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FLOW VISUALIZATIONS AND PIV ANALYSIS OVER VORTEX RIPPLES

Germain Rousseaux.*
***Université de Nice Sophia-Antipolis**
CNRS UMR 6621
Laboratoire J.-A. Dieudonné
Parc Valrose
06108 Nice Cedex 2
France

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ABSTRACT : *This article treats of the flow motion over the so-called vortex ripples which are generated by water oscillations above a sand bed. We focus mainly our experimental works on the morphology and the dynamics of transient flow patterns above real vortex ripples. With the help of flow visualizations and Particle Image Velocimetry measurements with a high-speed video CCD camera, we test numerical simulations, which predict the existence of a secondary vortex with a streamlines representation. However, our experimental findings show only one vortical structure and validate the observations of Bagnold in 1946 (using real ripples but with no visualization and measurement) and Sand Andersen & al. in 2004 (using model ripples) with respect to the existence of a transient jet.*

1 Introduction

Since the seminal experiments of Brigadier Ralph Alger Bagnold [1], sand ripples and their associated fluid flows have become a vivid field of research for physicists as an interesting example of fluid-structure interaction. Indeed, the fluid and the granular material interact in a complex way since the shape of ripples changes with sand transport which depends on fluid flow. In turn, the latter modifies the geometry of the patterns. Rolling-grain ripples, the initial state occurring when a flat fluid-granular interface start to deform, are notoriously difficult to observe since their size is of the order of a few millimeters compared to vortex ripples which are the saturated state of the sand bed and whose size scales with the amplitude of oscillation induced by water waves that is several centimeters [2–9].

Thanks to a particular cylindrical geometry ([4–9]) and particle image velocimetry measurements with a high-speed CCD camera coupled to a laser diode, we were able to show the existence of a transient eddy over rolling-grain ripples which appears at flow reversal and which scales with the ripple's wavelength [7]. Except at flow reversal, no hydrodynamical structure is seen during the rest of the oscillation period. This last observation appeared to be contradictory with previous theoretical works and experimental visualizations since rolling-grain ripples have been characterized so far with couples of recirculating cells corresponding to time-dependent streaming induced by the ripple shape. However, we calculated the time-average over one period of the observed total flow (which resumes to the time average of the time-dependent streaming) and the resultant steady streaming with the expected two recirculating cells per trough was observed [7].

In this article, we will focus mainly on the hydrodynamics associated to vortex ripples in order to contribute to clarify the basic phenomenology of the flow over real vortex ripples. This ends our introduction. In part 2, we review the literature and address the relative naive question : How many vortex characterize a vortex ripple ? Then, the beginning of part 3 introduces the experimental setup as well as the PIV techniques used to extract the flow field. In section 3.2, we compare our results with the numerical predictions. Finally, we analyze a vorticity plot before concluding.

2 One or several vortices with or without a transient jet ?

The literature about sand ripples is vast and we decided to select some relevant papers presenting the principal flow configurations that have been introduced so far. Some authors report for the existence of one or several vortex (vortices) over vortex ripples [1, 2, 4, 10–15]. Moreover, Bagnold [1] and Sand Andersen & al. [13] have shown that another transient structure (as described as a ”jet”) was present in addition to the vortex (vortices). That’s why, to produce quantitative visualizations and measurements for such a structure over real vortex ripples is essential as no consensus has emerged until now. We display on Figure 1, as a cartoon, three typical descriptions that we encountered in the literature (see below for the definition of the types of structures). Firstly, one primary vortex plus a counter-rotating secondary vortex (a). Secondly, one primary vortex plus a transient jet (b). Thirdly, one primary vortex plus a relic vortex (c).

