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Ultrasonic Doppler velocimetry in liquid gallium

Daniel Brito, Henri-Claude Nataf, Philippe Cardin
Julien Aubert, Jean-Paul Masson

Abstract For the first time, flow velocity is measured in a vortex of liquid gallium, using the pulsed Doppler shift ultrasonic method. At the top of a copper cylinder filled with liquid gallium, we spin a disk and create a turbulent vortex with a dominant nearly axisymmetric velocity field with little variation in the axial direction. The velocity profiles are shown to be well resolved and in quantitative agreement with earlier observations. Reliable velocity measurements in liquid gallium could be obtained only after serious problems due to the formation of oxides were solved. This work opens the way to performing accurate velocity measurements in other liquid metals; preliminary results for liquid sodium are shown.

1 Introduction

A wealth of optical methods is available to visualize or measure flows in transparent liquids. These methods cannot be used in opaque liquids such as liquid metals. However, in many situations, it would be very valuable to measure flow velocities in such liquids. This is particularly true in dynamo experiments, where liquid sodium is used because it is a very good conductor of electricity. Sodium is set into motion, with the hope that the flow, when sufficiently vigorous, will generate a magnetic field. Several such experiments are now being conducted (Gailitis et al. 2000, Stieglitz and Müller 2001) or planned (for a review, see Tilgner 2000). Our involvement in a project of experimental dynamo provided the motivation to devise a nonintrusive method to measure velocity in liquid metals.

In this respect, acoustic methods are particularly appealing. Acoustic waves interact with vortices in a fluid and vorticity can be measured from the spectrum of the scattered waves (Baudet et al. 1991) or from the refraction of the transmitted waves (Roux and Fink 1995). Another approach is to rely on small heterogeneities in the physical properties of the fluid to backscatter acoustic waves. The flow velocity is then derived from the Doppler shift of these scattered waves. With a single ultrasonic probe and a pulsed signal, one obtains a profile of the component of the flow velocity along the shooting direction (Takeda 1986). Several commercial instruments implement the pulsed Doppler shift method, and spectacular results have been obtained for various flows in water (e.g., Tokuhiro and Takeda 1993, Takeda and Kikura 1998). Application to liquid metal is more seldom, but successful tests have been reported for mercury (Takeda 1987, Kikura et al. 1998).

Liquid gallium is also a metal suitable for magnetohydrodynamic experiments (Brito et al. 1995, Odier et al. 1998). In this paper, we present the first velocity measurements in liquid gallium obtained with an ultrasound pulsed Doppler velocimeter. Our setup consists of a cylinder filled with liquid gallium, at the top of which spins a crenelated disk. We thus produce a nearly two-dimensional axisymmetric vortex. The effect of a transverse magnetic field on this vortex of liquid gallium, as well as that of the Coriolis force have been investigated (Brito et al. 1995, 1996). The flow was characterized through the magnetic field it induced, the associated electric potentials, and the pressure field at the top measured along a diameter with a row of Venturi tubes. All these measurements enable us to have a good description of the flow.

We think that our setup is very appropriate for making a quantitative test of the pulsed Doppler shift method in liquid gallium because the vortex is well behaved, reproducible, and nearly axisymmetric, yet turbulent.

A related configuration was investigated by Tokuhiro and Takeda (1993), who spun a rod at the top of a cylinder. Also using Doppler ultrasonic velocimetry, they documented a periodic instability occurring for Reynolds numbers above 650 in a water-glycerol mixture. The Reynolds numbers we produce are much higher (they range from 10^4 to 4×10^5), and because our disk is crenelated, the mean flow is much more dominant.

In the next section, we describe the experimental setup and the ultrasonic Doppler velocimeter. In Sect. 3, we present the velocity profiles measured in liquid gallium and in water. The focus is set on discussing their quantitative reliability. A comparison with velocities derived from streak photographs in water is performed. In Sect. 4, we discuss several problems that had to be solved before our tests with liquid gallium became successful. The problems are linked to the fast oxidation of gallium. In

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D. Brito (✉), H.-C. Nataf, P. Cardin, J. Aubert, J.-P. Masson
Laboratoire de Géophysique Interne et Tectonophysique
Observatoire des Sciences de l'Univers de Grenoble BP 53
38041 Grenoble Cedex 09, France
E-mail: Daniel.Brito@lgit.obs.ujf-grenoble.fr

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Sect. 5, we show preliminary velocity measurements performed in liquid sodium using the same experimental setup.

2 Experimental setup and velocimeter

2.1 Setup

The experimental setup is shown in Fig. 1. A vortex is produced inside a cylinder. The cylinder is made of copper and coated with a cataphoretic thin film which gives a black shiny appearance to the cylinder in Fig. 1 (see Sect. 4.3.5, for comments about this thin film). The inner dimensions of the cylinder are 80 mm (diameter) and 130 mm (height). The vortex is produced by spinning a 40-mm-diameter crenelated disk near the top of the cylinder (see Fig. 1b for details). The top surface is rigid and in contact with the fluid. Rotation rates up to 3,000 rev × $\min^{-1}$ have been tested. The cylinder is filled with either water or liquid gallium. The melting temperature of gallium is 29.8 °C. Physical properties relevant to the experiments are listed in Table 1.

Figure 1b gives a schematic representation of the fluid flow inside the cylinder. The flow is nearly axisymmetric, with a dominant azimuthal velocity $V_\theta = r\omega(r)$ in cylindrical coordinates, where r is the radius and ω the angular velocity. Centrifugation of the liquid by the disk also produces a nearly axisymmetric secondary flow with meridional components. In this paper, we will concentrate on measurements of the azimuthal velocities, and compare the profiles obtained for water and gallium.

As shown in Fig. 1a, velocities are measured with 8-mm-diameter ultrasonic transducers placed on the outer walls of the cylinder, on flat portions machined at some angle from the tangent as shown in Fig. 1c. The ultrasonic beam can thus be shot into the cylinder along three different directions, with incidence $i_{Cu} = 0$ ° (angle 0), 32 ° (angle 1), or 40 ° (angle 2). When the probe is moved along the contact surface, the cylindricity of the inner wall induces a spread in the angles of ±8 °, ±12 ° and ±10 °, respectively.

