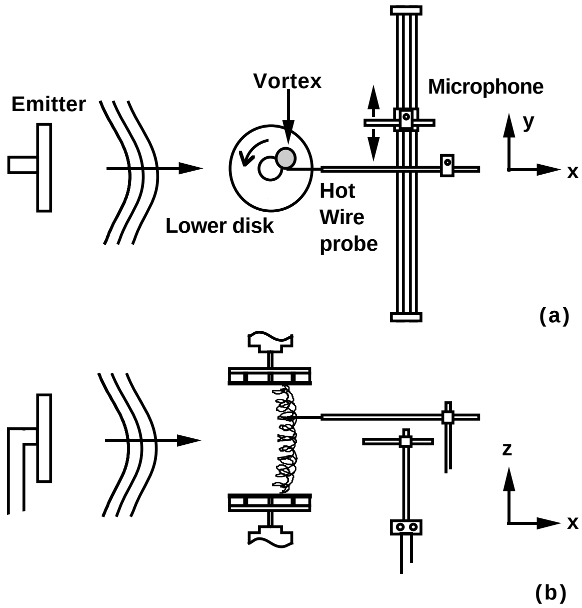

FIG. 1. Experimental setup. In (a), the upper view is displayed, with the vortex represented as a shadowed circle. In (b), a side view of the setup is shown.

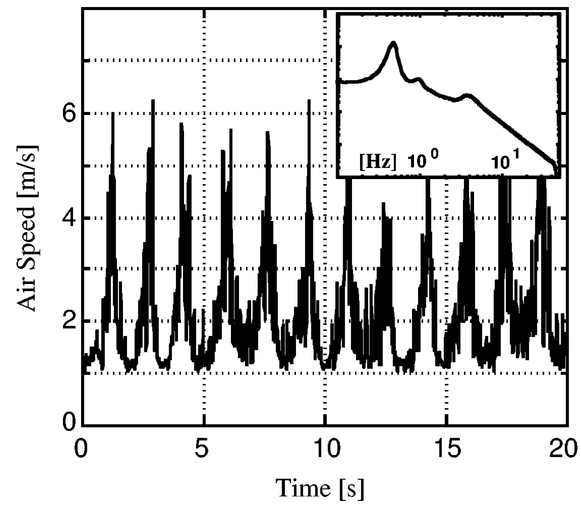

FIG. 2. The local air speed measured by the hot wire probe. Note the highly fluctuating character of the flow. The inset displays the power spectral density of the velocity. The peaks to the left correspond to the vortex precession frequency. To the right of the plot the straight part indicates the beginning of the inertial range.

parallel to the emitter in 0.5 cm steps, controlled by a stepping motor. The measured signal is amplified with a B&K model 2669B preamplifier and processed using an EG&G-PAR model 5302 lock-in amplifier, to get the in-phase and 90° out-of-phase components. In order to monitor the position of the vortex, a local velocity measurement is made using a TSI hot wire probe placed 9 cm below the upper disk and 4 cm from the rotation axis. All of the signals are filtered and digitized with a 16-bit data acquisition card.

Figure 2 shows a plot of the velocity as a function of time, at the location of the hot wire probe. The slow evolution is produced by the precession motion of the vortex, which passes the probe almost periodically. In the spectrum inset in Fig. 2, the low frequency peaks correspond to the vortex precession frequency and its second harmonic. The irregular higher frequency variations are due to the turbulent fluctuations; indeed the flow Reynolds number $R_e = D^2\Omega/\eta$ (η is the kinematic viscosity of air) exceeds 10^5 and the velocity displays a Kolmogorov-like spectrum at higher wave numbers. This signal is not intended to be used directly in the analysis of the flow, but only as a reference signal to synchronize the averaging process of the sound phase and amplitude, as we shall see below.

Figure 3 (○ symbols) shows the sound averaged amplitude ratio and phase difference with respect to the nonperturbed wave, measured behind the vortex. (The dashed line is drawn to guide the eye.) The average for each location on the y coordinate is calculated over the complete time series acquired at that place (6×10^5 points sampled at 200 Hz). Although this corresponds to an averaging time of 50 min, the curves are quite irregular. The reason lies in the vortex precession motion: Each mean value is composed of the sum of waves emerging from the vortex successively located at many different positions. As a result, most of the information about space and time coherence of the sound wave is lost. Although some features (phase and amplitude variations) can be recognized, a much clearer picture is obtained by conditioning the acoustic measurement to the position of the vortex. To do this, we use a method developed in a previous work [9]; it is based on synchronous averaging with an adaptive recognition of a regular pattern. The velocity signal is used to calculate the position of the vortex and then the acoustic features are coherently average conditioned to it. The result is shown by the solid lines in Fig. 3, for a position of the vortex aligned with the axis of the sound emitter.

