# A Low-cost Four-degree-of-freedom Motion-platform for Ship-borne Free Space Laser Communication

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*Abstract*—**Free space laser communication (FSOC) has been an emerging technology that is deployed in the marine ship communication field for enabling high-quality communications among moving ships due to its high anti-EM interference capability and good security. However, the system typically requires six dimensional supports of Acquisition, tracking and pointing in the moving environment, which is rather expensive. In this paper, we propose a novel four-degree-of-freedom solution based on the law of motion of the ship in wind waves derived from linear system theory; the solution uses a horizontal, a vertical and two rotating motions to simulate the laser movement caused by ship movement in the wind waves. To the best of our knowledge this is the first effort in this field; our approach significantly reduces the complexity and cost of the six-dimension based solution. Our experimental results demonstrate a realization of laser movement caused by ship roll movement in the wind waves, and verify the convenience and accuracy of the simulated ship-borne free space optical communication system.**

*Index Terms*—**ship-borne free space laser communication (FSOC) system, ship movement, simulated moving platform, wave spectrum**

## I. INTRODUCTION

The radio is the most common communication method used between ships today. It has advantages of fast data transfer and a wide range of transmission. The disadvantage is that the confidentiality is relatively poor, and vulnerable to eavesdropping and interference. The free space laser communication can avoid these shortcomings. The free space laser communication is a technology using the laser as a carrier and transmitting information in the space, without requiring any channel as the transmission medium [1]. Its major advantages are the high transmission speed, great capacity, beam direction and the high confidentiality. There is no need for acquiring permission to use radio frequencies and no need to use any fibber channel. The equipment has further features of a small occupying space, lightweight, low cost, and easy to install [2,3,4]. Clearly, the free space laser communication will be widely used in marine ship communication.

There are a lot of products of the fixed-point free space laser communication available currently. As it uses a point-to-point communication, it needs to be mounted on a tripod and manually aimed to target the recipients communicating points. When used for ship communication, as a carrier (ship) is moving, the free space laser communication equipment should also require the capability of auto-tracking and targeting. This requires the establishment of a tracking duplex communication platform. This communication platform not only has the functions of Acquisition, Tracking, and Pointing (ATP), but also needs to be adjusted to the ship's movement. This paper presents a ship-borne free space laser communications platform, which consists of a level mobile station, a vertical lift, and horizontal and two vertical rotating swinging tables, representing four types of movements. It does not need the six-dimensional movements to achieve ATP, because the beam along the direction of movement and rotation around the beam direction of the movement do not affect the duplex communication. According to the principle of ship motion, these four types of movements in a laser communication system (platform) can be reconstructed from the complexity of the ship in waves. Under laboratory conditions, we have simulated the relationship of ship movements under various conditions on the sea under different motion states for a communication system. An experimental platform has therefore been established for further study on a ship-borne free space laser communications system.

## II PRINCIPLE AND CALCULATION OF SHIP MOTION

### A. Principle of ship motion

Motion state of a sailing ship is very complex, due to the disturbance of wind, waves and current ship speed especially in a storm. Suppose the ship is a rigid body, the movement of the ship body can be decomposed into three linear and three angular displacements, which can

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be described using the Cartesian coordinate system as follows. In a balanced state, the center of ship gravity G is overlapped with the coordinate system origin O, x-axis is pointing towards the bow, and y-axis is in the horizontal plane of the ship. There are six movements: vertical roll and sway, horizontal roll and sway, longitudinal roll and sway, as shown in Figure 1.

