

Micro-Doppler Simulation Modeling and Analysis of the Ship

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Abstract. Ship have angular motions such as yaw, pitch and roll. It may induce additional frequency modulations on the returned radar signal, called the micro-Doppler effect. This paper describes the techniques used to simulate the ship rotation and the micro-doppler modelling.

Keywords:Ship motion; Response operators;Micro-doppler; Sea condition

1. Introduction

In the sway sea, ship has three-degree rotation in-addition to translation. The dynamics of such movements cause frequency modulations on the back-scattered signal and produces shifts in addition to the already present Doppler shift. The non-uniform motion produces modulations, which constitute features in the ship scattering echo.

If the target or any structure on the target has mechanical rotation in addition to its bulk translation, it might induce a frequency modulation on the returned signal that generates sidebands about the target's Doppler frequency shift. This is called the micro-Doppler effect [1,2]. Micro-Doppler described the target micro-motion features, reflecting the Doppler shift of the transient behavior. Ship in the waves, inspired a unique micro-Doppler modulation of the radar echo [3, 4] . It provides a new way for ship feature extraction and analysis .

This paper describes the techniques used to simulate micro-Doppler of ship models experiencing angular motions such as yaw, pitch and roll. The simulation incorporates ship motion modeling, ship micro-Doppler modeling.

2. Ship Motion in the Sea Sway

2.1. Wave Spectrum and Encounter Spectrum

Ocean waves are random in both time and space. It appears to composed of random waves of various lengths and periods. The surface can be represented as an infinite series of sine and cosine functions of different wave numbers oriented in all possible directions [5].

These characteristics are often summarized by the term irregular in the marine literature. The stochastic description is, therefore, the most appropriate approach to characterize them. In practice, it is usually assumed that the variations of a stochastic nature of the sea are much slower than the variations of the sea surface itself stationarity is assumed. Due to this assumption, the elevation of the sea can be considered a realisation of a stationary stochastic process.

After the wind has blown constantly for a certain period of time, the sea elevation can be assumed statistically stable. In this case, the sea is referred to as fully developed. If the irregularity of the observed

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waves is only in the dominant wind direction, so that there are mainly uni-directional wave crests with varying separation but remaining parallel to each other, the sea is referred to as a long-crested irregular sea. If there are data available from wave ride buoys, the sea spectrum can be determined using spectral estimation techniques. In cases where no wave records are available, standard, idealized, formulae can be used.

The 15th International Towing Tank Conference (ITTC) in 1978 recommended the use of the Modified Pierson-Moskowitz family. For this family, the significant wave height and different wave period statistics are used to parameterize each spectrum:

$$S_{\xi}(\omega) = \frac{A}{\omega^5} \exp\left\{-\frac{B}{\omega^4}\right\} \quad (1)$$

$$A = 0.78, \quad B = \frac{3.11}{h_{1/3}^2}, \quad h_{1/3} \text{ is average of the heights of largest } 1/3\text{rd of the waves.}$$

In the previous section, we have described regular waves from a stationary reference frame. When the ship is at zero speed, the frequency at which the waves excite the ship coincides with the wave frequency; and thus, the previous description is valid. However, when the ship moves, the frequency observed from the ship differs from the wave frequency. The frequency experienced by the ship is called the encounter frequency, and it is denoted by ω_e .

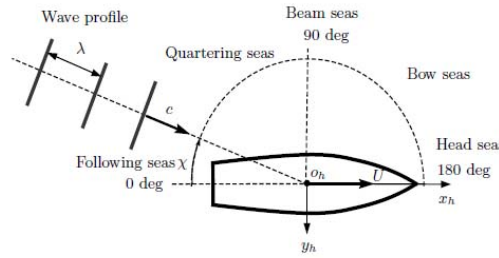


Figure 1. Ship Heading

If the ship moves forwards with an average speed v , the sea can be more conveniently described relative to a frame (o_h, x_h, y_h) that moves at the average speed of the vessel as shown in Fig 1. This figure also shows the adopted convention for the, so-called, encounter angle χ , and also the usual denomination for the different sailing conditions:

$$\omega_e = \omega + \frac{\omega^2}{g} v \cos \chi \quad (2)$$

When a ship is moving with a certain speed, the frequencies observed from the ship differ from those observed in a stationary frame: the frequencies change according to (2). This Doppler effect changes not only the frequency range of the spectrum but also its shape. The wave spectrum seen from the ship is called the wave encounter spectrum $S_{\xi}(\omega_e)$. Since the power of any magnitude is invariant with respect to the reference frame from which it is observed, for any PSD the following holds:

$$S_{\xi}(\omega_e) = \frac{S_{\xi}(\omega)}{\left|1 + \frac{2\omega}{g} v \cos \chi\right|} \quad (3)$$