The variation of the phase is now clear: It is advanced on one side of the vortex, whereas it is retarded at the opposite side of the vortex. The location of the point placed midway between the minimum and maximum of the phase shift curve gives the position of the vortex core (here $y = 0$ when the measurement is conditioned with the vortex aligned to the incoming sound direction). The distance over which the phase varies strongly is related to the extent of the vorticity in space. Although the results of geometrical acoustics cannot strictly be applied to a case where the sound wavelength is of the same order of the flow characteristic scale, they can nevertheless be used to discuss qualitatively our observations—as in optics, diffraction (scattering) effects would only add corrections. The magnitude of the phase shift $\Delta\Phi$ is related to the vortex strength γ by $\Delta\Phi \sim 2\nu_0\gamma/c^2$—$c$ is the

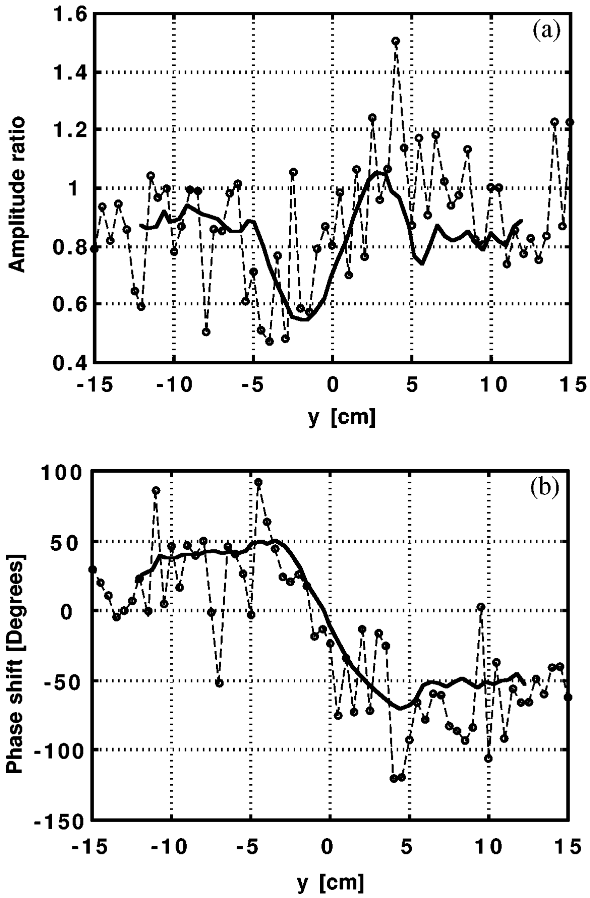

FIG. 3. Simple averages of amplitude and phase. (a) Amplitude ratio of the perturbed sound wave with respect to the nondisturbed one. (b) Phase shift produced by the turbulent vortex.

speed of sound in air. The measured value $\Delta\Phi \sim 120°$ then yields $\gamma \sim 3.4\ \mathrm{m^2\,s^{-1}}$, in agreement with velocity measurements which give $\gamma = 3.1 \pm 0.4\ \mathrm{m^2\,s^{-1}}$.

Looking at the amplitude, one observes an amplification at positive y locations and a corresponding attenuation on the opposite side. As the vortex extends through the complete disk gap, this corresponds to an almost vertical caustic line in the acoustic field. Referring again to geometrical acoustics, the deviation of a ray is related to the local vorticity ω by $d\theta/d\ell = \omega/c$ [2]. Caustics are then formed as a result of differential propagation in regions where the vorticity varies appreciably. For example, on the side of the vortex where its velocity is in the same direction as the propagating sound, a ray deviation increases as it passes closer to the core. A defocusing effect thus results; it is, of course, the opposite on the other side of the vortex. The argument agrees qualitatively with the observed amplitude variations; in particular, the focusing is strongest at the place where the phase shift is maximum, i.e., on the edges of the vortex core. A quantitative treatment would require one to include the scattering effects for which no general theory is available in the near field region where our measurement is made.