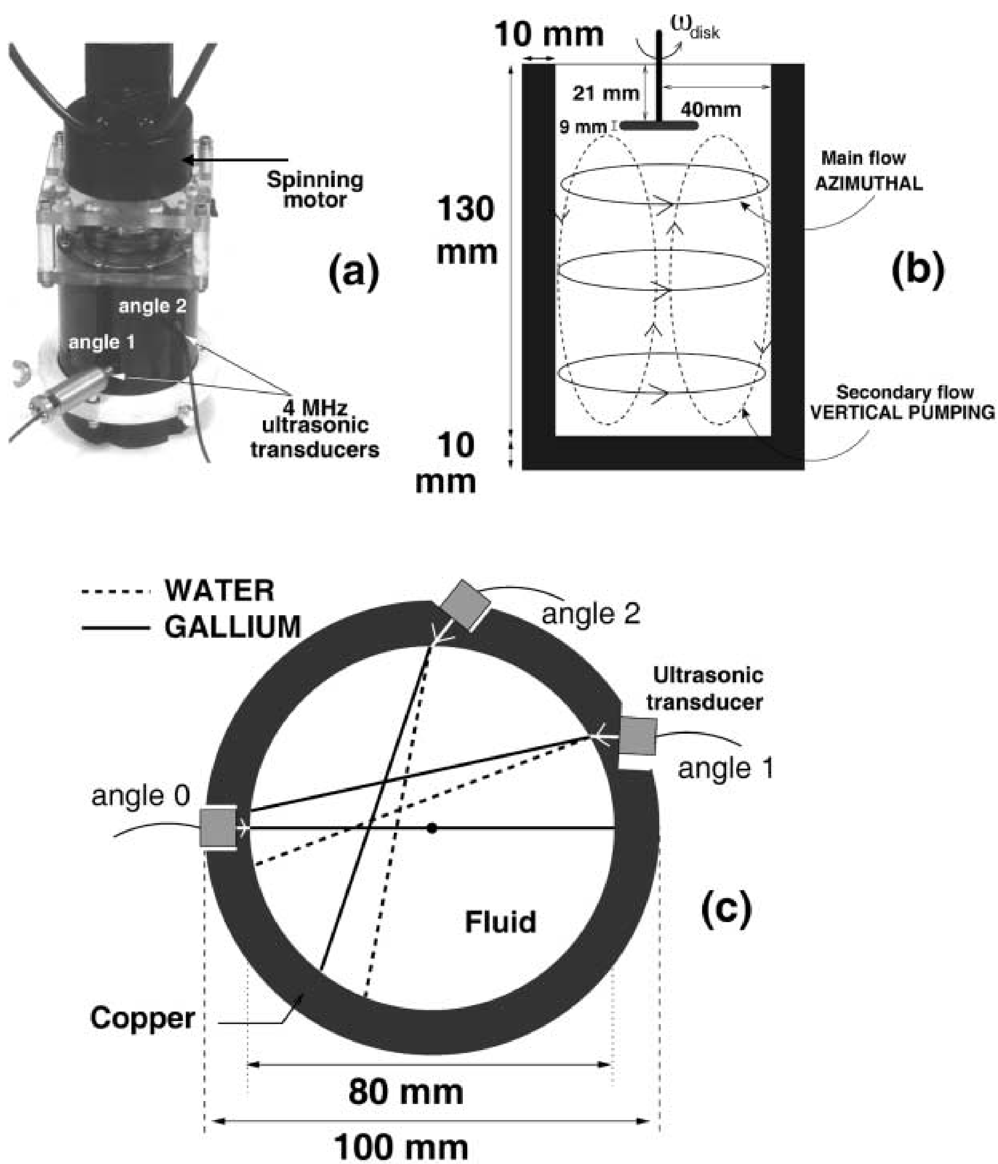


Fig. 1a–c. Experimental setup. **a** Photograph of the copper cylinder (coated with a black cataphoretic thin film) and motor that entrains a crenelated disk near the top of the cylinder. Two 4-MHz ultrasonic transducers are pressed on flat slits machined at three different angles (angles 0, 1, 2). **b** Vertical cross section of the cylinder with a schematic view of the fluid flow. **c** View from the top of the cylinder. The *lines* indicate the chords followed by the ultrasonic beams in liquid gallium (*solid line*) and water (*dashed lines*) for the three different angles

Table 1. Physical properties of water, liquid gallium (at 30°C), liquid sodium (at 120°C) and copper relevant to the experiment

	Symbol	Unit	Water	Gallium	Sodium	Copper
Density	ρ	Kg/m^3	1000	6090	932	8900
Kinematic viscosity	$\nu = \frac{\mu}{\rho}$	m^2/s	1.14×10^{-6}	3.1×10^{-7}	6.65×10^{-7}	
Sound velocity	c	m/s	1500	2860	2550	4760

At the copper-liquid interface, the beams are deflected according to the Snell-Descartes law $\frac{\sin i_{Cu}}{c_{Cu}} = \frac{\sin i_{liq}}{c_{liq}}$, where c_{Cu} and c_{liq} are the sound velocities in copper and in the liquid, respectively (see Table 1). The corresponding beams inside the cylinder are drawn for liquid gallium and water in Fig. 1c. We checked the refraction of the ultrasonic beams in both water and gallium by detecting echoes from a thin rod translated in the liquid. All the velocity profiles in water and gallium shown in this paper were shot from angle 1 at mid-depth of the cylinder.

2.2
Ultrasonic velocimeter

In the pulsed Doppler shift ultrasonic technique, a pulse of collimated ultrasounds is shot into the fluid. One then listens for echoes that come back from particles in the fluid. The delay time of the echo provides the distance of the particle, while the corresponding Doppler shift provides its velocity.

In a few tens of milliseconds, a profile of fluid velocities is obtained. Only the velocity component parallel to the ultrasonic beam is accessible. The length of the profile is proportional to the listening time, which depends upon the pulse repetition frequency (PRF). The spatial resolution is of the order of the ultrasound wavelength in the shooting direction, and depends upon the width of the ultrasonic beam in the perpendicular directions. Reliable velocities can only be obtained after a number of pulses (typically a few dozen) have been shot and analyzed. We use the DOP1000 multigate ultrasonic velocimeter from Signal Processing S.A. (Lausanne, Switzerland).

The ultrasonic transducers are 4-MHz probes, 8 mm in diameter (transducers TR30405, Signal Processing, Lausanne, Switzerland). From the sound velocities (Table 1) we deduce a wavelength of 0.375 mm in water and 0.715 mm in gallium. The pulse usually consists of 8 cycles. The spatial physical resolution in the shooting direction then reaches $8 \times 0.375 = 3$ mm in water and 5.7 mm in gallium. Because there is some overlap between the volumes sampled, velocity gradients are well retrieved below this physical limit. In open water, the divergence of the ultrasonic beam is ± 5 °. The diameter of the beam could then reach 15 mm. We think that it is less, because of the focusing effect of the cylindrical wall. Note that the deflection of the beam produced by the interaction of the acoustic waves with the fluid velocities is less than 1 ° in our conditions (Roux and Fink 1995) and is considered to be negligible.

The PRF is an essential parameter. The time t_{PRF} between two emissions determines the length of the profile, but it also controls the velocity resolution. Indeed, if the time between two emissions is long, fast particles have moved too much to yield echoes that correlate. The maximum depth D_{max} and velocity along the beam V_{max} that can be measured are linked by $D_{max} \times V_{max} = \frac{c^2}{8 f_e}$, where c is the sound velocity of the liquid and f_e is the emission frequency. At the other extreme, slow particles show no detectable displacements between two emissions if the repetition frequency is too high. In our experiments, we have carefully adjusted the PRF parameter (see Sect. 4.2).

Most profiles were constructed using 128 emissions per profile. The total acquisition time of a profile ranges from about 20 to 100 ms, depending on the PRF. Each profile is then treated as described in the appendix. In this paper, we focus on the mean properties of our turbulent vortex. Therefore, we present mean velocity profiles obtained by averaging a set of 256 successive profiles (they remain identical if only 64 profiles are averaged).

The Doppler shift method relies on echoes from particles in the liquid. Optimal particles have densities close to that of the liquid, so as to stay in suspension and follow the motions of the fluid. It is best if their acoustical impedance is different from that of the liquid, so as to reflect the ultrasounds efficiently. In water, we use a polyamide powder. In liquid gallium, we selected a powder of zirconium boride. The particles are about 50 μm in diameter and the density of ZrB_2 (6.17) is close to that of liquid gallium (6.09). This powder yields good results, but it is likely that natural gallium oxides also reflect ultrasounds efficiently (see Sect. 4.3).

The user of the DOP1000 velocimeter can adjust a number of parameters. We have already mentioned the key role of the PRF. Another important feature is the amplification level or time gain control (TGC). It controls the amplification level of the echoes before they are analyzed. In some cases, a simple exponential increase of the amplification as a function of the time delay is enough to provide good sensitivity along the whole profile. However, echoes from the walls can saturate portions of the profile and produce spurious velocity values (see Sect. 4.2).

