HIGH SPEED MARINE VEHICLES WITH AERODYNAMIC SURFACES: DEVELOPMENT OF A DYNAMIC MODEL FOR A NOVEL CONFIGURATION

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SUMMARY

A research programme on high speed marine vehicles fitted with aerodynamic surfaces started in Cranfield University in 2005. One of the configurations analyzed is a high speed prismatic planing hull with one or more aerodynamic surfaces; it is called a hybrid vehicle (HV). Two mathematical models have been developed for the dynamic behavior which is a combination of the very different behaviors of aircraft and ships. The first model estimates the equilibrium attitude of the HV at a certain speed. A parametric analysis for the influence of the configuration on the performance of the HV has been conducted (1). With the second model, the authors propose a set of ordinary differential equations of motion, derived in the frame of small-disturbance stability theory which has been used to investigate the longitudinal dynamic stability of the HV (2).

Ref. (1) and (2) present a complete description of the mathematical models, while this article summarizes the methodology adopted to develop these dynamic models and gives a brief summary of the results.

1 NOMENCLATURE

HV	Hybrid Vehicle, having both aerodynamic and hydrodynamic surfaces
WIGe	Wing In Ground effect, aerodynamic effect experienced by wings flying near the ground (at a height above the ground about a fraction of the aerodynamic chord)
R/W	Resistance to weight ratio, ratio between the sum of aerodynamic and hydrodynamic drag forces and the weght of the vehicle
SPPO	Small Period Pitching Oscillation: oscillation mode of airplanes after a small disturbance
SPEoM	Small Perturbations system of Equations of Motion

2 CONTEXT

Several new high speed marine vehicle configurations have been developed during the last two decades (3). For ‘very high speed vehicles’ (~50 kts), the aerodynamic forces can become of the same order of magnitude compared to hydrodynamic forces, especially for small vehicles (weight < 10 tons).

Although in some cases this can lead to stability issues, it offers a new range of possibilities to sustain the weight of the craft. High speed marine vehicles can be equipped with specifically designed aerodynamic surfaces and the aerodynamic lift can ‘alleviate’ the weight of the vehicle. This means less wetted length, less hydrodynamic drag and less required power. Such vehicles exploiting aerodynamic and hydrodynamic forces can find applications in several scenarios: high speed civil marine transport, military troop marine transport for littoral warfare and autonomous unmanned vehicles with airborne and seaborne capabilities.

3 PROBLEM STATEMENT

The dynamic models available in the literature focus either on marine vehicles or on ‘Wing in Ground effect (WIGe)’ vehicles. These models concentrate, respectively, on hydrostatic/hydrodynamic and aerodynamic forces; therefore they are not suitable for a vehicle experiencing hydrostatic, hydrodynamic and aerodynamic forces of the same order of magnitude.

4 METHODOLOGY

First of all, a configuration was selected comprising a HV having aerodynamic surfaces, operating near the ground (WIGe), and a high speed prismatic planing hull.

Since the HV shares the same dynamic characteristics as both WIGe vehicles and planing crafts, an analysis of the available dynamic models of these configurations has been conducted. A model for each has been implemented in Matlab, using a common template: xml file as input, graphical and excel files as output. The validity of these two dynamic simulation models has been tested against experimental and computational data and they have shown good agreement with previous work (4).

A mathematical framework to study the equilibrium state of the HV and its static stability has been developed by the authors, starting from the analysis of the static stability of WIGe vehicles and planing craft (1). Furthermore, a mathematical model has been developed to study the dynamic stability of the HV (2). Together, the static and the dynamic stability mathematical models constitute a useful tool for the conceptual and preliminary design of high speed marine vehicles having aerodynamic surfaces.

5 PROGRESS

5.1 SELECTED CONFIGURATION

The HV configuration combines the characteristics of a WIGe vehicle and a high speed marine vehicle:

- the aerodynamic surfaces of the HV operate in WIGe, since they are very close to the ground,
- the vehicle is in contact with the water at very high speed (>50 kts, 92.6 km/h or 57.5 mph), therefore it has to adopt a high speed marine configuration.

