AERODYNAMICALLY ALLEVIATED MARINE VEHICLES (AAMV): DEVELOPMENT OF A MATHEMATICAL FRAMEWORK TO DESIGN HIGH SPEED MARINE VEHICLES WITH AERODYNAMIC SURFACES

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SUMMARY

In the last few decades, interest in high speed marine vehicles, both in civil and military marine transportation, has motivated the marine engineering community to develop new configurations [1].

Among these, the ‘aerodynamic alleviation concept’ [2] consists of using one or more aerodynamic surfaces to alleviate the weight of marine vehicles. The advantages are: lower hydrodynamic drag better damping of heave and pitch accelerations. At Cranfield University a research programme to study AAMV started five years ago. Firstly, an AAMV equilibrium attitude model has been developed and implemented in MATLAB [3]. Similar to the Savitsky model for planing craft [4], this model is able to estimate the attitude of a given AAMV. Secondly, the vehicle stability has been studied by developing a specific system of equations of motion, using a small disturbances assumption [5]. This article presents a possible AAMV configuration that illustrates the potential of such configurations and how mathematical models can be used as design tools.

NOMENCLATURE

a	pitch moment arm of D_F (m)
[A]	aero- and hydrodynamic added mass matrix
AAMV	Aerodynamic alleviated marine vehicle
AAR	Aerodynamic Alleviation Ratio
AAZ	Aerodynamic Alleviation Zone
a_{ah}	pitch moment arm of D_{ah} (m)
a_{ws}	pitch moment arm of D_{ws} (m)
A_{ij}	$\partial F_i / \partial \ddot{\eta}_j$ (kg) ,(kg m)
AC_i	aerodynamic center of ith-aerofoil
[B]	aero- and hydrodynamic damping matrix
c	pitch moment arm of N (m)
c_L	Lift coefficient
c_D	Drag coefficient
c_m	Pitch moment coefficient
[C]	hydrodynamic restoring matrix
CG	center of gravity
[D]	aerodynamic WIGe matrix
D_{ah}	planing hull aerodynamic drag (N)
D_{ai}	i-th surface aerodynamic drag (N)
D_F	hydrodynamic friction drag (N)
D_{ws}	hydrodynamic whisker spray drag (N)
g	gravitational acceleration constant (m/s^2)
h/c	dimensionless height above the surface (CG height / wing’s chord)
L_{ai}	i-th surface aerodynamic lift (N)
lcg	CG longitudinal position, from transom (m)
m	mass of the AAMV at equilibrium (kg)
M_{ai}	i-th surface aerodynamic moment (Nm)
N	hydrodynamic potential force (N)
R/W	total resistance-to-weight ratio
RULM	Rectilinear Uniform Level Motion surface
T	thrust force (N)
TP	thrust force point of action
W	weight of the vehicle (N)
WIGe	Wing In Ground effect
α	Aerodynamic surface angle of attack (deg)
β	deadrise angle of the planing hull (deg)
ε	angle between T and the keel (deg)
ζ_i	coordinate of the i-th point in the body-fixed axes system, *z* axis
η_0	height above the surface, pos. upward (m)
η_1	surge displacement (m)
η_3	heave displacement, positive downward (m)
η_5	pitch rotation, positive bow up (rad)
$\dot{\eta}_i$	$\partial \eta_i / \partial t$
η_{ai}	angle between the i-th wing mac and the keel (deg)
ρ^i	density, ρ^a air, ρ^h seawater (kg m^{-3})
τ	trim angle, angle between the keel of the planing hull and the waterline (deg)
ξ_i	coordinate of the i-th point in the body-fixed axes system, *x* axis

1 INTRODUCTION

1.1 CONTEXT

1.1 (a) High Speed Marine Vehicles

In the last century the need of faster marine vehicles has led to many high speed marine vehicles concepts.

First experiments with hydrofoils were conducted in the UK (T. W. Moy, J. I. Thornycroft), in Italy (E. Forlanini), and in USA (E. Meacham, A. G. Bell, C. Baldwin) during the 1890s and after. In 1953 the first commercial hydrofoil started service, between Italy and Switzerland, on Lake Maggiore [6]. After the buoyancy, historically the oldest lift force used by marine vehicles, mankind learned to exploit hydrodynamic forces to sustain the weight of the vehicle, leading to a reduced hydrodynamic drag and, therefore, to a higher speed.

Between hydrofoil and conventional displacement ships, planing theory started to be studied in the early twentieth century so as to understand the physics underlying seaplanes. Later this research focused on the design of planing boats, and in the military field, between 1970s and 1980s, this concept saw its golden age, with more than 300 fast attack units and about 1500 patrol craft being constructed and exported worldwide only in the USA [1]. Later planing craft have been widely used for civil and military applications, leading to a thorough and extensive literature on planing theory.

In 1955 a new concept was developed by C. S. Cockerell, the “hovercraft”, as called by its inventor. It uses an air cushion to support the weight of the marine vehicle and to raise the hull above the water surface. A few decades later, in 1978, the BHC Super 4 hovercraft was capable of carrying 416 passengers and 60 cars for 150 miles. The marine vehicles exploiting this concept through an air cushion enclosed in a flexible “ring” are classified as ACV, or Air Cushion Vehicles. If the air cushion is enclosed between two solid hulls and two flexible skirts (one on the front and one in the rear), the marine vehicle is classified as SES, or Surface Effect Ships.

All these concepts can be classified using the well known “Lift” or “Sustention Triangle”, illustrated in Figure 1, where the three corners define primary means – buoyant lift, hydrodynamic lift and powered lift - by which lift is generated.