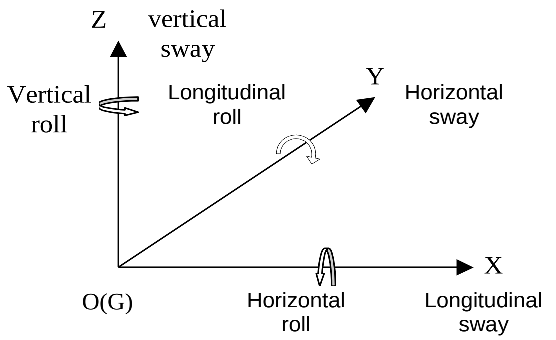


**Figure 1**. The ship's six degrees of freedom movement

Because of the orthogonal in the six movements, assume the ship’s six degrees of freedom movements in waves sway are independent of each other. In the case of small amplitude waves, the movements of ship’s body can easily be presented by a similar equation of motion. In the general, regardless the ship’s forward movement let us focus on the vibration around the centre of ship gravity. There are six movements caused by wind and waves: longitudinal sway $x(t)$, horizontal roll $\theta_x(t)$, horizontal sway $y(t)$, longitudinal roll $\theta_y(t)$, vertical sway $z(t)$, and vertical roll $\theta_z(t)$. Let Y(t) represent the six movements. Then Y(t) should satisfy with the equation of motion (1)[5,6,7].

$$\ddot{Y} + 2\gamma\dot{Y} + \omega_0^2 Y = \chi\omega_0^2 X(t) \tag{1}$$

where $\omega_0$ is the natural vibration frequency of the ship, $\gamma$ is the attenuation coefficient, $\chi$ is a correction factor (range 0-1), and $X(t)$ is the wave movement.

Equation (1) is a second-order linear ordinary differential equation. Thus the theory of linear systems can be applied to analyse it. Let the ship is as a linear transformation system, the wave movement $X(t)$ is an input, and the ship movement $Y(t)$ is a response output of the system. Then the two variables will meet the relationship as follows:

$$Y(t) = h(t) * X(t) \tag{2}$$

where $h(t)$ is the system impulse response function, and * is the convolution symbol. Equation (2) has a correspondence relationship in the frequency domain.

$$C(\omega) = H(\omega)\cdot B(\omega) \tag{3}$$

where $H(\omega)$ is the transfer function of the ship's movement

$$H(\omega) = \int_{-\infty}^{\infty} h(t)e^{-j\omega t}dt \tag{4}$$

$B(\omega)$ and $C(\omega)$ are the Fourier transform of $X(t)$ and $Y(t)$ respectively

$$B(\omega) = \int_{-\infty}^{\infty} X(t)e^{-j\omega t}dt$$

$$C(\omega) = \int_{-\infty}^{\infty} Y(t)e^{-j\omega t}dt \tag{5}$$

Apply the complex conjugation to equation (3) on both sides, and then multiply the both sides of the equation (3) respectively. We got the equation (6) as follows:

$$S_c(\omega) = |H(\omega)|^2 \cdot S_B(\omega) \tag{6}$$

where $S_B(\omega) = B(\omega)\cdot B^*(\omega)$, is the wave spectral density function, or a wave spectrum for short, indicating the average wave energy in different frequency distribution. $S_C(\omega) = C(\omega)\cdot C^*(\omega)$, is the ship's movement spectral density function, called a movement spectrum, indicating the average movement of energy in different frequency distributions under the wave action. Equation (6) shows that the movement spectrum can be calculated from the wave spectral density function as long as the transfer function has been obtained.

*B. Transfer Function*

According to equation (1), the ship's impulse response function $h(t)$ satisfies the following equation:

$$\ddot{h} + 2\gamma\dot{h} + \omega_0^2 h = \chi\omega_0^2\delta(t) \tag{7}$$

Apply Laplace transforms to equation (7), we got:

$$H'(p) = \int_0^{\infty} h(t)e^{-pt}dt = \frac{\chi\omega_0^2}{p^2 + 2\gamma p + \omega_0^2} \tag{8}$$

Substituting the $p$ with the pure imaginary number $j\omega$ in the equation (8), the system transfer function becomes:

$$H(\omega) = 2H'(J\omega) = 2\int_0^{\infty} h(t)e^{-j\omega t}dt$$

$$= \frac{2x\omega_0^2}{(\omega_0^2 - \omega^2) + 2\gamma j\omega} \tag{9}$$

where $j$ is the imaginary unit, and $\omega$ is the frequency of vibration.