As a matter of fact, it is useful to monitor the amplitude of the echoes as velocity profiles are computed. In Fig. 2, we show the amplitude of the echoes in the cylinder as a function of distance for both water and gallium using the echo mode of the DOP1000. The transducer is positioned at angle 0 (see Fig. 1), and the time between two emissions has been chosen so as to record ultrasonic waves that have bounced back and forth on the side walls of the cylinder. Nice peaks are clearly visible that correspond to waves that have bounced at the liquid-copper interface once or more. For water, a first small peak corresponds to multiple reflections within the entrance wall. These reflections are not as strong for gallium, due to a smaller impedance contrast. On the contrary, reverberations within the opposite wall are responsible for the broadening of the peaks in gallium. Note that even the relative amplitudes of the peaks depend upon the choice of the amplification level (TGC

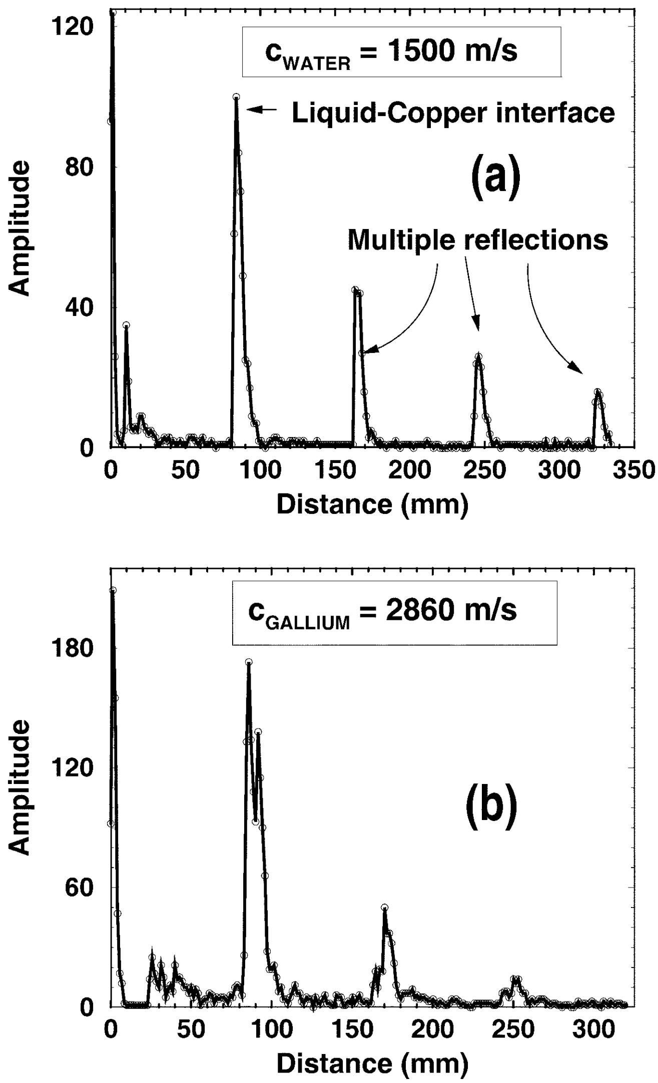


Fig. 2a, b. Ultrasonic echoes (arbitrary units) as a function of distance in mm recorded in the copper cylinder filled with **a** water or **b** gallium. The ultrasonic probe is at angle 0

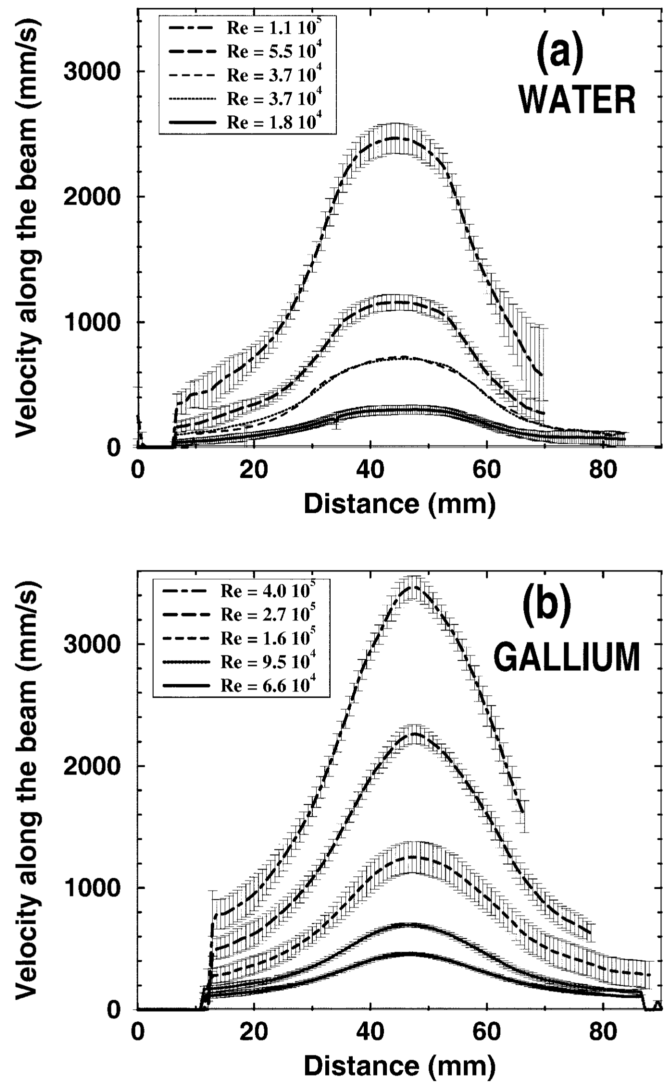


Fig. 3a, b. Velocity profiles as a function of distance measured at mid-depth of the cylinder from angle 1, in vortices of **a** water and **b** gallium. The different imposed Reynolds numbers are obtained by changing the rotation rate of the disk up to 3000 rev $\times$ min^{-1} in both cases. The *error bars* give the standard deviation of the velocity at each measured point of the profile

parameter). The low-amplitude echoes between the main peaks are those from the particles, which ultimately provide the velocity information.

3
Velocity measurements in vortices of water and gallium

3.1
Raw velocity profiles

Figure 3 shows velocity profiles measured at mid-depth of the cylinder from angle 1 in vortices of water (Fig. 3a) and gallium (Fig. 3b). Only the projection of the velocity vector along the ultrasonic beam is retrieved with the Doppler method. Each profile is for a given disk rotation rate from 500 to 3000 rev $\times$ min^{-1} Throughout the paper, we use the Reynolds number $\mathrm{Re} = \frac{\omega_{\mathrm{disk}} r_{\mathrm{disk}}^2}{\nu}$, this dimensionless number being based on the radius of the disk r_{disk}, the kinematic viscosity of the liquid ν, and the rotation rate of the disk ω_{disk}.

The profiles of Fig. 3 are consistent with the properties of the flow as sketched in Fig. 1b.

- The profiles are symmetric with respect to the mid-point of the beam in the cylinder (distance of about 45 mm), as expected for an axisymmetric flow. No bias is introduced by the divergence of the ultrasonic beam.
- The projection of the velocity along the beam is maximum at the mid-point, as it should be if the angular velocity of the liquid decreases with increasing radius. Note that at the mid-point, the (azimuthal) velocity vector is parallel to the beam.
- This maximum velocity increases with the imposed angular velocity of the disk.
- The velocity jumps abruptly from zero in the copper wall to its value in the liquid across a very thin vertical viscous boundary layer. The thickness of this layer scales as $\delta \simeq Re^{-1/3} \times r_{\mathrm{cylinder}}$ (e.g., Pedlosky 1987), yielding δ<1 mm, which is consistent with our measurements. Note that the layer is too thin to be resolved.