1.1 (b) Aerodynamically Alleviated Marine Vehicles

There is another lift force that can be exploited to ‘alleviate’ the weight of the vehicle, leading to reduced buoyancy and, therefore, to decreased hydrodynamic drag: aerodynamic lift. The use of one or more aerodynamic surfaces to alleviate the weight of the vehicle requires a modification of the ‘Sustention Triangle’, leading to the ‘Lift Pyramid’, illustrated in Figure 2. The lift pyramid has a fourth corner, representing aerodynamic lift.

To better explain the concept, some definitions have been introduced: ‘Aerodynamic Alleviation Zone’, ‘Aerodynamic Alleviated Marine Vehicles’, and ‘Aerodynamic Alleviation Ratio’ [7].

The **Aerodynamic Alleviation Zone (AAZ)**, illustrated in Figure 2, can be defined as the area representing the points where a combination of buoyancy, hydrodynamic lift and aerodynamic lift is used to sustain the weight of the vehicle. As the speed increases, hydrostatic force becomes lower, therefore a high speed marine vehicle equipped with aerodynamic surfaces, operates at cruise speed in a sub-zone called ’AAZ cruise speed’.

An **Aerodynamically Alleviated Marine Vehicle (AAMV)** is a high speed marine vehicle designed to exploit, in its cruise phase, the aerodynamic lift force, using one or more aerodynamic surfaces. The AAMV operates in the just defined AAZ.

The **Aerodynamic Alleviation Ratio (AAR)** is, at a certain speed, the ratio between the aerodynamic lift force and the total weight of the vehicle, defined by Equation (1):

$$AAR = \frac{L_a}{mg} \tag{1}$$

It indicates the percentage of the weight of the vehicle sustained by aerodynamic forces.

Many are the configurations that can be grouped under the definition of AAMV. In 1976, Shipps [8], among other air-supported waterborne vehicle, analyzed a new kind of race boat, known as the “tunnel hull” race boat: the two planing sponsons of the catamaran configuration act as aerodynamic end plates of the central channel flow or ram wing. These race boats immediately demonstrated better performance with respect to conventional monohull race boats and a new race boat class was created. The additional lift from aerodynamic forces can be 30 to 80% of the total weight, or AAR = 0.3 to 0.8. More generally, Shipps believed in the possible development of air supported waterborne vehicles, capable of better performance, and suitable for littoral warfare and other offshore scenarios. In 1978, Ward et al. [9] published an article on the design and performance of a ram wing planing craft: the KUDU II (KUDU I was mentioned in Shipps’ article). This vehicle can be considered an AAMV, since it has two planing sponsons separated by a wing section. It is a vehicle with aerodynamic and hydrodynamic surfaces, designed to exploit both aerodynamic and hydrodynamic lift. In his article Ward presented the results of some trials: the KUDU II was able to run at 78 kts (about 145 km/h, 90 mph). In 1978, Kallio [10], of the David W. Taylor Naval Ship Research and Development Center (USA), performed comparative tests between the KUDU II and the KAAMA. The KAAMA is a conventional mono hull planing craft. The data obtained during comparative trials show that the KUDU II pitch motion, in sea state 2, at about 40 to 60 knots, is about 30% to 60% lower than the conventional planing hull KAAMA's pitch motion. In 1996, Privalov and Kirillovikh [11] presented a design vehicle called TAP, Transport Amphibious Platform. The TAP consists of two hulls, like a catamaran, and a fuselage, a wing and an aerodynamic tail in between the hulls. It moves always in contact with the water and uses an aerodynamic cushion effect, obtained by forcing the powerplant gas jets beneath the platform between the hulls. In 1997, Doctors [2] proposed a new configuration called 'Ekranocat' for which he mentioned the 'aerodynamic alleviation concept'. The weight of the catamaran is alleviated by aerodynamic lift, thanks to a more streamlined superstructure than in traditional catamarans. The theoretical analysis and computed results show that reductions in total drag around 50% can be obtained at very high speed. The very high speed marine vehicles used by F1 Powerboat Racing teams are perfect examples of extreme AAMV. For these vehicles, at high speed, the AAR can reach values of 0.9 to 0.95.

At the end of the range, when AAR = 1, are the so called Wing In Ground vehicles (WIG), also illustrated in Figure 2. Rozhdestvensky [12] says that a WIGe vehicle:

> ``...*can be defined as a heavier than air vehicle*
> *with an engine, which is designed to operate*
> *in proximity to an underlying surface for*
> *efficient utilization of the ground effect.''*

And the wing in ground effect is defined as:

> *...an increase of the lift-to-drag ratio of a*
> *lifting system at small relative distances from*
> *an underlying surface.*

An extensive and thorough review of WIGe vehicles can be found in [13].

1.2 PROBLEM STATEMENT

Methodologies for aircraft and marine craft exist and are well documented, but air and marine vehicles have always been investigated with a rather different approach. Marine vehicles have been studied by analyzing very accurately hydrostatic and hydrodynamic forces but approximating very roughly the aerodynamic forces acting on the vehicle. On the contrary, the dynamics of Wing In Ground effect (WIGe) vehicles has been modelled focusing mainly on aerodynamic forces, paying much less attention to hydrostatic and hydrodynamic forces. AAMV experiences aerodynamic and hydrodynamic forces of the same order of magnitude, therefore neither the high speed marine vehicles nor the airborne vehicles models of dynamics can be adopted.