There exist several techniques in order to visualize the hydrodynamical structures associated to vortex ripples. Bagnold used silver particles above both real ripples and an artificial ripple model [1]. He reported for one or severals vortical structures depending on the flow parameters as well as another pattern called by him the ”jet”: *when the flow has just begun to move backward in the reverse direction, a jet of water now begins to squirt down the outward slope of the ripple, between the crest and the departing vortex. This jet flicks a volley of grains from the crest downwards parallel with the outward ripple slope*. More recently, Sand Andersen & al. also observed a ”jet” using a triangular model ripple [13]. In addition, these authors introduced a nice theoretical model of the circulation of the vortex taking into account the different forces acting on it. With a wave-tank, Earnshaw & Greated [12] followed the motion of the center of the vortex over a rigid undulated bed but they did not show any visualizations of the structure except a cartoon which features a primary vortex and a ”relic” vortex produced during the last half-period. Scherer & al., using Kalliroscope particles as tracers [4], observed a single vortex with a v-like shape in a cylindrical geometry but their experiments were confined to low frequencies over pre-formed real vortex ripples because of the impossibility to visualize the vortex (because of dye mixing) at high frequencies corresponding to the actual frequencies of ripples formation. The experiments of Ourmières & Chaplin [14] feature two vortices which are created and shed, one during each half of the wave cycle. Once the vortex is ejected, it moves upward and interact with the one produced earlier (the ”relic” vortex) and we can wonder if this ”relic” vortex is not at the origin of the primary vortex shedding. In some cases, these authors reports for a smaller secondary vortex coupled to the primary vortex shed every half-period (Fig. 11 & 12 in [14]).

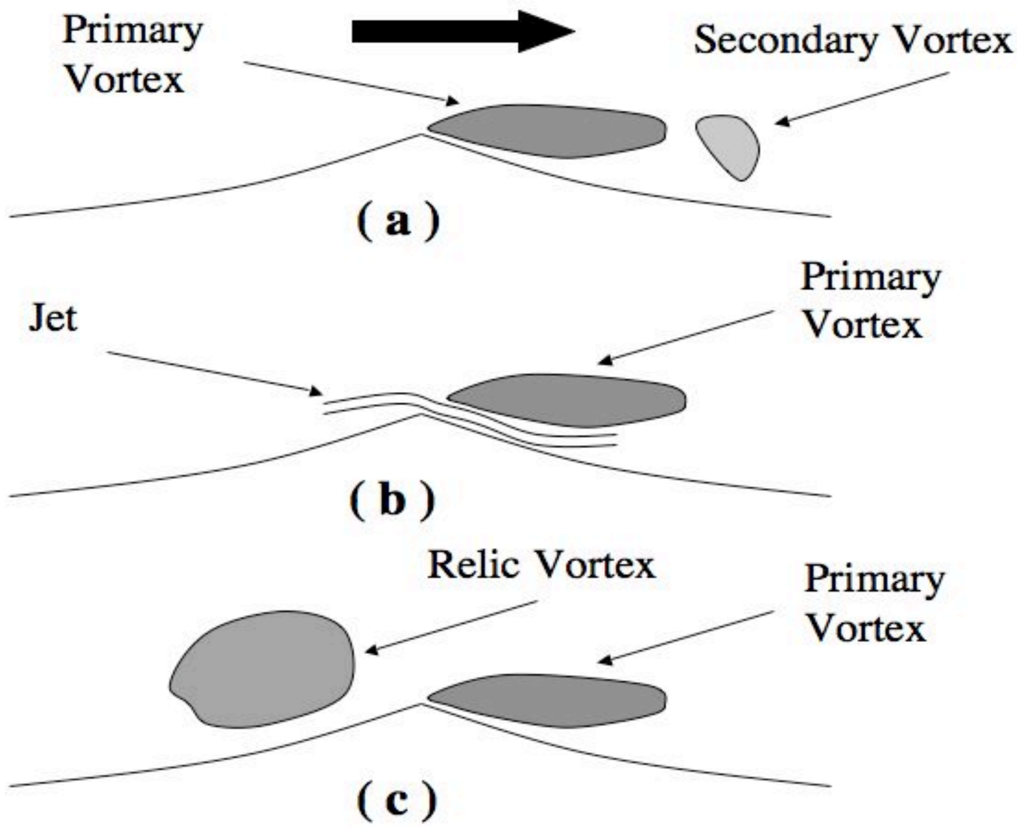

FIG. 1: Three types of hydrodynamical structures over vortex ripples as described in the literature. The black arrow corresponds to the background flow direction before reversal.

