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論　　文　　名	「Motion Prediction of a Multi-hull Maritime Navigation Vessel in Dynamic Positioning Mode Based on Maneuvering Equations」
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論文要旨

The Quadmaran vessel is a multi-hull maritime navigation vessel and is expected to be utilized for high-density water quality observation in aquaculture farms. Quadmaran is a newly developed concept and has four identical hulls, whose configuration can be changed to better suit different sailing needs, such as dynamic positioning (DP), docking navigation (DN) and straight navigation (SN). To assess the feasibility of the Quadmaran vessel, it has been utilized and tested at aquaculture farms. Sea area tests in 2019 were conducted at an oyster farm in Nanao Bay, Ishikawa Prefecture, Japan. Ultra-high density automatic water quality measurements were conducted at 80 points and 5 points each in the water depth direction in half a day for 400 points. The data collected by the Quadmaran vessel clarified the daily fluctuations in water temperature that have not been known until now. In cooperation with the numerical calculations, efforts have begun to increase the accuracy of ultra-high resolution water quality simulations.

The Quadmaran vessel acquires the required data by arriving at the set location with sensors. Affected by external turbulence, whether it can accurately maintain the location and complete relevant actions is essential to the reliability of the obtained data. The Quadmaran vessel is equipped with four hulls that can operate independently. This hull configuration allows smooth sailing even on farms with many obstacles. Moreover, it also makes DP relatively easier, and paves way for the DP control system design to be much more straightforward than the traditional generalship methods. The DP control system has also been successfully developed based on providing appropriate thrust to the four thrusters

according to the position information. According to our previous sailing data on the farms, the vessel performed very well even in weather conditions with winds. The Quadmaran vessel provides reliable technical support for high-precision water quality monitoring in the aquaculture industry. The quality and reliability of the collected data depends directly on the DP system, and therefore studying and understanding the vessel motion during DP becomes essential for improving precision. There is an urgent need for a mathematical model that can describe the motion of the Quadmaran vessel during DP.

Research on DP for ships has been conducted for more than 40 years, and great effort has been put into it. However, most of these are targeted at large general ships, and there are limited studies on the DP models for small multi-hull vessels such as the Quadmaran vessel. This study aims to build a motion prediction model to better understand the maneuvering motion status of the Quadmaran vessel during DP. It aims to seek functional limits, such as the maximum number of environmental forces that can be withstood, and the required thrust output to keep the vessel from moving even during meteorological conditions such as strong winds. With a working prediction model, it also paves way for applications such as on drone water helipads.

The numerical calculation model in this study is constructed based on the Maneuvering Modeling Group (MMG), which was first proposed by Ogawa, A et al. in 1978. There is also much research on ship maneuverability based on this model. However, the research vessel of this study has a unique hull structure, and the motion during DP is not only slow but also reciprocates around the target point. It means the sway motion of the vessel is equal to, and sometimes dominant, the surge motion. There are currently no models available to understand the motion characteristics of such a multi-hull vessel in DP mode. Therefore, a computational model is developed to predict the motion of the Quadmaran vessel during DP. Firstly, based on the assumption of quasi-static motion considering that the average speed while in DP does not exceed 0.25m/s and the yawing rate is consistently less than 0.026rad/s, a computational model is established by the basic data just obtained through static PMM (Planar Motion Mechanism) tests including static drifting and static turning. Meanwhile, the modeling of wind load on the hulls and the superstructure using the database of wind load tests is carried out to improve the efficiency of the prediction model. Four cases of the Propeller Open Test (POT) are also conducted to grasp the propeller performance characteristics in all four quadrants, under working conditions of different directions of rotation and inflow. Verification tests are carried out in calm water and actual sea areas to validate the motion prediction model. Secondly, the power units are being upgraded, and the vessel also has better performance and faster operating efficiency. As a result, the assumption of quasi-static motion may no longer be suitable. In addition, it is expected that an accurate computational model can provide valuable information to improve the performance of the vessel and aid in the design of control systems. Therefore, a computational method using the dynamic PMM tests is applied to better understand and grasp the maneuvering performance of the vessel during DP.

This research advances our understanding of the maneuverability of such a unique multi-hull with special motion characteristics. It has a good reference value for the future improvement of the Quadmaran vessel's DP control algorithm. Meanwhile, this study is also a new attempt at the PMM experimental method. From the results, the universality of the PMM experimental method has also been well confirmed.

This thesis is organized as follows:

Section 1 describes the status of aquaculture in recent years and the urgent need for improvement. Based on this background, research and development of various technology has also been advanced. This thesis lists some technologies being adopted, especially the development of the Unmanned Surface Vehicles (USVs) industry, and then leads to the study's research objective and points out its characteristics and unique technical advantages. Emphasizes the importance of the research object's DP function and surveys similar motion model precedents for the motion characteristics. Based on this, the author judges that the research on such unique vessel shapes and movement characteristics still needs to be improved. There needs to be more than the existing models to deeply understand its hydrodynamic and maneuverability characteristics, pointing out the necessity and value of this research.

