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Non-Acoustic Detection Of Moving Submerged Bodies In Ocean

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Abstract:
Although, acoustic techniques are currently the mainstay for detection and tracking of submerged bodies like submarine and autonomous underwater vehicles (AUV), advent of silent submarines and the ensuing reduction of acoustic signatures and development of anechoic coatings is making detection very difficult especially in shallow water environment. Though there are some promising non-acoustic techniques such as magnetic anomaly detection, LIDAR, bioluminescence detection etc for the same purpose, they have some inherent limitations which restrict their use for detection over a wide area and from a large distance. Against this backdrop detection of physical manifestations such as turbulent wake and internal waves generated due to platform movement by optoelectronic techniques increasingly becoming popular for detection and tracking of moving underwater objects. We present here the general features of turbulent wake and internal waves generated by moving submerged bodies and discuss the optoelectronic techniques for their detection.

Key word: *Sonar, MAD, SAR, Kelvin wake, turbulent wake, internal wave, shadowgraph*

1.Introduction

Though electromagnetic (EM) waves have their presence in almost all areas of human life starting from military to civilian, certain limitations like high attenuation in water medium precluded their use for underwater applications, thus leaving this domain to sound waves which have obvious advantage over EM waves regarding range in underwater environment. Hence in present scenario acoustic technique such as SONAR (Sound Navigation and Ranging) is the mainstay for detection and tracking of underwater moving objects. Sonars are of two types, active and passive. Active sonar transmits a pulse of sound and then receives the echo produced after reflection by target. But by sending a powerful burst of sound it reveals its position making it an easier target for attack or helping the enemy to take evasive action. Passive sonar uses underwater microphones called hydrophones arranged in the form of an array to detect sound coming from distant targets. By comparing sound received by each hydrophone it is possible to determine the direction of incoming sound. In addition the received sound after comparing with pre recorded sound, the nature of source generating sound can be determined. Hence passive sonars detect, localize and identify enemy submarines if the vessel generates enough noise. But with the development of quieter submarines with many noise reduction techniques such as precisely balancing rotating parts to minimize vibration, mounting machinery on sound absorbing platforms, and covering submarine with anechoic materials which absorb sound, the noise signatures of submarines reduce significantly and are likely to be reduced further. Other concerns in the acoustic methods are range of acoustic transducers which is limited and the effect of ambient noise in the oceanic environment. Hence to detect targets over a wide area in ocean, large numbers of acoustic sensors are to be deployed. Also acoustic sensors may be confused by the decoys fired form enemy platforms which generates similar sounds of submarine. Hence there have been attempts to find alternative methods for detection over a wide area of ocean.

One of the techniques is magnetic anomaly detection. The body of submarine is made up of steel. Because massive amount of steel disturbs the earth's local magnetic field, a magnetic anomaly detector (MAD), a device sensitive to changes in local geomagnetic field can be used to detect submerged submarines. But the strength of magnetic anomaly signal reduces as cube of the distance and hence range is limited upto some thousand feet. Also noises like naturally occurring concentrations and random fluctuations in the geomagnetic field due to solar activity sometimes mask the actual submarine. Moreover, unlike sound and light, magnetic field is a non-propagating phenomenon. Hence it is difficult to determine the directionality of source of disturbance in case of long range magnetic surveillance. Also small AUV's can act as dummy submarine with coils that reproduce magnetic signature of an actual submarine.

Other promising method is LIDAR (Light detection and ranging). Although sea water is opaque to most electromagnetic radiation; blue green light can penetrate a considerable distance through sea water. Similarly to radar an intense pulse of blue-green laser can be transmitted and the reflected light from submarine can be detected by a suitable photo detector. However, surface of submarine hull may tend to absorb more light than the surrounding water, in which case it would be detected as a hole in the naturally occurring level of oceanic backscattering. There are some other concerns too. Many false targets are likely to be detected by such mechanism, since there are plenty of submerged objects in ocean other than submarines including marine animals such as blue whale. The intensity of blue-green light is attenuated by a maximum factor of approximately two for every seven meters it travels through water. Hence this may not be useful for long range detection.

There have been attempts to detect heat emitted by submarines. Conventional and especially nuclear submarines draw in substantial quantities of seawater specifically for the purpose of cooling as it relies on recycling of water through a boiler, a steam turbine and a cooling system (whose heat sink is sea water) to convert heat energy produced in the reactor to mechanical energy. About 20% of the thermal energy produced by the reactor goes into propulsion. The rest 80% of the energy goes to surrounding sea water through cooling of boiler and through the heat generated by electrical systems. While this appears to be massive, heat transfer calculations reveal that at a speed of about five knots, the temperature immediately behind the submarine only rises by about 0.2 degrees Celsius. This temperature differential will diminish rapidly as the submarine moves further away at a rate of $(x/D)^{-0.5}$ where x is the distance downstream of submarine and D is the diameter of submarine. The warmer water being less denser rises to the surface and eventually encounter water of the same temperature at which point it will not rise further and therefore not detectable.