At Cranfield University, one aspect of its research has been to bridge this gap by developing a new model of dynamics, which takes into account the equal importance of aerodynamic and hydrodynamic forces. In particular two mathematical models have been developed:

- a system of equations of equilibrium, to estimate the equilibrium attitude of an AAMV,
- a system of equations of motion, to estimate the static and dynamic stability of an AAMV.

2 MATHEMATICAL MODELS

Also if available models of dynamics cannot take into account both aerodynamic and hydrodynamic forces at the same time with equal accuracy, it is necessary to develop a new model of the dynamics for AAMV. First of all, a possible AAMV configuration has been chosen: it consists of a high speed prismatic planing hull plus one or more aerodynamic surfaces. These aerodynamic surfaces are always operating at very low altitude above the surface, and for this reason they operate 'In Ground Effect (IGE)'. Therefore, the second step has been the analysis of the models of dynamics of planing craft and of WIGe vehicles, and from these a mathematical framework suitable for the AAMV dynamics has been developed.

The two mathematical models have been presented by authors in [3] and [5], and a detailed description can be found in [7]. They are briefly presented in the following sections.

2.1 CONFIGURATION

The configuration presented in this section represents a "class" of "modular" configurations: the AAMV mathematical framework is able to analyze each combination of these elements. For examples, if no aerodynamic surfaces are used, the model will analyze a planing craft configuration. The elements of a general AAMV configuration are (Figure 3):

- a high-speed prismatic planing hull, the hydrodynamic surface, with constant deadrise angle β,
- one or more airfoils (aerodynamic surface/s), operating in ground effect,
- one or more aero- or hydro-propulsion systems.

Mathematical models can analyze high speed (full planing regime) equilibrium states, but the AAMV is supposed to have waterborne capability at rest. Hydrodynamic and aerodynamic surfaces can be fitted with control systems, but this work is limited to a control-fixed analysis.

2.2 AXIS SYSTEM

Briefly they are: one earth-axis system and two body-axis system, right-handed and orthogonal.

2.2 (a) Earth-axis System (*x*O*z*)

The directions of the axis are fixed in space. The *z*-axis is oriented vertically downward; the *x*-axis forwards and parallel to the undisturbed waterline and the origin is fixed at the undisturbed waterline level.

2.2 (b) Body Axis Systems

The origin O is coincident with the CG of the AAMV. The *x* and *z* axis lay in the longitudinal plane of symmetry, *x* positive forward and *z* positive downward. Two systems are used:

- aero-hydrodynamic axes ($\eta_1 O \eta_3$), the *x*-axis being parallel to the steady forward velocity V_0,
- geometric axes ($\xi O \varsigma$), the *x*-axis ξ being parallel to the keel of the planing hull.

Aero-hydrodynamic axes are the counterpart of the aerodynamic axes (called also wind or body-wind axes (UK) or stability axes (US) used for airplanes.

2.3 AAMV EQUATIONS OF EQUILIBRIUM

A mathematical method is proposed that can calculate the equilibrium attitude of the AAMV [3], starting from geometric, inertial, aerodynamic and hydrodynamic characteristics of the vehicle.

2.3 (a) Brief Literature Review

As regard hydrodynamic forces, the model is based on the work of Savitsky. Savitsky [4] carried out an extensive experimental programme on prismatic planing hulls and obtained some empirical equations to calculate forces and moments acting on planing vessels. He also provided simple computational procedures to calculate the running attitude of the planing craft (trim angle, draft), power requirements and also the stability characteristics of the vehicle. The model of Savitsky [4] has been further developed recently [14], and it is still one of the reference methods used for the preliminary design of planing craft.

As regard aerodynamic forces in ground effect at equilibrium, it is well known that they depend not only on the angle of attack but also on the height above the ground of the aerodynamic surface [15], [16]. A semi-empirical approach is preferred to evaluate the resultant aerodynamic forces. Using experimental and/or numerical values, a matrix for different angles of attack at different heights above the surface is obtained, and the aerodynamic force at a certain height with a certain angle of attack is obtained through interpolation.

2.3 (b) Hypotheses

The model concentrates on the analysis of an equilibrium state characterized by a rectilinear trajectory, a constant speed and a constant altitude above the surface, which will be referred as Rectilinear Uniform Level Motion (RULM). The vehicle is supposed to be always in contact with the water, and in a calm water situation. Waves are not taken into account.

2.3 (c) Forces and Moments

The forces and moments acting on the vehicle are illustrated in Figure 4. They can be divided into four groups:

- gravitational (weight, W),
- thrust (propulsion force, T),
- aerodynamic (lift, drag and moment from the 1st and 2nd aerodynamic surface, L_{ai}, D_{ai}, M_{ai} and aerodynamic drag of the hull above the surface, D_{ah}),
- hydrodynamic (potential force, N, frictional force, D_F, whisker spray drag, D_{ws}).

For a detailed description of each force see [3].

2.3 (d) System of Equations of Equilibrium

Once all the forces and moments are known, a system of equations of equilibrium can be developed. The system is:

- **surge equation**: sum of the vertical forces = 0,
- **heave equation**: sum of horizontal forces = 0,
- **pitch equation**: sum of pitch moments = 0.

The CG of the AAMV has been chosen as the moments’ point of reference.

