A Novel Sea Wave Simulation Test Environment Construct for Shipborne Weapons Systems

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Abstract: A key technology problem with respect to approval testing and evaluation is that of simulating sea wave impact in shipborne weapons systems, both in terms of land-based and sea-based tests. There are two main methods in use at present: the first method is to build large-scale water pool, in which the shipborne weapons system under test is mounted to a special model ship; the second method is to simulate sea wave impact via a six degree of freedom motion simulation platform. Because of their extremely high costs and engineering implementation difficulties, the two methods have not generally been used in practice. In this paper, a flight path and sea wave impact simulation system which transfer test data via CAN bus was designed and developed, and five mathematical models of typical flight paths (such as a horizontal line path) and three levels of sea wave impact models were established. The sea wave impact models were superimposed to flight path models via equivalent theory and coordinate mappings; and realistic fighter flights path and sea wave impact environments were, in shipborne weapons system land-based tests, constructed via an input simulation in which the mixed signal is input to the control loop of weapon system under test. The models and methods in this paper were used in a battery of naval gun approval tests, and the tracking performances of the shipborne weapons systems were simulated via MatLab. The simulation test results indicate that the new simulation method and system can meet the requirements of shipborne weapons Operational Test and Evaluation (OT&E) protocols completely.

1 INTRODUCTION

Shipborne weapon system mainly include carrier-borne main gun, antiaircraft gun, high speed missile defense gun, and guided missile launching system, etc, whose Approval Test and Evaluation (AT&E) includes both land-based test and sea-based test. Only get passed in land-based AT&E, could shipborne weapon system be loaded on ship for sea test. While in land-based test, how to simulate the effect of sea wave impact to shipborne weapon system has been an insoluble problem for decades (He, C., et al, 2013).

In recent years, besides developmental test and evaluation (DT&E), some relevant OT&Es are also required in AT&E of shipborne weapon system. OT&E is that test and evaluation conducted by an independent OT&E agency to provide feedback on system design and the systems potential to be operationally effective and operationally suitable. OT&E for shipborne weapon system in AT&E, also known as initial OT&E, belongs to operational evaluation of navy. The initial OT&E is conducted on a production or production-representative system using typical operational personnel in a realistic combat scenario (Defense Acquisition University, 2012). In the AT&E of high-tech shipborne weapon system, some problems as no evaluation means for certain technical index and its operational effectiveness, mutual restriction between test sample size and confidence level of inference, unrealizable boundary conditions, limited failure reproduction methods, difficulties in providing near battlefield environment and realistic target, etc, are inevitable with conventional test theory and methods. Therefore, in order to solve the above-mentioned problems, research on simulation test and evaluation technology is becoming more and more important,

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which has become a valid supplement means for field live firing test.

Currently, many Chinese experts and technical staff have carried out some research on simulation test and evaluation in AT&E of shipborne weapon system. The common methods include mathematical simulation and hardware in the loop simulation (HWIL), as used in simulation of sea wave impact on shipborne weapon system (Cao, G. H., et al, 2009). Owing to its good performance price ratio (Wang, X., Shen, T. S., and Zhou, X. D., 2004), signal injection simulation method is used widely in simulation of target properties, background and interference, as literature (Wu, J. H., et al, 2012) carries out theoretical research on injected simulation test of closed loop for performance evaluation of infrared capture and tracking equipment, and literature (Du, H. J., Lei, J. and Yu, H., 2010) studies the application of infrared dynamic background simulation with injected technology. As in M&S of target flight path, most achievements focus on programming algorithm of unmanned flight path (Fu, X. W. and Gao, X. G., 2004), optimal design of path parameter based on target properties (Bian, X. L., Sheng, H. J. and Dai, D. C., 2011), and some advanced algorithms as artificial ant colony algorithm and improved gravitational search algorithm in path planning of unmanned air vehicles (Liu, M., et al, 2011, Li, P. and Duan, H. B., 2012).

