Interactive visualizations of the large-scale data generated by the DNS of isotropic turbulence on 4096^3 grid points

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1 Introduction

Recent development of supercomputers enables us to perform large-scale numerical simulations with huge degree of freedom. High Reynolds number (*Re*) turbulence is one of the most challenging problems in computational fluid dynamics. Recently it has become possible to perform direct numerical simulations (DNS's) of turbulence at the Taylor micro-scale Reynolds number $R\lambda$ of $O(1000)$ with the number of grid points over 4096^3. The statistical properties of high *Re* turbulence can be studied by the analysis of such DNS data (e.g. see [1-4]).

A visualization of intense vorticity iso-surfaces in DNS of homogeneous isotropic turbulence with 4096^3 grid points and $R\lambda$=1131 (figure 1 form [1]) shows that intense vorticity regions form tube-like structures with radius of the order of the Kolmogorov length scale η, and at high *Re* clusters of these tubes form large-scale vortical structures of the order of the integral length scale *L*. However, it is generally difficult to fully understand the structure of high-*Re* turbulence in which a wide range of scales coexists.

In order to understand the structure of high-Reynolds number turbulence, interactive visualizations of turbulence would be very effective. But we have to overcome the difficulties associated with the fact that the data is so huge. Fortunately, the recent developments of computer technology prevail not only in supercomputers but also in workstations. So it is expected that by using leading-edge information technologies on a recent high-spec workstation with large memories we can interactively visualize the large-scale data of high *Re* turbulence.

In this paper we briefly introduce the DNS data of high-*Re* turbulence on 4096^3 grid points, demonstrate our recent interactive visualization, and show the results of the interactive visualization of high-*Re* turbulence.

2 DNS data of high Re turbulence

A series of DNS data of high *Re* forced turbulence was generated on the Earth simulator by numerically solving the incompressible Navier-Stokes equations using an alias-free Fourier spectral method. The details of the DNS method are described in [2, 4]. The maximum Taylor micro-scale Reynolds number ($R\lambda$=1131) was attained by the DNS with N^3=4096^3 grid points and $k_{max}\eta$=1.0, where k_{max} is the maximum wavenumber. The key parameter values in the DNS are listed in Table 1.

Table 1. Parameter values in the DNS of high Re turbulence

N	Re	$R\lambda$	$k_{max}\eta$	L	l	h
4096	36500	1131	1.0	1.1	$3.4\ 10^{-2}$	$5.1\ 10^{-4}$

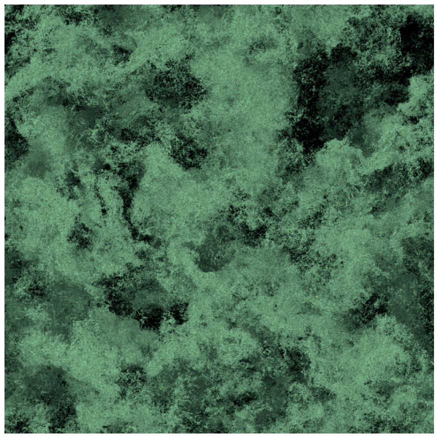

Fig. 1 A visualization of high vorticity regions obtained by the DNS of turbulence with 4096^3 grid points and $R\lambda$=1131 (from [1]). High contrast between intense vorticity regions and weak vorticity regions can be observed.

3 Interactive visualization of large-scale data

3.1 Key technologies

In order to visualize the large-scale volume data generated by the large-scale DNS of homogeneous isotropic turbulence, we use NewVES (New virtual endoscopy software using fast volume rendering), which was originally developed for medical applications such as computer-aided diagnosis and was improved for the large-scale data. [5] NewVES uses various optimization techniques to achieve an interactive speed; the techniques include (1) empty volume skipping, (2) early ray termination, (3) volume segmentation and (4) multiple and adaptive resolution representation.

