韓國海洋工學會誌 第11卷 第3號, pp.116~123, 1997. 8

◉ 論　文

A Study on the Motion Characteristics of a High-Speed Catamaran

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(97년 7월 3일 접수)

고속쌍동선의 운동특성에 관한 연구

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Key Words : Seakeeping Analysis(내항성 해석), Dynamic Response(동적응답), Ride Quality (승선감), High-Speed Catamaran(고속쌍동선), Wave Spectrum(파도 스펙트럼)

초 록

세계적으로 수요가 증대하고 있는 고속선의 설계시 승선감 또는 내항성은 필수적으로 고려되어야 하는 중요요소이다. 고속선은 필연적으로 과도한 운동을 동반하며 그로 인해 승객들은 극심한 멀미와 구토 등 불쾌한 승선감을 경험하게 된다. 근래에 항공 및 육상 교통수단들의 고급화에 따라 해양 운항선사들도 선박품질의 고급화와 쾌적한 승선감 확보에 비상한 관심을 보이며 승객 유치 및 승선률 제고를 도모하고 있다. 본 논문은 고속쌍동선에 대한 내항성능을 추정하고 그 해석결과를 실험과 비교하였다. 상하동요 및 종동요 간의 선형 연성 운동방정식을 사용하였고, 규칙파에 대한 상하동요의 응답특성 곡선을 구하였다. 또한, 불규칙파에 대한 운동응답을 추정하기 위하여 ITTC 파도 스펙트럼을 적용하였으며, 본 고속쌍동선의 운동성능에 미치는 선수 및 선수각의 영향을 고찰하였다.

1. INTRODUCTION

The worldwide market of car-ferry catamarans is growing rapidly. Its tendency of demand is characterized by increasing the speed up to 50 knots and enlarging the size up to 100 m. The high speed is achieved by designing a light-weight ship and carefully controlling the weight of every parts and equipments. Designing such a large-size high-speed vessel requires an accurate understanding of wave loads imposed on the vessel in waves.

In addition to that a high speed ship is inevitably accompanied by the excessive motion which causes passengers to experience extremely unpleasant discomfort, such as seasickness,

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nausea, and vomit. As the airborne and landborne vehicles are highly upgraded these days, the ship-operating companies begin to focus on the embodiment of pleasant ride quality and aim at expanding their business by increasing the number of passengers.

The operation of a high-speed catamaran in waves produces greater emphasis on the aspects of vessel motions and resultant structural loads. This is due to the larger encounter frequencies arising from the higher speed, by which increase in acceleration is attended. It is thus required to investigate the motion characteristics of a ship and to effectively reduce motion magnitudes relative to the free surface.

The analytical treatment of most models for motions and loads of ships in waves is primarily via frequency domain analysis, which is applied to linear dynamic systems.[1)2)] It is also possible for high speed catamarans in both controlled and uncontrolled modes of operation to use frequency domain methods. This approach is done by the stochastic equivalent linearization procedures (i.e. describing function).[3)] It is widely known that linear frequency domain models are generally adequate for the predictions of wave-induced motions and loads.[3)]

A catamaran of 80m class became recently popularized in worldwide car-ferry market. Since the seakeeping characteristics or ride quality is an important factor to consider necessarily in designing such a vessel, it is absolutely required to develop a method for determining and reducing its motions and loads. The need for increased habitability of a ship requires to develop efficient methods including the consideration of adequate types of Ride Control System (RCS) which employs various forms of lifting surfaces, such as foils and trim tabs.

The present paper describes frequency domain models for determining motions of a high-speed catamaran in waves. It presents the results of motion analysis for regular and irregular waves and of comparison with the experimental results. It also shows the influence of ship speed and heading angle on vertical acceleration of the catamaran in irregular waves and investigates the reasonable causes of their effects. The details are described in the following sections.

2. SUBJECT CATAMARAN

The car ferry ensures fast transportation of passengers and vehicles on international routes. Usually a high-speed catamaran is designed based on the concept of a light aluminium alloy. The design particulars of the high-speed catamaran used in this paper are listed in Table 1 and its profile view is shown in Fig. 1. The motion characteristics of the catamaran is investigated in the present paper.