The **surge equation** states that the sum of the aerodynamic drags, the component of potential and friction hydrodynamic forces parallel to the velocity, and the whisker spray drag has to be equal to the component of the thrust parallel to the velocity.

$$\begin{aligned}&-D_{a1}-D_{a2}-D_{ah}+\\&-N\sin(\tau)-D_F\cos(\tau)-D_{WS}+\\&+T\cos(\tau+\varepsilon)=0\end{aligned}$$

(2)

The **heave equation** states that the sum of aerodynamic lift, vertical components of the potential and friction hydrodynamic force and the vertical component of the thrust has to be equal to the weight of the AAMV:

$$\begin{aligned}&L_{a1}+L_{a2}+N\cos(\tau)-D_F\sin(\tau)+\\&-W+T\sin(\tau+\varepsilon)=0\end{aligned}$$

(3)

The **pitch equation** states that the sum of the aerodynamic moments, hydrodynamic moments and the moment generated by the thrust force has to be equal to zero.

$$\begin{aligned}&L_{a1}\left[\xi_{AC1}\cos(\tau)+\zeta_{AC1}\sin(\tau)\right]+\\&+D_{a1}\left[\xi_{AC1}\cos(\tau)+\zeta_{AC1}\sin(\tau)\right]+M_{a1}+\\&+L_{a2}\left[\xi_{AC2}\cos(\tau)+\zeta_{AC2}\sin(\tau)\right]+\\&+D_{a2}\left[\xi_{AC2}\cos(\tau)+\zeta_{AC2}\sin(\tau)\right]+M_{a2}+\\&D_{ah}a_{ah}+D_{ws}a_{ws}-N\cdot c-D_F\cdot a+\\&T\left[\xi_{TP}\sin(\varepsilon)+\zeta_{TP}\cos(\varepsilon)\right]=0\end{aligned}$$

(4)

with the conditions

$$a_{ah}=a_{ws}=0$$

A method to solve this system of equations is illustrated in [3].

2.4 AAMV EQUATIONS OF MOTION

A system of equations of motion for AAMV [5] has been developed, with which is possible to estimate the static and dynamic stability of this vehicle. A static stability criterion has been developed and presented in [3].

2.4 (a) Brief Literature Review

As regard aerodynamic force, the approach used for WIGe vehicles has been adopted.

In the 1960's and the 1970's Kumar [17],[18] started research in this area at Cranfield University (College of Aeronautics). He carried out several experiments with a small test craft and provided the equations of motion, the dimensionless stability derivatives and studied the stability issues of a vehicle flying IGE.

In 1970's Irodov [19] presented a simplified analysis for the longitudinal static stability of WIGe vehicles. He linearized the equations of motion about a trimmed, straight and level flight path, deriving a simplified static stability criterion for this configuration.

Staufenbiel [20] in the 1980's carried out extensive work on the influence of the aerodynamic surface characteristics on the longitudinal stability in wing in ground effect. The equations of motion for a vehicle flying IGE were defined, including non linear effects.

More recently, Chun and Chang [21] evaluated the stability derivatives for a 20 passenger WIG vehicle, based on wind tunnel results together with a vortex lattice method code. Using the work of Kumar and Staufenbiel, the static and dynamic stability characteristics have been investigated.

As regard hydrodynamic forces, the equations of motion used for planing craft have been adopted.

Martin [22] derived a set of equations of motion for the surge, pitch and heave degrees of freedom and demonstrated that surge can be decoupled from heave and pitch motion.

Using the coefficients of Martin, Zarnick [23] defined a set of highly nonlinear integro-differential equations of motion, with coefficients determined by a combination of theoretical and experimental results.

Troesch and Falzarano [24],[25] studied the nonlinear integro-differential equations of motion and carried out several experiments to develop a set of coupled ordinary differential equations with constant coefficients, suitable for modern methods of dynamic systems analysis. Troesch, with Hicks [26], later extended his previous work and expanded the nonlinear hydrodynamic force equations of Zarnick using Taylor series up to the third order.

2.4 (b) Hypotheses

The model analyses the AAMV static and dynamic stability, starting from an equilibrium state. As before, this equilibrium state is characterized by a rectilinear trajectory, a constant speed and a constant altitude above the surface (RULM). The vehicle is supposed to be always in contact with the water, and in a calm water situation. Waves are not taken into account.

2.4 (c) Forces and Moments

Forces and moments acting on the AAMV are:

- weight,
- hydrostatic forces,
- hydrodynamic forces,
- aerodynamic forces,

Aerodynamic and hydrodynamic control systems' forces are supposed to be constant (control fixed analysis), as well as aero- or hydro-propulsion forces.

Depending on the steady forward velocity of the AAMV, it is possible to make assumptions on the forces which are negligible. The present work concentrates on the study of RULM. The steady forward speed (and the geometrical configuration of the AAMV) is such that the main forces are the hydrodynamic and aerodynamic ones, with a small contribution of hydrostatic forces (buoyancy) to the restoring forces.

Decoupling of Equations of Motion

The AAMV, represented as a rigid body, has 6 degrees of freedom. To describe its motion a set of six simultaneous differential equations of motion is needed but a decoupled system of equations of motion can be derived. For airplanes, in the frame of small perturbations approach, the lateral-longitudinal coupling is usually negligible. This is still valid for WIGe vehicle [21]. For planing craft, as demonstrated in [22], not only the lateral-longitudinal coupling is usually negligible, but also the surge motion can be decoupled from the heave and pitch motion. Therefore it is assumed that the AAMV has a negligible longitudinal-lateral coupling. In this work, only the longitudinal motion of the AAMV is analyzed, taking into account: surge, heave forces and pitch moment.

2.4 (d) System of Equations of Motion

A detailed analysis of the system of equations of motion developed for AAMV is presented in [5].