Other interesting phenomenon called bioluminescence seems to be another detection technique**.** The oceans are populated with organisms like dinoflagellates that emit light when they are disturbed. The moving submarine will naturally cause a local disturbance of the surrounding bioluminescent organism population inducing them to emit light. The intensity of such emission is a function of population density of species, environmental conditions and the speed of subsurface vessel that disturbs the species. The peak of this emission spectrum is in the blue to blue green region (.48 μ) which is the wavelength that can be transmitted in sea water with less attenuation. Hence such effects may be detectable above the ocean surface and may be used to detect the location of subsurface vessels. However, the emission of light by excited organisms at one depth may induce other organisms closer to the surface to emit light. But the presence and population density of such organisms vary with season, geographical location and depth. Also at a particular location their position changes with time. Other limitation for the detection of bioluminescence is the overpowering background noise contributed by the sun and the moon which would render a detection system useless during the day-time and possibly also under certain night-time conditions.

Other possible detection methods are detection of different characteristic emanations from modern submarines. particles of paint that slough off the outer surface of the submarine, minute quantities of radioactive substances that escape into sea water through nuclear reactor cooling substance (in case of nuclear submarine) or other effluents that leave a distinctive chemical trail indicating the presence of submarine in that area. The detection of such trail requires direct measurement of very minute quantities of chemical substances at different areas and at different depths of ocean which is very difficult and time consuming.

Apart from these techniques the physical surface effects caused by a submerged vessel may be detectable either by accurate measurement of the ocean surface height or by imaging the ocean's surface. The major physical surface characteristic is the wake developed by a vessel when it is mobile. The characteristics of the wake will be a function of the speed, depth and size of the vessel. Three separate hydrodynamic phenomena are either directly or indirectly caused by the wake - the Bernoulli hump, Kelvin waves, and the surface effect of underwater turbulence and internal waves. If a submarine travels at high speed near the surface of the ocean it produces a characteristic hump of water which is sometimes referred to as the Bernoulli hump. The shape of this disturbance is independent of speed and depth but the size is proportional to D^2U^2/h^2, where D, U, and h are the diameter, speed and operating depth of submarine respectively. Hence it decreases rapidly with decreasing speed and increasing depth. For example, the height of the hump reduces from about six centimeters to one millimeter when a given submarine reduces speed and increases depth from 20 knots and 50 meters to five knots and 100 meters, respectively. Kelvin waves are produced by both ships and submarines and are responsible for the characteristic "V" shaped wake that can be seen to linger behind a moving vessel as shown in Fig.1. They have an angle of approximately 39º which is independent of the size of the vessel or the speed at which it is travelling. The height of wave reduces exponentially with increasing depth and decreasing speed. Also it decays behind the submarine with square root of the distance. These waves are dominant for submarines moving at low depth and high speed. Using the above example, the wave size reduces from about two centimeters to immeasurably small.

Figure1. Kelvin waves formed by a moving boat

Most of the above mentioned techniques have two basic limitations. First, they belong to the class of problems involving low signal- to - noise ratio that is inherent and difficult to overcome. Second, they can be defeated simply by operating submarine at higher depths. In this backdrop the turbulent wake and internal wave generated by submerged bodies seem to be the most promising phenomena for detection.

2. Turbulent Wake And Internal Waves

The ocean is a stratified medium as density, salinity and temperature changes continuously, especially with depth in the upper 1000 meters as shown in the Fig.2.

Since this is the operating zone of the submarine, when a submarine moves it will disturb these profiles due to its propeller motion and displacement of water by it. There will be mixing of layers of water having different density and temperature. This creates a turbulent wake downstream of submarine.