Since NewVES realizes fast volume rendering as software and uses Remote Desktop Protocol (RDP), it does not require any special graphics card. However it requires large memory for the visualization of large-scale volume data. NewVES uses Streaming SIMD Extensions (SSE) and is optimized for the CPUs with multiple cores, so that its volume-rendering speed depends on not only the performance of each CPU but also the number of CPUs. Table 2 shows the computer configuration that we used for the visualizations in this paper.

Table 2. Computer configuration

Computer	Dell PowerEdge R910
Processor	Intel Xeon E7520 (4 cores, 8 threads, 1.866GHz)
Memory	512GB(8GB*64)

3.2 Interactive visualizations

To use the NewVES, we need to generate volume data for visualization from the original scalar data, e.g. amplitude of vorticity. In this process, the original value of the scalar (usually expressed as a single-precision (4Byte) or double-precision (8Byte) floating-point number) on each point is converted into a 2Byte integer in the range of [0,7000]. Therefore, a set of volume data for NewVES with N^3 grid points is $2N^3$ Bytes, so that to visualize the volume data on 4096^3 grid points by NewVES, 128GByte is a requisite minimum and 256GByte is recommended for the stable performance.

Once the whole volume data are loaded on the memory of workstation, viewpoints, threshold values, and the other parameters can be changed interactively in NewVES. Although the result depends on several parameters, the performance of about 14 frames/sec was obtained in the volume rendering of the 40963 data on the computer given in table 2. Examples of such visualization are shown in Figure 2.

(a)

(b)

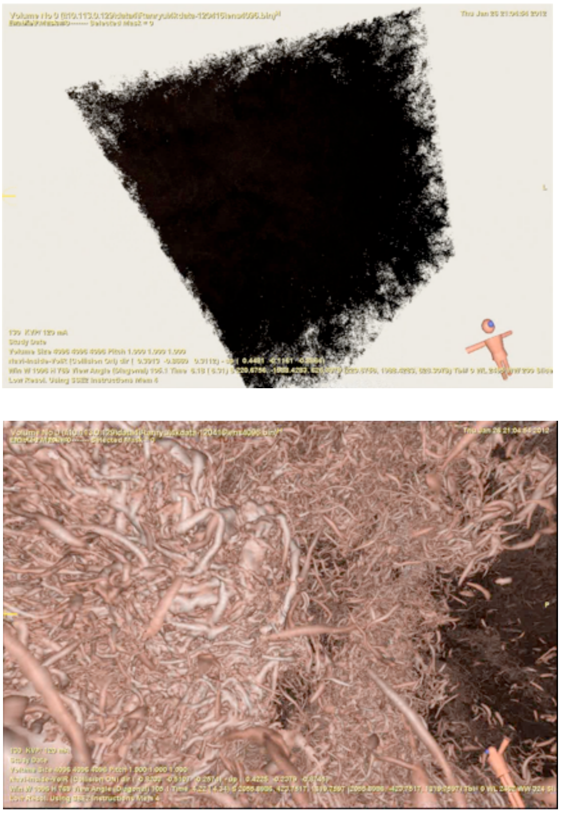

Fig 2 Examples of interactive visualization of the intense vorticity regions obtained by the DNS of isotropic turbulence with 4096^3 grid points. (a) A view from outside and (b) an immersive view.

3.3 Observations by interactive visualizations of high Re turbulence

Interactive and immersive visualizations of high Re turbulence show that there are several dense regions of the intense tube-like vortices and that there is a very sharp contrast between the dense and the void regions. The dense regions appear to correspond to the strong thin shear layers, a part of which were recently observed and were analyzed in detail. [6,7] It is expected that the immersive visualizations provide new insights for our understanding of the global structure of the thin shear layers.

4 Conclusion

New fast volume-rendering software was tested on a workstation with 512GByte memory, using the large-scale data generated by the DNS of isotropic turbulence on 40963 grid points. Interactive and immersive visualizations of such a huge data were realized in the performance of about 14 frames/sec.

Using the software to visualize high vorticity regions, we observed several dense regions of the intense tube-like vortices, which appear to correspond to strong thin shear layers (see e.g. [6,7]). The global structure of the dense regions of the intense tube-like vortices will be discussed in the conference.

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