International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 28, No. 2, June 2018, pp. 113–119; https://doi.org/10.17736/ijope.2018.jc712

http://www.isope.org/publications/publications.htm

# Characteristics of Internal Waves Generated by a Self-propelled Model Under a Pycnocline

Ke Chen, Hongwei Wang, Yunxiang You, Xinshu Zhang and Minhua Shu
State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University
Shanghai, China

**In this paper, experiments are conducted for the characteristics of internal waves generated by a self-propelled model translating steadily 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 $Fr = U/N_{max}D$ ranges from 0.44 to 10.33. Two regimes of the internal waves are distinguished by the critical Froude number $Fr_c = 2.95$. For $Fr < Fr_c$, the internal waves are stationary to the model and usually called body-generated waves. The maximum peak-peak amplitude $A_m$ first increases and then decreases with $Fr$ and the peak Froude number $Fr_p = 1.03$, indicating a resonant response. For $Fr > Fr_c$, the internal waves are nonstationary to the model and usually called wake-generated waves. The maximum peak-peak amplitudes do not have an explicit growth trend with $Fr$ similar to the towed model but change within a range.**

## INTRODUCTION

Internal waves (IWs) 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 interest 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: 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: the sphere itself, wake collapse, excitation from the recirculation zone, and random turbulence. Robey (1997) proposed a more general classification consisting of 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 nonstationary, and the sources are complicated.

Numerous theoretical studies have been proposed since the work of Lighthill (1967) on generalized anisotropic wave motions. Theoretical methods, such as 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 some obvious discrepancies still remain. For a towed sphere, Robey (1997) improved the theoretical model. He designed a volume source in the shape of a cylinder of aspect ratio 3:1 instead of a sphere of aspect ratio 1:1 for the body source, and he considered a nonstationary 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 agree well with the experimental data.

Experimental works also show that there is a transition from body-generated IWs being dominant to wake-generated IWs being dominant as the source translational speed increases. The critical condition is related to the Froude number $Fr = U/ND$, where $U$ is the source speed, $N = [-(g/\rho_0)(d\rho/dz)]^{1/2}$ 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, $0.5 < F = U/NR < 12.5$). 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 the speed of the towed sphere after the transition with the critical Froude number $Fr_c = 2$. Wang, Chen, and You (2017) further investigated one sphere and three slender bodies with different aspect ratios, finding that the critical Froude number is linearly dependent on the aspect ratio.

Besides the above-mentioned works, several studies (Schooley and Stewart, 1963; Lin and Pao, 1973; Gilreath and Brandt, 1985; Voropayev et al., 1999; Meunier and Spedding, 2006; Brucker and Sarkar, 2010; Chen et al., 2016) were also involved with wakes or IWs generated by the propeller or self-propelled slender body translating in a stratified fluid considering a real submarine. Although these works have revealed some important features of IWs, they hardly discuss characteristics such as the transition or the wave patterns. Therefore, we present this experimental work on the IWs generated by a self-propelled model in a density-stratified fluid with a pycnocline to show the characteristics of the transition, wave amplitudes, and wave patterns.

Received July 10, 2017; updated and further revised manuscript received by the editors August 22, 2017. The original version (prior to the final updated and revised manuscript) was presented at the Twenty-seventh International Ocean and Polar Engineering Conference (ISOPE-2017), San Francisco, California, June 25–30, 2017.

KEY WORDS: Stratified fluid, pycnocline, self-propelled model, internal waves, body-generated internal waves, wake-generated internal waves, antisymmetric internal wave.