According equation (9), the amplitude-frequency transfer function and the phase frequency transfer function of the system can be calculated as follows:

$$|H(\omega)| = \frac{2x\omega_0^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\gamma^2\omega^2}}$$

$$= \frac{2x}{\sqrt{(1-\Lambda^2)^2 + 4\mu^2\Lambda^2}} \tag{10}$$

$$\Phi(\omega) = \arctan\frac{-2\gamma\omega}{\omega_0^2 - \omega^2} = \arctan\frac{-2\mu\Lambda}{1-\Lambda^2} \tag{11}$$

where $\Lambda = \frac{\omega}{\omega_0}$ is the tuning factor and $\mu = \frac{\gamma}{\omega_0}$ is the attenuation coefficient.

### *C. Description of wave movement*

The wave in a real environment is a random irregular movement. It can be described by the wave spectrum. The semi-empirical formula of ocean wave spectrum, presented by a Chinese marine sector [5] is

$$S_b(\omega) = \frac{0.74}{\omega^5} \cdot \exp\left[-\frac{96.2}{\omega^2 U^2}\right] \tag{12}$$

where $\omega$ is a wave frequency, and U is average wind speed. When the ship navigates in the speed V and at an angle $\beta$ between the moving direction and wave (moving direction for simplify), the corresponding formula for the wave spectrum is

$$S_B(\omega) = \frac{S_b(\omega)}{1 + (2\omega / g)V\cos\beta} \tag{13}$$

where g is the acceleration of gravity.

Figure 2 gives a set of spectrum curves in case of the speed V = 30 m / s, moving direction $\beta$ = 0 ° with different wind speeds. From Figure 2, the movement of energy will be concentrated in the range $0.05 < \omega < 0.4$ and the wave frequency will be between 0.1 and 0.4.

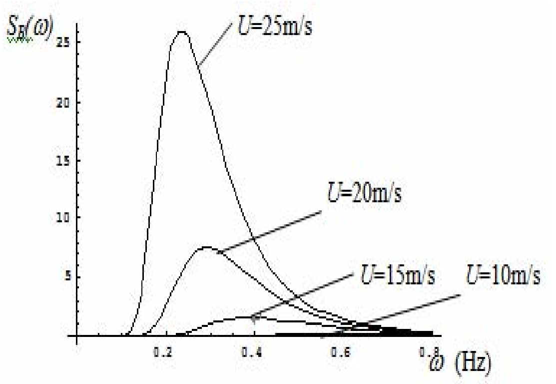


**Figure 2** Spectrum curves at speed V = 30 m/s, moving direction $\beta$ = 0 ° with different wind speeds.

According to the definition of the wave spectrum, there is a relationship between the spectrum and the average amplitude A (w), which is under a simple harmonic motion (unit regular waves) at a specific frequency w with an interval Δω [5]

$$A^2(\omega) = 2S_B(\omega) \cdot \Delta\omega \tag{14}$$

Phase distribution of wave movement $\varphi_B$ ($\omega$) is also random, generally being considered of a uniform distribution between in (0-2$\pi$).

### *D. Ship Motion Calculation*

In order to simulate the ship motion, we need to find out the function of all degrees of moving freedom changing with time Y(t). As a result of random wave movement, the ship movement is also random. We can take data ($\omega_k$, $S_{Bk}$ , $\varphi_{Bk}$) (k = 1 - N) with interval time $\Delta\omega$ in the wave spectrum space as a set of the samples of wave movement:

$$X(t) = \sum_{k=1}^{N} \sqrt{2S_{Bk} \cdot \Delta\omega} \cdot \cos(\omega_k t + \varphi_{Bk}) \tag{15}$$

Applying equations of (5), (10), (11) to calculate sample ship motion spectral values ($\omega_k$, $S_{Ck}$, $\varphi_{Ck}$), (i: 1-N)

$$S_{Ck} = \left|H(\omega_k)\right|^2 S_{Bk}\,,$$

$$\varphi_{Ck} = \Phi(\omega_k)\varphi_{Bk} \tag{16}$$

we then obtain a sample of ship motion

$$Y(t) = \sum_{k=1}^{N} \sqrt{2S_{Ck}\Delta\omega} \cdot \cos(\omega_k t + \varphi_{Ck}) \tag{17}$$

This determines one of degree of freedom movement. Similarly we can derive algorithms to calculate other five freedoms of ship movement.