- The error bars in Fig. 3 indicate the standard deviation at each measured point of the experimental profile. As expected for these high Reynolds numbers, the flow is turbulent. But the energy of the fluctuating part is only a few percent of the mean flow, as already seen in previous studies (Brito et al. 1995). Note that the sample volume (see Sect. 2.2) is larger than the distance between two measured points.

For a given disk rotation rate (for example at 3,000 rev $\times$ min^{-1}), the maximum velocity is higher for gallium than for water. This is a direct consequence of the difference between the two ultrasonic paths : as shown in Fig. 1c, the path in liquid gallium is less refracted than that in water. Hence, the azimuthal velocity measured at the mid-point is higher for gallium than for water (as long as the angular velocity decreases less rapidly than $1/r$ with radius).

In Fig. 4, we plot the maximum velocity of each profile as a function of the Reynolds number. The maximum disk rotation rate is still 3,000 rev $\times$ min^{-1}, but because gallium has a lower kinematic viscosity than water, higher Reynolds numbers are reached for gallium. We observe that the maximum velocity increases linearly with Re when Re is above about 5×10^4 (for both water and gallium). In this high Reynolds number regime, the liquid is entrained very efficiently. Velocities as high as 3.5 m $\times$ s^{-1} are well recovered by the velocimeter. For smaller values of the Reynolds number, the liquid is more influenced by the presence of the lateral walls. Hence, the liquid is less entrained, as we will see better in the next section.

3.2 Angular velocities

Radial profiles of the angular velocity $\omega(r)$ can be retrieved from the raw velocity profiles, as shown in the appendix. The profiles extend from the minimum radius at the mid-point of the beam to the outer wall.

Figure 5 shows the normalized angular velocity profiles $\omega(r)/\omega_{disk}$ computed from the raw profiles shown in Fig. 2a and 2b. Each profile is composed of two 'branches', which correspond to the two sides of the raw profile.

First, we note that the two branches superpose remarkably well as a function of radius for both gallium and water, in particular in the central part of the vortex (at small radius). It demonstrates that the fluid flow is indeed axisymmetric. It also shows there is no bias introduced by the velocimeter: velocities far from the transducer are recovered as well as those close to it, at least when the parameters of the instrument are well tuned (in particular the PRF). This could be due to the focusing effect of the cylindrical interface, which reduces the intrinsic divergence of the ultrasonic beam.

We checked that the velocity profiles do not depend on the vertical coordinate when Re $\geqslant 10^4$, as already inferred from other measurements (Brito et al. 1995). Indeed, all profiles measured from the top to the bottom of the cylinder are essentially identical for a given disk velocity, for

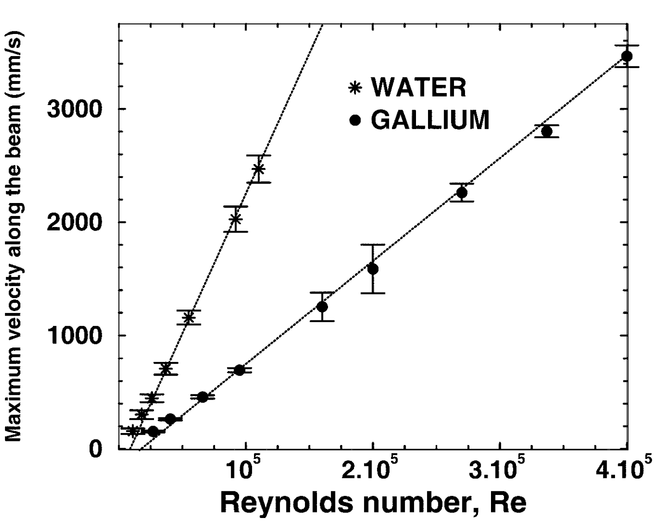
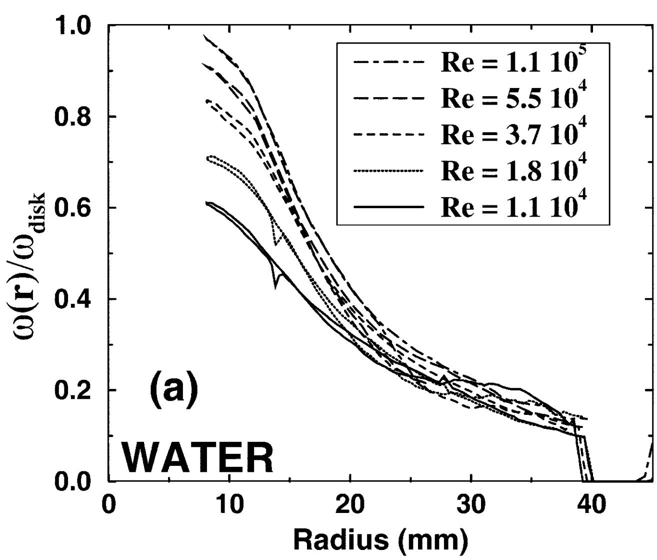


Fig. 4. Maximum velocity of profiles as a function of the Reynolds number in vortices of water and gallium



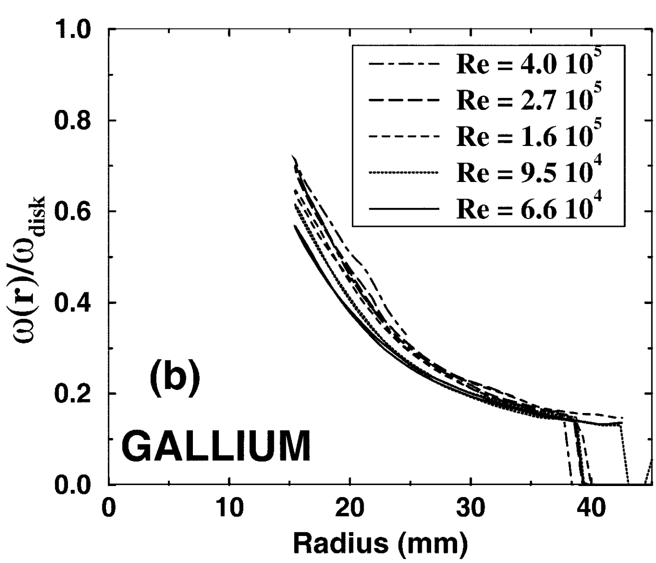


Fig. 5a, b. Normalized angular velocity profiles $\omega(r)/\omega_{disk}$ in vortices of **a** water and **b** gallium for different Reynolds numbers both water and gallium, and from the two shooting angles (1 and 2), except in very thin layers near the boundaries.

Although velocities do not vary with height, the angular velocity in the liquid does not necessarily match that of the disk, as can be seen in Fig. 5. However, as the entrainment velocity increases, the angular velocity of the liquid at the center gets closer to that of the disk: we are entering the *vortostrophic* regime. This is more clear for water, because the geometry of the ultrasonic path permits to retrieve the angular velocities from the outer wall down to a radius of 8 mm, instead of 15 mm for gallium (see Fig. 1c).

For a given Reynolds number (hence for disk rotation rates that differ by a factor of about 3, which is the ratio of the kinematic viscosity of water over that of gallium) the radial profiles of non-dimensional angular velocity in water and gallium superpose perfectly, as shown in Fig. 6.

For Reynolds numbers above about 5×10^4, the angular velocity of the liquid at the center of the cylinder matches that of the disk. This is also when the high Reynolds number regime in Fig. 3 is reached.

3.3 Comparison with velocities deduced from streak photographs

We have seen the good quality and coherency of the velocity profiles measured with the ultrasonic Doppler technique, for both water and gallium. In this section, we compare these profiles with angular velocities derived with a completely different method.

