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A New Application of the Digital Synthetic Schlieren in Lab Experiments of the Internal Waves

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Abstract: Laboratory experiment is an important method in the study of ocean internal waves, and the schlieren technique is an effective way to observe the internal waves in the laboratory. The digital synthetic schlieren technique is mostly applied to two-dimensional density-stratified flows. The technique is improved by setting up the Charge Coupled Device (CCD) vertically to shoot the reference images in this research. Then the three-dimensional density-stratified flows can be detected in this way. The authors attempt a set of lab experiments to verify the rationality of this technique. There is a horizontally moving spherule with constant velocity at the interface of the two-layer stratified water in the experiment. The moving spherule generates internal waves between the two-layer fluids. The authors successfully capture the three-dimensional structure of the internal waves generated by the horizontally moving spherule. It is obvious that the internal waves have characteristics of the Kelvin Internal Wake and the quantitative parameters agree well with the previous studies. The experimental results reveal that the improved digital schlieren technique is rational and feasible in the lab internal waves observations. The detailed three-dimensional structure of the internal waves, the internal wave energy distribution and propagation in the whole field and the nonlinear interactions between the internal waves can be further studied through this method in the future.

Keywords: Internal Waves, Synthetic Schlieren, Kelvin Internal Wake

1. Introduction

The ocean internal wave is a kind of fluctuation inside the seawater with stable density stratification, and its maximum amplitude appears inside the ocean. Internal waves play an important role in the ocean dynamic process, transferring energy from large-scale motion to small-scales, until it becomes turbulence and dissipate [1, 2]. The internal wave induced mixing process is a key factor to maintain the ocean stratification, especially the diapycnal mixing, which is conducive to the transport of mass and heat, thus playing an important role in the marine environment and marine ecological protection.

With the development of offshore oil industry, more and more marine engineering researchers become concern about the destruction of the drilling platform and the petroleum pipeline. The ocean internal waves could generate strong ocean currents that would directly interact with the offshore structures, which is a major energy source in destroying the drilling platform and the petroleum pipeline [3]. However, it is difficult to estimate the acting force between the ocean internal waves and the offshore structures.

Since Garrent and Munk established the GM ocean internal spectrum model, people have made great progress in the study of the generation, evolution and depletion of the ocean internal waves [4, 5]. However, due to the non-negligible nonlinear interaction of the internal waves and the influence of the ocean fine structure on the internal waves, there are no clear conclusions on where the internal wave energy comes from, where it goes, and the possible internal wave field variations over the time and region.

For a long time, the ocean internal wave observations are mainly through various high-resolution and fast-dense sampling electronic instruments represented by CTD and ADCP, as well as remote sensing methods such as SAR images taken by synthetic aperture radar [6, 7, 8]. As the researches focuses on the internal wave dynamics, especially to try to understand the internal wave generation, interaction, evolution and dissipation mechanism, then the internal wave theory and experimental research are vigorously developed through mechanics and applied mathematics to better explain the role of internal waves in the entire ocean energy balance.

2. Internal Wave Laboratory Observation

The laboratory experiment of ocean internal waves is mainly focus on the mechanism research [9, 10, 11]. It is a good way to study the structure of the internal waves. Based on the lab results, the researchers could further get the relationships among internal wave parameters, environmental parameters, geometric shapes and sizes of the stressed objects and the internal wave induced forces, providing the technical support to the security of ocean oil exploitation and improving of the production efficiency. The commonly used observation methods and facilities are briefly summarized as follows.

2.1. Conductivity Meter

Generally, the medium used in the laboratory internal wave experiment is a salt solution. The density of the salt solution is a function of temperature and conductivity. Once the temperature is determined, it is only a function of conductivity. Therefore, the density vertical distribution of the stratified fluid and the density variations of the fixed point can be measured by the conductivity meter. It is an effective measurement method in the laboratory internal wave experiment.

The most typical one is the laboratory internal wave dynamic measuring instrument developed by Lu Hongmin et al (1995). It mainly consists of inductive conductivity probe, probe moving mechanism, probe movement controller, conductivity measuring instrument, analog-to-digital conversion interface board, control and record storage computer, and measurement, control, acquisition and processing software. In order to simultaneously measure the density at different depths of the same cross section in the water tank, a multi-probe internal wave dynamic measuring instrument can be used. Each probe measures a conductivity time series at a certain depth, and the time series of vertical displacements of different isopycnal surfaces can be obtained by multi-time series curves.