Longitudinal Linearized Equations of Motion

From [5], the system of longitudinal linearized equations of motion, written in the aero-hydrodynamic axis system is:

$$[A]\ddot{\eta} + [B]\dot{\eta} + [C]\eta + [D]h = 0$$

(5)

where

$$\eta = \begin{bmatrix} \eta_1 \\ \eta_3 \\ \eta_5 \end{bmatrix}$$

(6)

and h, also called η_0, is the (perturbed) height above the waterline.

Matrix [A] is the sum of the mass matrix, hydrodynamic added mass matrix and aerodynamic 'added mass' terms (usually called 'accelerations derivatives'). Matrix [B] is the sum of aerodynamic damping matrix and hydrodynamic damping matrix. [C] is the hydrodynamic restoring matrix and [D] represents the wing in ground effect, to take into account the influence of the height above the surface.

By defining a state space vector as:

$$v = [\dot{\eta}_1 \quad \dot{\eta}_3 \quad \dot{\eta}_5 \quad \eta_3 \quad \eta_5 \quad \eta_0]^T$$

(7)

The system of equations of motion (5) can be transformed in the Cauchy standard form (or state space form) (see [5]):

$$\dot{v} = [H]v$$

(8)

From the state space matrix [H] in equation (8), the characteristic polynomial of the AAMV longitudinal dynamics can be derived and, using a stability criterion as the Routh-Horwitz criterion, the stability of the vehicle can be evaluated.

3 ANALYSIS OF AN AAMV CONFIGURATION

Co-author Williams' research focused on the use of suitably shaped multihull geometries to achieve efficient aerodynamic lift for high-speed sea vessels [27]. To establish the extent to which this aerodynamic lift will benefit the craft performance, the authors worked in collaboration. Williams designed a possible AAMV configuration, illustrated in Figure 5, and estimated its aerodynamic coefficients. These have been used as input for the mathematical model illustrated in this paper to assess the equilibrium attitude characteristics of this AAMV.

3.1 INPUT DATA

Input data are the geometrical, hydrodynamic, aerodynamic, propulsive, and inertial characteristics of the vehicle. Two vehicles are considered, illustrated in Table 1: an AAMV configuration (AAMV-01), and a planing craft configuration (PC-01) are compared to illustrate the benefit of aerodynamic alleviation. In fact PC-01 is a planing craft with the same geometrical, hydrodynamics and inertial characteristics of AAMV-01, the only difference being the fact that PC-01 does not have any aerodynamic surface.

As regard environment characteristics, the following values have been adopted:

- air density: 1.23 kg/m^3,
- seawater density: 1025.9 kg /m^3,
- gravity acceleration constant: 9.81 m/s^2,
- seawater viscosity: 1.19*10^{-6} m^2/s.

3.1 (a) AAMV-01 aerodynamic characteristics

The aerodynamic coefficients (lift, drag and moment) depend on both the angle of attack and, due to the wing in ground effect, the height above the surface. To estimate these aerodynamic coefficients, the mathematical model uses a two dimensional interpolation, to derive a matrix of values for each aerodynamic coefficient.

Numerical tests were run by Williams [27] on the configuration shown in Figure 5, which is the part of AAMV-01 above the waterline. A Fluent computational fluid dynamics model was run for 4 different heights above the surface (2.5m, 5m, 7.5m, and 10m) and at three different angles of attack. The values of these angles of attack depend on the height above the surface analyzed, since the range of angular displacement of the vehicle is restricted by the collision of the trailing edge of the aerodynamic surface with the waterline. Lift and drag coefficients are shown in Figure 6.

3.2 AAMV-01 VS PC-01 ANALYSIS

In Figure 7 through Figure 9 are compared the equilibrium attitude characteristics of AAMV-01 and PC-01 configurations. As can be seen, the aerodynamic surface substantially changes the planing craft behavior.

3.2 (a) Trim Angle, Draft and CG Height above the Surface

As shown in Figure 7, aerodynamic forces generated by AAMV-01 aerodynamic surface change the trim equilibrium angle of the vehicle. In particular, for the same speed, the angle is augmented, but the most interesting aspect is the shape of the curve. While for the PC-01 configuration it can be seen the classical trim curve for planing crafts can be seen, for the AAMV-01 there is a second range of speed where the trim angle resume its augmentation. This is due to the fact that the pitch-up moment generated by aerodynamic forces is augmenting, and it counteracts more and more the hydrodynamic pitch-down moment.

As regard the height above the waterline of the centre of gravity (CG), the AAMV-01 vehicle is lifted up more than the PC-0 configuration, up to 65% more at very high speed (Fn 4.4). This lead also to a reduced draft at the transom of the AAMV-01, leading to the reduced hydrodynamic drag illustrated in the next sections.

3.2 (b) Lift and Drag, Aerodynamic and Hydrodynamic

In Figure 8 are shown aerodynamic and hydrodynamic lift-to-weight ratios, and aerodynamic and hydrodynamic drags of the two vehicles.

As regard lift-to-weight ratios, obviously for the PC-01 the sum of hydrostatic and hydrodynamic lift is sustaining 100% of the weight of the vehicle (not exactly 100% since the thrust force has a vertical component). Instead for the AAMV-01, the aerodynamic lift constitutes a source of lift of the same order of magnitude of the hydrodynamic lift. In fact it can be observed that AAR = 0.1 at Fn = 1.5 (about 28 kts), but AAR = 0.5 at Fn = 4.0 (about 76 kts), meaning that the aerodynamic lift force is sustaining 50% of the total weight of the AAMV-01.

