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Instability in Flows over Permeable Obstructions

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Abstract

Flows over permeable obstructions are typically characterised by coherent, Kelvin-Helmholtz-type vortices that form at the top of the obstruction. These vortices dominate the vertical mixing of mass and momentum into and out of the obstruction, thereby strongly influencing the velocity profile and residence time in the obstruction. In this paper, recent experimental results are used to identify the conditions required for vortex formation in both unidirectional and oscillatory flows.

Introduction

Flows over permeable obstructions are ubiquitous in the environment. From seagrass canopies and coral reefs to forests and urban skylines (often termed urban 'canopies'), aquatic and atmospheric flows commonly encounter permeable arrays of obstructions protruding from a boundary. Through the exertion of drag, these permeable obstructions have the capacity to dramatically modify the flow. The obstruction flow resistance is characterised by the drag length scale, L_D, given by

$$L_D = n\,(C_D a)^{-1}, \qquad (1)$$

where C_D is the bulk drag coefficient of the obstruction, a is the obstruction frontal area per unit volume and n is the obstruction porosity. The lower the drag length scale, the greater the drag exerted by the obstruction. In obstructions with sufficiently low values of L_D, the exerted drag creates an inflection point in the vertical profile of velocity. This inflection point renders the flow unstable to a Kelvin-Helmholtz-type vortex instability (figure 1).

Figure 1: Vortex instability, as indicated by a dye streak, in unidirectional laboratory flow over an array of cylinders (from [7]). The mean flow is from left to right.

These coherent vortices dominate the vertical mixing of mass and momentum into and out of the obstruction (figure 2). This figure displays the cospectrum of streamwise and vertical velocities in a laboratory flow over an array of rigid cylinders. The cospectrum is narrow-banded and centred around peaks at f_v

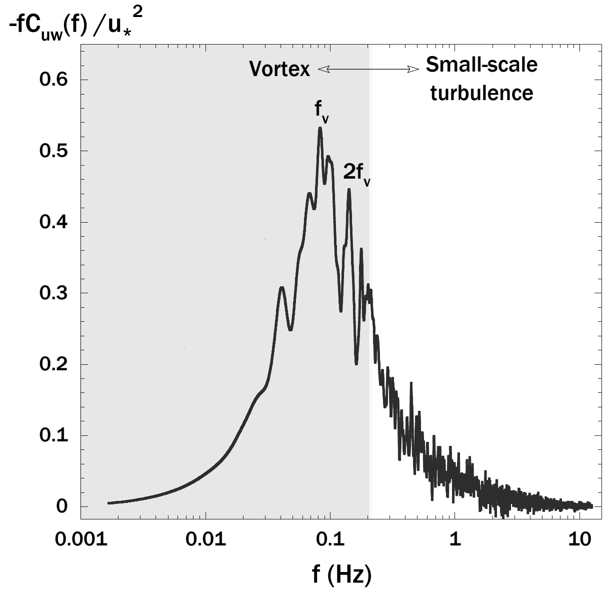

Figure 2: The normalised cospectrum (C_{uw}) of horizontal velocity (u) and vertical velocity (w) at the top of an array of rigid cylinders in a laboratory flow (taken from [9]). Over 80% of the area under the cospectrum (and therefore of the interfacial momentum transport) is generated at frequencies lower than $3f_v$ and attributed to the coherent vortices (where f_v is the frequency of vortex passage).

(the frequency of vortex passage) and $2f_v$. By integrating the cospectrum, it can be seen that nearly 80% of the interfacial vertical momentum transport is generated (at low frequencies) by the coherent vortices [9]. Therefore, if we want predictive capability for the velocity profile in such flows, or the rate of exchange of heat or dissolved and particulate species between the obstruction and the surrounding fluid, we first require an understanding of the conditions under which vortex generation occurs. Here, the necessary conditions for vortex generation in both unidirectional and oscillatory flows are examined; the latter is particularly relevant to shallow coastal flows over seagrass and coral systems.

Similarity across systems

It is important to note that while the geometries of permeable obstructions in the environment can vary significantly, there is clear flow similarity across systems [5]. For example, regardless of whether the permeable medium is aquatic vegetation, terrestrial vegetation, a coral reef or an urban canopy, there is a clear and consistent correlation between vortex length scales and L_D. Likewise, in all such systems, the values of vertical mixing efficiency and turbulence anisotropy are very similar, and significantly greater than those in turbulent boundary layer flow.