2.2. Tracer Particle Visualization

Tracer particle visualization is a method of observing water point motion in laboratory experiments. The small, insoluble solid particles are sprinkled into the stratified fluid, and their density is distributed over the range of the experimental stratified fluid density, so that they can scatter much more evenly over the entire depth of the fluid. Since the volume of the particles is small enough, they move approximately with the fluid as the fluid moves, so that the movement of the particles can represent the movement of the fluid particles.

In recent years, fully automatic and efficient particle image velocimetry (PIV) has emerged. It is mainly used for internal wave measurement of two-dimensional water tank, and can obtain real-time flow velocity distribution of the whole flow field. The PIV system mainly includes an imaging subsystem and an analysis display subsystem, which is a set of special equipment. For related introduction, see the study by Dossmann et al. [12]

2.3. Schlieren Technique

The schlieren technique is applied in various scientific research fields, and it can display the optical non-uniformity of various transparent fluid media. People can further analyze the distribution and the flow state of physical quantities such as density, temperature and pressure of these media. If the density, temperature or pressure of the medium is uniform, the light does not refract or the refractive index is equal when passing through the medium; if the distribution of properties such as density, temperature or pressure is not uniform, the refractive index of the light is also uneven. This will result in uneven changes in the brightness of the background image. Therefore, the physical quantities distributions of the medium can be obtained by analyzing the light and dark conditions in the image, and the flow condition can be derived by further analysis.

In recent years, color filters have been applied to schlieren technique. Since the refractive index is not uniform, the light passes through the filter forming various colors in the image, and the different colors are divided into many grades, so that the image can be quantitatively analyzed to obtain quantitative results. See the study by Settles et al for details [13].

Since the image obtained by the schlieren method is the result of the accumulation of the refractive index on the path of the light passing through the medium, it is mainly applied to the two-dimensional water tank, and the physical quantity of the medium is uniform in the direction of light travel.

3. Experiment on Internal Waves Generated by a Towing Spherule

3.1. Experimental Principles

The propagations of the internal waves are three-dimensional, anisotropic and dissipative [14]. Most previous researches could not show the full three-dimensional internal wave fields due to the limited spatial coverage of the sensors. The authors make some improvements of the digital synthetic schlieren technique, and apply it to the three-dimensional density-stratified flows. At last, the lab experiments are carried out to get the three-dimensional structure of the internal waves generated by a horizontally moving spherule with a constant speed at the interface of the two-layer stratified water.

The current digital synthetic schlieren technique is most used only for experimental study of two-dimensional thin tank [15]. For three-dimensional tank with greater thickness, however, integral effect could lead to the changes of the density, which are added together along the whole thickness, resulting in low resolutions of the photographs. So, the CCD is set up vertically to the three-dimensional tank and the background templates are put outside the bottom of the tank. In order to eliminate convergence and divergence effect of the surface water, there covers a pane of glass with the same thickness as the tank at the water surface.

