Abstract 「論 文 の 内 容 の 要 旨」

論文題目　A Study on Motion Response and Wave Energy Absorption Characteristics of a Ship with an Active Control System

（アクティブ制御システムを有する船の運動応答と波エネルギー吸収特性に関する研究）

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Improving ride comfort has been a long term issue in the transportation industry. Vast research has been conducted and many inventions have been made since the first internal combustion engine was invented. In the marine field, several approaches have been proposed and tested to reduce the roll motion of the ship, for instance: rudder roll stabilizers, anti-roll tanks and fin-roll stabilizers. The methods adopted in those studies covered passive control, active control, simulation, numerical study and validation experiments. However, research concerning the heave and pitch motion reduction is scarce. For road vehicles, one of the most promising and widely used techniques for ride comfort is known as suspension. It normally consists of springs, dampers, tires and some linkages. It allows a certain reduction of the vibration disturbance caused by road roughness, hereby providing better road-holding ability and ride quality. An improvement of ride comfort can be achieved by applying proper control strategies, or mounting advanced shock absorbers. Besides, energy harvesting from the vibration motion has also drawn attention to some researchers.

It is known that a wave surface file is more complicated than a road file in respect of the magnitude and frequency of the surface elevation. Several questions have naturally been raised regarding an application of the suspension system in vessels: would it be feasible to build a ship with suspensions? Would the suspensions be effective in reducing the oscillation of the cabin? Would the energy conversion from kinetic form into electrical form be practical and valuable?

A company named Nauti-Craft Pty Ltd located in Australia, has developed a passive reactive interlinked hydraulic system and implemented it on a catamaran. A sea trial of the full model ship was carried out in 2014. Its videos showed a high level of ride comfort and stability. There are other inventions using the active control method, which can be regarded as a more immediate and effective approach. Velodyne Marine located in California has developed a catamaran in 2012, which was equipped with a full active suspension that consisted of state-of-art actuators and air suspensions. The sea trial showed great stability of the deck at high forward speed. Those two applications of the suspension system on vessels only considered the aspect of eliminating the motion of the cabin. However, it can also be used to capture wave energy.

Since 2008, a novel ship, namely Wave Harmonizer (WHzer), has been developed. It has a suspended cabin and control systems aiming not only at reducing the motion of the cabin, but also at converting kinetic energy between the cabin and the hulls into electrical energy.

The WHzer Type 1 in shape of a trimaran, had three small planning hulls and one big submerged hull. One suspension, which consisted of a spring and an oil damper, was mounted between the cabin and one of the planning hulls. It was found that strong dampers had relatively higher efficiency in reducing the motion of the planning hulls but not the motion of the cabin.

The WHzer Type 2 was a catamaran. It had two suspensions on each hull, located at the front and rear part of the hull. The test results indicated that the heave and pitch motion reduction of the cabin were improved along with an increase of the damping coefficient. The results also suggested that the relative displacement between the cabin and the hulls could produce sufficient kinetic energy to be reused.

Instead of oil dampers, a so-called electronic damper was designed and applied to the WHzer Type 3. A stepping motor, working as a generator, was connected to a load resistor in series, therefore forming an electrical circuit. The current flowing through the generator can be modified by tuning the magnitude of the load resistor. It consequently adjusts the angular velocity of the pinion, hereby the relative velocity between the cabin and hulls. The outcome can be seen as equivalent to the result obtained by an oil damper. The results of a towing tank test showed that the electronic damper was feasible. Smaller load resistances produced larger current, hereby stronger damper coefficients, which contributed more to the heave and pitch motion reduction of the cabin.

A semi-active motion control system was developed for the WHzer Type 4. The ship structure was similar to the Type 3, except that the number of motors in one control system was increased from one to two. The control system analyzed the feedback signals of the acceleration of the cabin as well as the relative velocity between the cabin and hulls to determine the execute time of the motion-control system. The results of a towing tank test showed that the heave and the pitch of the cabin were reduced significantly around its resonance frequency, meanwhile the amount of wave energy harvested achieved was noticeable. From Type 1 to Type 4, the ship could only support heave and pitch motion of the cabin and the hulls, while that of the roll was impossible due to the characteristics of the suspension structure.

In this research, WHzer Type 6 was proposed and developed. A model ship with length of 1.6m was built and tested. It has one compression spring at each corner, namely control spot of Front-Left, Front-Right, Rear-Left and Rear-Right, respectively. The springs were mounted between the cabin and the hulls in such a way that two of them fit on each hull and were located symmetrically from the center of the buoyancy of the ship. Four brushed DC motors were employed and set on the deck above the springs, so that one motor was in charge of one control spot. One shaft of each M/G was connected to a pinion gear whose teeth meshed with that of a rack. The rack was vertically fixed on a hull, therefore the vertical relative displacement between the cabin and the hulls could be converted into the rotation of the M/G, and vice versa. Using four modified racks, two set of Watt's link and two pantographs, the roll motion of the cabin was attainable.