Studies on influence of sea wave impact to ships are primarily computer-based simulation, such as simulation of ship's motion on irregular random wave (Yin, Q. and Chen, H. W., 2007), M&S for IMU of shipborne weapons in the condition of sea waves (Luo, Y., 2007). Some navy department has developed a load simulation system for type AT&E of naval gun servo system (Li, G., Xu, L. Q., and Chen, K., 2004). Considering the features of land-based test, technicians in Baicheng Ordnance Test Center of China developed a sea wave impact simulation system for land-based test of shipborne weapons (He, C., Dong, Q. S., Han, Y. H., et al, 2009), which uses moment motor to simulate the load of servo system (He, C., Dong, G. L, Cai, C. Y., et al, 2011).

Generally, four aspects are addressed in this paper. Firstly, we introduce the design of sea wave impact simulation system based on CAN bus and Ethernet. Then, we build the impact model of sea wave and kinematic model of ship on the sea. After that, we build models for five kinds of typical target's flight path. At last, we realize the simulation of sea wave impact through injection of ship movement disturbance on standard target's flight path directives, which is based on the principle of equivalent substitution. Thus, the problem of sea wave impact simulation in land-based test of shipborne weapon system is solved.

2 DESIGN OF SEA WAVE IMPACT SIMULATION SYSTEM

2.1 System Composition

Sea wave impact simulation system is designed as a distributed measurement and control system based on CAN bus, which takes on good environmental adaptation, and can generate standard signal automatically, flight path signal, and superposed signal of flight path and sea wave impact. Besides, it can carry out handshaking communications with weapon system under test according to specific protocols. Ethernet is adopted for communication between front-end computer and control computer of weapon system. Different kinds of data format and communication protocols for various weapon system are considered in the system design, which takes on good generality and extensibility. System chart is shown in figure 1.

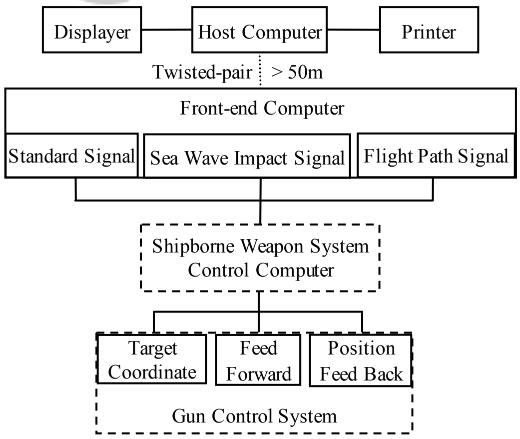

Figure 1: System chart of sea wave impact simulation system.

The sea wave impact simulation system is composed of host computer, front-end computer and communication network. In figure 1, dashed box indicate control computer that generates control instruction signals and gun control system of shipborne weapon system under test.

2.2 Operation Principle

As a control equipment in DT&E of shipborne weapon system, sea wave impact simulation system substitutes weapon fire control system to control the movement of naval gun and simulate the impact of sea wave, its specific functions are as follows:

- Generating five typical flight path's signals to drive shipborne weapon system;
- Simulating the movement of ships according to models of sea wave impact;
- Superimposing effect of sea wave impact on typical flight path's signals based on the principle of equivalent substitution;
- Controlling shipborne weapon system with superposed signal;
- System self-checking and dangerous area restriction for gun firing.

According to actual target flying parameters, simulation system can generate typical flight path's signals to drive gun for real time target tracking, and shoot at proper time. Thus, tracking and firing accuracy of weapon system can be tested, which provide technical gist for its DT&E.

Ship swing movement under different levels of sea wave can be simulated according to sea conditions in combat field of shipborne weapon system, its effect can be mapped to flight path through coordinate transformation and equivalent substitution method. Thus, sea wave impact on shipborne weapon system is modelled for land-based test, to establish the natural environment conditions for OT&E of weapon system.

3 COORDINATE SYSTEMS

3.1 Earth Coordinate System

Earth coordinate system *A-xyz* is an east-north-up coordinate system; it is also a static coordinate system with origin *A* fixed on any earth surface point. Axis *Ax* is located in horizontal plane with north as positive direction; Axis *Ay* is perpendicular to ground plane with upwards as positive; therefore, according to the rule of right hand, axis *Az* is in horizontal plane with east as positive direction. Obviously, plane *xAy* is a vertical plane, while plane *xAz* is ground plane, as shown in figure 2.