Instability in Unidirectional Flow

Consider a vertically-unbounded flow over a permeable obstruction. Vortex formation is quantified through the swirl, S, which defines rotational motion in the flow [1]. Therefore, it can be said that

$$S = f\left(L_D, h, u_*, \nu\right), \tag{2}$$

where h is the obstruction height, u_* is the shear velocity and ν is the fluid viscosity. Through dimensional reasoning, the problem statement becomes

$$\frac{SL_D}{u_*} = f\left(\frac{h}{L_D}, \mathrm{Re}_* = \frac{u_* L_D}{\nu}\right). \tag{3}$$

Equation (3) indicates that there are two controls on vortex generation in unbounded unidirectional flow. The first is bed drag control: if h/L_D is low, then the permeable obstruction is too short (or too sparse) to represent a stronger momentum sink than the bed. In such cases, the velocity profile will not contain the inflection point required to generate the Kelvin-Helmholtz-type instability. The second control is viscous damping: at low values of Re_*, viscosity will be sufficient to damp the instability. These controls on vortex generation are addressed in the following two sections.

Bed Control (as indicated by h/L_D)

The impact of h/L_D on vortex generation is detailed in figure 3, which summarises the results of several recent experimental studies. When $h/L_D < 0.1$ (figure 3(a)), the bed represents a greater momentum sink than the (short and/or sparse) obstruction. Therefore, in this regime, the flow resembles rough boundary layer flow and there is no inflection point in the profile [12]. Above this threshold, obstruction drag dominates bed drag and coherent interfacial vortices are generated. Vortex penetration into the obstruction is approximately $0.3L_D$ [5]. Therefore, for $0.1 < h/L_D < 0.3$ (figure 3(b)), the generated vortices penetrate fully to the boundary. In aquatic systems, the penetration of enhanced mixing and turbulent stress to the bed has important implications for sediment transport and sediment-water fluxes. For $h/L_D > 0.3$ (figure 3(c)), the vortices do not penetrate to the boundary, separating the obstruction into an upper zone where vertical exchange is rapid, and a lower zone where vertical mixing is much slower [13, 7].

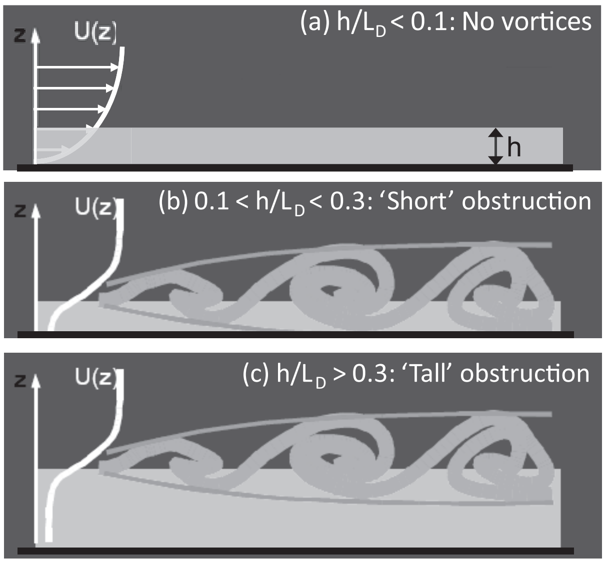

Figure 3: Three regimes of obstructed shear flow, dictated by the ratio of the height of the obstruction (h) to its drag length scale (L_D). Vortex generation is observed only when $h/L_D > 0.1$. When $h/L_D > 0.3$, the obstruction is sufficiently tall such that the vortices do not penetrate to the boundary.

Viscous Control (as indicated by Re_*)

The Reynolds number range at which viscous damping becomes important has yet to be fully investigated. In the laboratory setting, the instability has been observed down to $\mathrm{Re}_* \approx 300$ [6, 11]. Numerically, it has been observed down to $\mathrm{Re}_* \approx 100$ [3]. It is anticipated that while viscous control may prevent the onset of instability in small-scale systems (e.g. flows over sediment beds, $L_D \sim O(\mathrm{mm})$), it is unlikely to represent a significant constraint in larger-scale systems such as aquatic vegetation canopies ($L_D \sim O(0.1 - 1\ \mathrm{m})$).