Fig. 1 The Profile View

Table 1 Design Particulars of the Car-Ferry Catamaran

Length overall (m)	81.3
Length at design waterline (m)	77.8
Beam overall (m)	19.5
Draft at full displacement (m)	2.9
Service speed at 90% MCR and full load displacement (knots)	37.5
No. of passengers (person)	600
No. of vehicles	50 Cars + 4 Buses
Propulsion Engine	Disel Engine × 4 sets, 5420 kW × 1000 rpm
Propulsor	Waterjet × 4 sets

3. EQUATIONS OF MOTION

In order to calculate the motion of a catamaran in waves, the six degrees of freedom should be considered. However, in this paper only the longitudinal equations of motion which are primary motions are analysed and the translational mode of x-axis is neglected. The speed V is assumed constant even if the draft changes significantly. Then the equations of motion are formulated relative to an axis system whose origin is at the center of gravity. A right-handed coordinate system shown in Fig. 2 is selected.

The heading angle β is defined as 180° for head sea and 0° for following sea. The incident waves are assumed unidirectional sinusoidal waves. The surface wave elevation relative to calm water is represented as

$$\eta = A \sin \left[\omega_e t - k(x \cos\beta + y \sin\beta) \right] \tag{1}$$

where A is wave amplitude, k is wave number, λ is wave length, ω is circular wave frequency, and ω_e is encounter wave frequency;

$$\omega_e = \omega - kV\cos\beta \tag{2}$$

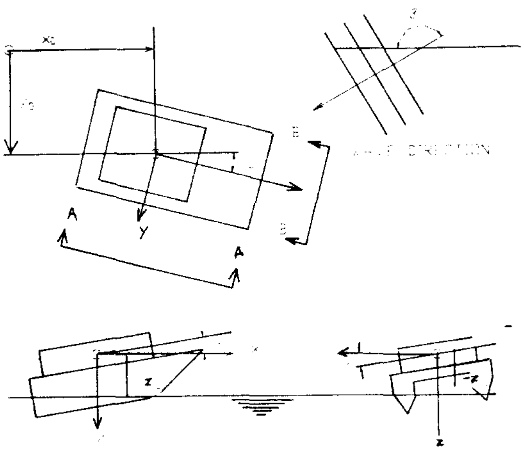

Fig. 2 The Coordinate System

The geometric difference of a catamaran from a conventional monohull vessel is basically twin hulls. Its motion, however, can be handled practically in the same manner as conventional monohull cases. The equations of motion are simplified and the linearized coupled ordinary differential equations of motion for vertical motions (i.e., heave and pitch coupled motions only) are obtained as follows.[1),2),3)]

$$\begin{aligned} Z_{\ddot z}\ddot Z &+ Z_{\dot z}\dot Z + Z_z Z \\ &+ Z_{\ddot\theta}\ddot\theta + Z_{\dot\theta}\dot\theta + Z_\theta\theta = Z_{waves} \end{aligned} \tag{3}$$

$$\begin{aligned} M_{\ddot\theta}\ddot\theta &+ M_{\dot\theta}\dot\theta + M_\theta\theta \\ &M_{\ddot z}\ddot Z + M_{\dot z}\dot Z + M_z Z = M_{waves} \end{aligned} \tag{4}$$

where $Z_{\ddot z}$ is the sum of mass and added mass of the vessel. $Z_{\dot z}$ is damping coefficient which depends on the encounter frequency and Z_z is restoring force coefficient which depends on the waterline area. Other coefficients are defined similarly. The hydrodynamic forces are determined for each sidewall hull separately, and the total effect on the vessel is found by their sum. They are obtained from integration of local vertical forces via the well-known new strip theory methodology. This procedure is based upon the assumption of no interference between the separate hulls, which is a generally valid result for high speed operating conditions for catamarans. The equations of motion for horizontal modes of motion are also derived in the same manner as those for vertical ones.

4. METHOD OF ANALYSIS

The motion in an irregular seaway is determined by the following steps[2)] :

A suitable wave spectrum is first chosen for the particular seaway in which the vessel is to operate. In this study an irregular wave system of 2.5 m significant wave height using ITTC spectrum shown in Fig. 3 is considered as follows.[4)]

$$S(\omega)=\frac{A}{\omega^5}\exp\left(\frac{-B}{\omega^4}\right) \tag{5}$$

$$A=\frac{173H_{1/3}^2}{T},\quad B=\frac{691}{T_1^4} \tag{6}$$

where T_1 is averaged period and $H_{1/3}$ is significant height of waves. As illustrated in Fig. 3, the wave energy is concentrated in the frequency range between 0.6 rad/sec and 0.9 rad/sec. This implies the possibility of an excessive magnitude of motion when the heave (Response Amplitude Operator) lies in the condition of resonance.