We measured angular velocities in water using the streak photograph technique. The copper cylinder was replaced by a transparent polycarbonate cylinder. A horizontal slice of the cylinder was lit, and a B-pause photograph was taken from below using a mirror. Angular velocities were deduced from the length of the tracks of aluminum flakes.

In Fig. 7, we compare two radial profiles of the angular velocity in water. The points with error bars are from the streak photographs at $Re = 1.5 \times 10^4$ and the curve is a Doppler profile for the same Reynolds number. The two profiles superpose extremely well. Both display a thin boundary viscous layer near the outer wall, across which the angular velocity must jump from zero (no slip boundary condition) to about 10% of ω_{disk}.

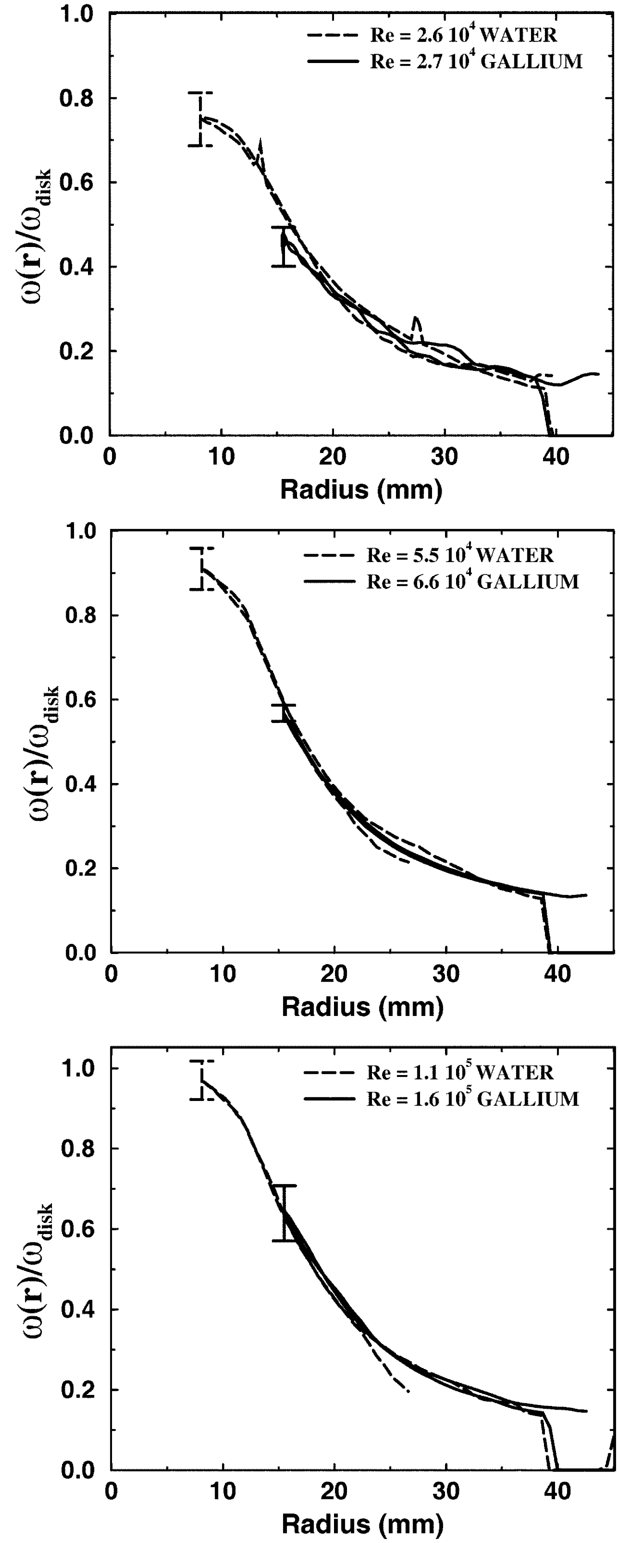


Fig. 6. Comparison of water and gallium angular velocity profiles at three different Reynolds numbers. The *error bars* shown for the smallest radius on each profile is representative of the error bars at every radii

4 Methodological aspects

Although one advantage of the ultrasonic Doppler velocimeter is that is does not require any calibration, there are a few phenomena that can introduce biases in the measurements. The biases can be in distance and in velocity. For gallium, additional problems arise from the formation of oxides that affect the transmission of the ultrasonic waves, as we discuss below.

4.1 Biases in distance

According to the geometry of our setup shown in Fig. 1 and to the sound velocities given in Table 1, the mid-point of the raw velocity profiles should lie at a distance of 42 mm for water and 45 mm for gallium (note that distances are given assuming that the sound velocity for the whole profile is that of the liquid). Instead, we find it at 45 ± 0.5 mm and 48 ± 0.75 mm, respectively, for all

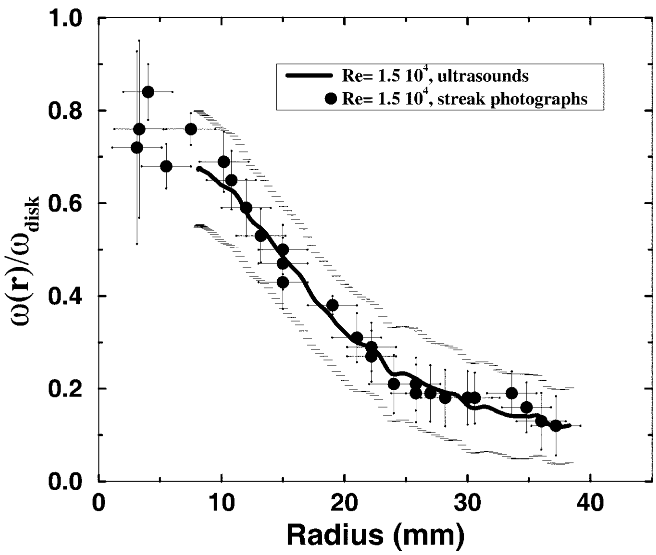


Fig. 7. Comparison of the radial profiles of angular velocity in a vortex of water measured with the streak photograph technique (*points with error bars*) and with the DOP1000 velocimeter (*continuous line bracketed by the standard deviation*)

Reynolds numbers using the de-aliasing method described in the appendix. This implies that the origin of the profiles is offset by some 3 mm. In fact, this offset is directly seen in the raw profiles: the first data points in the liquid are at a distance of 6 mm in water and 10 mm in gallium, instead of the expected 2.5 mm and 5 mm.

By using the actual mid-point of the profiles, we can correct for this small bias. The radial profiles of the angular velocity shown in Fig. 5 illustrate that the profiles then reach the expected radius of 40 mm.

4.2
Biases in velocity

A close look at the two profiles for $Re = 3.7 \times 10^4$ in Fig. 2a reveals that one of these yields spurious zero velocities for some 4 mm inside the liquid. This happens when the echoes from the particles in the liquid are too strong and saturate the signal. This can be solved by adapting the filter applied to the signal, the TGC parameter. Note that the profiles are otherwise completely identical. Spurious velocities also appear when the echoes are not strong enough.

At the other end of the profiles, where the ultrasonic beam encounters the opposite copper wall, another bias exists. We see that the velocity does not decrease down to zero, but remains instead at a roughly constant level. This is because we are getting echoes from particles that have been hit by the ultrasonic beam reflected off that wall and vice-versa. In Fig. 5a tiny notches at $r \simeq 14$ mm may be artefacts due to the beating of the scattered waves with a static echo for the same shot.

