

## EXCITATION OF INERTIAL MODES IN A CLOSED GRID TURBULENCE EXPERIMENT UNDER ROTATION

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Translating a grid in a closed volume of fluid is a convenient way to generate an approximately homogeneous and isotropic turbulence when a compact system is needed, e.g. when experiments are performed in a rotating frame [1, 2, 3, 4]. Such flow excited by a grid translation is, in general, composed of a superposition of (i) a reproducible flow (determined through ensemble averaging) and (ii) a non-reproducible turbulent flow. In the presence of background rotation, both of these two flow components may excite inertial waves [5], which propagate because of the restoring nature of the Coriolis force. The excited inertial waves are respectively (i) reproducible—and therefore detectable in the ensemble average—and (ii) non-reproducible—detectable in the individual realizations only— [6]. In a closed container, inertial waves may appear in the form of standing inertial modes, which are the eigenmodes of the container geometry [7, 8]. Excitation of inertial modes in grid-generated turbulence has been first observed by Dalziel [1] and are also visible in the experiments of Morize and Moisy [9] and Moisy *et al.* [10]. They have been characterized by Bewley *et al.* [3], who found good agreement between the measured frequencies and the numerical results of Maas [8].

We investigate here the structure of these inertial modes and we explore to what extent they may be reduced [6]. A square water tank is mounted on a rotating platform, and velocity fields in a vertical plane are measured using a corotating Particle Image Velocimetry system. Two grid configurations have been used: a “simple” grid, of mesh size 40 mm, and a “modified” grid, on the top of which a set of inner sidewalls is attached. We demonstrate that, in the latter configuration, the amount of energy stored in the inertial modes is drastically reduced compared to the former one.

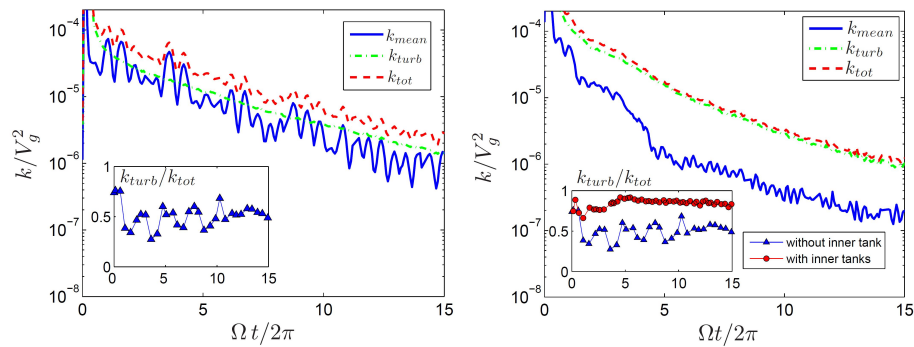


Figure 1: Total (dashed), mean (continuous) and turbulent (dashed-dotted) kinetic energies as a function of the number of tank rotations  $\Omega t/2\pi$  from 40 realizations performed at  $\Omega = 0.84 \text{ rad s}^{-1}$ . Left: simple grid. Right: modified grid with inner tanks. Inset: Ratio of turbulent to total kinetic energy as a function of  $\Omega t/2\pi$ .

We make use of the standard Reynolds decomposition to separate the reproducible inertial modes from the turbulence,  $\mathbf{u}(\mathbf{x}, t) = \mathbf{U}(\mathbf{x}, t) + \mathbf{u}'(\mathbf{x}, t)$ , where the ensemble average  $\mathbf{U}(\mathbf{x}, t) \equiv \overline{\mathbf{u}}(\mathbf{x}, t)$  is computed over 40 independent decay experiments. We compute the kinetic energies associated to each flow component, namely  $k_{tot}(t) = \langle \mathbf{u}^2(\mathbf{x}, t) \rangle$ ,  $k_{mean}(t) = \langle \mathbf{U}^2(\mathbf{x}, t) \rangle$ , and  $k_{turb}(t) = \langle \mathbf{u}'^2(\mathbf{x}, t) \rangle$ . The time evolution of these 3 energies is shown in Fig. 1(a), for an experiment performed at a rotation rate of  $\Omega = 0.84 \text{ rad s}^{-1}$ . Both the energy of the total and the mean flow show, superimposed to their overall decay, marked oscillations corresponding to the inertial modes. On the other hand, the turbulent energy shows a monotonic decrease.