Once the encounter wave spectrum has been obtained, it is necessary to relate it to the motion of the ship. The simplifying assumption is the motion response of the ship is linear with respect to the wave amplitude in

regular waves. The approach uses the so-called Amplitude Response Operators (RAO) and relates the sea elevation to the particular motion component under consideration. In this method, the forces and moments are integrated over the wetted surface taking into account the load conditions, the geometry of the hull and the sailing conditions. It has been reported that the method approximates the response of the vessel accurately.

2.2. Ship Motion Response Operators

The relationship between ship motion and wave height versus regular wave frequency is commonly called the Response Amplitude Operators (RAO) [5]. This relationship represents a linear approximation of the frequency response of the ship motion in regular waves. Under the linearity assumption, superposition can be applied to determine the motion of the ship; and therefore, a connection to the stochastic model for describing irregular waves given in the previous section can be established.

The RAO depend on the geometry of the hull and load conditions of the vessel as well as its speed and direction with respect of the waves. The motion of a ship in six degrees of freedom is considered as a translation motion (position) in three directions: surge, sway, and heave; and as a rotation motion (orientation) about three axis: roll, pitch and yaw.

$$Rao_i(\omega_n) = |Rao_i(\omega_n)| \exp(j\phi_{i,n}) \quad (4)$$

The RAOs are determined using strip theory computations in which the forces and moments are integrated over the wetted surface of the hull. The RAO are usually tabulated as function of the wave frequency instead of encounter frequency. To transform the RAO to encounter frequency, we simply have to use the transformation given in (17). For example, figure 5 shows the RAO corresponding to roll motion of a multi-role naval vessel as a function of the wave frequency ω .

The motion spectrum is then given by

$$S_z(\omega_e) = |R_{z\zeta}(\omega_e)|^2 S_\zeta(\omega_e) \quad (5)$$

2.3. C. Simulation of Ship Motion

To simulate the motion of a ship given the motion spectrum, we can proceed in a similar manner as we did to simulate the elevation of the sea surface, i.e., as a finite sum of sinusoidal components with a random initial phase:

$$\theta_i(t) = \sum_{n=1}^N \sqrt{2S_z(\omega_{e,n})} \Delta\omega \cos(\omega_{e,n}t + \beta_{i,n}) \quad (6)$$

$$\theta_i(t) = \sum_{n=1}^N |Rao_i(\omega_{e,n})| \sqrt{2S_\zeta(\omega_{e,n})} \Delta\omega \cos(\omega_{e,n}t + \beta_{i,n}) \quad (7)$$

3. Ship Micro-Doppler Model

Mathematics of the ship micro-Doppler effect can be derived by introducing rotation to conventional Doppler analysis. Ship can be represented as a set of point scatterers. The point scattering model may simplify the analysis while preserving the micro-Doppler effect.

Let us consider the geometry depicted in Fig 2. The radar is stationary and located at the origin Q of the radar co-ordinate system $(\varepsilon, \zeta, \eta)$. The ship moves along a straight trajectory which lies on the (ε, ζ) plane and is oriented at an angle α with respect to the radar line of sight. (U, V, W) is Observation coordinate system. The U direction is the radar line of sight. The origin O is on the target. For the purpose of mathematical analysis, a reference co-ordinate system (X, Y, Z) is introduced, which has the same translation as the target but has no rotation with respect to the radar coordinates $(\varepsilon, \zeta, \eta)$. Thus, the reference co-ordinate system shares the same origin O with the Observation coordinate (U, V, W) and is assumed to be at a distance R_0 from the radar.