Other vortices were seen by both Hara & Mei [11] and Blondeaux & Vittori [10] in their numerical simulations. According to Blondeaux & Vittori (see their Fig. 8 in [10] displaying streamlines), a secondary vortex ejects the primary vortex so is responsible for the detachment. Yet, Andersen reports for only one vortical structure associated to vortex ripples in its computations [2]. Nevertheless, his simulations dealt with turbulent flow and he only calculated mean velocity and vorticity fields. More recently, Eidsvik has described for the first time in a numerical work with a RANS model the role of the jet with respect to the sand flux: *As the near bottom flow accelerate to the right, say near wave phase 30, there is a speedup along the upslope ripple side ending in a jet from the ripple crest. Below this jet a clockwise recirculating vortex is formed. As the free flow maximum is approached, near wave phase 90, this vortex becomes large, with a systematic negative near bottom transport. As the free flow decelerates, near the wave phase 180, the near bottom lead transports the vortex effectively backward and upward. As the free flow changes sign, the clockwise vortex approaches the ripple crest, forming the new near bottom jet and counterclockwise recirculating vortex. At about maximum negative free flow, near wave phase 270, the clockwise vortex center is about a ripple wavelength from where it turned back and about a ripple crest higher. For large Reynolds number flows the turbulent intensity may be very high during the whole wave period and sediments may be entrained over most of the ripple and ejected into the bulk flow by the crest jet, recirculating vortex and intense turbulence* [15].

3 Experiments

3.1 Experimental setup and techniques

We report here for experiments on flow visualizations and velocity measurements with a cylindrical geometry. The setup consists in two concentric cylinders of Plexiglas which are linked on the top and the bottom by two circular plates. The bottom plate oscillates at a fixed displacement amplitude A and frequency f as it is driven by a brushless motor. The top plate is made of transparent Plexiglas. The mean radius of the cylinders is 135.5 mm and the gap size between the cylinders is 19.0 mm. We put a layer of mono-disperse spherical glass beads (diameter d = 0.11 mm < viscous boundary layer δ = 0.56 mm at 1 Hz and density $\rho_s = 2.49\times10^3$ kg/m3) between the cylinders and fill the gap with water [4–9]. Hence, in our experiments, an initial flat bed of granular media immersed in water is submitted to an oscillatory motion. Thus the granular-fluid interface is under a periodical shear [4–6]. After an initial destabilization (rolling-grain ripples) and a coalescence process of the primary patterns, the interface reaches a saturated regime (vortex ripples) after a transition.

The water is seeded with a polymer powder from ORGASOL (diameter d_p = 0.06 mm and density $\rho_p = 1.03\times10^3$kg/m3). A laser sheet is created in the middle of the gap with a laser diode from Lasiris (685 nm, 50 mW) which is embarked on the setup as a C.C.D. camera with a macro zoom (12.5 mm - 75 mm). Flow visualizations are done with the CDD camera at 25 images per second. In addition, we perform Particle Image Velocimetry (P.I.V.) with a high-speed video camera (FastCam Super 10k from Photron : 250 pictures per second and 540×480 resolution) under continuous light from the laser diode. The resolution is 0.047 mm per pixel in our experiments. The image processing is done on a personal computer with the software Davis 7 from Lavision. We used the so-called ”multipass” calculations starting from a 64×64 pixels by pixels interrogation window to a 12×12 pixels by pixels window in order to evaluate the velocity vectors.

In our previous study on the hydrodynamics of sand ripples [7], only the flow over the rolling-grain ripples was studied. Here, we describe the flow characteristics of the final vortex ripples.

3.2 Description of the flow over real vortex ripples

With respect to the experimental results reported in the rest of the paper, we decided to display roughly the quarter of period corresponding to the salient effects. The flow over a vortex ripple during each half period is physically similar to the sudden accelerated flow behind a backward facing step. For small velocities, the oscillatory Stokes flow follows the ripple’s shape and is laminar. Then, a single bubble of recirculation appears (Fig. 2 (a)), increases in size (Fig. 2 (b), (c) & (d)) before being ejected from the ripple’s trough (Fig. 2 (e)) and being replaced by a transient ”jet” directed in the opposite direction to the background flow (Fig. 2 (f)). From the Particle Image Velocimetry measurements (PIV), the experimental streamlines for real vortex ripples made of glass beads were computed. On the Figure 3, neither a secondary vortex nor a relic of the primary vortex created during the previous half period is observed. This clearly shows that neither a relic vortex nor a secondary vortex could be at the origin of the primary vortex ejection and one should expect another mechanism to be in action.