Instability in Oscillatory Flow

The vast majority of numerical, experimental and field studies of flows over permeable obstructions have focused on steady, unidirectional flow. However, there is a wide range of benthic coastal obstructions (e.g. seagrass meadows, kelp forests, coral reefs) which, due to light availability, tend to exist in shallow, and therefore typically wave-dominated, environments. There is a clear lack of understanding about the structure of obstructed oscillatory flow, in particular whether the coherent vortices observed in unidirectional flow are generated at all. For an effectively-unbounded oscillatory flow, definition of the conditions required for vortex generation can be expressed initially as

$$S = f\left(L_D, h, U_o, T, \nu\right), \tag{4}$$

where U_o is the amplitude of the oscillatory velocity well above the obstruction and T is the wave period. It follows by dimensional reasoning that

$$ST = f\left(\frac{h}{L_D}, \mathrm{Re}_w = \frac{U_0^2 T}{2\pi\nu}, \mathrm{KC} = \frac{U_0 T}{L_D}\right). \tag{5}$$

The third parameter on the right-hand side of equation (5) is the Keulegan-Carpenter number. It can be interpreted as the ratio of the timescale of flow oscillation (T) to the timescale for shear formation at the top of the obstruction (L_D/U_o).

Methodology

To investigate the impact of Re_w and KC on vortex generation in oscillatory flow, experiments with arrays of cylinders were conducted in a wave flume. The identification of vortex generation was achieved through long-exposure photography of illuminated, neutrally-buoyant Pliolite particles. Cylinder arrays of three densities ($a = 6$, 12 and 20 m^{-1}) were exposed to a variety of wave conditions; each condition is characterised by its values of U_o and T, which were varied in the ranges $0.8 - 18$ cm/s and $12.5 - 80$ s, respectively. For reference, the full experimental configuration is given in [10]. The still water flow depth (9.0 cm) and array height ($h = 3.0$ cm) were fixed. The impact of h/L_D on vortex generation in oscillatory flow is not investigated here. The underlying assumption is that, in environmental oscillatory flows, the wave period is sufficiently short that the shear layer created at the top of the obstruction will not grow down to the bed on any given half-cycle. Thus, the bed is unlikely to stabilise the flow, such that h/L_D is unimportant.

An example of vortex generation in oscillatory flow is shown in figure 4. This image (in which the flow is from left to right) is taken $0.08T$ before the time of flow reversal above the array. In these experiments, three regimes of oscillatory flow (based on vortex generation) were observed. In Regime I, full vortex generation occurs during each half-cycle. In Regime II, the char-

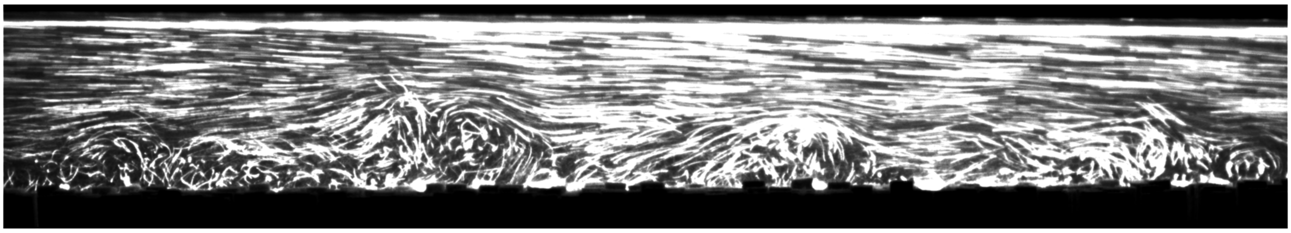

Figure 4: Vortex generation in oscillatory flow over a permeable medium ($a = 20$ m^{-1}, $T = 12.5$ s, $U_o = 18$ cm/s, flow is from left to right). A street of four vortices can be clearly seen at the top of the cylinder array. The horizontal field of view is 37 cm here, such that the spacing between adjacent vortices is approximately 9 cm, or $2.4L_D$.

acteristics of vortex generation are displayed in an incomplete fashion. In Regime III, vortex generation is entirely absent.

Temporal Control (as indicated by KC)

The separation of these three flow regimes is clearly evident in Re_w−KC space (figure 5). Vortices are observed when both $\mathrm{KC} > 5$ and $\mathrm{Re}_w > 1000$. This suggests that there are two controls on vortex generation in oscillatory flow. The first is a temporal constraint, bearing in mind that KC represents the ratio of the flow oscillation timescale to the timescale required for shear formation at the top of the obstruction. When $\mathrm{KC} < 5$, there is insufficient time for the necessary levels of shear, and then the vortex instability, to develop at the top of the obstruction before flow reversal.