An active control system was proposed and constructed for WHzer Type-6. It consisted of three modes: skyhook mode, MPPT mode and integrated mode. The skyhook mode aimed at reducing the motion of the cabin so as to improve its ride comfort. The MPPT mode was applied at a maximum power point so as to capture the wave energy as much as possible. The integrated mode was a combination of the skyhook mode and the MPPT mode. By tuning the impact factor of the MPPT mode or the I gain of the skyhook controller, a certain level of the motion reduction of the cabin and the energy harvesting ability could be achieved.

At the skyhook mode, an I controller was designed to correct the motion of the cabin. The acceleration at each control spot of the cabin was detected by a G-sensor, then sent back to its corresponding I-controller. The error from between the processing signal and the set point was calculated, and according to it a correcting command voltage was produced by the controller. The voltage was applied to the M/G, which consequently produced a torque acting on the cabin and the hulls. In this way, new acceleration of the cabin was generated. This loop continues until the set point was reached. At the MPPT mode, the maximum power point was tracked until the impedance of the source and its load were matched. Electronic loads of the MPPT controller were tuned at a given oscillation frequency to find the MPPs. At the Integrated mode, both the skyhook mode and the MPPT mode were executed. The command signal from the two modes were multiplied by an impact factor, then added up to form a new command voltage for the M/Gs.

Several experiments were carried out to investigate the performance of the proposed ship structure and control systems, which included a dry test and a wet test. The dry test consists of a free decay test of the cabin, a motor driven test and a bench test. The natural frequency of the cabin, coulomb friction and the dead zone of the suspensions were investigated. A bench test was implemented to validate the concept of the control system. In it, the hulls were vertically oscillated by a powerful machine at various frequencies and the heave response of the cabin was observed under the skyhook mode and the MPPT mode. The results indicated that the heave motion of the cabin can be significantly reduced at the skyhook mode. With an I gain of 573, more than 50% of the heave was eliminated. It also told that higher I gain contributed more on the reduction of heave, at the expense of consuming more energy. The test at the MPPT mode implied that the MPPs can be reasonably found by a 1 DOF simulation program. The effect of the skyhook mode and the MPPT mode was validated.

A tank test was implemented under regular wave conditions, with a towing speed of 0m/s and 1.5m/s, respectively. The heave, pitch and roll of the cabin and the hulls, the power production at the M/Gs terminal, the relative displacement between the cabin and the hulls were discussed at each control mode. The motions at the rigid mode and the free mode were tested as well, and were used as a reference system for motion reduction evaluation of the skyhook mode.

It was found that at the skyhook mode, the motion of the cabin was greatly suppressed, especially around its resonance frequency. When the I gain was set as 573, the heave response of the cabin was less than 60% of the incident wave amplitude, that of the pitch and the roll were lower than 50% of the incident wave slope. Reducing the gain of the I controller, decreased the ability of the motion elimination of the cabin, meanwhile making it consume less energy. Specifically, at head wave conditions, with an I gain of 115 and a forward speed of 0m/s, the motion reduction of the cabin in terms of heave and pitch were barely observed. At the forward speed of 1.5m/s, the motion reduction at the heave and pitch of the cabin was obtained at a great level. However, the elimination of the roll of the cabin was only achieved around its resonance frequency. Moreover, it was seen that at some frequencies the motion of the hulls was increased while that of the cabin was reduced.

At the MPPT mode, it was seen that the highest wave energy capture width ratio at 0 forward speed was about 27% at 5.5 rad/s, while that at 1.5m/s was about 82% at 9 rad/s. At a given frequency, the maximum power was captured at either the case with an impact factor of 1 or that of 3, while that of 1/3 was generally the lowest. It implied that the one DOF simulation program provided a reasonable prediction on the MPPs, although applied it on a six DOF model may cause deviation. The motion response of the cabin and the hulls were increased compared to that at the rigid mode at some frequencies, which implied that the ride comfort was sacrificed for harvesting wave energy.

At the integrated mode, it was observed that when the skyhook mode was in the dominating position, a certain motion reduction of the cabin can be achieved, accompanied with a large amount of energy consumption. In contrast, when the MPPT mode was in the dominating position, certain amount of wave energy was captured, however, the heave of the cabin was enlarged at some frequencies compared to that at the rigid mode. It suggested that the motion response of the ship and the power production of the system were analogous to that at the dominating mode. Moreover, it is possible to achieve an equilibrium of the energy consumption/production or motion reduction/increase.

The research was mainly conducted on an experimental investigation basis. A simulation program with two or higher degrees of freedom should be developed so as to provide a deeper and more precise insight into the motion response and the power production of the novel catamaran.