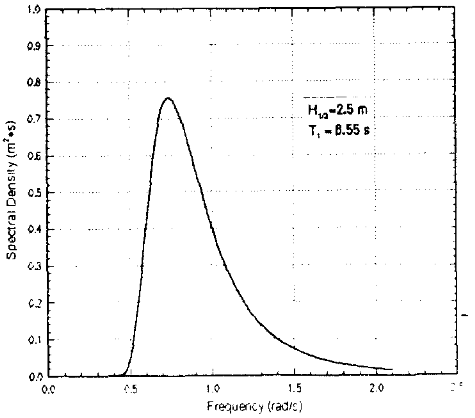

Fig. 3 The ITTC Wave Spectrum

Next a plot is obtained in which the ordinates represent the amplitude of motion with respect to a base encountering frequency distribution. This can be obtained analytically or by experimentation with regular or irregular waves in a towing tank. In this study it was obtained analytically in regular waves and extended to irregular waves.[1)]

To get the amplitude of motion analytically the external force due to waves and the hydrodynamic coefficients (added masses and damping coefficients corresponding to the encounter frequencies) are required. The external force was obtained by Froude-Krylov force assumption although the high frequency component of motion is not completely addressed. The hydrodynamic coefficients are calculated basically by NSM suggested in the reference[1)].

The diagram of the amplitude of motion is modified so that the ordinate represents the ratio or the square of the motion amplitude divided by the square of the wave amplitude. This diagram is termed the response amplitude operators (RAO) or simply the transform spectrum. The RAO diagram is transformed into a base of absolute wave frequency to be integrated with the wave spectrum. Fig. 4 shows such a diagram as obtained for heave motion in the present study.

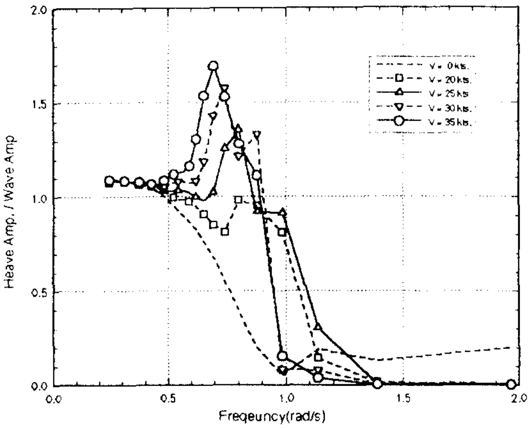

Fig. 4 Heave Response in Regular Head Waves

By integration of multiplying the ordinates of wave spectrum by the ordinates of RAO for the corresponding wave frequencies, the motion in irregular sea is obtained. This is formulated by the following equation describing the RMS (Root Mean Squared) magnitudes of heave.[2)3)]

$$\sigma_z=\sqrt{\int_0^{\infty}|T_z(\omega)|^2 S(\omega)d\omega} \tag{7}$$

where σ_z is RMS value of heave amplitude and $T_z(\omega)$ is heave RAO. For vertical acceleration the encounter frequency should be multiplied as follows

$$\sigma_{\ddot{z}}=\sqrt{\int_0^{\infty}|T_z(\omega)|^2 S(\omega)\omega_e^4 d\omega} \tag{8}$$

where $\sigma_{\ddot{z}}$ is RMS value of vertical acceleration.

5. ESTIMATION OF SEAKEEPING PERFORMANCE

5.1 Effect of Ship Speed

It is widely known that the seakeeping performance becomes worse as the speed of a vessel increases.[5] Although this is due to various complicated reasons, the most important two factors can be pointed out as follows. First, the increase of vertical acceleration, which is one of the major measurement of seakeeping performance, is proportional to the square of encounter frequency as equation (8). Thus in head sea condition the encounter period decreases or the encounter frequency increases as vessel speed increases. This is readily shown by the last relation of equation (2).

Secondly, the frequency range of the peak magnitude of Heave RAO moves closer to the frequency range of concentrated energy, usually to the lower frequency side of wave spectrum.

Fig. 5 shows the vertical acceleration with varying the ship speed as a parameter for the cases of head sea, beam sea, and following sea. In the case of head sea the calculated result is compared to the experimental ones. These experimental results were obtained from a series of towing tests performed at Korea Research Institute of Ships and Ocean Engineering for the present high-speed catamaran.[6] They illustrate considerably a good agreement.

