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EXPERIMENTAL STUDY OF ISOTROPIC TURBULENCE UNDER TIME-DEPENDENT FORCING

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Abstract We investigate experimentally the response of isotropic turbulence to step-function like perturbation in external forcing. The real-time image compression system we developed enables us to perform continuous Lagrangian Particle Tracking measurements at high Reynolds number. Therefore we can follow the evolution of the structure functions, such as $D_{LL}(r)$, $D_{NN}(r)$, and $\langle \delta_r \mathbf{u} \cdot \delta_r \mathbf{a} \rangle$, over both the dissipative and the inertial range, from which we study the response of both energy dissipation and energy cascade to non-stationary large scale forcing.

INTRODUCTION

Statistically stationary turbulence, *i.e.*, flow fields whose statistics do not depend on time, have been extensively studied. For stationary turbulence, the mean rate of energy injection into the flow is balanced exactly by the mean energy dissipation rate. On the contrary, for non-stationary turbulence, such a balance is violated. For example, the energy injection rate is zero in the decaying turbulence behind a gird [1, 2, 3]; in homogeneous shear [4, 5] or rapid distortion [6], there exists strong anisotropic large-scale forcing; and the energy input can also be isotropic but periodic in time when studying turbulence under modulation [7, 8, 9, 10, 11, 12]. Much insight on turbulence can be gained from investigations on these non-stationary flows. Of special interest is the isotropic turbulence with varying forcing since even in stationary turbulence the instantaneous energy injection rate is fluctuating and it has been observed in numerical simulations [5] that the peaks of instantaneous energy dissipation rate lag behind the peaks of instantaneous energy injection rate. The response of turbulence to unsteady energy injection can therefore reveal the turbulent energy cascade process. Previous studies on modulated turbulence [8, 9, 10, 11, 12], however, focused on the energy dissipation alone. The energy cascade in the inertial range remains to be investigated.

Here we present results from an experimental study of an isotropic turbulent water flow under a step-function like perturbation in large-scale forcing. We measure the structure functions, such as the second-order velocity structure functions $D_{LL}(r)$ and $D_{NN}(r)$, over both the inertial and the dissipative ranges, and follow their evolutions after the perturbation.

EXPERIMENTAL SETUP

The turbulent flow is generated in the Lagrangian Exploration Module (LEM), an icosahedron shaped water container with 12 independently driven propellers, one on each vertex (see fig. 1a). The edge length of the icosahedron is 40 cm and the apparatus contains 140 liters of water. Schematically, the turbulence in the LEM can be thought of as a superposition of six von Kármán swirling flows, each created by a pair of counter-rotating propellers. The icosahedron geometry gives a spatially symmetric arrangement of the axes of these six von Kármán flows in order to produce highly isotropic turbulence at the center. It has been shown [13] that when the propellers are rotating at the same frequency, the turbulence in the center region of the LEM (approximately 15 cm in diameter) is nearly homogeneous and isotropic. As the propeller speed increases, the energy injection rate into the flow increases and the Reynolds number of the flow increases accordingly.

In our experiments we start with all 12 propellers rotating at a given speed and then increase the speeds of all propellers simultaneously to a higher value. We probe the response of the turbulent flow to this increase of external forcing (and hence the Reynolds number) by measuring the structure functions using Lagrangian Particle Tracking (LPT). For that purpose, the turbulent flow is seeded with nearly neutrally-buoyant polystyrene tracer particles with diameters smaller than the Kolmogorov scale η of the flow. The measurement volume in the center of the apparatus is illuminated by a frequency-doubled Nd:YAG laser (wavelength of emitted light is 532 nm). The laser is pulsed (Q-switched) to increase output power and the averaged continuous output power is 80 W. The motion of the tracer particles in the measurement volume are then recorded by three cameras (See fig. 1b). The images are processed to find particle trajectories in three dimensions, from which we obtain velocities and accelerations by successive differentiation [14, 15]. The Eulerian structure functions can be easily computed from LPT data because several hundreds of tracer particles are followed at any given time.