Take a horizontal roll as an example, an inherent rolling cycle for a ship under 100 tons is in the range of 3-5s. In this paper, we assume T = 4s. The horizontal roll attenuation coefficient $\mu$ will be in the range of 0.05-0.075. Assume $\mu$ =0.06 and the correction factor $\chi$ = 0.5, the frequency transfer function H (w) of the shop can be determined by the equations of (10) and (11). Sample the wave spectrum within the scope of $0.05 < \omega < 0.4$ with interval $\Delta\omega$ = 0.01 under the conditions of the average wind speed $U = 15m/s$ , the speed of ship V = 30 m/s, and moving direction of the ship $\beta$ = 0 °. It gives a sample of wave movement similar to equation (15). The ship motion spectrum corresponding to the above-mentioned wave spectrum sample can then be obtained using equation (16). And then the ship motion, similar to equation (17), can be deduced.

## III. THE MOVEMENT OF A LASER COMMUNICATION SYSTEM

A ship laser communications system, generally, cannot be installed on the point of ship's centre of gravity. Thus, the movement of the ship laser communications system will be different from the movement of the ship's body in the wind and waves. Assume that the centre of platform of communication system is located at

$(x_{L0}, y_{L0}, z_{L0})$ in the coordinate system of the Figure 1. The location of the ship as a rigid body in waves is expressed by six-dimensional vector $\vec{\mathbf{B}}$. The position of the laser communication systems in the wind and waves, that is the centre and rotation direction of two-dimensional laser communication platform (Note: the direction of the device is not the direction of laser output) is expressed as the six-dimensional vector $\vec{\mathbf{L}}$. We have

$$\vec{\mathbf{B}} = (x_X, y_B, z_B, \theta_{XB}, \theta_{YB}, \theta_{ZB})^T \quad (18)$$

$$\vec{\mathbf{L}} = (x_L, y_L, z_L, \theta_{XL}, \theta_{YL}, \theta_{ZL})^T \quad (19)$$

where superscript $T$ is the matrix transpose operator. $\theta_{XB}, \theta_{YB}, \theta_{ZB}$ are the rotation angles of laser communication platform in the earth coordinate system. $\theta_{XL}, \theta_{YL}, \theta_{ZL}$ are the three types of rolling angles of the ships, i.e., horizontal roll, longitudinal roll and vertical roll. They are in the relationship as follows:

$$\theta_{XB} = \theta_{XL}, \theta_{YB} = \theta_{YL}, \theta_{ZB} = \theta_{ZL} \quad (20)$$

However, the location of laser communication system platform in three directions in the coordinate system is not only related to the location of the ship, but also related to the three types of rolling angles of the ship and their coordinates, that is

$$\begin{aligned} x_L &= x_B + z_{L0}\theta_{YB} + y_{L0}\theta_{ZB} \\ y_L &= y_B + z_{L0}\theta_{XB} + x_{L0}\theta_{ZB} \\ z_L &= z_B + y_{L0}\theta_{XB} + x_{L0}\theta_{YB} \end{aligned} \quad (21)$$

It can be expressed using transformation matrix:

$$\vec{\mathbf{L}} = \mathbf{M}_L \vec{\mathbf{B}} \quad (22)$$

where
$$\mathbf{M}_L = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{L0} & y_{L0} \\ 0 & 1 & 0 & z_{L0} & 0 & x_{L0} \\ 0 & 0 & 1 & y_{L0} & x_{L0} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The equation above indicates that once the ship's position vector and the location of laser communication system in the ship are known, we can calculate the location of laser communication system platform in the wind and waves, and therefore simulate the movement of the laser communication system in the wind and waves.