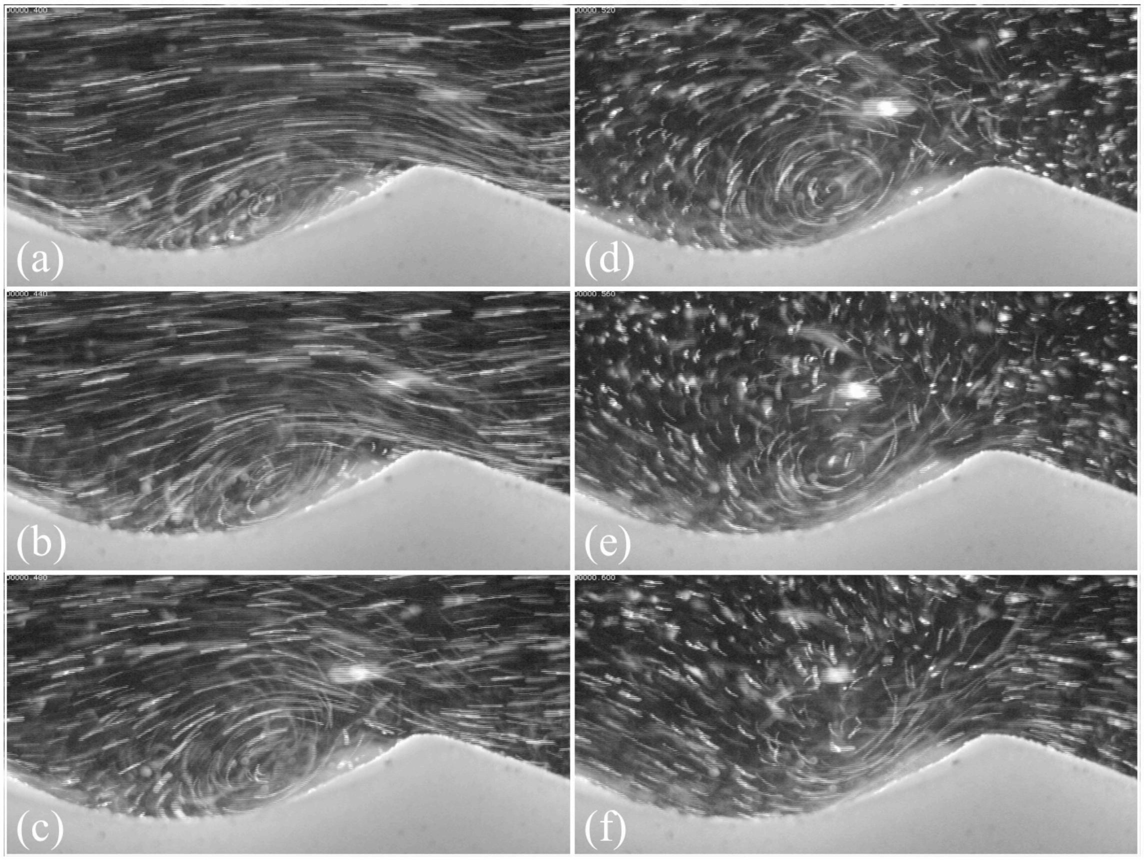

FIG. 2: Film of the flow over vortex ripples with tracers illuminated by a laser sheet. The main flow goes to the left. The parameters are : f = 1Hz − A = 1.2cm − d = 110μm − t = 81300s − Δt = 40ms − λ = 2cm − h = 0.36cm.

Indeed, a close examination of the Figures 3 (g) & (h) reveals, as described by Bagnold [1] and reported by Sand Andersen & al. for model ripples (Fig. 2 in [13]), the formation of a rapid transient "jet" of fluid along the ripple slope which appears when the primary vortex shedding happens. The "jet" corresponds to high velocities values close to the ripple slope in Figures 3 (g) & (h). This scenario is similar to the one observed for the rolling-grain ripples which are characterized also by a rapid transient "jet" which does appear just during the ejection of the reversal eddy and which occupies the entire through between two successive ripples [7]. Physically, the "jet" can be explained by the confinement of the shear flow between the ripple's slope and the departing vortex. Hence, one observes a stream of rapid fluid. Blondeaux & Vittori calculated the streamlines associated to the flow over vortex ripples [10]. They observed a secondary vortex which they interpreted to be at the origin of the primary vortex expulsion (Fig. 8 (h) in [10]).

