Experiments on Internal Waves Generated by a Self-Propelled Model in a Stratified Fluid

Hongwei Wang, Ke Chen, Yunxiang You, Xinshu Zhang, Minhua Shu
State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University,
Shanghai, China
Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration,
Shanghai, China

ABSTRACT

In this paper, experiments are conducted for the characteristics of internal waves generated by a self-propelled model translating horizontally below the strong pycnocline of a density stratified fluid. The translational speed of the self-propelled model ranges from 0.06 to 1.4 m/s, the corresponding Froude number $Fr$ from 0.44 to 10.33. Two cross-track conductivity probe arrays are arranged at two along-track positions to obtain the density fluctuation characterizing the internal wave. Two regimes of the internal wave are distinguished by the critical Froude number $Fr_c$. For $Fr<Fr_c$, the correlation velocity of internal wave $U_{iw}$ is nearly equal to the translational speed $U$ of the model, indicating that the internal waves are stationary to the model and the Froude number $Fr_{iw}$ associated with $U_{iw}$ varies within the range 0.4–1.5, showing that such internal waves are non-stationary to the body and termed as wake-generated waves. For the variation of the maximum peak-peak amplitudes $A_m$ versus $Fr$, $A_m$ reaches its maximum when $Fr_p=1.03$. For $Fr<Fr_p$, the maximum peak-peak amplitude $A_m$ increase with $Fr$ and the wave patterns for such waves are dominated by stationary body-generated waves. For $Fr_2<Fr<Fr_c$, the maximum peak-peak amplitude $A_m$ decreases with $Fr$ and the influence of wake-generated waves gradually increases, but the wave patterns for such waves are still dominated by stationary body-generated waves. For $Fr>Fr_c$, the dimensionless maximum peak-peak amplitude $A_m$ do not have an explicit growth trend with $Fr$ but change within the range 0.04–0.07, and the internal waves under such conditions are dominated by non-stationary wake-generated waves.

KEY WORDS:  Stratified fluid; Self-propelled model; Internal waves; Body-generated internal waves; Wake-generated internal waves.

INTRODUCTION

Internal waves (IW) are generated by a submerged model such as a towed sphere, a cylinder or a self-propelled body and its associated turbulent wake in a stratified fluid are of great interests in oceanic hydrodynamics. Several classifications of IWs are proposed based on experimental observations. Lin et al. (1993) indicated that three regimes of IWs generated by a towed sphere could be identified, i.e. Lee waves, forced waves and waves generated by the gravitational collapse of the turbulent wake. Bonneton et al. (1993) classified the IWs into four regimes with respect to the different sources, i.e. sphere itself, wake collapse, excitation from the recirculation zone and the random turbulence. Robey (1997) proposed a more general classification consisting only two types, body-generated and wake-generated IWs. The body-generated IWs are Lee waves, generated by the sphere itself and the following stationary separation bubble whose area is nearly equivalent to the recirculation zone. The wake-generated IWs are highly non-stationary and the sources are complicated.

Numerous theoretical studies have been proposed since the work of Lighthill (1967) on generalized anisotropic wave motions. Theoretical methods, e.g. the kinematic phase line approach (Keller and Munk, 1970), the stationary phase approach (Miles, 1971) and the far-field asymptotic method (Gray et al., 1983), were developed based on a point source or a dipole for body-generated IWs. An oscillating source (Dupont and Voisin, 1996) and a wake-collapse source (Milder, 1974) were proposed to simulate the wake-generated IWs. The results obtained by these theories generally show certain reasonable agreements to the experimental results while still remain some obvious discrepancies. For a towed sphere, Robey (1997) improved the theoretical model. He designed a volume source in shape of a cylinder of aspect ratio 3:1 instead of a sphere of aspect ratio 1:1 for the body source and considered a non-stationary wake source characterized by a turbulent eddy. For such an eddy, its translational speed equaled the wave speed, its length was taken from a Strouhal argument (Chomaz et al., 1993), and the diameter was given by the wake growth law (Pao and Lin, 1988). The computed wave patterns and amplitudes agreed well with the experimental data.

Experimental works also discovered that the IWs have a transition from body-generated dominant to wake-generated dominant with the growth of the source translational speed. The critical condition is related to the Froude number $Fr = U/ND$, where $U$ is the source speed, $N=\sqrt{(g/\partial p/\partial z)^{1/2}}$ is the buoyancy frequency and $D$ is the diameter of the sphere. Hopfinger et al. (1991) and Bonneton et al. (1993) studied the regime of IWs generated by a towed sphere and its turbulent wake in a linearly density stratified fluid. Wave patterns were visualized by a rake of fluorescein dye technique for $Re=UD/\nu=3000$ and 0.25$<Fr<6.25$ (according to the literature, 0.5$<F=U/ND<12.5$). Results show that the body-generated IWs are dominant when $Fr=2$ and are replaced by the IWs generated by the large scale coherent structures when $Fr>2$. Robey (1997) conducted experiments on a towed sphere with a pronounced thermocline near mid-tank depth and noticed the diversity between the speed of the IWs and of the towed sphere after the transition with the critical Froude number $Fr_c=2$. Wang et al. (2012) further investigated a