## IV. THE SIMULATION PLATFORM FOR LASER COMMUNICATION SYSTEM MOTION

Although the laser communication system position vector in the wind and waves varies with time in six degrees of freedom movements, there are two movements that have no effect to the laser communication. One is the movement along the centre of the laser output of the antenna, and another is the device's rotation around the optical axis. So in fact, the simulation of laser communication in the wind and waves can be achieved if four degrees of freedom movements are known. The six-dimensional vector $\vec{\mathbf{L}}$, which expresses the states of the movement and direction of the communication platform, should be converted into four-dimensional vector $\vec{\mathbf{S}}$ that is used to control the laser communication system motion simulation platform:

$$\vec{\mathbf{S}} = (y_S, z_S, \theta_{YS}, \theta_{ZS})^T = \mathbf{M}_S \vec{\mathbf{L}} \quad (23)$$

The communication platform developed is composed of four parts. They are a level mobile station, a vertical lift, a rotary table and a swinging desk. The rotation angles of the rotary table and the swinging desk remain unchanged in the converting process from the six-dimensional vector $\vec{\mathbf{L}}$ to the four-dimensional vector $\vec{\mathbf{S}}$. That is,

$$\theta_{YS} = \theta_{YL}, \qquad \theta_{ZS} = \theta_{ZL} \quad (24)$$

The movements of the level mobile station and the vertical lift $y_S, z_S$, are not only related to the displacement components of the six-dimensional motion vector $x_L, y_L, z_L$, but also related to the rotating component $\theta_{YL}, \theta_{ZL}$. The six-dimensional motion vector of a real world ship motion system includes the component $x_L$, which is along the direction of movement of ships. But there is no such a movement along x in our developed platform. This means that the movement components $y_S, z_S$ in the plane $x = 0$ will be used to substitute the movement components $x_L, y_L, z_L$ in the plane $x = x_L$, and also ensure that their physical functions are the same. Therefore

$$y_s = y_L + x_L\theta_{ZL} \qquad z_S = z_L + x_L\theta_{YL} \quad (25)$$

The corresponding transition matrix can be expressed as

$$\mathbf{M}_S = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & x_L \\ 0 & 0 & 1 & 0 & x_L & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Up to now, we have successfully convent the six movements (longitudinal sway, horizontal roll, horizontal sway, longitudinal roll, vertical sway, and vertical roll) of the ship in waves to the corresponding movements of the laser communication simulation platform. In a real world, the actual sea waves are in a big scale of movement. The distance between communicating ships in the real sea is also larger than that in the laboratory. In the simulation platform, the movement components $y_S, z_S$ can therefore be reduced in proportion to the actual height of waves caused. Note that, in the scaling process, the rotation angles $\theta_{YS}, \theta_{ZS}$ remains unchanged. Based on this scaling principle, the experimental platform of ship-borne laser communications system has been established.