We found another more subtle cause of bias in velocity. Figure 8a compares two raw velocity profiles for a vortex in water with the same Reynolds number, $Re = 3.7 \times 10^4$. The only difference between the two profiles lies in the choice of the PRF. This parameter controls thè 'listening' time of the velocimeter, hence the length of the profile. However, it also trades off with the velocity that can be measured.

As we have seen in Sect. 2.2, if the time between two emissions is too short, the particles have not moved enough and the velocimeter fails to properly resolve the Doppler shift. The signal-to-noise ratio is then low and the recovered velocity is biased to low values. This is why the profile with $t_{PRF} = 128$ µ*s* is too low in Fig. 8a. In Fig. 8b, we report the maximum measured velocity as a function of t_{PRF} for several Reynolds numbers. These curves display a plateau for which the measured velocity becomes independent of the selected PRF. In fact, velocity slightly decreases along this plateau (by less than 10%). The strong velocity bias seen in Fig. 8a occurs for smaller t_{PRF}.

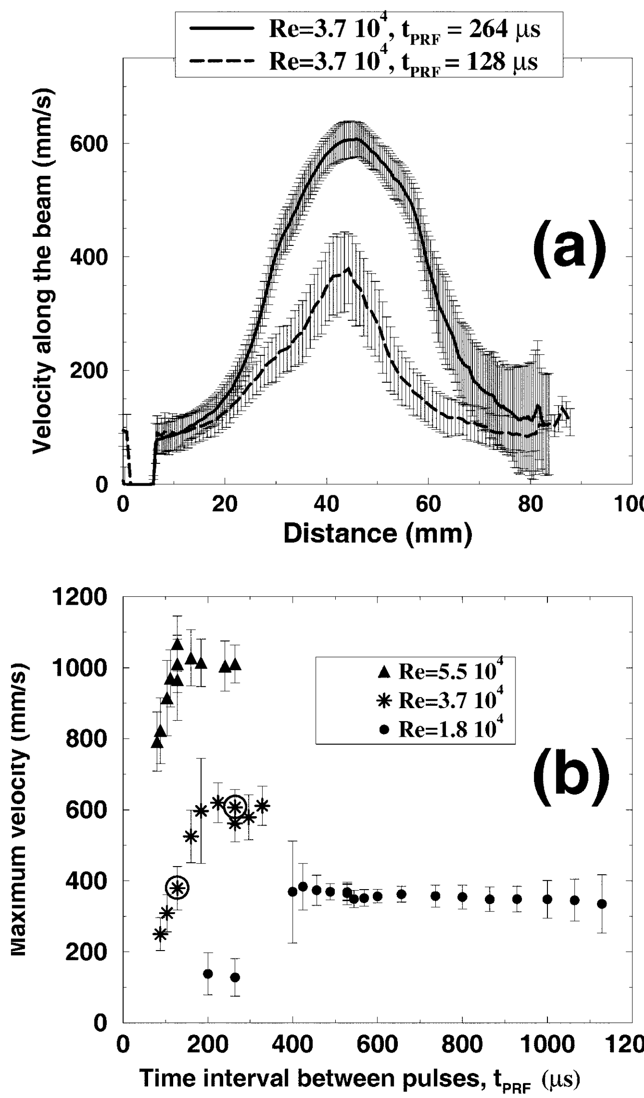


Fig. 8. **a** Velocity measurement in a vortex of water as a function of distance for an identical Reynolds number $Re = 3.7 \times 10^4$ and different times between two emissions t_{PRF}. Velocities are underestimated when the PRF is not carefully chosen. **b** Maximum measured velocity (mm/s) as a function of the selected t_{PRF} in µs, for three Reynolds numbers. The *two circled stars* for $Re = 3.7 \times 10^4$ correspond to the two profiles shown above

Therefore, there is an optimum t_{PRF} slightly above this fall-off, for which the correct velocity is measured.

When the disk velocity increases, the optimum t_{PRF} decreases, and the width of the plateau diminishes because profiles with large t_{PRF} present too much time-aliasing to be recovered (see appendix). The optimum t_{PRF} roughly varies as the inverse of the disk velocity. A similar behavior is observed in gallium experiments. All results presented in this article are for the optimum t_{PRF}.

Following these observations and in order to find the suitable time between successive pulse emissions, one should first start with the largest possible t_{PRF} and then reduce it until the maximum velocity collapses.

4.3
Problems with oxides in liquid gallium

At this stage, we hope to have shown that excellent velocity measurements could be obtained in liquid gallium, using pulsed Doppler shift ultrasonic velocimetry. In this section, we emphasize that this was not an easy task, as several difficult problems had to be solved before we could obtain these results.

4.3.1
Oxides

The main difficulties are linked to the exceptional affinity of liquid gallium with oxygen. Gallium oxides cover the surface of liquid gallium in a few minutes when it is in contact with the atmosphere. An oxygen content as low as 2 ppm is enough for oxidation to start (personal communication, Rhône-Poulenc). The two main gallium oxides are GaO_2 (density = 4.77) and Ga_2O_3 (density = 6.44) (Downs 1993). GaO_2 forms a very fine dark powder, which is easily seen at the surface of shiny gallium.

4.3.2
Effect of oxides on ultrasonic velocimetry

As soon as oxides have had time to develop enough, it becomes impossible to obtain reliable profiles with the ultrasonic velocimeter. Within a few minutes, the profiles become asymmetric, the measured velocity decreases, and finally one loses the profile completely, starting from the far wall. At first, we thought that these problems were due to a decrease in the population of particles, since the velocimeter returns zero velocities when it gets no echo. A simple test shows that this is not the case. If we start an experiment with clean gallium (as discussed below) at angle 0, we observe that the amplitude of the echo progressively decreases and finally disappears. This means that the ultrasonic beam looses its energy by scattering: there are too many particles. The scattering could take place in the volume of the liquid or on the walls, or both. We will see from tests discussed below that scattering from oxide particles on the walls is probably the main source of attenuation of the ultrasonic beam.

4.3.3
Cleaning

There are two options to avoid problems with gallium oxides: either always operate gallium under an oxygen-free atmosphere, or remove the oxides. With the first option, one could use argon or nitrogen, but we have seen that even a minute proportion of oxygen is enough to start oxidation. We have chosen the second option. As described in Brito et al. (1995), liquid gallium can be cleaned by letting it react with a 10% solution of HCl in ethanol. We perform this treatment for a few hours each time before filling the cylinder.

4.3.4
Cylinder material

We used three different materials for the cylinder. First, we used polycarbonate, as described in Brito et al. (1995). Visual observations were then possible when the liquid was water (see Sect. 3.3). We built a second cylinder in Nylon 6/6 : this material was chosen because its sound velocity is very close to that of liquid gallium, so that refraction was minimal. Finally, a copper cylinder was constructed, with which all measurements presented in this paper were obtained.

In all three cases, we could get good velocity measurements for the first few runs. However, after a few days or a few weeks, the profiles started deteriorating, even though the gallium was cleaned before each refill. The reason seems to be that oxides clutter on the walls and cannot be completely removed, even though we tried various mechanical and chemical treatments. This observation confirms the role of oxides on the walls as the primary source of disturbance for ultrasonic velocimetry.

4.3.5
Coating

The final step for obtaining reliable and lasting velocity measurements was to coat the walls of the copper cylinder with a 2-μm-thick cataphoretic film. With this coating, oxides do not stick to the walls. Starting with purified liquid gallium, we can typically run the experiments for about 1 h without encountering problems due to oxides. We then have to empty and clean both the cylinder and the gallium before starting a new run. The run-time could probably be lengthened if the experiments were performed in an oxygen-free atmosphere.