As regard aerodynamic and hydrodynamic drags, since for the AAMV-01 a substantial part of the weight of the vehicle is sustained by aerodynamic lift, a lower hydrodynamic lift is required, resulting in a much lower hydrodynamic drag compared to the PC-01. An interesting aspect of this is that, roughly in correspondence with the trim curve slope change (Fn = 4.0), there is a change of slope of the AAMV-01 hydrodynamic drag curve. Most importantly, it leads to a change of slope also of the total drag, and this is a great advantage if compared to the ever-growing behavior of PC-01’s total drag.

3.2 (c) Lift-to-Drag ratios and Resistance-to-Weight Ratios

The difference between the PC-01 and AAMV-01 trim equilibrium angles leads to an AAMV-01 hydrodynamic lift/drag ratio slightly lower than that of the PC-01, but the AAMV-01 can average this with a high aerodynamic lift/drag ratio. This leads to a total AAMV-01 lift/ total drag ratio higher than the correspondent vale for the PC-01.

It can be observed that the values are not so high (between 10 and 5), and other high speed marine vehicles perform better than that, but this work is merely a study to illustrate the advantages of adding an aerodynamic surface, or properly shape the structure above the water of the vehicle, to obtain substantial advantages. Low efficiencies are due to the fact that the planing hull has not been optimized to be coupled with an aerodynamic surface. Anyway, the AAMV-01 total lift/drag ratio (5.38) is more than 75% higher than that of the PC-01 (3.05).

This substantial advantage is shown also in the resistance-to-weight ratio graph. As for total drag curve, also here it can be observed the AAMV-01 curve "plateau", at about Fn = 4.0. This means that an AAMV-01 equipped with a power system able to generate a thrust equal to 0.2 of the total weight, is able to go at whatever speed up to Fn = 4.4, while a PC-01 with the same propulsive system is able to reach, at maximum, a speed of Fn = 3.

4 CONCLUSIONS

The AAMV hybrid aero-hydro dynamics constitutes a new field of study. Two mathematical models have been developed to analyze the equilibrium state and the small perturbations dynamics of this new configuration.

To highlight the advantages of the aerodynamic alleviation concept for high speed marine vehicles, two vehicles have been compared: a high speed planing craft (PC-01) and an AAMV configuration (AAMV-01). The AAMV underwater section is equal to the PC-01, but the section above the water has been aerodynamically shaped to exploit aerodynamic lift and minimize the aerodynamic drag created (Figure 5).

Using a numerical implementation of the mathematical models developed, it has been demonstrated that:

- aerodynamic forces substantially influence the AAMV dynamics,
- at the same speed, AAMV-01's CG is higher than the PC-01's CG, due to the aerodynamic lift,
- the aerodynamic lift, at high speeds, sustains up to 50 to 60% of the total weight of the vehicle, leading to a much lower hydrodynamic and total drag with respect to the PC-01 vehicle,
- also if the AAMV-01 lift-to-drag ratio is not very high, the resistance-to-weight ratio of AAMV-01 is up to 40% lower than the PC-01 resistance-to-weight ratio.

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Maurizio Collu holds the current position of Research Fellow at Cranfield University. He is responsible for the study of high speed marine vehicles with aerodynamic surfaces. He is involved also in renewable energy projects. His previous experience includes a PhD on the dynamics of AAMV, under the supervision of Prof. M. H. Patel [7]. He presented a paper on the dynamic stability of AAMV at the *International Conference on Marine Research and Transportation 2007 (ICMRT 07)* and a paper on AAMV equilibrium attitude at the *RINA 8th Symposium on High Speed Marine Vehicles (HSMV 08).*

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Dr Florent Trarieux is a lecturer at Cranfield University in the Offshore Engineering & Naval Architecture Group. His interest in High Speed Marine Vehicles leads him to launch an innovative research program at Cranfield in three main areas: coupled aero-hydrodynamics, novel concept design and control of hybrid vehicles at the air-water interface.

VEHICLE CHARACTERISTICS		AAMV CONFIGURATION	COMPARISON PLANING CRAFT
Geometry	**u.m.**	**AAMV-01**	**PC-01**
Propulsion			
(ξ, ζ) TP	[m]	(0,0)	(0,0)
ε [deg]	[deg]	0	0
Aerodynamic surface (one wing)			
mac	[m]	50	/
S	[m^2]	1250	/
η	[deg]	0	/
(ξ, ζ) AC_1	[m]	(17.5, 3.0)	/
profile	\	Clark Y + 2 hulls (Figure 5)	/
Hydrodynamic surface (prismatic planing hull)			
beam	[m]	9.75	9.75
β (deadrise)	[deg]	31.6	31.6
A_h (frontal area)	[m^2]	0	43.9
Inertial			
lcg (from transom)	[m]	20.0	20.0
vcg (from keel)	[m]	3.0	3.0
mass	[kg]	300000	300000