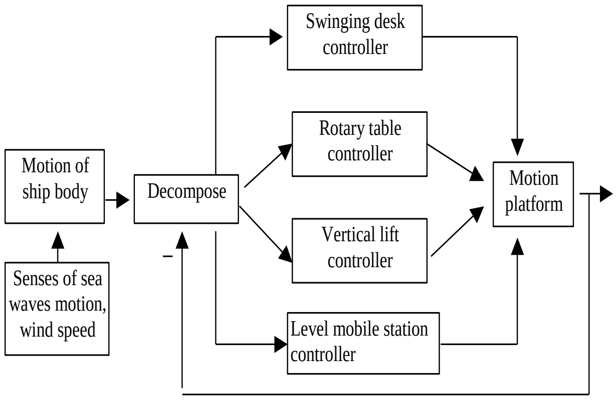


Figure 3-a Laser Communication system

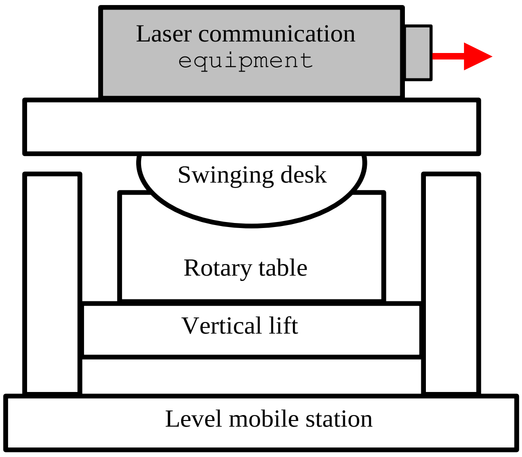


Figure 3-b Model of the motion-platform

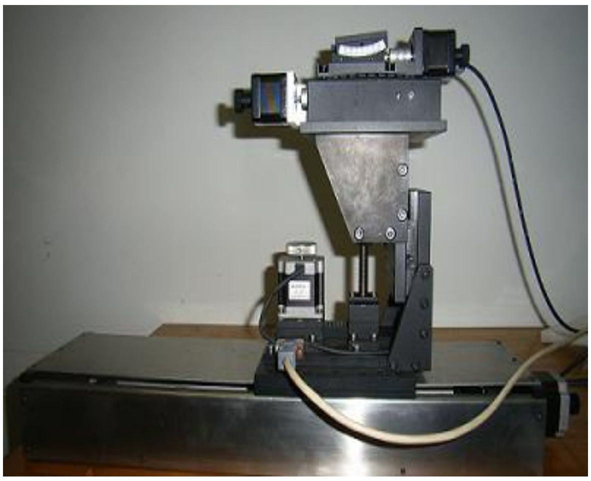

Figure 3-c Photo of the motion-platform

Figure 3 shows the Laser Communication system, which contains a number of senses, a computer, four controllers and motion platform with laser communication equipment. The computer, based on the information of sea waves, wind speed and ship move, decompose to four separate motions/rotations and send them to related controllers that control the motions of four parts of the motion platform driven by step motors. A step angle 1.8°, can be broken into 5, 10, 20, 25, 40, 50, 100, 125 by two two-axis controllers. The RS232 port of the controller is connected to the COM port of a computer, which calculates the movement of each freedom degree. The parameters of the motion platform are as follows. The level mobile station moves up to 400mm in length. The vertical lift's moving distance is up to 75mm. The maximum speed is 16mm/s. The rotation range of the rotation table is 0° - 360°. The scope of swing angle of the swinging desk is -15° - 15°, and the maximum rotation speed is 8°/s.

## V. SIMULATION RESULTS

In this section, we give simulation examples to illustrate how the communication motion-platform works. The simulation software implemented by VB 6.0 and the MS Access database is used to store the experiments data. The experiment comprises a sequence of simulations under different conditions, for example, the wind speed is divided to twelve grades (Table I shows the details), and the ship speed is of five grades (Table II shows the detail). Figure 4 shows the spectrum curves where the ship speed is fixed at grade 2(10 km/h) and the wind speed is 15.5m/s, 19.0m/s, 22.5m/s, and 26.5m/s respectively.

TABLE I. WIND SPEED GRADES

| Wind speed grade | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Wind speed(m/s) | 0.4-1.5 | 1.6-2.3 | 2.4-4.4 | 4.5-7.9 |
| Wind speed grade | 5 | 6 | 7 | 8 |
| Wind speed(m/s) | 8.0-10.7 | 10.8-12.8 | 12.9-17.1 | 17.4-20.7 |
| Wind speed grade | 9 | 10 | 11 | 12 |
| Wind speed(m/s) | 20.8-24.4 | 24.5-28.4 | 28.5-32.6 | > 32.6 |

TABLE II. SHIP SPEED GRADES

| Ship speed grade | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Ship speed (km/h) | 5 | 10 | 20 | 30 | 50 |

Figure 5 shows wave *X(t)* direction motion curves and ship body *Y(t)* motion curves on the ship speed grade 4 (30km/h) and wind speed grade 5. Figure 6 shows the relationship between average amplitude of wave and ship horizontal sway with the ship speed fixed at grade 4. Figure 7 shows the relationship between average amplitude of ship horizontal sway and wind speed with the ship speed fixed at grade 4. Figure 8 shows the relationship between average amplitude of wave and ship speed on the fixed wind speed at grade 4. Figure 9 shows the relationship between average amplitude of ship sway and ship speed with the fixed wind speed of grade 4.