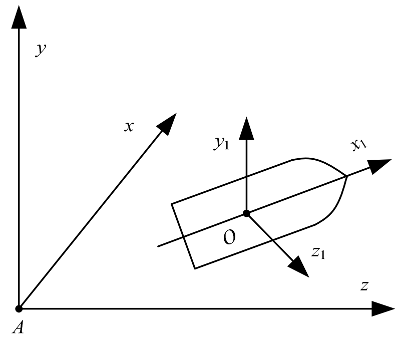

Figure 2: Earth coordinate system.

3.2 Hull Coordinate System

Ship hull coordinate system $O\text{-}x_1y_1z_1$ is a moving coordinates system, as shown in figure 3.

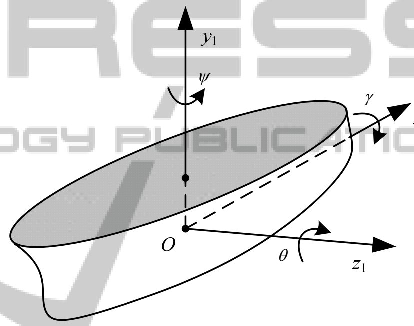

Figure 3: Hull coordinate system.

In figure 3, origin *O* is usually fixed in gravity center G of ships, Ox_1 is parallel with roll axis and point to prow, vertical axis Oy_1 points upward, and *Oz* is parallel with pitch axis and point to starboard. Ox_1, Oy_1 and Oz_1 are considered as roll axis, yaw axis and pitch axis separately.

3.3 Coordinate System Transformation

Coordinate system transformation refers particularly to coordinate transforming between earth coordinate system and ship hull coordinate system. Making translation of earth coordinate system *A-xyz* to take on coincident origin as hull coordinate system, relative attitude of hull coordinate system $O\text{-}x_1y_1z_1$ to earth coordinate system *A-xyz* can be determined by three attitude angles.

The pitching angle θ, yawing angle ψ, and rolling angle γ are defined as follows:

Pitching angle θ: included angle between hull longitudinal axis Ox_1 and horizontal plane. Included angle θ with hull longitudinal axis upon horizontal plane is positive; on the contrary, it is negative.

Yawing angle ψ: included angle between projection of hull longitudinal axis Ox_1 on horizontal plane xAz and axis Ax. Yawing angle ψ is positive while projection line of hull longitudinal axis is on the anticlockwise side; on the contrary, it is negative.

Rolling angle γ: included angle between Oy_1 and vertical plane containing hull longitudinal axis $Ox1$. Seeing along axis Ox_1 from ship stern, if Oy_1 lies on the right-hand side of vertical plane, γ is positive; on the contrary, γ is negative.

Three angle parameters defined above are also known as hull attitude angles, which can be used to derive transform matrix $L(\gamma, \theta, \psi)$ from hull coordinate system $Ox_1y_1z_1$ to earth coordinate system $Axyz$. We assume the origin and each coordinate axis of hull coordinate system and earth coordinate system coincide. Then, we get three elementary matrixes by rotating angles of ψ, θ and γ around corresponding axis in turning by the definition of attitude angle. The product of these three elementary matrixes is transform matrix $L(\gamma, \theta, \psi)$.

Certain vector $(x, y, z)^{\mathrm{T}}$ in earth coordinate system $Axyz$ can be transform to hull coordinate system $Ox_1y_1z_1$ via equation (1).

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = L_x(\gamma)L_z(\theta)L_y(\psi)\begin{pmatrix} x \\ y \\ z \end{pmatrix} = L(\psi, \theta, \gamma)\begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad (1)$$

Where

$$L(\psi, \theta, \gamma) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, \ a_{11}=\cos\theta\cos\psi,$$

$a_{12} = \sin\theta$, $a_{13} = -\cos\theta\sin\psi$, $a_{21} = -\sin\theta\cos\psi\cos\gamma + \sin\psi\sin\gamma$, $a_{22} = \cos\theta\cos\gamma$, $a_{23} = \sin\theta\cos\psi\cos\gamma + \cos\psi\sin\gamma$, $a_{31} = \sin\theta\cos\psi\sin\gamma + \sin\psi\cos\gamma$, $a_{32} = -\cos\theta\sin\gamma$, $a_{33} = \sin\theta\sin\psi\sin\gamma + \cos\psi\cos\gamma$.