4.3.6
Particles

All experiments in gallium we reported on used 50-μm zirconium boride particles to backscatter the ultrasonic waves. ZrB_2 was chosen because its density (6.17) is close to that of liquid gallium. However, we also performed a few tests with ‘pure’ gallium and found it to be just as echogene, probably because of small oxide particles again.

5
Preliminary flow velocity measurements in liquid sodium

As mentioned in the introduction, one of the motivations for our study is the possibility to measure flow velocities in dynamo experiments using liquid sodium. Having shown the merits of our experimental setup to develop the Doppler velocimetry technique in liquid gallium, we show the results of preliminary tests in liquid sodium.

Experimenting with liquid sodium introduces two difficulties: high temperature (sodium melts at 98 °C) and the violent reactivity of sodium, which requires specific handling methods. The experimental setup has been modified accordingly. In order to avoid contact of sodium with oxygen or water, the whole setup was placed in a dedicated Argon atmosphere chamber operated by the Direction des Réacteurs Nucléaires of the Commissariat à l'Energie Atomique in Cadarache, France. The polycarbonate disk was replaced by a stainless-steel equivalent. For minimizing leakage problems, the cylinder was only three-quarter filled, and the disk positioned at mid-depth. The geometry of the cylinder was kept unchanged, but we tried three different materials: naked copper, copper with a cataphoretic deposit (as for gallium), and stainless steel.

The experiments were carried out with liquid sodium at a temperature of 120 °C. We used a high-temperature transducer TR40408 from Signal Processing, which can operate up to 150 °C. The beam it produces is about 60% wider than that of the TR30405 probe.

Figure 9a shows the echo from the wall and its multiples measured using the stainless-steel cylinder. The sound velocity of liquid sodium derived from this record is in agreement with the predicted value (see Table 1). The naked copper cylinder yielded weaker echoes, while no echo at all was seen with the cataphoretic-coated copper cylinder.

In contrast, the best velocity profiles were obtained using the naked copper cylinder. Figure 9b displays the raw profiles and their standard deviations for three different disk rotation rates. The transducer is at angle 1 and the ultrasounds travel along a chord bottoming 10.5 mm off the axis of the cylinder. The profiles look not too different from their equivalents in water and gallium and the maximum velocity clearly increases with the disk rotation rate. Nevertheless, the profiles are much more noisy and the maximum mean velocities are between two and three times lower than expected, even if we account for the effect of the cylinder being only three-quarter filled. We think that this is due to a poor signal-to-noise ratio in these experiments. Results obtained with the stainless-steel cylinder were similar but of poorer quality, because of the high impedance contrast at the solid/liquid interface. Rather unexpectedly, the cataphoretic-coated copper cylinder yielded the worst results.

No particles were added to the sodium. Pure sodium was too transparent to ultrasounds and we had to let it oxidize to get sufficient echoes from oxide particles.

These preliminary measurements in liquid sodium are encouraging. It remains to perform a work similar to what we have presented for gallium: determine the best container material and optimize the amount of oxides and/or other particles.

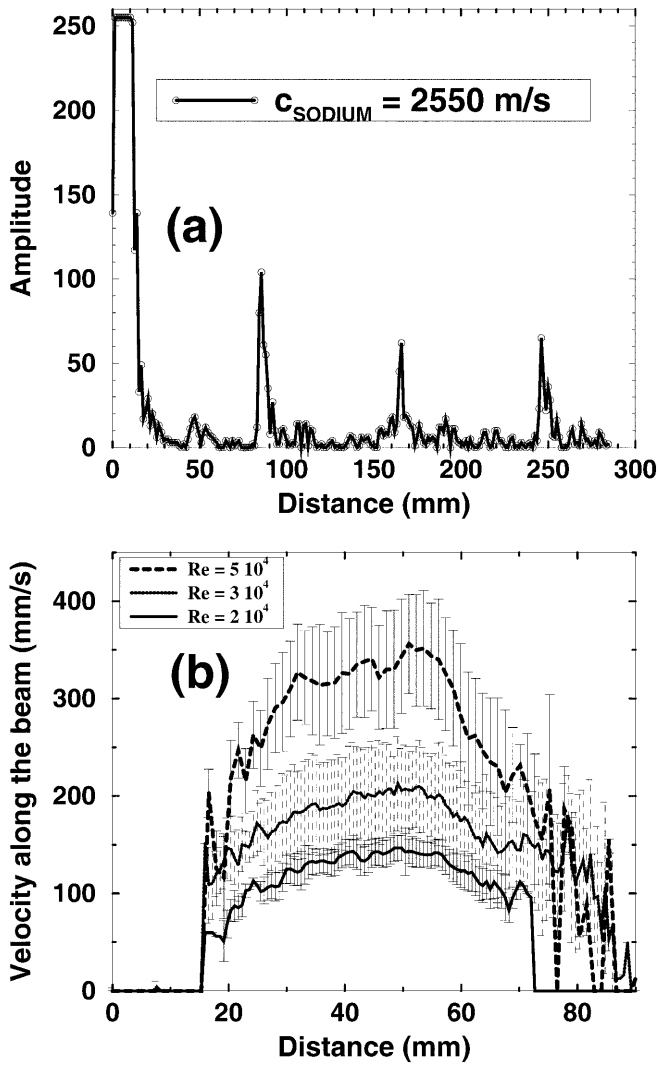


Fig. 9. **a** Ultrasonic echoes (arbitrary units) as a function of distance (mm) recorded in a cylinder of stainless steel filled with sodium. The ultrasonic probe is at angle 0 (see Fig. 1). **b** Velocity profiles as a function of distance measured at mid-depth of the cylinder from angle 1 (see Fig. 1) in vortices of liquid sodium at 120°C obtained in a cylinder of naked copper, for three different disk rotation rates

6 Conclusions

We have shown the first velocity measurements performed in a vortex of liquid gallium, using the pulsed Doppler shift DOP1000 velocimeter. Reliable profiles have been obtained. Comparisons with earlier experimental results for the same setup demonstrate the high quality of the velocity measurements. Comparisons with velocity profiles for water in the same setup illustrate that the dynamics of this type of flow is controlled by its Reynolds number.

The main problems we have encountered are due to the very fast oxidation of gallium. Oxides form a powder that sticks to the walls of the container and scatters the ultrasounds, making it impossible for them to propagate far enough. We were able to overcome this difficulty by 'cleaning' the gallium and the container before each series of runs. Cleaning of the container was efficient only when a thin cataphoretic film protected the copper walls from gallium oxides deposits. Running the experiments in an oxygen-free atmosphere would probably minimize these problems.

Our results open new perspectives for the investigation of fluid flow in liquid metals. They should lead to developments in the context of experimental dynamos, where fast motions are set in large volumes of liquid sodium.

Preliminary tests of the pulsed Doppler shift ultrasonic method in liquid sodium using the same setup show that the technique should work well.

Appendix: Treatment of velocity profiles

In this appendix, we explain how we convert the raw velocity data recorded by the DOP1000 velocimeter into time-averaged profiles of the angular velocity ω as a function of radius. Figures 10a–d show the successive steps of the processing and Fig. 11 illustrates the projection of the measured velocity V_{dop} into the azimuthal velocity component V_θ.

As already mentioned in Sect. 2.2, one set of velocity profiles is typically composed of 256 individual profiles, each of them measured successively in time. The total recording time of a set is determined by the product of parameters t_{PRF} $\times$ *number of pulses per profile* $\times$ 256 and ranges from about 5 to 25 s.

The four individual velocity profiles shown in Fig. 10a are from a set of 256 velocity profiles, each of which was recorded with $t_{PRF} = 208$ μs and 128 emissions per profile. Along the Y-axis, velocities are given in their original binary-coded values, spanning a range from −128 to +127. Given the sign convention of the velocimeter (velocities counted positive when the fluid moves away from the probe) and the sense of rotation of our disk, all measured velocities should be positive. We see that this is not the case in the central part of the profile, where the values have been clearly aliased into the negative side. This happens when the fluid velocities are larger than the set maximum velocity (V_{max} parameter).