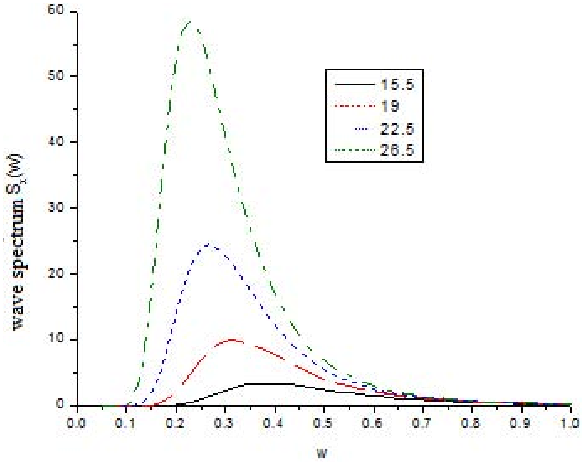


Fig4 a -- wave spectrum curves

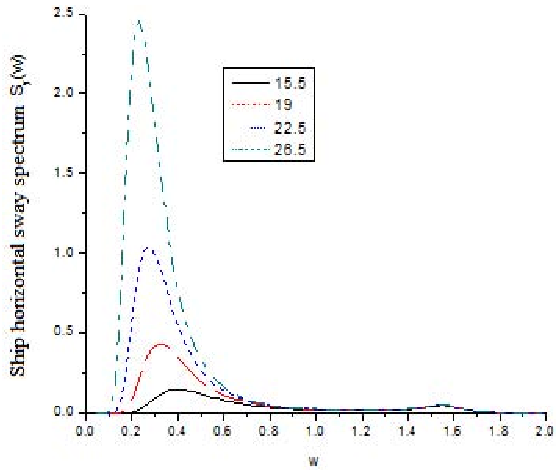


**Fig4 b** ship horizontal sway spectrum curves

**Figure 4** show the Spectrum curves on the ship speed is fixed and different wind speed

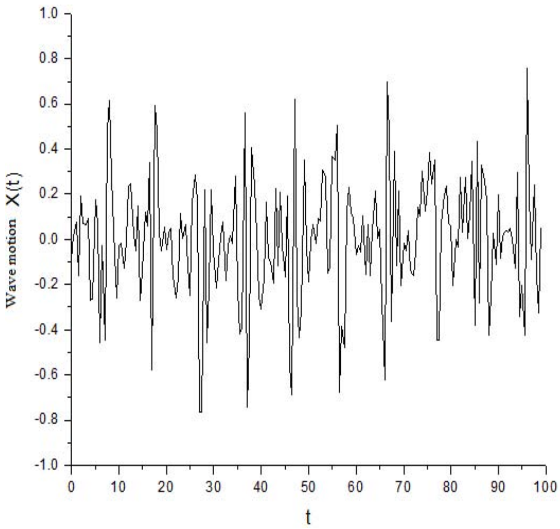


**Fig 5-a** Wave *X(t)* direction motion curves

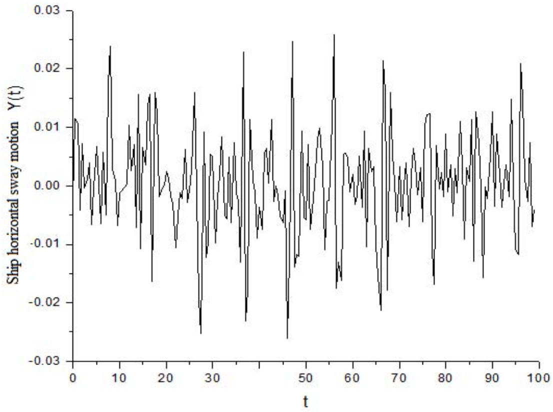


**Fig 5-b** Ship horizontal sway *Y(t)* motion curves

**Figure 5** wave motion curves and ship motion curves with ship speed and wind speed fixed

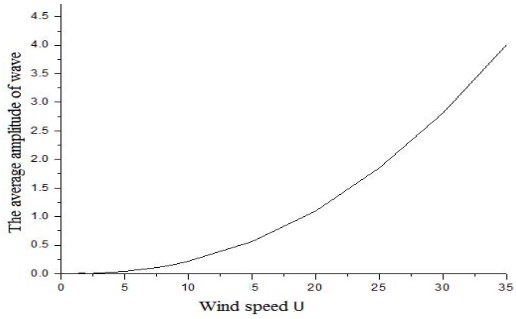


**Figure 6** the relationship between average amplitude of wave with respect to a fixed ship speed.

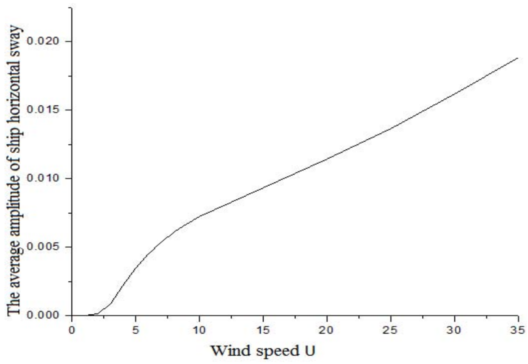


**Figure 7** show the relationship between average amplitude of ship horizontal sway and wind speed on the on the ship speed fixed.

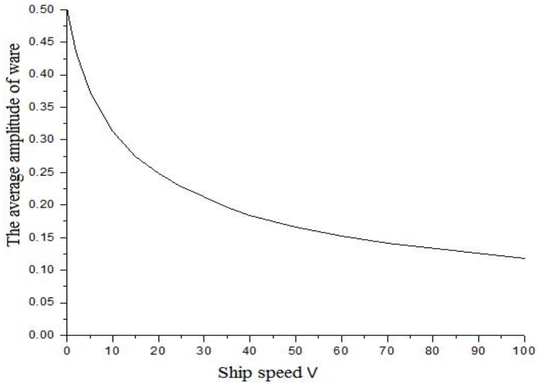


**Figure 8** show the relationship between average amplitude of ware and ship speed on the fix wind speed.

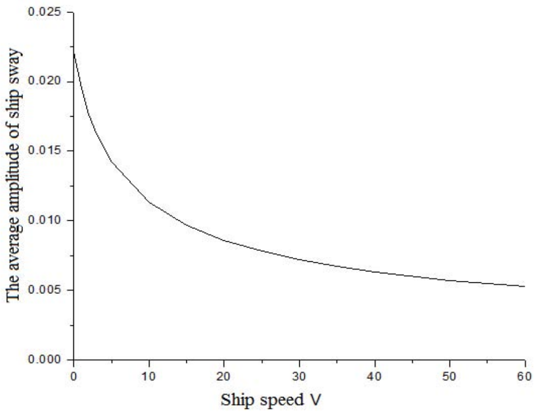


**Figure 9** shows the relationship between average amplitude of ship sway and ship speed with respect to the fixed wind speed.

In the above figures, the unit for the average amplitude is metre, for the wind speed is metre/second, for ship speed is kilometre/hour, and time is in second. Comparing the experimental results with theoretical calculations, the average error of wave amplitude is less than 0.47%, which satisfies the working requirements of free space laser communication.

Based on the experiment above, we can easily make the motion-platform work in an appropriate state, which in turn greatly reduces the interference of the wave, wind and ship motion, hence assuring the laser communication equipment is within working conditions. From the statistics results of communication simulation under different conditions of wave, wind and ship motion, we see that 99.5% communications were successful.

## VI. CONCLUSIONS

Laser communication has the following advantages:

- narrow beam
- large capacity
- high data transferring rate
- anti-electromagnetic interference ability
- high confidentiality

In addition, the equipment has the features of lower power consumption as well as a small and lightweight system structure. It is an important complement to future communications between ships. This paper, based on the differential equations of ship motion, presented a linear relationship model between waves and ship motion, calculated the movement spectrum from the wave spectrum, established the ship sway movement law, and achieved a computer manipulation control for the motion platform. The structure of motion simulation platform, consisting of the level mobile station, the vertical lift, the rotary table and the swinging desk, is simple and easy to implement. Simulation results demonstrate that the motion-platform works well and effectively overcomes the disturbance of the wave, wind and ship motion. It satisfies the requirements of the laser communication equipment working conditions.

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