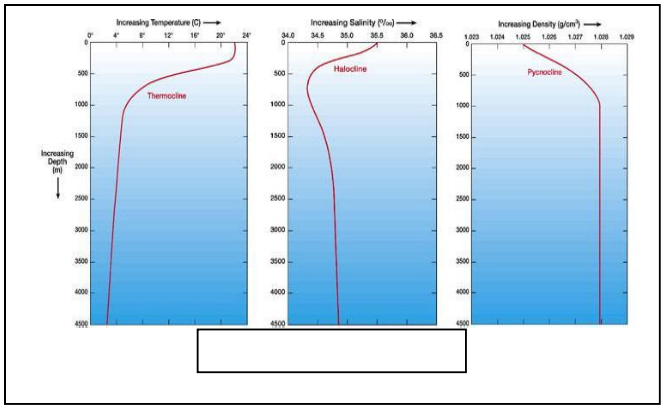

Figure 2: Ocean stratification

A wake is defined as the non-propagating disturbance produced by a moving body. The cooler (denser) water below the submarine and warmer (less dense) water from top of submarine will be drawn into the wake and gets mixed up. Hence the turbulent wake will have a different density profile with respect to the background. Immediately downstream of the vehicle, the wake, which may contain fluid of nearly constant density, will grow at the same rate in all directions as $(x/D)^{0.25}$ and maintains a circular cross section. However, as the turbulent energy of the wake decays with increasing distance from the body, the restoring action of buoyancy begins to inhibit the vertical expansion of the wake and at the same time enhances the horizontal growth. After reaching a critical time and distance the uniformly mixed wake can no longer maintain itself in the ambient density gradient. At some point behind the body, the wake reaches a maximum vertical size followed by a collapse and spreads horizontally as the fluid returns under the action of gravity to the level at which its density is the same as the environment. Its cross-sectional shape first becomes elliptical and then finally approaches that of a flat rectangle. The critical time for the onset of wake collapse has been found to be dependent on T, where T is the Brunt-Vaisala period, which is defined as $T = \dfrac{2\pi}{\left[\dfrac{g}{\rho_0}\dfrac{\partial \rho}{\partial z}\right]^{1/2}}$

where g is the acceleration due to gravity, ρ_0 is the ambient density $\partial\rho/\partial z$ is the ambient vertical-density gradient. It can be interpreted as the oscillating period of a fluid particle under infinitesimal perturbation and is a fundamental characteristic of a stratified fluid. When the time scale of wake motion approaches the Brunt-Vaisala period, the wake will be influenced by stratification. The values of the Brunt-Vaisala period, T, depend on ocean density gradients, which can range from 10^{-4} to 10^{-7}/m or less in the natural ocean. The results obtained from laboratory experiments by many researchers indicate that the onset time for wake collapse increases with T and is roughly one-third of it. The dynamics of this turbulent wake is dependent on two non-dimensional fluid parameters such as Reynold's number (R) defined as $\rho UD/\mu$ and Froude number (F) defined as UT/D, where ρ,U,D,μ are density of medium, speed of submarine, diameter of submarine and kinematic viscosity of ocean water respectively. For small Reynolds number the viscous forces dominate the inertial force and the wake is laminar. As the Reynolds number increases, the wake becomes unstable and a regular flow pattern in the wake of the body can be observed. At still higher Reynolds numbers, the flow pattern becomes irregular and a turbulent flow is formed. The vertical wake height is proportional to $(F)^{1/4}(t/T)^{-3/4}$ and after collapse reaches to a constant value when t=T. The horizontal wake width is proportional to $(F)^{1/4}(t/T)^{1/2}$. The root mean squared longitudinal turbulent fluctuation decays as 0.75 power of distance and increases linearly with speed. The vertical fluctuations decay linearly with distance and increase with 1.25 power of speed. The turbulent kinetic energy decays as t^{-1} upto the collapse. However, after this time the decay rate sharply decreases when the field of turbulence was replaced by internal gravity waves. The vertical and horizontal growth of wake is shown in Fig.3.

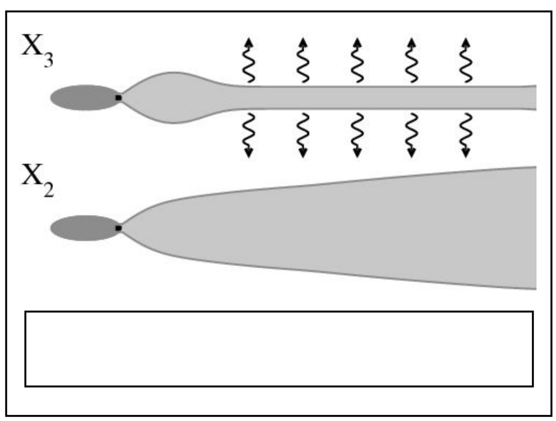

Figure 3: Horizontal and vertical growth of turbulent wake. X_3 is the vertical height and X_2 is horizontal width of wake

For T=4 minutes, a submarine moving at a speed of 10 knots the horizontal width and vertical height of wake are 400 ft and 50 ft approximately while for T = 40 minutes with same submarine velocity the horizontal width and vertical height of wake are 250 ft and 80 ft respectively. When turbulent wake collapse vertically, it generates internal waves in the ocean which travels both horizontally and vertically with distinct features such as frequency, speed and amplitude and propagation. These are periodic variations in the temperature and density of water with a frequency $\omega = \cos\Theta/T$, where Θ is the angle which direction of propagation make with vertical. These represent a significant mechanism for the transport of momentum and energy within the ocean. Internal waves are also generated due to ocean currents and flow over irregular structure in the ocean. Internal waves typically have much lower frequencies and higher amplitudes than surface gravity waves. Wavelengths vary from centimeters to kilometers with periods of seconds to hours respectively. Largest vertical amplitudes occur in the interior of the fluid, sometimes of the order of 100m.