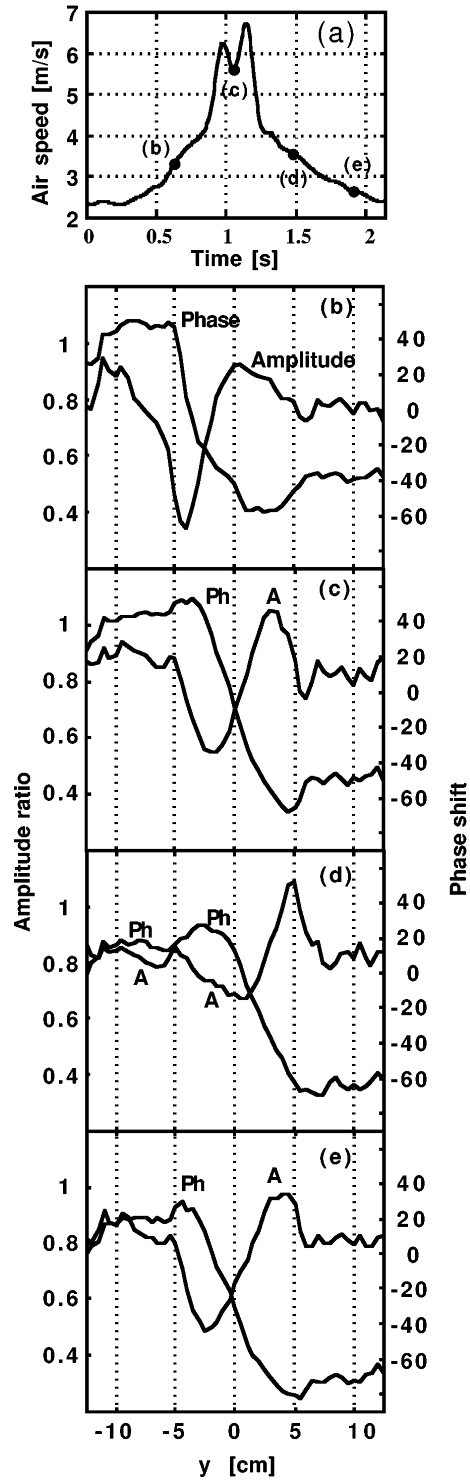

FIG. 4. In (a), the coherent average of the velocity signal is shown. The dots indicate the stage in which the coherent average of the sound signal was calculated. (b)–(e): Coherent averages of phase shifts and amplitude ratios.

We also remark that an overall change $\Delta\theta$ in the direction of sound propagation is not observed in our measurement. One expects $\Delta\theta \sim \gamma/\pi dc \sim 0.5 \times 10^{-4}$ radians; at the distance between the vortex and the measurement point, this corresponds to a displacement of 0.15 mm that cannot be resolved with the 0.5 cm steps used for the microphone motion.

The above discussion shows that the vortex position, strength, and core size can be obtained from the deformation of sound wave fronts propagating through it. In a nonstationary flow we now show that it is possible to follow the vortex dynamics. This is possible because the time scale associated with the sound wave is well separated from the typical time scales of the turbulent flow, as pointed out in Ref. [12]. It allows the averaging procedure to remove the random fluctuations in the amplitude and phase induced by the turbulent component of the velocity field and to recover the mean values associated with the stationary component belonging to the vortex structure. Figure 4 shows the results of our coherent averaging technique applied at various positions of the vortex precession motion. In Fig. 4(a), the coherent average of the hot wire signal is shown. Here four points labeled (b)–(e) are marked to show the stage at which the phase and amplitude are calculated. The steepest part of the phase curve gives the position of the vortex core; it moves from left to right from stage 4(b) to 4(d). In 4(e), it has returned to the center of the plot. In fact, the sound wave pattern follows the vortex motion. The phase shift varies between 100° and 120°, which shows that the vortex strength varies during the precession motion.

In conclusion, we stress the interest of such a dynamic measurement of wave fronts, as a probe of vorticity distribution. In the case of an isolated vortex considered here, we have shown that the phase profile gives access to the vortex strength while the amplitude profile is linked to the vorticity variations.

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