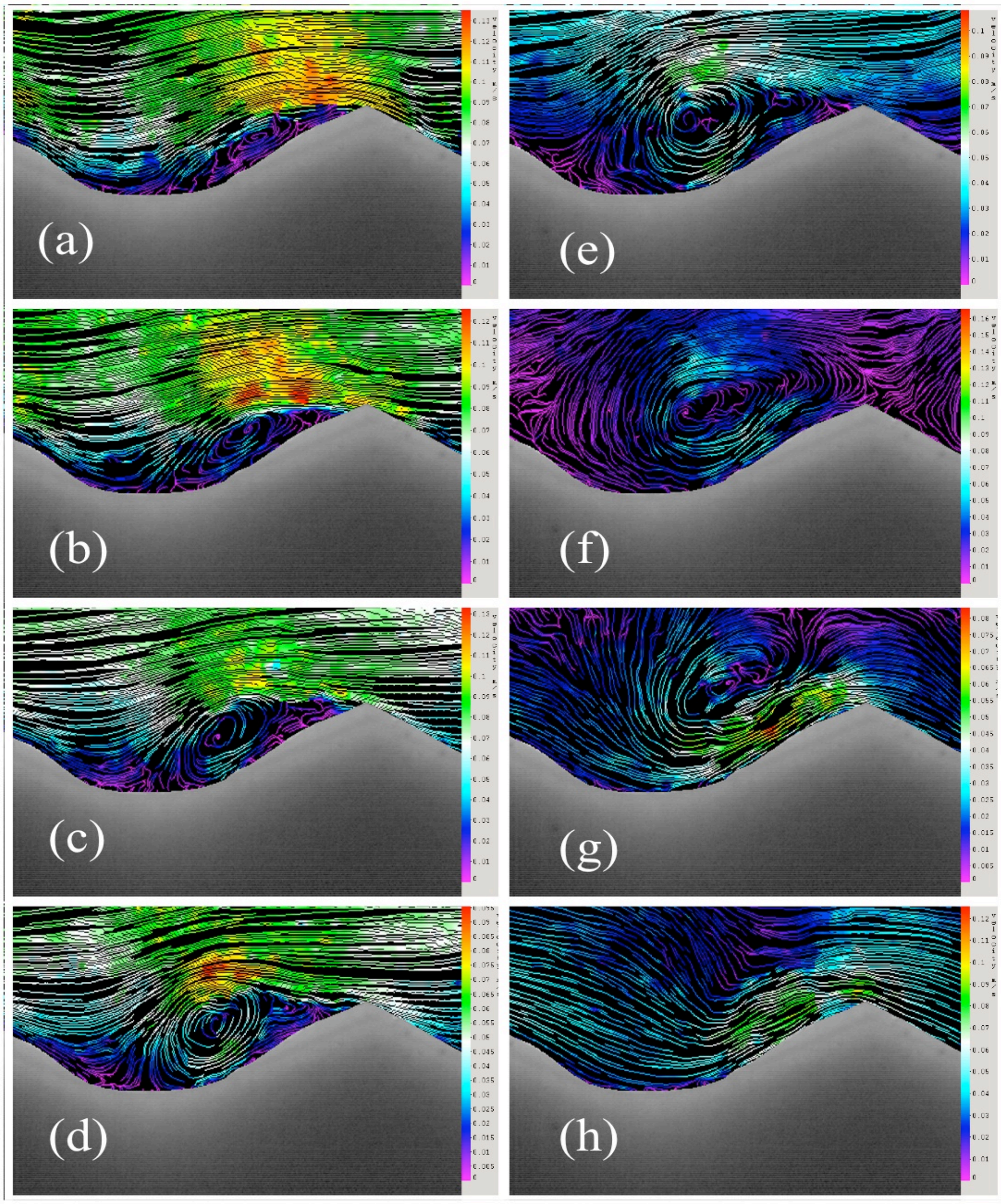

FIG. 3: Experimental streamlines above vortex ripples obtained by PIV measurements. The colors correspond to the modulus of the velocity. The main flow goes to the left : the background flow reversal corresponds roughly to Figure (f). The parameters are : f = 1Hz − A = 1.5cm − d = 110µm − t = 5700s − $\Delta t = 40$ms i.e. $Re_\delta = 2A/\delta = 53.2$, $h/\lambda = 0.18$ and $A/\lambda = 0.69$ (to compare with Blondeaux and Vittori Figure 8 and Sand Andersen et al. Figure 2).