At large scales, internal waves are influenced both by the rotation of the Earth as well as by the stratification of the medium. The frequencies of these geophysical wave motions vary from a lower limit of the Coriolis frequency (inertial motions) up to the Brunt–Väisälä, or buoyancy frequency (buoyancy oscillations). The horizontal currents associated with these waves extend to the surface. These surface currents modify the roughness and steepness of the surface waves which can be detected by synthetic aperture radar (SAR). The surface manifestations of internal waves are linked to the presence of a thin film of natural organic material and oil that are commonly found on the ocean's surface which are swept into a regular pattern due to internal wave. The details of wake formation and subsequent generation of internal waves is shown in the Fig. 4.

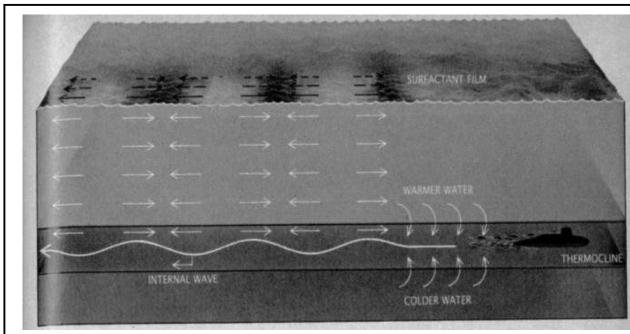

Figure 4: Generation of internal wave due to submarine movement

The detection of internal waves by SAR is an airborne technique and cannot be implemented in systems intended for use inside water. So in the following section different optoelectronic techniques that can be used for detection of turbulent wake and internal waves deep inside the water column are explained.

3.Optoelectronic Techniques For Turbulence Detection In Ocean

The turbulent wake and subsequent generation of internal waves are mainly due to change in density gradients of ocean caused by submarine movement. The relationship between the optical refractive index and the density of a fluid is given by, $(n-1)=\kappa\rho$ (Gladstone–Dale Equation); where, *n* is the optical refractive index, ρ the density of the fluid and κ is a constant coefficient which is a function of the laser wavelength and the fluid characteristics. That is, the refractive index gradient is linearly related to density gradient or the change in refractive index gradient will yield the change in density gradient of a fluid. Following techniques use this principle.

3.1 Shadowgraph Technique

Pioneered by Dvorak (1880), the shadowgraph is the simplest form of optical system suitable for observing a flow exhibiting variations of the fluid density. Shadowgraph techniques have been used for centuries to look at flows that are not visible to the human eye such as heat dissipation or shock waves. Fig.5 shows the optical setup of a typical shadowgraph system. Light rays will be passed through the turbulent area and focused onto a film. Variations in refractive index caused by change in density gradients in the fluid due to turbulence distort the collimated light beam. This distortion creates a spatial variation in the intensity of the light, which can be visualized on the screen as regions of bright and dark regions. A shadow effect is generated because a light ray is deflected so that the position on the recording plane where the undeflected ray would arrive now remains dark. At the same time the position where the deflected ray arrives appears brighter than the undisturbed environment. Shadowgraphs technique gives qualitative information about the presence of turbulence but not about direction of refraction.

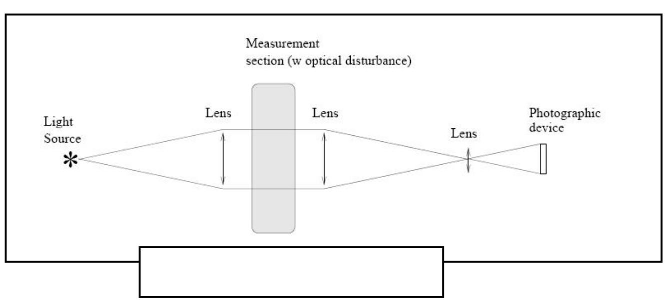

Figure 5: Shadowgraph techniques

3.2. Schlieren Technique

Schlieren photography is a visual process that is used to photograph the flow of fluids of varying density. The Schlieren method was devised by Foucault and developed by German physicist August Toepler in 1864 to study supersonic motion. The basic set-up is shown in Fig.6.

