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Author

Luchini, Paolo

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Surprising behaviour in the large-wavelength approximation of turbulent flow past a wavy bottom

P. Luchini

Dipartimento di Ingegneria industriale, Università di Salerno, 84084 Fisciano, Italy
luchini@unisa.it

Knowledge of the stress exerted by turbulent flow over a wavy bottom is an essential ingredient in the analysis of sediment transport by rivers, open channels and tides, in addition to being relevant to the understanding of turbulent flow per se and of some proposed drag-reduction devices. In a geophysical context this kind of flow is often studied in either the short-wavelength limit, where a boundary-layer type of structure applies (Jackson & Hunt 1975) or the large-wavelength limit, where a shallow-water type of analysis is generally used. Target of the analysis, in the case of a small sinusoidal perturbation of the bottom, is in particular the quadrature component of the induced modulation of the bottom shear stress, which has implications on the morphological evolution of a sandy bottom. For a general overview, see *e.g.* Charru, Andreotti & Claudin, *Annu. Rev. Fluid Mech.* (2012).

A contribution towards the systematization of the large-wavelength limit was given by Luchini & Charru (*J. Fluid Mech.* 665, 516–539, 2010), who derived a consistent shallow-water equation for turbulent flow past a slowly varying bottom, and gave examples based on an eddy-viscosity turbulence model. It should be noted that in the leading approximation, where the velocity profile adapts quasi-statically to the local channel depth, stress and depth are in phase; a quadrature component only appears at the next order of approximation. In Luchini & Charru's expansion the first-order velocity perturbation is produced by an equivalent force proportional to the x-derivative of the mean velocity, just as in the corresponding laminar-flow analysis of Benjamin (*J. Fluid Mech.* 1957). Because of this quadrature component the stress phase *leads* the bottom undulation phase, a fact which has a destabilizing effect if the bed is sandy and incoherent.

In order to ascertain the applicability in this context of a turbulent eddy viscosity, Luchini & Russo (*J. Fluid Mech.* 790, 104–127, 2016) performed direct numerical simulations of plane channel flow with an imposed volume force mimicking the effect of the variable bottom. What they found, however, surprisingly pointed in the opposite direction: the wall stress produced by the applied volume force has such a sign as to make the stress phase *lag* the bottom undulation. In addition, the results of the simulation were incompatible with *any* (positive) eddy viscosity.

A subsequent set of direct numerical simulations performed with an immersed-boundary technique (P. Luchini, *Eur. J. Mech. B/Fluids* 55, 340–347, 2016) allows all of these results to be reconciled. As will be shown at this conference, the quadrature component of the wall shear stress induced by turbulent flow past a wavy boundary changes sign as a function of wavenumber, in striking contrast with what happens in laminar flow. In addition, this change occurs at a smaller wavenumber than those usually included in direct numerical simulations of turbulence in a periodic computational box, and can only be detected by the use of a very large computational box.

The new picture that emerges of the stress exerted by turbulent flow over a wavy bottom is one where the stress phase *leads* the bottom undulation over a wide range of wavenumbers, including those of the classical experiments by Hanratty *et al.* in the 1980's, but *lags* in the true large-wavelength (shallow-water) limit. Its behaviour in this limit is qualitatively consistent with the simulations conducted through an effective volume force, but has no equivalent in laminar flow nor, apparently, in flow predicted through a turbulence model.