Among high speed marine vehicles, the planing craft configuration has been chosen as the authors considered that the HV should have also a free flight capability (or at least wing in ground flight), therefore the configuration with hydrofoils as hydrodynamic surfaces is not suitable. The selected HV configuration is shown in Figure 1.

5.2 WIGe VEHICLES AND PLANING HULL CRAFT DYNAMICS

A three step approach has been adopted for both WIGe vehicles and planing craft configurations:

1. investigation of the available mathematical models on the vehicle’s dynamics,
2. selection of a mathematical model,
3. implementation of the selected mathematical model in MATLAB.

The implementation of mathematical models representing WIGe vehicles and planing craft dynamics needed to be validated against data available in the literature, therefore some previous works on WIGe vehicles dynamics (5), (6) and planing craft dynamics (7) have been selected. Two programs, developed in MATLAB, start from the geometrical, inertial, aerodynamic and hydrodynamic characteristics of the vehicle (input) and estimate the equilibrium attitude (1st output) and the modes of oscillation of the vehicle (2nd output). The results, as seen in (4), are in good agreement with the cited references; therefore they constitute a valid basis for the development of a HV dynamics model.

5.3 HYBRID VEHICLES DYNAMICS

5.3 (a) System of equations of equilibrium (longitudinal plane)

An analysis of all the hydrostatic, hydrodynamic and aerodynamic forces and moments acting on the HV has been conducted to develop a system of equations of equilibrium in the longitudinal plane (Figure 1). The model can estimate the equilibrium attitude of the HV across a range of speeds. It has been implemented in Matlab and a parametric analysis of the influence of the wing area, the wing position and the position of the CG on the performance has been conducted (1).

In Figure 2 the influence of the wing area on R/W is illustrated. The three configurations are identical except for the area of the wing (this HV configuration has one wing). The speed range can be divided in two zones by the speed at which the curves cross each other (about Froude number 2.9, 40 knots), called V_X. In the speed range $V_0 < V_X$, the total drag of the planing craft configuration is lower than the total resistance of the HVs with wing. For $V_0 > V_X$, the HVs with wing experience less drag. If the requirement of the vehicle is to reach a speed $V > V_X$, the configurations with wing will require a power propulsion lower than the planing craft. In Figure 3, the influence of η, the angle between the mean aerodynamic chord of the wing and the keel of the planing hull is presented. The three configuration used have $\eta=0$ deg (chord parallel to the keel), $\eta=5$ deg and $\eta=10$ deg. R/W is lower for an increased η, due to the fact that increasing η, the angle of attack of the wing is increased. In Figure 4, the influence of the longitudinal position of the CG (center of gravity) on R/W is shown. This parameter has the most significant influence on the resistance. At high speed, a lower R/W is obtained when the CG is shifted rearward.

5.3 (b) System of equations of motion (small disturbances framework, longitudinal plane)

A mathematical model which can address the static and dynamic stability of the HV is required. Starting from the ordinary differential equations of motion used for WIGe vehicles and planing craft, the authors developed a model to describe the longitudinal motion of the HV after a small disturbance.

Static Stability

The static stability analysis is presented in (1). Briefly, starting from the developed system of equations of motion, the static stability of the HV has been derived using the Routh-Hurwitz criterion. A criterion to estimate the static stability of the HV has been identified, and a simplified version of the same condition has been derived for the reduced order system of equations of motion (reduced because the influence of the surge motion has been neglected). This condition for the HV is very similar to the static stability condition developed by Irodov for the WIGe vehicles (8). In fact, Irodov stated that a WIGe vehicle is stable if

"the (aerodynamic) center in height will be located upstream of the (aerodynamic) center in pitch"

It means that dividing the total lift in two components, the lift due to a variation of the pitch angle (L_{alpha}) and the lift due to a variation of the height above the surface (L_{height}), the point of action of force L_{height} should be located upstream of the point of action of force L_{alpha}.

Similarly to Irodov, the authors (1) propose that a HV is stable if

"the hydrodynamic center in heave should be located downstream of the aerodynamic center in height"

It means that dividing the hydrodynamic lift due to a heave variation (L_{hyd}) from the lift due to a variation of the height above the surface (L_{height}), the point of action of L_{height} should be located downstream the point of action of L_{hyd}. This criterion requires validation against experimental data, but it constitutes a relatively straightforward 'thumbnail rule' to estimate the static stability of the novel hybrid configuration.