Due to the target's rotation, any point on the target move to a new position in the reference coordinate system (X, Y, Z) . The new position can be calculated from its initial position vector multiplied by an initial rotation matrix determined by Euler angles $\theta = (\theta_{roll}, \theta_{pitch}, \theta_{yaw})$, where the angle θ_{yaw} rotates about the z-axis, the angle θ_{roll} rotates about the x-axis, and the angle θ_{pitch} rotates about the y-axis, as illustrated in Figure 2. The corresponding initial rotation matrix is defined by

$$\mathbf{Rot}(\theta) = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (8)$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{roll}(t) & \sin\theta_{roll}(t) \\ 0 & -\sin\theta_{roll}(t) & \cos\theta_{roll}(t) \end{bmatrix} \begin{bmatrix} \cos\theta_{pitch}(t) & 0 & \sin\theta_{pitch}(t) \\ 0 & 1 & 0 \\ -\sin\theta_{pitch}(t) & 0 & \cos\theta_{pitch}(t) \end{bmatrix}$$

$$\times \begin{bmatrix} \cos\theta_{yaw}(t) & -\sin\theta_{yaw}(t) & 0 \\ \sin\theta_{yaw}(t) & \cos\theta_{yaw}(t) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

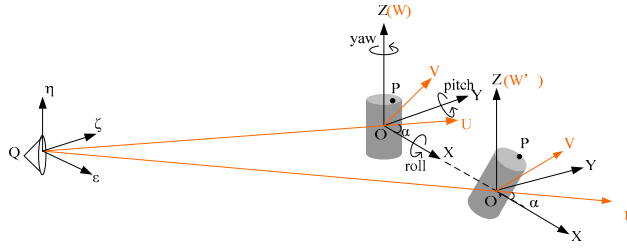


Figure 2. Radar and target geometry diagram

A point scatter P at $\mathbf{r}(0) = (x_0, y_0, z_0)$ represented in the target local coordinates (X, Y, Z) will move to a new location in the reference coordinate system and the unit vector of the rotation becomes

$$\mathbf{r}(t) = \mathbf{Rot}(\theta)\mathbf{r}(0) \quad (9)$$

Shown in Figure 3, three-dimensional rotation induced the scattering points of the radial distance changes relative to the radar can be approximated as:

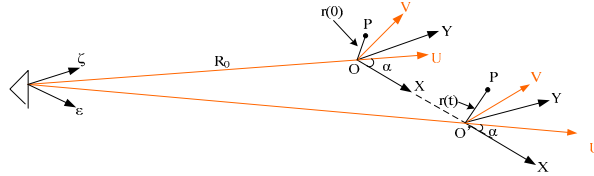


Figure 3. Target motion plan

$$\mathbf{R}_{\Delta}^{rot}(t) = (\mathbf{Rot}(\alpha(t))\mathbf{r}(t)) \cdot \mathbf{I}_U \quad (10)$$

The \mathbf{I}_U is U-axis unit vector, $\alpha(t)$ is the angle between radar line of sight and the direction of target motion, in a relatively short period of time $\alpha(t)$ can be considered constant. $\alpha(t) \triangleq \alpha_0$

$$\mathbf{Rot}(\alpha(t)) = \begin{bmatrix} \cos\alpha_0 & -\sin\alpha_0 & 0 \\ \sin\alpha_0 & \cos\alpha_0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (11)$$

Ship P point scatter Micro-Doppler is

$$f_{micro-doppler} = \frac{d\mathbf{R}_{\Delta}^{rot}(t)}{dt} \quad (12)$$

4. Simulation

In this section, simulation results are given in order to validate the theoretical analysis. A landing craft is modeled using scattering points modelling, detailed dimensions are shown in Fig 4.

The radar bandwidth is 100MHz and the carrier frequency is 3GHz. The radar pulse repetition frequency is 500Hz. suppose the radar transmits the linear-frequency modulated (LFM) signal.

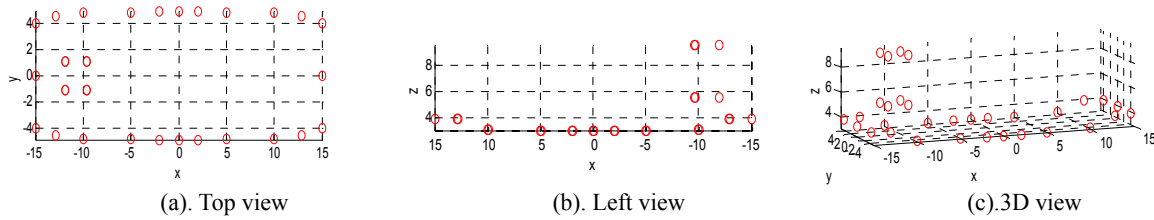


Figure 4. Ship scatter points model

In Figure 3, the sea state is three. The sea spread direction is along the line of radar sight. In Figure 4, the sea state is four.