In the inset of Fig. 1(a), we plot the ratio of the turbulent to the mean energy: we see that turbulence represents only  $50 \pm 10\%$  of the energy in the flow. This quite low ratio indicates that the energy injected with the simple grid configuration is evenly distributed among the reproducible inertial modes and the “true turbulence”. It is therefore questionable to consider this turbulence as freely decaying, because of the possible energy transfer from the inertial modes to the turbulence. The oscillations in Fig. 1(a) have been analysed in details by computing the temporal spectrum of the ensemble-averaged flow  $\mathbf{U}(\mathbf{x}, t)$ . The spectrum shows a series of peaks for frequencies  $\sigma$  in the range  $[0, 2\Omega]$ , as expected for inertial modes. By performing a band-pass filtering of  $\mathbf{U}(\mathbf{x}, t)$  at the peak frequencies, it is possible to extract the spatial structure of each inertial mode. The two dominating modes, of vertical wavenumber unity, are shown in Fig. 2, with associated frequencies perfectly matching the numerical predictions of Maas [8].

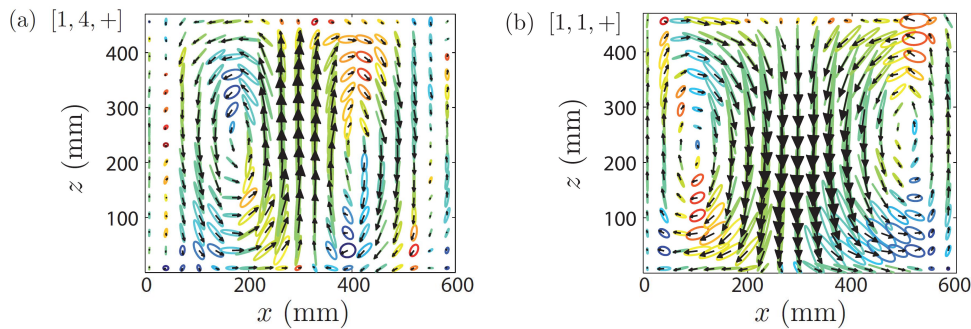
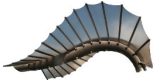


Figure 2: Spatial structure of the 2 dominating inertial modes. The ellipses show the velocity orbit, and the arrows illustrate the velocity field at a given arbitrary phase of the oscillation. The color traces the ellipticity  $-1 < \epsilon < 1$ .

In the modified grid configuration, a set of three parallelepipedic PVC tanks, each consisting in 4 vertical sidewalls, without top and bottom walls, is attached on the top of the grid. Since our grid is translated from the bottom to the top, the inner tanks are *upstream* of the grid, so that the volume of working fluid is the same as in the simple grid configuration. The time evolution of the 3 kinetic energies is shown in Fig. 1(b) for this modified configuration. In comparison with Fig. 1(a), the oscillations due to the inertial modes are strongly reduced, both for the mean and the total kinetic energies. We also see that the turbulent kinetic energy is now significantly larger than the one of the ensemble-averaged flow. This can be better seen in the inset of Fig. 1(b), showing that turbulence contains, after a transient of about one tank rotation, approximately  $85 \pm 5\%$  of the total kinetic energy, a value much larger than the 50% obtained with the simple grid configuration. This result proves the efficiency of the modified grid to strongly reduce the production of inertial modes, and therefore to generate a turbulence which is presumably closer to the idealized situation of a free decay.

The present results suggest that the standard assumption of statistical homogeneity may not be appropriate to describe decaying rotating turbulence in a closed container, confirming the findings of Ref. [3]. This calls for the development of new theoretical tools to describe the interaction of turbulence with reproducible inertial modes. However, we have also shown that careful changes in the geometry of the grid allow us to strongly reduce the excitation of reproducible inertial modes, and hence to achieve a nearly “pure” rotating turbulence state. This modified configuration therefore suggests that it is indeed possible to investigate the properties of freely decaying homogeneous turbulence in confined geometry.

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