<u>*Dynamic Stability*</u>

To estimate the modes of oscillation of the HV the stability derivatives are needed. As described in (2), there are existing methods to estimate their values but experimental data are required to determine the dynamic behavior of the HV. It is however possible to make a comparison between the dynamics of conventional airplanes, WIGe vehicles, planing craft and the HV (Table 1). With respect to the planing craft configuration, the HV also has to take into account the influence of the small changes of the height above the sea surface of the aerodynamic surfaces (h) and the surge velocity and acceleration disturbances ($\partial x/\partial t$ and its derivative). With respect to WIGe vehicles, the HV also has to take into account the vertical position disturbance (z), since this greatly influences the hydrostatic and hydrodynamic forces acting on the HV.

6 CONCLUSIONS

Due to the novelty of the HV configuration, two mathematical models have been developed to analyze its equilibrium attitude and static/dynamic stability (1) (2). The first model has been used to develop a parametric analysis, and the results are that:

- diminishing the longitudinal distance between the transom of the hull and the CG or
- increasing the surface area of the wing or
- increasing the angle between the wing mean aerodynamic chord and the keel (η)

leads to a decreasing R/W for the HV. In particular, the positive effect of shifting the CG rearwards is more significant than increasing the surface area of the wing. The increase of angle η has the smallest positive effect. With the second model, following the approach of Irodov for WIGe vehicles (8), a criterion to estimate the static stability of HVs has been developed. Furthermore, Table 1 shows the differences in dynamic characteristics between HVs and other airborne and seaborne vehicles.

7 FUTURE WORK

The equilibrium attitude model will be used to further develop the parametric analysis. Taking into account all the configuration parameters analyzed, one or more optimized configurations will be proposed and compared with existing airborne and waterborne configurations.

The static/dynamic model will be used, similarly to the first model, to perform a parametric analysis on how the main HV configuration characteristics influence the stability of the vehicle. In order to enhance the accuracy of the calculations, the authors will investigate alternative methods for estimating the hydrodynamic stability derivatives.

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Vehicle configuration	SPEoM equations (Longitudinal plane)	Characteristic polynomial	Roots of the SPEoM
Airplane	4 equations $(\partial x/\partial t, \partial z/\partial t, \partial\theta/\partial t, \theta)$	4th degree	2 oscillatory solutions: phugoid, SPPO
Planing craft	4 equations $(\partial z/\partial t, z, \partial\theta/\partial t, \theta)$	4th degree	2 oscillatory solutions: porpoising (least stable root)
WIGe vehicles	5 equations $(\partial x/\partial t, \partial z/\partial t, \partial\theta/\partial t, \theta, h)$	5th degree	2 oscillatory solutions + 1 negative real root: phugoid, SPPO, subsidence mode
HV	6 equations $(\partial x/\partial t, \partial z/\partial t, z, \partial\theta/\partial t, \theta, h)$	6th degree	See 5.3 (b)

Table 1: comparison between the dynamics of conventional configurations and the HV