4 MODELING OF STANDARD TARGET FLIGHT PATH'S SIGNAL

Generally, standard target flight path's signals can be divided into five basic types as horizontal uniform speed linear path, horizontal uniform acceleration linear path, gliding descent (with uniform speed) path, diving flight (with uniform acceleration) path and horizontal circling path with constant speed.

4.1 Horizontal Linear Path

Horizontal linear paths include horizontal uniform speed linear path and horizontal uniform acceleration linear path, as shown in figure 4.

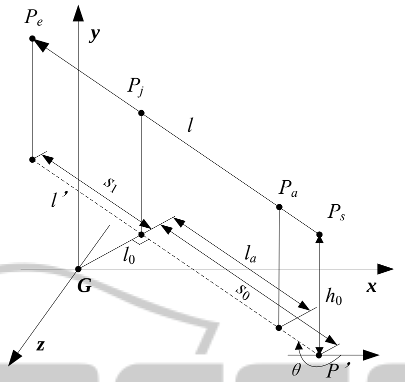

Figure 4: Schematic diagram of horizontal linear path.

In figure 4, P_s is path starting point, P' is projection of path starting point on horizontal plane, P_a is speedup point of target, P_j is shortcut point, P_e is path terminal point, G is position of gun; l is flight path of target airplane, dashed line l' is projection of flight path on horizontal plane. We take G as origin of coordinate, and assume X-axis located in horizontal plane pointing to north, Y-axis perpendicular to horizontal plane pointing upwards, and Z-axis perpendicular to X-axis pointing to east. Thus, coordinate system of G-xyz is built.

Modelling parameters of horizontal linear path are as follows:

- Starting path s_0 (m): lateral distance between path starting point and gun position. Both horizontal linear paths indicate movement path from starting point P_s to shortcut point P_j to terminal point P_e, namely target starts flying from s_0, goes through path shortcut point and in the end reaches s_1 to stop;
- Terminal path s_1 (m): lateral distance between path end point and gun position;
- Speedup path l_a (m): lateral distance between acceleration point and gun position;
- Speedup time T (s): Speedup duration time of target flying;
- Path altitude h_0 (m): vertical distance between target and horizontal plane;
- Lateral range l_0 (m): vertical distance between gun position G and path projection l';
- Target initial speed v_0 (m/s): initial flight speed of target, referring to target linear speed for circling path;

- Target acceleration a (m/s^2): constant acceleration of target speedup flying;
- Course angle θ (mil): included angle from north to target flying direction with clockwise as positive, which is used to determine travel direction of target in horizontal plane.

Starting point coordinates of horizontal linear path can be expressed as equation (2).

$$\begin{cases} x_0 = \sqrt{l_0^2 + s_0^2}\cos\alpha \\ y_0 = h_0 \\ z_0 = \sqrt{l_0^2 + s_0^2}\sin\alpha \\ \alpha = \theta - \pi - \arctan\left(\dfrac{l_0}{s_0}\right) \end{cases} \tag{2}$$

On speedup point, we get the equation (3). And at terminal point of speedup, we get the equation (4).

$$\begin{cases} x_1 = \sqrt{l_0^2 + l_a^2}\cos\beta \\ y_1 = h_0 \\ z_1 = \sqrt{l_0^2 + l_a^2}\sin\beta \\ \beta = \theta - \pi - \arctan\left(\dfrac{l_0}{l_a}\right) \end{cases} \tag{3}$$

$$\begin{cases} x_2 = \sqrt{l_0^2 + (l_a - v_0 T - \frac{1}{2}aT^2)^2}\cos\gamma \\ y_2 = h_0 \\ z_2 = \sqrt{l_0^2 + (l_a - v_0 T - \frac{1}{2}aT^2)^2}\sin\gamma \\ \gamma = \theta - \pi - \arctan\left(\dfrac{l_0}{l_a - v_0 T - \frac{1}{2}aT^2}\right) \end{cases} \tag{4}$$