Section 2 introduces the research object in detail and shows its functional characteristics and geometric dimensions in various navigation modes. Moreover, some applications for different water conditions are mentioned, including the propeller guard developed for aquatic plant problems in shallow sea areas. Moreover, the actual application achievement is listed. This way, a comprehensive and intuitive feeling of the object vessel is constructed.

Section 3 describes the mathematical model. Moreover, the hydrodynamic force, the propeller thrust, and the wind load are introduced sequentially. Two models based on quasi-static assumption and dynamic PMM tests are introduced separately for hydrodynamics. Then the calculation method of propeller thrust is introduced. Due to the Quadmaran vessel's shape characteristics, the wind force acting on the vessel is also considered in this study. A computational model for the entire vessel is established based on the wind load test results on a single hull and the superstructure. Due to the practical difficulties of the experimental verification on a whole actual vessel, computational fluid dynamics (CFD) is adopted to verify the rationality of the computational.

Section 4 describes in detail the experimental methods, conditions, and equipment of the model tests conducted to reveal the forces (including moment) acting on the hulls and the propeller thrust. The model tests are carried out based on the assumption of quasi-static motion, including static drift and static turn tests. Furthermore, dynamic PMM tests with high accuracy are also conducted. POT in four quadrants is conducted to obtain the propeller performance curves. Moreover, in order to validate the computational prediction model's correction, experimental validations are conducted in a calm water area and an actual sea area.

Section 5 presents the results of the tests described in Section 4. Specifically, the process of obtaining the hydrodynamic derivatives and the verified results for measured forces in pure sway, pure yaw, and pure yaw with a constant angle test is shown. It notes that the same experimental method is also applied in DN and SN modes to explore the hydrodynamic characteristics in various sailing modes (hull configurations). The performance curve of the propeller in four quadrants is then plotted. Both the prediction models have also been applied to simulate and predict navigation trajectories in calm water and actual sea areas. The results are also added.

Section 6 summarizes the findings of the study.

This thesis utilizes two mathematical model based on the quasi-static motion assumption and the dynamic PMM tests to establish a motion prediction model for a multi-hull vessel during DP. The hydrodynamic derivatives in motion equations of the Quadmaran vessel while in DP are successfully summarized, and the hydrodynamic characteristics are analyzed through continuous comparison between two models. The validation of the mathematical prediction models is further carried out by running the Quadmaran vessel in calm water and actual sea areas. From the results, it can be understood that simple static drift and static turn tests are somewhat feasible to understand the maneuvering characteristics. However, the dynamic PMM test method has better accuracy. This new attempt based on dynamic PMM tests can be highly effective for motion prediction of a slow-moving multi-hull vessel.

審査結果の要旨

四胴型自動航行船は水質データ自動取得時に定点保持形態になることで定点を保持している。定点保持の位置精度の確保や風等の外力により定点を保持できない可能性もあり、外力下における挙動を明らかにする必要がある。本研究では水槽試験において PMM 試験やプロペラ試験を実施することにより操縦流体力等の基礎データの取得、四胴型自動航行船に生じる風荷重のモデル化等が行われており、四胴型自動航行船の定点保持時の操縦運動を明らかにしたものであり、以下の主要な成果を得ている。

(1) 定点保持時の四胴型自動航行船の形態は、当該船を上から見て X 型の特殊な船型と言え、従来の船舶とは全く異なる操縦流体力となる。水槽における static PMM 試験により操縦流体力を明らかにした。また、pure sway test、 pure yaw test 等の dynamic PMM 試験を実施し、この特殊船型の操縦流体力を明らかにした。

(2) Propeller Open 試験が行われプロペラ性能を明らかにした。定点保持時はプロペラの正転のみならず逆転も行われる。これを鑑みた試験を実施し、定点保持時に使用される条件下での推力係数等が明らかにされた。

(3) 定点保持時に四胴型自動航行船の船体及びデッキに生じる風荷重の計算モデルが構築された。この計算モデルは数値流体力学を用いたシミュレーション結果と検証し良好な一致を得た。

(4) 四胴型自動航行船の試験機を用いて実海域試験を実施し、風速 2m/s から 5m/s の時は 2m 以内の定点保持精度を確保出来ることを明らかにした。また、static PMM 試験のみの操縦流体力を考慮した場合より、dynamic PMM 試験による操縦流体力を考慮した時の方が定点保持時の時系列シミュレーション精度を大幅に向上させることを明らかにした。

(5) 定点保持形態の操縦流体力に加えて自動着岸時の形態における操縦流体力についても PMM 試験により明らかにした。自動着岸時の形態は四胴型自動航行船を上から見て T 字型の形態となり前後非対称形態となる。このような場合、swaying 時の前後方向の流体力が無視できないことが明らかになった。この傾向は定点保持時の操縦流体力とは極めて異なる現象であることが分かった。

以上の諸成果により、これまで明らかにされてこなかった四胴型自動航行船の操縦流体力の特性を明らかにし、風等の外力下での操縦性能を明らかにし、本船の定点保持時の挙動を予測することに成功した。四胴型自動航行船は自動水質計測等の調査船として実運用され始めており関連分野の学術的・産業的な発展に貢献するところ大である。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。学位論文審査

委員会は、本論文の審査および最終試験の結果から、博士（工学）の学位を授与することを適当と認める。