This effect can easily be removed by de-aliasing the binary files (using a continuity test). Figure 10b gives the resulting de-aliased profiles.

The following step consists of time-averaging the 256 corrected profiles and converting the binary units into physical units (mm $\times$ s^{-1}). The resulting mean profile is plotted in Fig. 10c, together with the standard deviation about that profile.

In the last step, the velocity along the ultrasonic beam V_{dop} is converted into the azimuthal velocity $V_\theta = r\omega(r)$. To do that, we first determine the symmetry point of the profile (point O' in Fig. 11) by least square inversion: the result of this inversion is given by the vertical bar in Fig. 10c. (Note that the position of point O′ is theoretically known, as we know the angle of incidence i_{Cu} and the sound velocities in copper, gallium, and water. However, we generally have a small discrepancy between the pre-

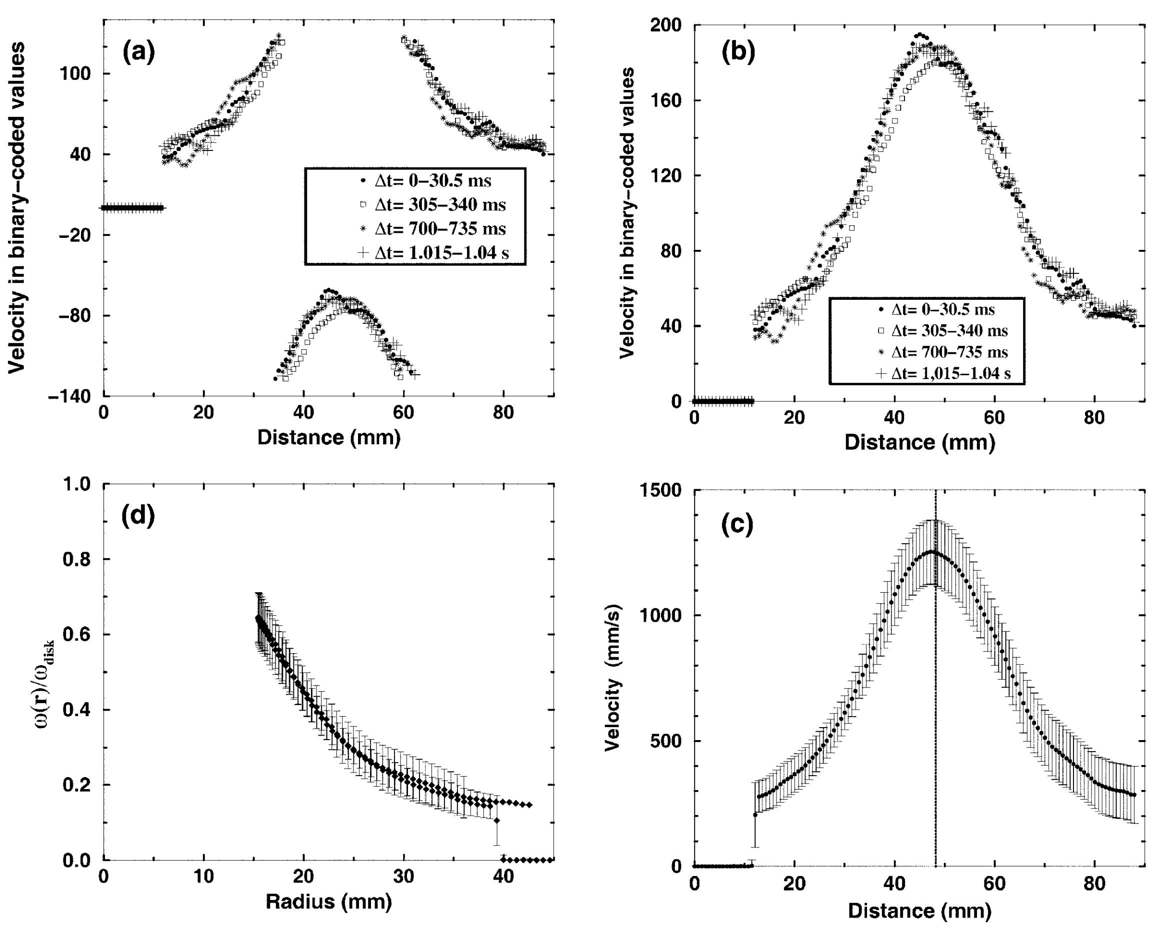


Fig. 10a–d. Successive steps of the processing of a velocity file recorded by the DOP1000 during an experiment with liquid gallium where $Re = 1.6 \times 10^5$. **a** Original binary-coded velocity values as a function of distance for four profiles. **b** De-aliased profiles. **c** Time-averaged profile in physical units (mm/s), obtained by taking the mean of the 256 successive individual de-aliased profiles. The *error bars* are the standard deviation about that mean profile. The *vertical bar* is the symmetry point O'. **d** Time-averaged angular velocity $\omega = V_\theta / r$ scaled with ω_{disk}, as a function of radius

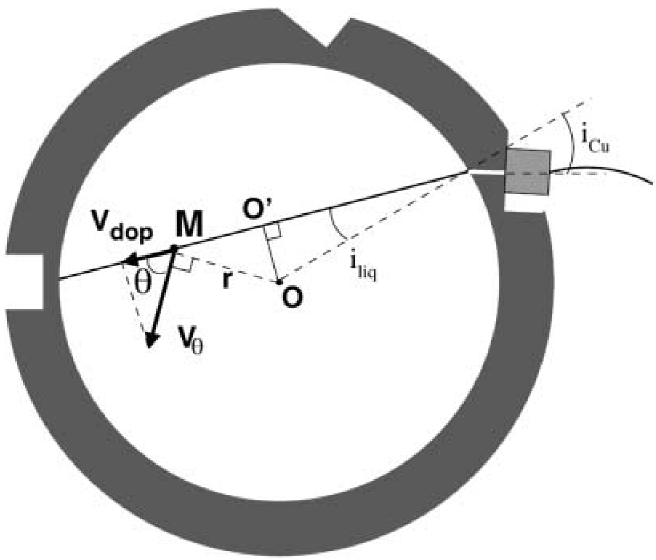


Fig. 11. View from the top of the cylinder. The DOP1000 measures the component of the velocity along the beam, V_{dop}. O' is the mid-point of the chord. $V_\theta(M)$ is obtained by projecting $V_{dop}(M)$ on the perpendicular to OM

dicted value and the one obtained from the inversion, as discussed in Sect. 3.2).

Once we have the distance of point O' in Fig. 10c and knowing the distance OO' = r_0 from the geometrical parameters of Fig. 11, we can project V_{dop} into V_θ:

$$V_\theta(r) = V_{dop}(M) \cdot \frac{r(M)}{r_0}$$

where $r(M) = \sqrt{r_0^2 + O'M^2}$.

Dividing $V_\theta(r)$ by the radius r, we finally obtain the time-averaged angular velocity ω as a function of radius r as shown in Fig. 10d, here scaled to the disk angular velocity ω_{disk}. The two branches of that profile, which superpose almost perfectly, come from the two sides of the original bell-shaped profile.

Note that for high rotation rates, the retrieved angular velocity at the center reaches the imposed disk velocity when an effective value $i_{\text{Cu}} = 40°$ is selected for angle 1. This is within the bounds determined from the geometry of the machined portions for angle 1 (32 ± 12), and this value is used throughout for all profiles.

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