4.1.1 Mathematical Model of Horizontal Uniform Speed Linear Path

While the target takes on horizontal uniform speed linear motion, we get the equation (5) under *G-xyz* coordinate system.

$$\begin{cases} x(t) = x_0 + v_0 \cdot t \cdot \cos\theta \\ y(t) = h_0 \\ z(t) = z_0 + v_0 \cdot t \cdot \sin\theta \end{cases} \tag{5}$$

4.1.2 Mathematical Model of Horizontal Uniform Acceleration Linear Path

While the target takes on horizontal uniform acceleration linear flight, we get the equation (6).

$$\begin{aligned} x(t) &= \begin{cases} x_0 + v_0 t \cdot \cos\theta & t \in [0, t_0] \\ x_0 + s_1 \cdot \cos\theta & t \in (t_0, t_0 + T] \\ x_0 + s_2 \cdot \cos\theta & t \in (t_0 + T, t_e] \end{cases} \\ y(t) &= h_0 \\ z(t) &= \begin{cases} z_0 + v_0 t \cdot \sin\theta & t \in [0, t_0] \\ z_0 + s_1 \cdot \sin\theta & t \in (t_0, t_0 + T] \\ z_0 + s_2 \cdot \sin\theta & t \in (t_0 + T, t_e] \end{cases} \end{aligned} \tag{6}$$

Where

$$s_1 = v_0 t + \frac{1}{2}a \cdot (t - t_0)^2,$$

$$s_2 = v_0 t + \frac{1}{2}aT^2 + aT \cdot (t - t_0 - T).$$

4.1.3 Programming

Programming with MatLab is done according to mathematical model of horizontal linear path.

Taking target motion acceleration 0 m/s^2, we get simulated directive signal for horizontal uniform speed linear path, as shown in figure 5.

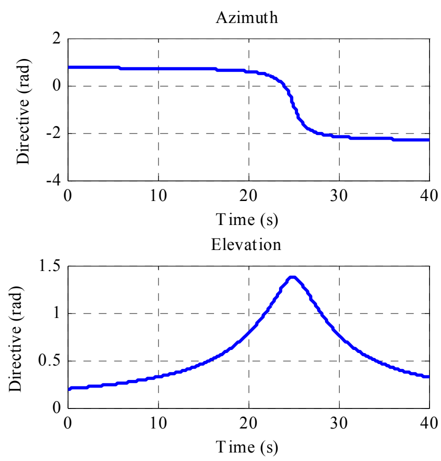

Figure 5: Simulated directive signal for horizontal uniform speed linear path.

4.2 Simulation of Target Path Signal

As to the above-mentioned path signals, azimuth directives for gun control system can be calculated as the equation (7). And elevation directive angle as the equation (8).

$$\psi(t) = \operatorname{arc\,cot}\left(\frac{x(t)}{z(t)}\right) \tag{7}$$

$$\vartheta(t) = \arctan\left(\frac{y(t)}{\sqrt{x^2(t)+z^2(t)}}\right) \tag{8}$$

5 PATH SIGNAL MODELLING WITH THE INFLUENCE OF SEA WAVE

5.1 Equivalent Substitution Method

Equivalent substitution is a common method in scientific research. As a quick and valid means for solving physical problem, the idea and method of equivalency are of far reaching importance in AT&E method research of weapon system.

Equivalent substitution method transform the actual complicated physical problem and process to an equivalent, simple and easy to research problem or process, under the guarantees of some kind of equal effect (characteristic and relationship).

5.2 Path Signal Model Under Sea Wave Interference

Additional motions as rolling, pitching, yawing and heaving would occur while ships sailing in wave. Owing to their minor amplitude, yawing and heaving can be ignored, and so we can assume the additional motions of ships in sea wave are mainly rolling and pitching. Roll and pitch cause hull attitude change in real time, which makes the trace command of naval gun to adjust according to hull attitude angle in order to track target flight path normally. Therefore, directive signal of naval gun's tracking target path under sea wave interference can be simulated by modified standard path signal with hull attitude angle. If we adopt this kind of modified path signal, actual working conditions of naval gun in sea wave could be equivalently simulated, which makes performance evaluation of weapon system more rational and credible.