Among the large numbers of experiments we have carried out, we selected a particular set of experiments in order to make a quantitative comparison with the numerical simulations of Blondeaux & Vittori. More precisely, our Figure 3 is the experimental counterpart of the Figure 8 from Blondeaux & Vittori's paper with dimensionless parameters which are very close (however, see the conclusions for a reappraisal). Their parameters are: $Re_\delta = 2A/\delta = 50$, $h/\lambda = 0.15$ and $A/\lambda = 0.75$. Indeed, these last authors describe the flow over ripples with three control parameters which are : $Re_\delta = 2A/\delta$ the Reynolds number based on the size of the viscous layer known as the Stokes layer ($\delta = \sqrt{\nu/\pi f}$ where ν is the fluid kinematic viscosity and f the oscillation frequency), h/λ and A/λ where h, λ and A are respectively the ripple height, the ripple wavelength and the oscillation amplitude. Hence, these parameters take into account both the influence of the fluid flow and the ripple geometry. The parameters of the Figure 3 are : f = 1Hz − A = 1.5cm − d = 110µm − t = 5700s − $\Delta t = 40$ms i.e. $Re_\delta = 2A/\delta = 53.2$, $h/\lambda = 0.18$ and $A/\lambda = 0.69$. We checked that we have reached the saturated state of the vortex ripples by examining the evolution of the wavelength/heigth of the patterns [6, 9]. We insist on the fact that Blondeaux and Vittori have claimed for the existence of a secondary vortex thanks to their plots displaying streamlines thats why we decided to compare with their streamlines representation [10].

Experimental vorticity plots are difficult to obtain since the size of the real vortex ripples in our experiments are of the order of the centimeter contrary to the experiments with model ripples whose size are of the order of ten centimeters. Here, we report for vorticity measurements in Fig. 4 when the vortex has its largest extent. We observe a strong vorticity blob (in red) turning anticlockwise superposed to a clockwise vorticity blob (in blue) situated on the lee side of the ripple. We do not observe a secondary vortex. In addition, the vortex features an undulating tail reminiscent of a Kelvin-Helmholtz instability due to the background flow shearing a dead zone with lower velocity behind the ripple...

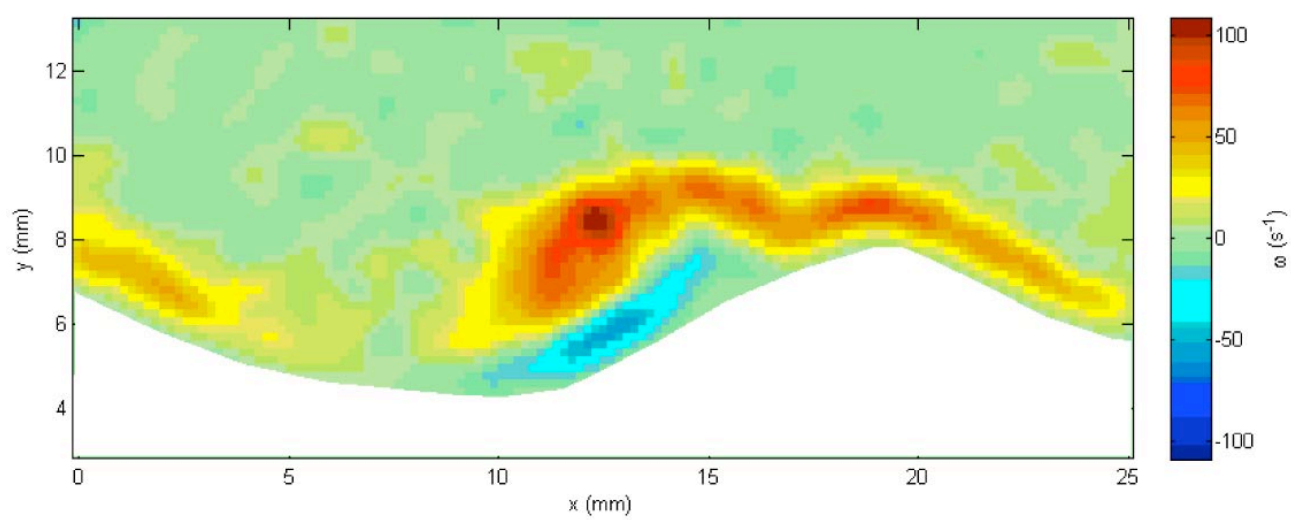

FIG. 4: Vorticity above vortex ripples. The parameters are the same as the Fig. 3.
The background flow is coming from the right.