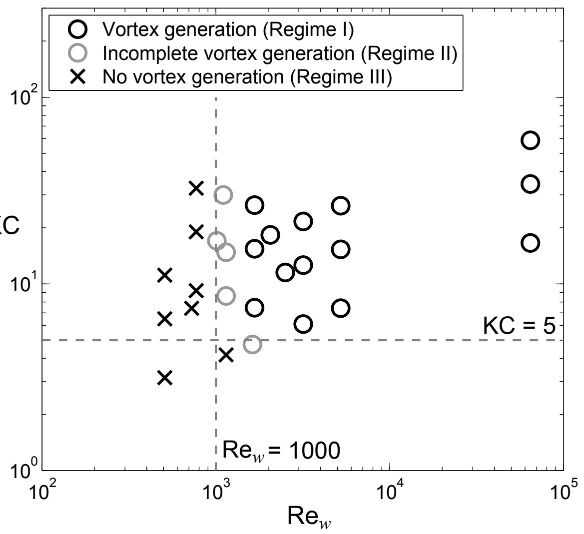

Figure 5: The conditions required for vortex formation in oscillatory flow over a permeable obstruction ($\mathrm{KC} \gtrsim 5$ and $\mathrm{Re}_w \gtrsim 1000$).

Viscous Control (as indicated by Re_w)

The second control on vortex generation in oscillatory flow is the stabilising effect of viscosity. When $\mathrm{Re}_w < 1000$, fluid viscosity is sufficient to prevent the onset of instability. It is interesting to note that the threshold Reynolds number for instability here is orders of magnitude lower than that for the transition to turbulence in an oscillatory boundary layer over a smooth bed ($O(10^4 - 10^5)$, [4]). Viscous effects are expected to be more pronounced in oscillatory environmental flows than in unidirectional flows. While a threshold of $\mathrm{Re}_* \sim O(100)$ may be exceeded in most obstructions under even the slightest unidirectional flow, this is not the case for the $\mathrm{Re}_w > 1000$ threshold described here. For example, typical coastal seagrass canopies exposed to swell waves are anticipated to fall in the range $10^2 < \mathrm{Re}_w < 10^6$ [10].

Obstruction element flexibility

It is important to note that laboratory and numerical models typically make the assumption of rigid obstruction elements; indeed all experimental results quoted here use a rigid model array. However, many environmental obstructions (such as seagrass and kelp canopies) are sufficiently flexible so as to move under both unidirectional and oscillatory flows. In unidirectional flows, elements of a flexible obstruction (which are deflected in the direction of flow) wave vertically at the frequency of vortex passage [6]. This element motion serves to diminish the flux of momentum into the obstruction [8]. In oscillatory flows, flexible elements obviously oscillate at the wave period. This motion clearly influences the vertical profile of flow velocity [2], although the impact of flexibility on vertical mixing in oscillatory flow is not fully understood. The coupling of obstruction element and fluid motion is an important (and often ignored) aspect of flows over permeable obstructions. Our lack of understanding of this coupling currently limits the applicability of model results to real coastal canopies.

Conclusions

Permeable obstructions are prevalent near the bottom boundary of aquatic and terrestrial flows. Flows over such obstructions are characterised by the generation of a street of coherent vortices at the top of the obstruction. As a result, the impact of the obstruction on the flow, turbulence and vertical mixing can be profound. Here, the conditions required for vortex generation in unidirectional and oscillatory flows over permeable obstructions have been demonstrated. In particular:

(1) In unidirectional flow, the height of the obstruction relative to its drag length scale defines three regimes of flow. Vortices are generated when the obstruction is sufficiently tall and/or dense that $h/L_D > 0.1$. Viscous control of this instability has yet to be fully explored for unidirectional flow, and may be relevant in small-scale systems (e.g. flow at the sediment-water interface).

(2) Recent experimental results have demonstrated that the vortex instability is observed in oscillatory flows when the wave period is sufficiently long that the Keulegan-Carpenter number (KC) exceeds 5. Furthermore, viscous control of the instability is expected to be important in oscillatory flows; the threshold Reynolds number (Re_w) is approximately 1000. Understanding vortex generation in oscillatory flows is important in the prediction of residence time in ecologically-significant benthic habitats that exist in shallow (and therefore, typically, wave-dominated) coastal regions.

Acknowledgements

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