Steps for modelling of path signal under sea wave interference are as follows:

- Build up kinematic model of ships in sea wave;
- Get transition matrix from earth coordinate system to hull coordinate system according to attitude angle of ship motion;
- Transform target path coordinates from earth coordinate system to hull coordinate system;
- Calculate azimuth directive and elevation directive in hull coordinate system by triangle transformation formula;
- Save directives in target path flying time, get path signal model under sea wave interference.

5.3 Simulation Analysis

Simulation and analysis mainly include modelling of ship movement, path signal modelling in earth coordinate system, coordinates transformation from earth coordinate system to hull coordinate system, and path signal tracking simulation under sea wave interference.

5.3.1 Ship Movement Simulation

Programming for ships motion in sea wave is done according to related literatures, which realizes the simulation of ship movement in sea wave.

We get simulation result for attitude angle of ship movement in sea wave as shown in figure 6, where heavy real line part is taken for modelling of path signal under sea wave interference.

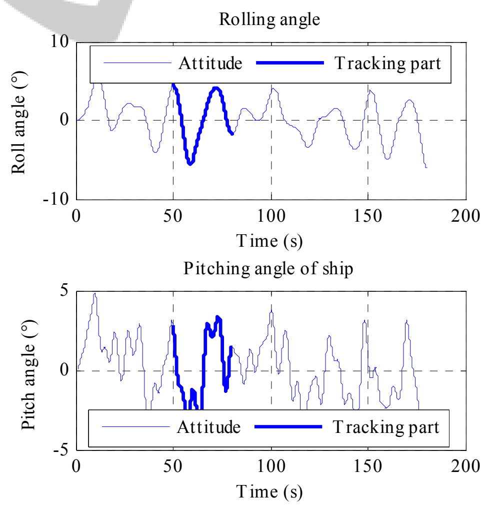

Figure 6: Simulation of ship movement in sea wave.

5.3.2 Path Signal Modelling Under Sea Wave Interference

Actually, the path signal is azimuth and altitude angle of target's flying path seeing from hull coordinate system. Therefore, if we take ship attitude angle in earth coordinate system as the coordinate rotation angle for building coordinate-transformation matrix, three-dimensional coordinate of target can be transformed from earth coordinate system to hull coordinate system, and then target path signal in hull coordinate system could be obtained. Modelling of gliding descent (diving flight) path, circling path, horizontal uniform speed (acceleration) linear path under sea wave interference can be realized according to this idea.

Take gliding descent (diving flight) path as an analysis example, if we take the bold real line part in figure 6 as the attitude of ship motion, target path signal under sea wave interference is shown in figure 7 where real line indicates standard path signal in earth coordinate system, and dot dash line is path signal under sea wave interference. In this way, path signal disturbed by ship attitude change in sea wave has much difference to static ship attitude.

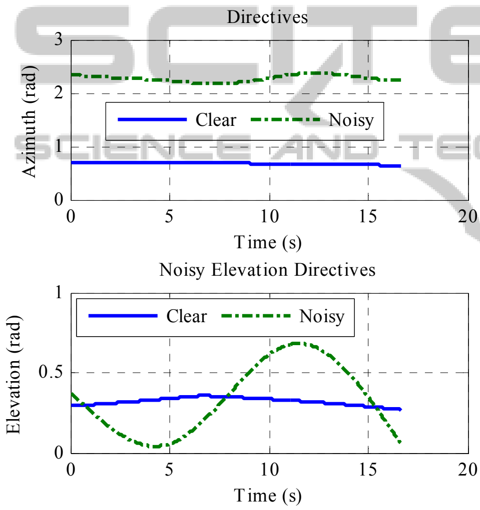

Figure 7: Path signal modelling under sea wave interference.

6 TRACKING SIMULATION OF GUN CONTROL SYSTEM

We take five flight paths under three levels of sea condition (0, 4 and 7) to carry out simulation test for operational performance evaluation of certain type of shipborne weapon system.

Figure 8 and figure 9 shows respectively directives and tracking error for horizontal uniform speed linear path and circling path with constant speed. Where, solid lines indicate clear standard path directive and tracking error without sea wave interference, dot dash lines indicate situations under level 4 sea condition, and dotted lines represent situations under level 7 sea condition.