MEASURING TECHNIQUE FOR STUDYING NON-STATIONARY FLOWS

Long-time continuous measurement is necessary for the study of non-stationary turbulence, which is a more stringent requirement compared to the case of stationary flows for which the statistics can be collected from many short-duration recordings with arbitrary time gaps in between. For image-based LPT measurements, it is very difficult to store the raw images in real time because the data-rate is too high for any standard disk storage devices and the amount of data is too large for reasonable computer memory size. It is, however, possible to compress the raw images significantly since only

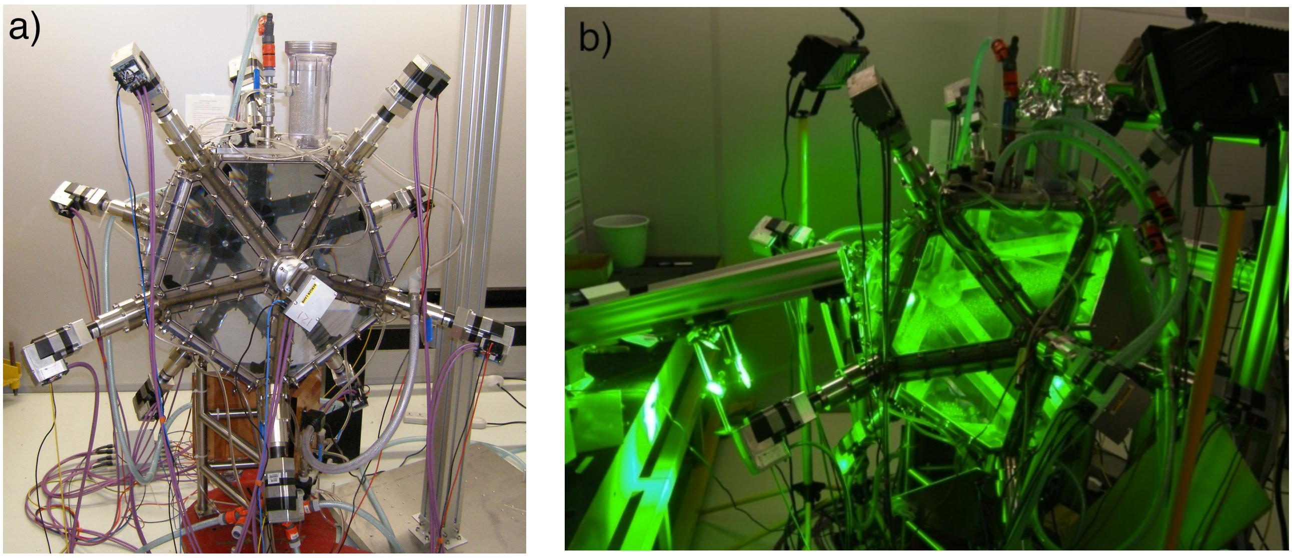

Figure 1. Lagrangian Exploration Module. a) The icosahedron shaped vessel with the 12 motors, mounted through the vertices of the icosahedron. b) The LEM during an experiment. A frequency-doubled Nd:YAG laser beam, incident from the left, was illuminating the measurement volume in the center of the apparatus. Three high-speed cameras, mounted on the right, were recording the movement of tracer particles in the measurement volume [13].

a small fraction of pixels on any given image contain information of the tracer particles. Most of the pixels correspond to the dark background. A simple sparsification algorithm that saves only pixels with intensity values above a threshold can therefore achieve a compression ratio of order 100, as demonstrated in [16, 17]. The same strategy is used here. We used the high-speed CMOS cameras Phantom V640 (Vision Research Inc.) that are equipped with optic fiber interfaces for real-time data downloading. The camera sends images through the fiber interface to an FPGA (field programmable gate array), where the images are compressed: Only those pixels above a given intensity threshold are saved, together with their positions. The compressed images are so small that they can be saved directly to a hard drive. Using this technique, we can record continuously as long as the storage space on the hard drive allows.

For our particular experiment using the step-function perturbation, we measure continuously until the turbulence reaches the stationary state with the new forcing, which takes a few minutes. We then revert the forcing back and repeat the measurement again. The forcing and the recording are synchronized so we can collect statistics at the same time after perturbation from different realizations.

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