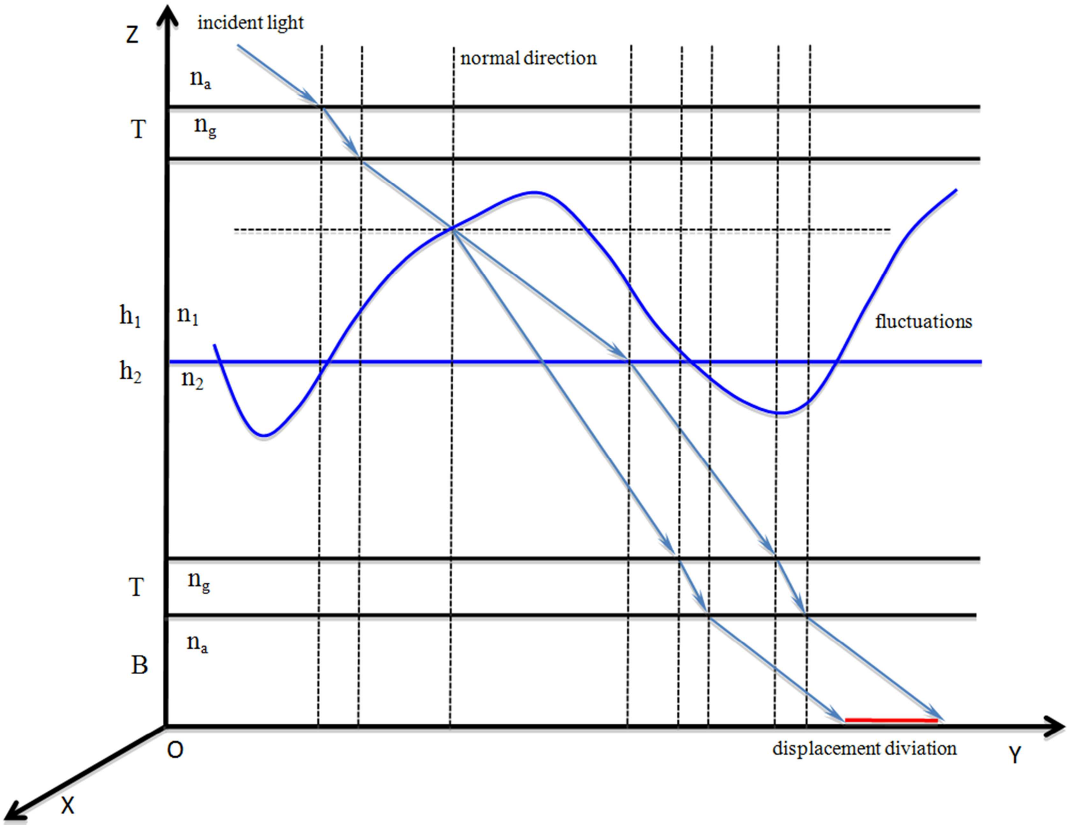

Figure 1. *The refracting differences of the incident light passing through the background field and the experimental field. na, ng, n1, n2 is the refractive index of the air, glass, upper and lower flows respectively. The glass thickness, upper and lower flow height, the distance between the tank bottom and background template is indicated as T, h1, h2 and B, respectively.*

As can be seen from Figure 1, *x*-axis is along the width direction of the tank and *y*-axis is along the length direction with *z*-axis pointing up vertically to the horizontal level of the tank. The light will pass through the whole water depth of the tank and refract along the *z*-axis. For two-layer stratified flows, the densities of the two layers are constants, so the light refraction is definite once the background stratified of the water is determined. Therefore, the light refractions indicate the density fluctuations, which contain the information of the internal waves.

The light would pass through the upper glass, the upper flows, the lower flows, the lower glass and the air in turn, reaching the background template. Assuming the normal direction of the wave surface is always vertical to the horizontal level, it can be deduced the relationship between the wave amplitudes and the displacement deviations of the background template images.

Considering the light refractions in the *y-o-z* plane: the light would refract at the interface of the water when the water is calm and at the wave surface when there are fluctuations. The displacement deviation is indicated in Fig. 1, assuming the vertical distance between the wave surface and the initial stratified interface is ζ, the incident angle is *i*, the refraction angles from top to bottom is i', θ_1, θ_2, θ_3, and θ_4, respectively.

For background field when the water is calm, there is:

$$\eta_1 = T\tan i' + h_1\tan\theta_1 + h_2\tan\theta_2 + T\tan\theta_3 + B\tan\theta_4 \quad (1)$$

For the experimental field when there are density fluctuations, there is:

$$\eta_2 = T\tan i' + (h_1 - \zeta)\tan\theta_1 + (h_2 + \zeta)\tan\theta_2 + T\tan\theta_3 + B\tan\theta_4 \quad (2)$$

Where η_1 and η_2 is the distance between the projection point on y-axis of the incident light and the point reaching the background template for background and experimental field respectively.

Then the displacement deviation along the y-axis is:

$$\Delta\eta = \eta_2 - \eta_1 = \zeta(\tan\theta_2 - \tan\theta_1) \quad (3)$$

For definite stratified layer, $tan\theta_2$-$tan\theta_1$ is a constant, so it could be found that the displacement deviation is proportional to the wave amplitude, that is

$$\Delta\eta \propto k\zeta \quad (4)$$

It could be written as

$$\Delta\eta = k\zeta + b \quad (5)$$

When there are no fluctuations, the displacement deviation is zero, so b equals zero, therefore there is

$$\Delta\eta = k\zeta \quad (6)$$

It could be got that the coefficient k through the linear fitting between the different displacement and the upper layer water thickness by changing the height of the interface, and then the internal wave amplitudes could be calculated if the displacement deviations were known.