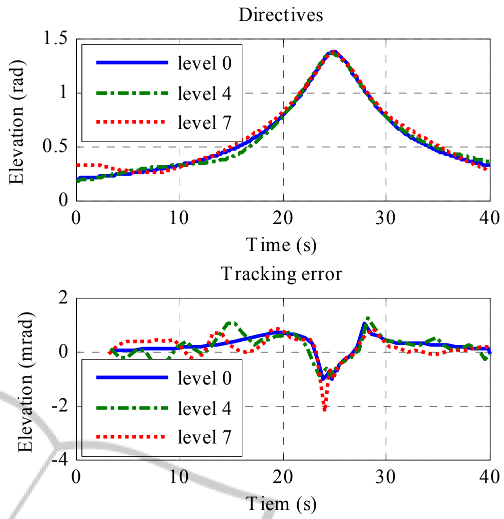

Figure 8: Horizontal uniform speed linear path.

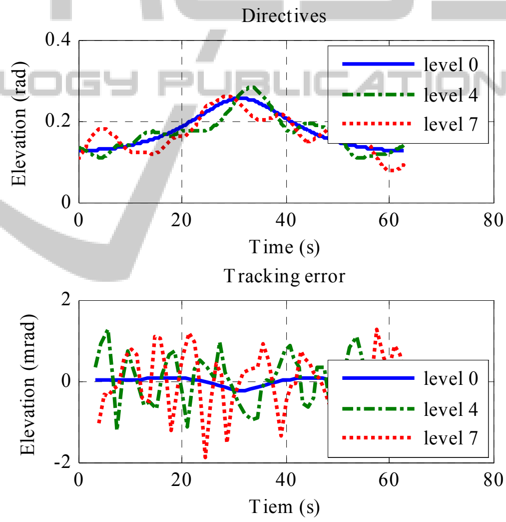

Figure 9: Horizontal circling route with constant speed.

7 CONCLUSIONS

In this paper, we propose a novel sea wave impact construction method for land-based AT&E of shipborne weapon system according to the requirements of OT&E. Based on the established ship movement model in sea wave and target flight path model, we use the equivalent substitution method and coordinate transformation to superpose sea wave impact effect on ships to the standard flight path signals. Thus, a novel multiplexed control signal is constructed, which realizes the simulation of real marine environment in land-based test of the shipborne weapon systems.

The designed sea wave impact simulation system can be used to substitute fire control system of shipborne weapon system in land-based test, which realizes the simulation of flight path signal and sea wave impact effect on ships by multiplexed control signal input method. In this way, the requirements of OT&E for shipborne weapon system are satisfied.

The novel method has been verified in T&E of certain type of naval gun weapon system. Tracking errors for different flight path under three levels of sea conditions (level 0, 4, and 7) are listed in Table 1.

Table 1: Maximum tracking error of target path under different sea conditions.

Path type	Level 0 $h_{1/3} = 0$ m	Level 4 $h_{1/3} = 1.2$ m	Level 7 $h_{1/3} = 6.0$ m
A	1.0575	1.2167	2.2064
B	1.7228	1.8463	2.0570
C	1.8087	2.0232	2.5734
D	1.8097	1.9197	3.0981
E	0.2379	1.2565	1.9102

In table 1, A denotes horizontal uniform speed linear path; B is horizontal uniform acceleration linear path; C is gliding descent path; D is diving flight path; E is circling path.

As shown in table 1, maximum tracking errors under level 4 sea condition for five typical target paths rise from 6.07% to 428.16% compared with that under level 0 sea condition, while maximum tracking errors under level 7 sea condition could rise from 19.40% to 702.94%. It is thus clear that tracking errors of shipborne weapon system for different flight paths diverse from each other, and they increase according to sea wave condition level.

The sea wave impact simulation system and the method introduced in this paper have been successfully applied in land-based AT&E of many weapon systems. Application results indicate that the system takes on features of correct principle, scientific method, easy to operate, high measuring accuracy, and stable control characteristics. Besides, the application of sea wave impact simulation system could shorten test period remarkably with less consumption and improved quality by providing a realistic target flight path in a realistic combat scenario (sea battlefield environment).

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