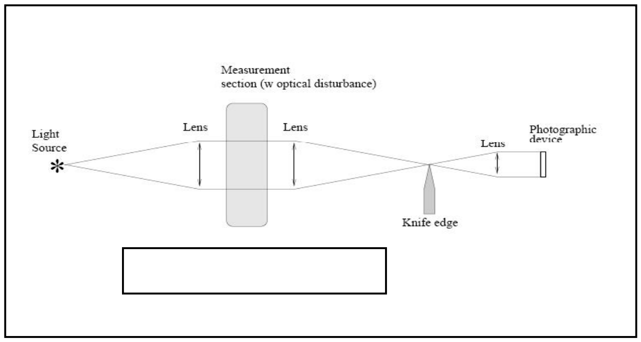

Figure 6: Schlieren technique

In the Schlieren system the light source is refocused in a small area and a cutoff is inserted to reduce light from the light source. A vertical knife-edge is inserted at the center of the re-focused light source. If no light is refracted then the knife-edge reduces the light source by half, resulting in a gray image, whereas if light is refracted shifts in the focused image of the original light source causes more or less of the focused light to be blocked by the cutoff. If the focused image is shifted down the resulting region becomes darker and if shifted up, then more of the original light gets through to the film plane. A knife-edge cutoff thus provides information about the amount of light shifted along a single axis.

3.3.Laser Beam Deflection Technique

This is a novel optoelectronic technique proposed by Tatavarti et al. (1996). The principles and detection techniques are explained in Fig.7 and Fig. 8.

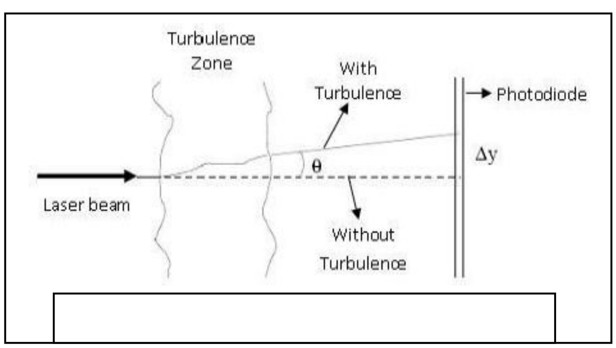

Figure 7: Principles of laser beam deflection (LBD) technique

The light emitted by laser diodes will be transmitted through a water medium and will be detected by position sensing photodiodes which will give out put in the form of electric current proportional to the intensity of light falling on it and the position on photodiode where laser beam falls. If hydrodynamic turbulence is present in the water medium, it will deflect the laser beam and change the intensity of laser when laser propagates through it. This change in the intensity and the deflection of laser beam due to turbulent water medium will be measured by photodiode and will give proportional output electric current. The output current of photodiode depends upon the distance between laser and photodiode, nature of turbulence in the medium, power output of laser source, and the nature of photodiode. This output current will be processed by the optical beam position and power measurement system to get the change in intensity and the amount of deflection of laser which are related to the nature of turbulence in the medium.

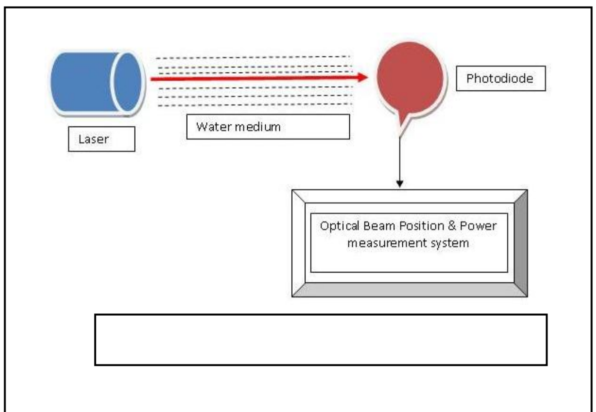

Figure 8: Laser Beam Deflection (LBD) technique

4.Conclusion

The detection of submerged vessels over a wide area and from large distance will bring a sea change for both military and civilian applications. While there are proven methods using acoustic and non-acoustic techniques, range, signal to noise ratio and accuracy are continuing to be technological bottlenecks for their application and hence detection of turbulence by optoelectronic techniques seems to be most promising. At the same time underwater turbulence and its measurement is complex due to fast changing flow characteristics in both space and time. Although principles and techniques are understood to a certain extent, still a lot of works are to be done in this area to understand and exploit this for suitable application.

5.Acknowledgement

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