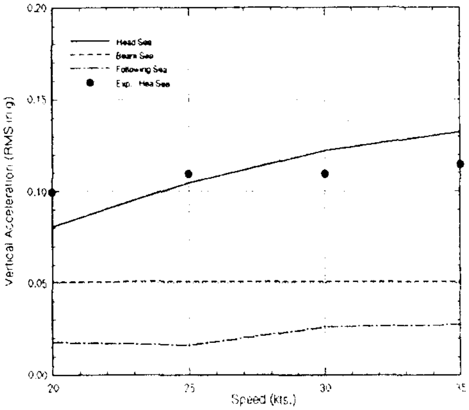

Fig. 5 Vertical Acceleration at Midship with Varying Ship speed

It is also found from Fig. 5 that the increase of vertical acceleration with ship speed is not so large as the case of conventional low speed ships. This seems to be a contradictory result to the previous explanation of the present section. However, a close inspection of Fig. 3, wave spectrum, and Fig. 4, heave RAO, unveils the reason.

As speed increases, the resonance region of heave RAO moves to the lower frequency side. Thus in the case of conventional low-speed ships, the vertical acceleration increases with the increase of speed as was explained by the two reasons stated before.

However, in the case of high speed ships, the vertical acceleration does not increase noticeably but even decreases sometimes as the ship speed increases.[6] This fact is explained by the following example.

When the ship speed is 25 knots, the resonance region of heave RAO of the catamaran is found in Fig. 4 around the frequency range between 0.6 rad/sec and 0.9 rad/sec. This frequency range corresponds very closely to the frequency range of peak magnitude of wave energy in Fig. 3 of wave spectrum. So if the speed is increased further or greater than 25 knots, the resonance region of heave RAO moves to the even lower frequency side, which is now outside the frequency range of peak wave energy. Then this matching condition of heave RAO and wave spectrum would result in an unnoticeable increase or even decrease of vertical acceleration. Nevertheless, it does not mean that the seakeeping problem is not important for high-speed ships because the absolute magnitude of response is still large and is regarded very severe considering the smaller scale and lighter weight of high-speed ships compared to the low-speed ones.

A simple method to reduce the ship motion is to decrease the speed of vessel for conventional ships.[5] It may still be a good method for high speed ships in much higher waves than 2.5m.[6] This is because the wave spectrum of 4.0m wave height is shifted to the lower frequency side and comes out of the resonance condition. However, it cannot be a good solution when the significant wave height is around 2.5 m, at which severe motion response occurs most frequently for high-speed ships. Therefore, to produce a high-class ship with good seakeeping performance, one understands that the active method, such as active ride control system, is not an option but a necessity.

Vertical acceleration is a measure of seakeeping performance and is estimated by an analysis in the frequency domain. ISO requires the results of 1/3 octave band analysis of vertical acceleration and proposes a standard by specifying the articles 2631/3.

Fig. 6 shows the 1/3 octave band data of RMS vertical acceleration recommended by ISO 2631/3 seasickness criteria for 30 minutes and 2 hours. It also shows the RMS vertical accelerations at midship obtained by calculations and experiments for ship speeds 25 knots and 35 knots at head sea condition. Circles are used to show the experimental results clearly. The calculation results and experimental results show good agreement qualitatively except that calculation yields larger peak magnitudes and lower corresponding frequencies than experiments.

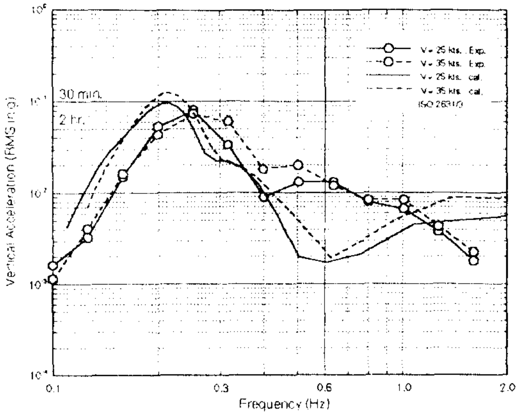

Fig. 6 1/3 Octave Band Data of Vertical Acceleration at Midship

The present calculation method is thought being capable of predicting the seakeeping performance. Assessment of seakeeping performance with the present method reaches a conclusion that the present catamaran does not possesses a very good seakeeping capability for a long voyage. Such a poor quality of seakeeping performance is inevitable for high-speed ships.

5.2 Effect of Heading Angle

Fig. 7 illustrates the RMS values of vertical acceleration in the unit of g (gravity) with varying the heading angle as a parameter.

It shows that the largest vertical acceleration occurs in the case of bow sea and the smallest in the case of quartering sea. This is again explained by equation (2), or the relation between speed and encounter frequency, and the relation between heave RAO and wave spectral density function.