Table 1: Characteristics of the analyzed configurations

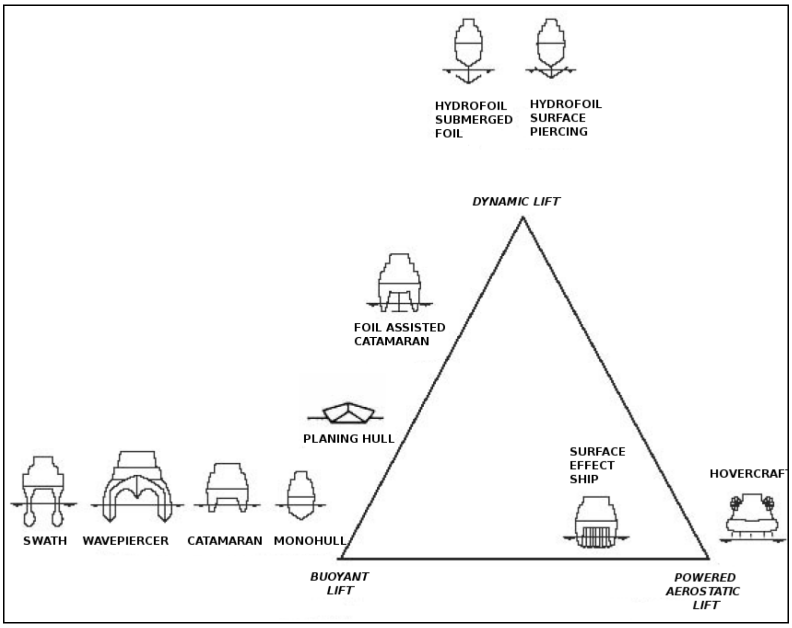

Figure 1: Lift or sustention triangle

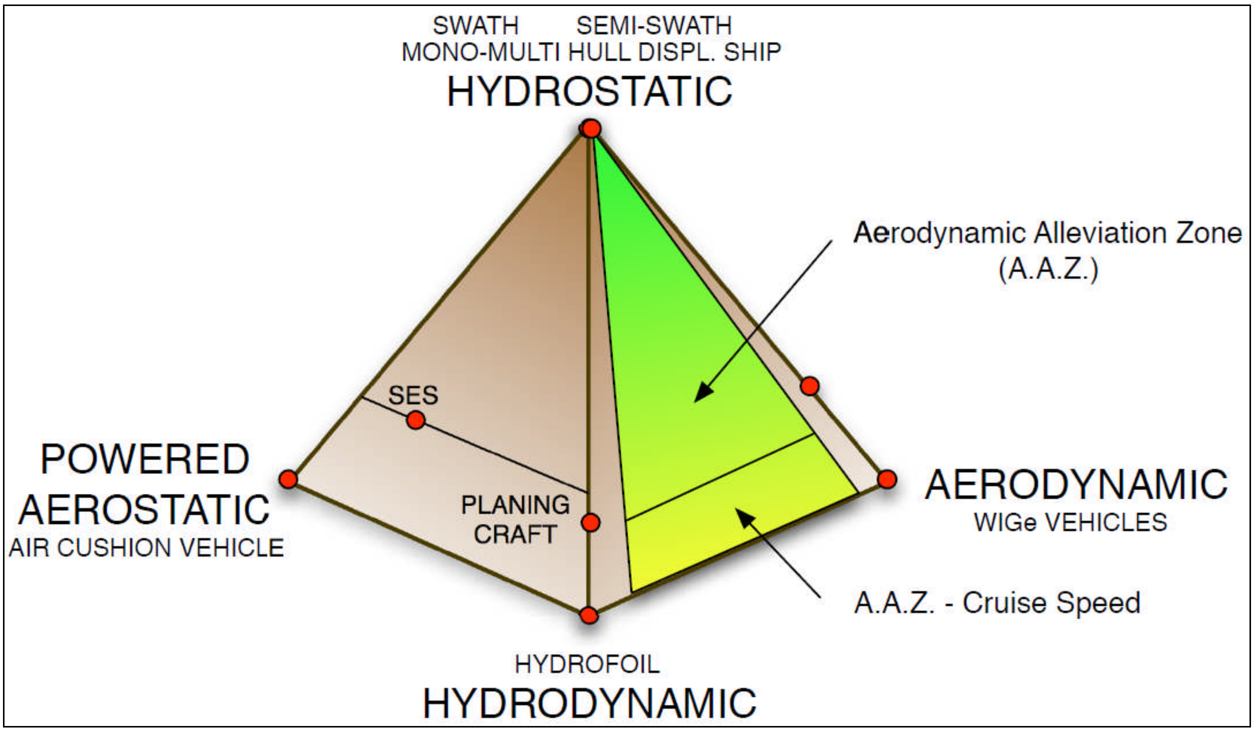

Figure 2: Lift pyramid [7]