Through the pixelated processing method put forward by Sutherland et al [16], the displacement deviations could be got by comparing different experimental field images photographed by the CCD to the background field image. Therefore, the spatial distribution and temporal variations of the internal wave field could be calculated out.

3.2. Experimental Contents and Steps

The experiments are carried out in the three-dimensional internal wave and stratified flow tank in the Key Laboratory of Physical Oceanography in Ocean University of China. The authors conduct an experimental study on the internal waves generated by a moving spherule with a constant velocity at the interface of the two-layer stratified water. The main research content has five parts.

1. Setup an experimental device for internal wave generation. Including the experimental water tank system, the towing system, velocity and measuring device, the deployment of the moving spherule and the debugging of the optical imaging instrument. They constitute a complete internal wave experiment visual measurement system.
2. Carry out the simulation experiment on the generation of internal waves at the interface of the two-layer stratified water. The main purpose is to capture digital images of the internal wave field.
3. Write program according to the experimental parameter. Process the image data and extract the information, then generate the visual image of the internal wave field.
4. Perform parameters optimization and improvement on the experimental device and the optical system based on the experimental data obtained.
5. Compare the experimental image with the existing internal wave theory and numerical simulation results.

Figure 2 gives the sketch of the experimental settings. It could be seen that the experiment system consists of three parts: water tank with size 3.475 m × 1.005 m × 0.26 m, spherule towed system with a diameter 0.025 m spherule and digital synthetic schlieren system with the background template filled with random dots.

The experimental steps are as follows:

1. Set up the experimental apparatus and adjust the experiment instruments. Make sure the CCD is vertical to the horizontal level.
2. Pour the two-layer stratified water into the tank through the double cylinder method. The thickness of the upper layer and the lower layer is 3 cm and 17 cm respectively.
3. Shoot the background field termed *A*.
4. Make the pycnocline decrease 0.4cm through the adding quantitative freshwater to the upper layer and siphon the same brine from the lower layer. Then shooting the background field termed B.
5. Repeat the step d four times and shooting the background fields termed *C, D, E* and *F*, respectively. The background field *F* is the final background field with upper layer 5 cm and lower layer 15 cm.
6. Drag the spherule at the depth of the pycnocline and shooting the experimental fields.

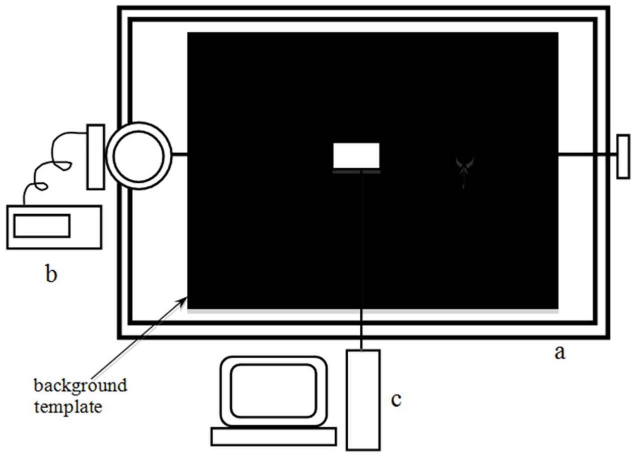

Figure 2. *Sketch of the experimental settings. The tank, spherule towed system and digital synthetic schlieren system is indicated as a, b and c respectively.*

3.3. Experimental Results

The density is 1.005 g/cm^3 and 1.043 g/cm^3 for the upper and lower layer water, respectively. The coefficient k at each pixel is calculated out through the linear fitting by comparing the background A, B, C, D, E with F respectively. The CCD shoot six frames per second, the authors calculate the internal wave field generated by the moving spherule at every moment by comparing each frame with the background field *F*.