In (a) of Figure 3 and Figure 4, the ship pitch and roll are shown. The micro-Doppler due to ship motion of pitch is shown in (b) of Figure 3 and Figure 4. The relative amplitude of micro-Doppler in condition of sea state 3 is lower than sea state 4. In (c) of Figure 3 and Figure 4, micro-Doppler of ship due to roll motion are shown. It is obviously that the frequency and the amplitude of the micro-Doppler which is induced by roll motion are higher compared to the pitch motion induced.

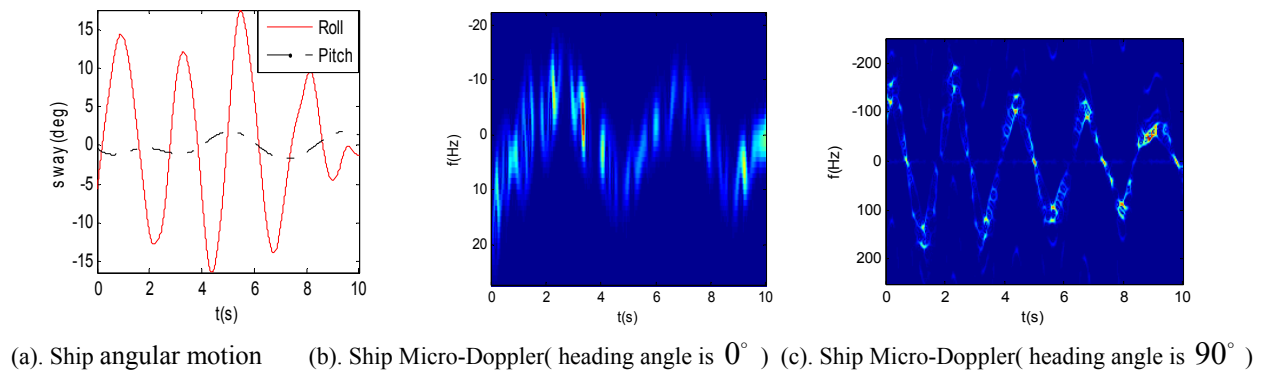


Figure 5. Ship Micro-Doppler in Sea State 3

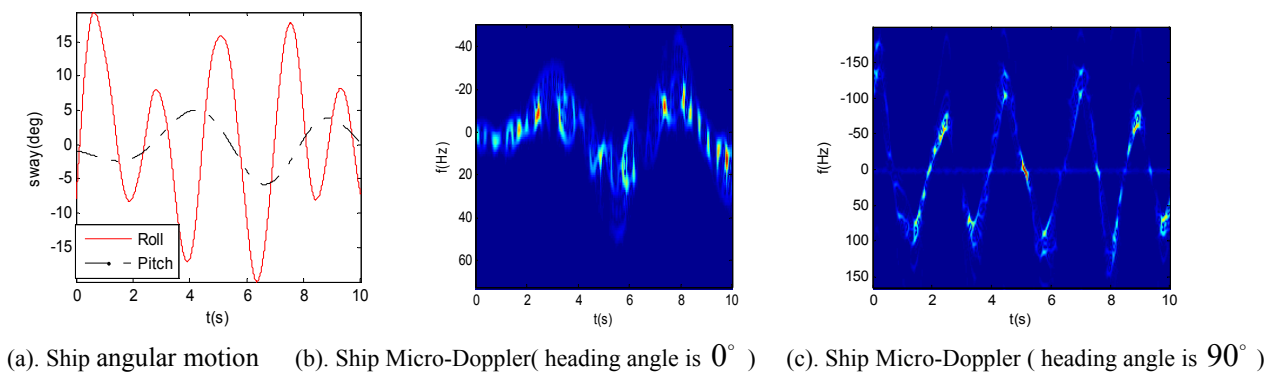


Figure 6. Ship Micro-Doppler in Sea State 4

5. Conclusion

In this paper, we analyzed Micro-Doppler effects of ships with angular motion in different sea states. The micro-Doppler is closely related to targets motion parameters and radar parameters.

This has been achieved by breaking the task into two steps. Firstly theories of seakeeping are used to simulate the angular motion of ship. Secondly, the point scatterer model are used, in conjunction with

information about ship motion, such as pitch and roll, to simulate the ship micro-Doppler. A number of numerical examples are presented to demonstrate the effectiveness of the proposed model.

6. References

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