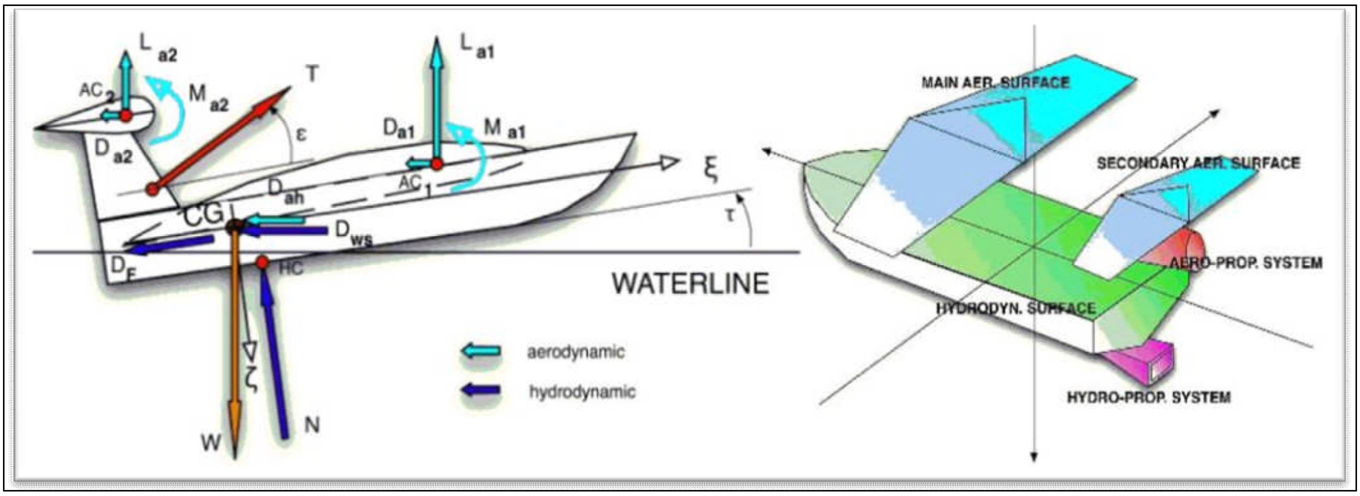

Figure 1: Hybrid Vehicle selected configuration

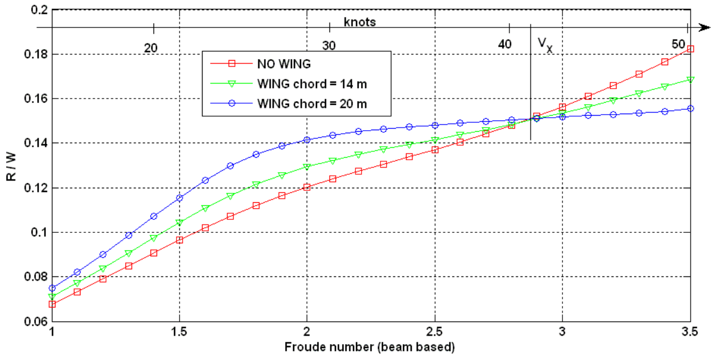

Figure 2: influence of the wing area on the resistance to weight ratio

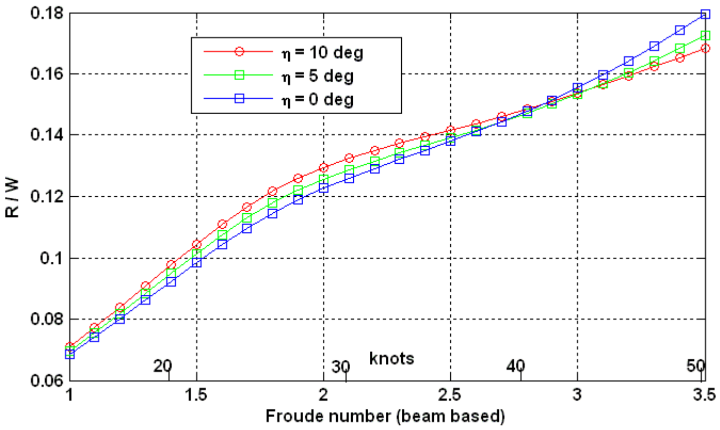

Figure 3: influence of η on the resistance to weight ratio

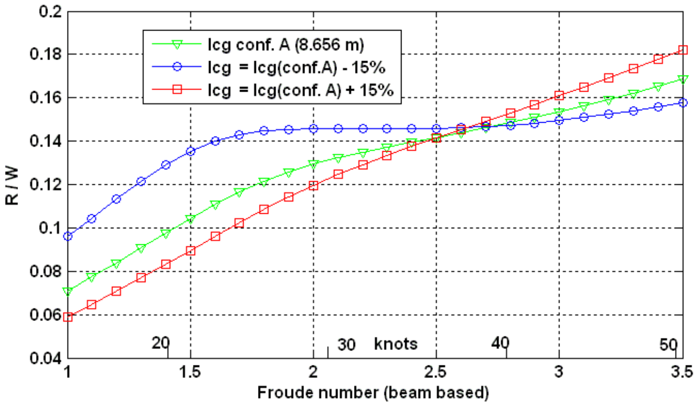

Figure 4: influence of the CG longitudinal position on the resistance to weight ratio