Sand Andersen et al. [13] reported also for two counter-rotating blobs of vorticity, one close to the ripple which does correspond to the presence of a vortex (Fig. 2 in red of [13]) but the other patch (in blue) is located above the primary blob (and not under as in our system) and this latter does not correspond to a coherent structure: it is necessary because vorticity is divergenceless. Hence, according to our point of view, a criterion based on vorticity alone is not enough in order to identify a vortex. Several criteria have been proposed in the literature and no consensus was reached so far [16–19]. We would define the vortex above a ”vortex ripple” as the wrapping of streamlines appearing on the lee side of the ripples at each half-period turning anti-clockwise (clockwise) when the flow is coming from the right (left). In addition, these streamlines correspond roughly to the path followed by the seeded particles with a sufficient time of exposure. Of course, the ”sufficient” will depend on the flow parameters...

However, more advanced studies are needed in order to sharpen this picture as one can also define the vortex as the flow part which is at the origin of a grains transport opposite to the main flow during each half period. Hence, particle tracking velocimetry of the grains should be coupled to PIV measurements in order to characterize the extension and features of what is called ”the vortex” in the expression ”vortex ripples”...

Finally, how can we explain the discrepancy between our experimental visualizations and the numerical simulations? One must notice that the numerics treat the ripple shape as fixed. Hence, the velocity vanishes on the boundary. A major improvement would be to introduce a slip boundary condition for velocity taking into account the fact that the ripple is a porous media. Moreover, the main oscillating flow modifies at each half-period the shape of the ripple’s crest (a small protuberance of triangular shape is inclined in the direction of the background flow) because of grains transportation: hence, it can contribute to alter the fluid response as a back-reaction effect...

Of course, it is possible that the secondary vortex described by Blondeaux & Vittori be so weak that the PIV is unable to detect it. Yet, it is not clear at all that the secondary vortex predicted numerically be masked by the strong average flow since this secondary vortex appears precisely close to the flow reversal that is when the average flow is the weakest.

However, despite this important difference, our experiments are consistent with the numerical simulations of Blondeaux & Vittori, especially the triangular shape of the inclined primary vortex before the ejection if one compares the Figure 8 (h) in [10] and our Figure 3 (f). Of course, the numerical work of Eidsvik is closer to what we observed [15].

4 Conclusions

We have provided experimental evidences for the observation of one vortical structure associated to a transient jet over real vortex ripples confirming earlier observations of Bagnold [1] with real ripples and Sand Andersen & al. [13] over model ripples concerning the presence of the ”jet”. In the same time, our experimental findings clarify the previous experimental and numerical works which reported so far on the existence of a secondary vortex and which according to Blondeaux & Vittori [10] should explain the ejection of the primary vortex which seems to be, following our results and the ones of Sand Andersen & al. [13], due to the creation of the jet between the vortex and the ripple slope. Our observations are similar to the description given by Eidsvik in his numerical simulations [15].

However, our experiments as those of Bagnold and Sand Andersen & al. could be questioned. Indeed, it is well known that oscillating sand in static water is not equivalent to oscillating water above a fixed bed from the point of view of pressure distribution [20] despite the fact that the grains are submitted to the same shear flow if their size is smaller than the Stokes boundary layer (see the additional theoretical note by G.I. Taylor following the paper of Bagnold [1]). Hence, it is crucial that subsequent studies in large wave tank be conducted in order to confirm or not that the jet stream is a basic feature of real vortex ripples as observed at the beach. In addition, future studies should concentrate on the relative influence of the grains transport induced by both the vortex and the strong shear induced by the confined stream (”jet”) between the ripple slope and the departing vortex compared to the background oscillating flow. One should also take into account the porous character of the ripples as well as the modification of the shape of the ripple crest by sand motion induced by the flow...

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Copyright Statement

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