Figure 3 gives a transient internal wave field that the CCD shot. It is noticeable that the crests and troughs have a symmetry distribution about the moving spherule trajectory, which is a typical characteristic of the Kelvin Internal Wake. The characteristic agrees well with the previous studies [17]. In addition, it could be figured out that the average velocity of the moving spherule is 0.0302 m/s; the average internal wave amplitude is 0.05 m, which is approximately half the spherule radius; the wave length is 0.05 m, which is approximately twice the spherule diameter; the wave velocity is 0.03 m/s, which is similar to the average velocity of the moving spherule.

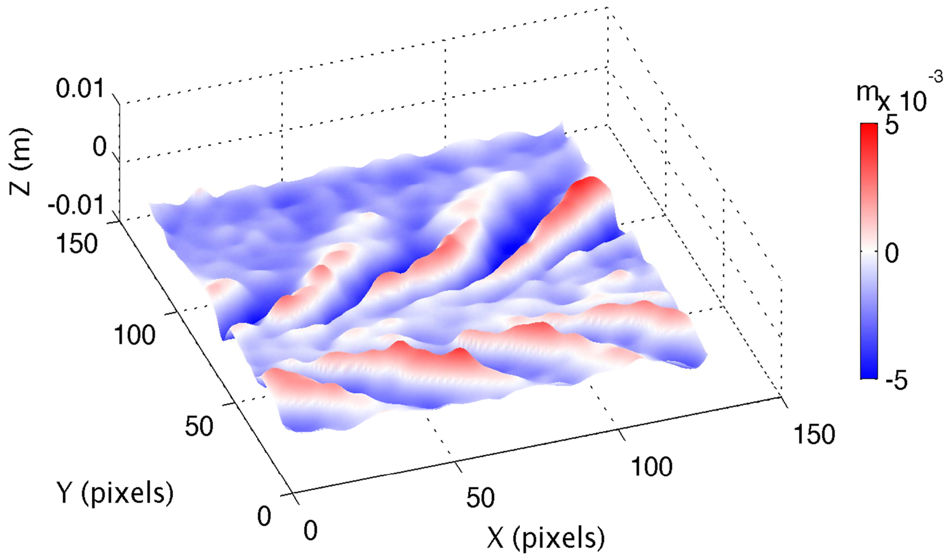

Figure 3. *Amplitudes of the transient internal wave field.*

3.4. Experimental Discussions

The generation of internal waves by moving objects in marine stratified fluids is a form of ocean internal waves. Wave-wave, wave-flow, wave-vortex interactions often occur in the wakes of such internal waves. Wave breaking and turbulent mixing often occur in the central region of the inner wake. Due to the wave-wave nonlinear interaction, this internal wave also appears some random feature. The various perturbations induced by the moving objects in the stratified fluids are one of the causes of internal wave generation, while at the same time the internal waves propagate out the local momentum and energy of the fluid. It is of great academic significance and application value to study the internal wave wakes generated by the moving objects in stratified fluids, to define the three-dimensional spatial structure such as Kelvin angle, and to explore the temporal and spatial variation of the internal wave wakes.

In the paper, the traditional digital schlieren technology is improved, which makes it possible to do three-dimensional visual measurement of internal waves generated by moving objects in stratified fluid. Due to its non-interfering, non-contact and three-dimensional wave field transient recording characteristics, the research of laboratory internal waves become quantified and accurate. It can provide experimental bases for the detection of internal ocean waves, and provide reference data for remote sensing detection and inversion of ocean internal waves. It can also be used as an important basis to verify internal wave theory and numerical simulation results.

4. Conclusions

Visual measurement of the internal wave field generated by moving objects in stratified fluids is of great significance for oceanographic research, especially military oceanography. The internal waves induce the density field variations and cause the refractive index changes of the medium to light. The digital schlieren technique uses this to capture the corresponding deformation of the random dot matrix layout background image. The internal wave field density distributions and flow field variations can be obtained through extracting and calculating the captured image information. In this paper, the authors make some improvements of the digital synthetic schlieren technique and apply it to the three-dimensional density stratified flows. The three-dimensional characteristics of the internal wave field generated by a moving spherule are well displayed through a set of lab experiments. In future studies, the relationships between the internal waves and the environmental parameters, velocity distribution of the internal wave field and the structure of the inner Kelvin angle will be further discussed.

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