According to the last relation of equation (2), the encounter frequency ω_e for following sea case increases to a certain point and decreases later as the ship speed V increases. The encounter frequency of following sea is lower than that of head sea after all, especially much lower than the frequency range of concentrated wave energy. Since the vertical acceleration is proportional to the square of encounter frequency, it is smaller for following sea than head sea.

When large head waves are upcoming, the ship is steered to avoid head sea condition resulting in possibly bow sea condition. Vertical Acceleration of the present high-speed catamaran, however, is even larger for bow sea than that for head sea. Fig. 7 shows this result clearly. Large vertical acceleration causes an unsafe and uncomfortable navigation. This means the change of heading angle for improving bad ride condition in head sea does not guarantee an effective result or drives the ship into an even worse situation.

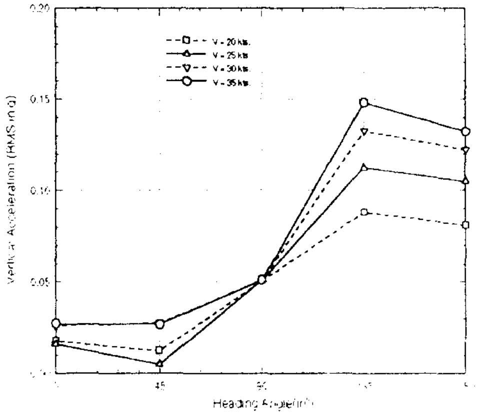

Fig. 7 Vertical Acceleration at Midship with Varying Heading Angle

Fig. 8 shows the 1/3 octave band of RMS vertical acceleration at midship of the present high-speed catamaran given by the same ISO 2631/3 criteria as Fig. 6. The calculated results of vertical accelerations at 35 knots for the cases of head sea, beam sea, and following sea are compared with the ISO criteria.

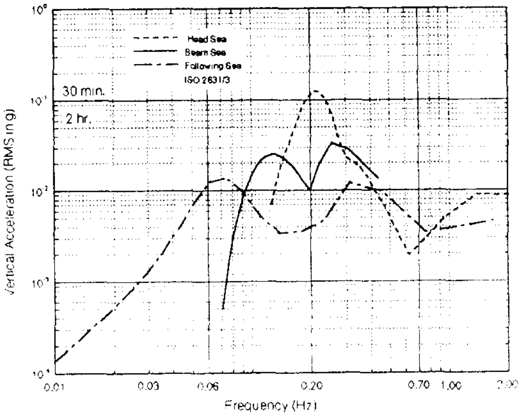

Fig. 8 1/3 Octave Band Data of Vertical Acceleration at Midship

As the heading angle decreases from head sea (β =180°) to beam sea (β =90°) and to following sea (β =0°), vertical acceleration decreases as shown in Fig. 5, two peaks appear in latter two cases, and the distance of frequency between the two peaks becomes larger. It is conceived that the peak at the lower frequency is due to the peak of wave energy spectrum and the one at the higher frequency is due to that of RAO.

6. SUMMARY AND CONCLUSIONS

The seakeeping performance of a high-speed catamaran was analysed by investigating the relation between the wave spectral density function and the heave response amplitude operator (RAO). It turned out that the range of operating or design speed and thus its encounter frequency lies in the resonance region of external wave force spectrum.

The effect of ship speed on the motion characteristics of a high-speed catamaran was investigated.

The traditional simple method of reducing ship motion has been to decrease the ship speed for conventional ships. It was, however, shown that it cannot always produce a good result for high-speed ships. It is because changing the ship speed may cause the resonance condition between the RAO characteristics and the wave spectrum.

The result of motion analysis was compared with the experimental results and they show considerably a good agreemet. They were then compared with the ISO 2631/3 standard criteria. It was concluded that the present high-speed catamaran does not possess a very good seakeeping characteristics.

The effect of ship's heading angle on the motion characteristics of the catamaran was also investigated. It was shown that motion characteristics of the catamaran is worst in bow sea case.

When large head waves are upcoming, the ship operator has traditionally steered to avoid head sea condition resulting in possibly bow sea condition. It was shown, however, that the change of heading angle for improving bad ride condition in head sea does not guarantee an effective result or drives the ship into an even worse situation.

It is thus recommended to adopt an active ride control system. The development of an optimal ride control system is not a simple job. However, it is much more efficient compared to the change of hull form. Therefore, the design of an effective ride control system becomes one of major procedures in designing a high-speed ship and requires further work and so does the estimation of seakeeping performance systematically using various design parameters.

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