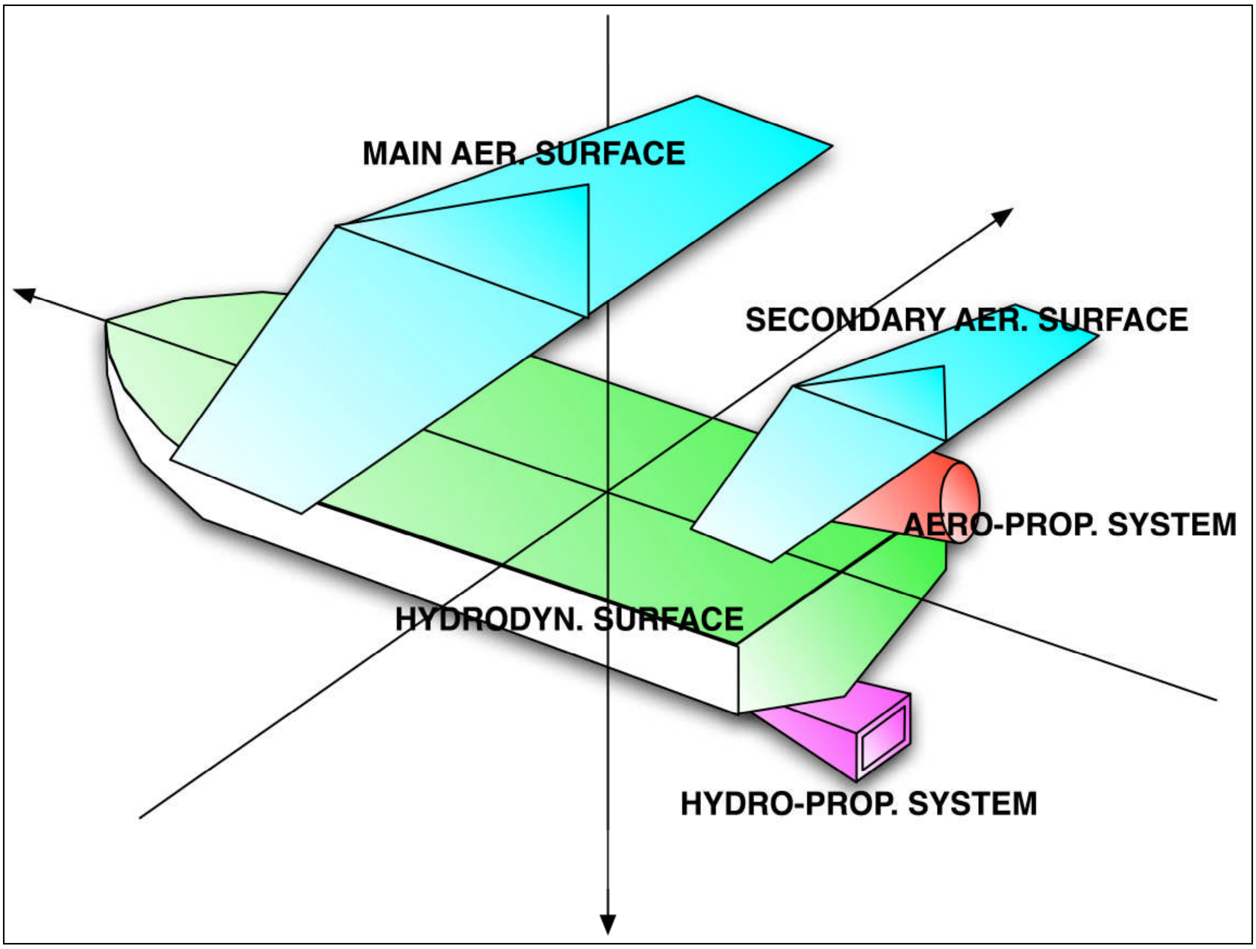

Figure 3: Aerodynamically Alleviated Marine Vehicle (AAMV): class of configurations

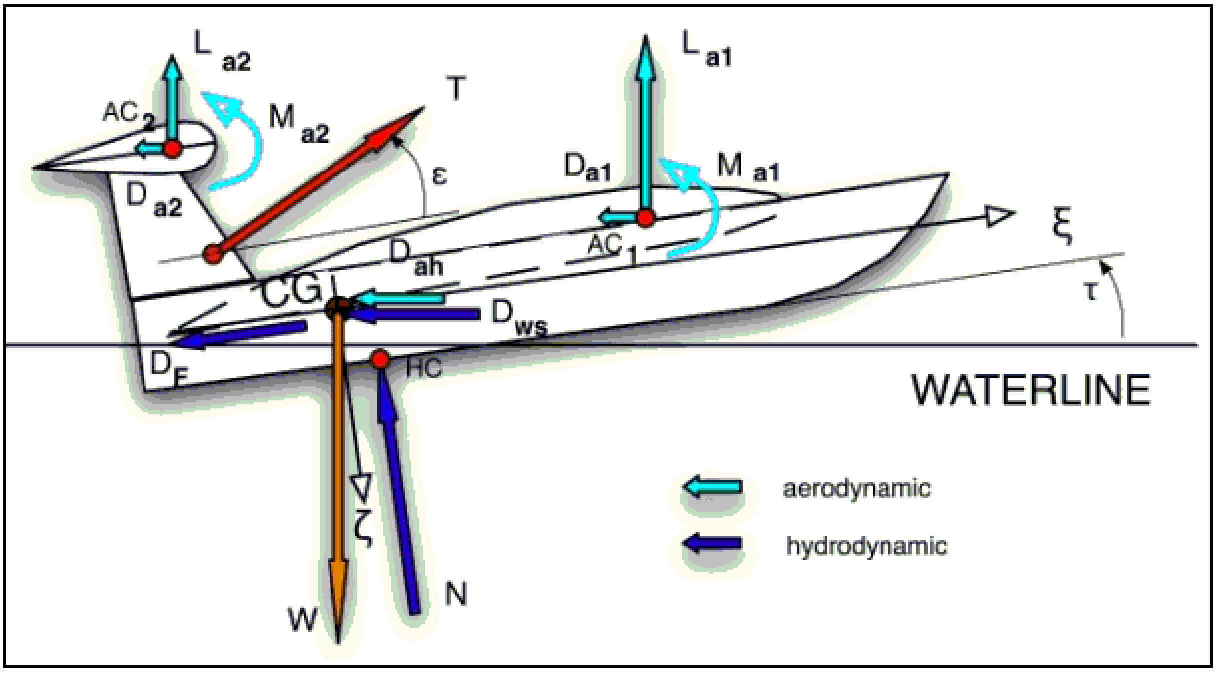

Figure 4: forces and moments acting on the hybrid vehicle

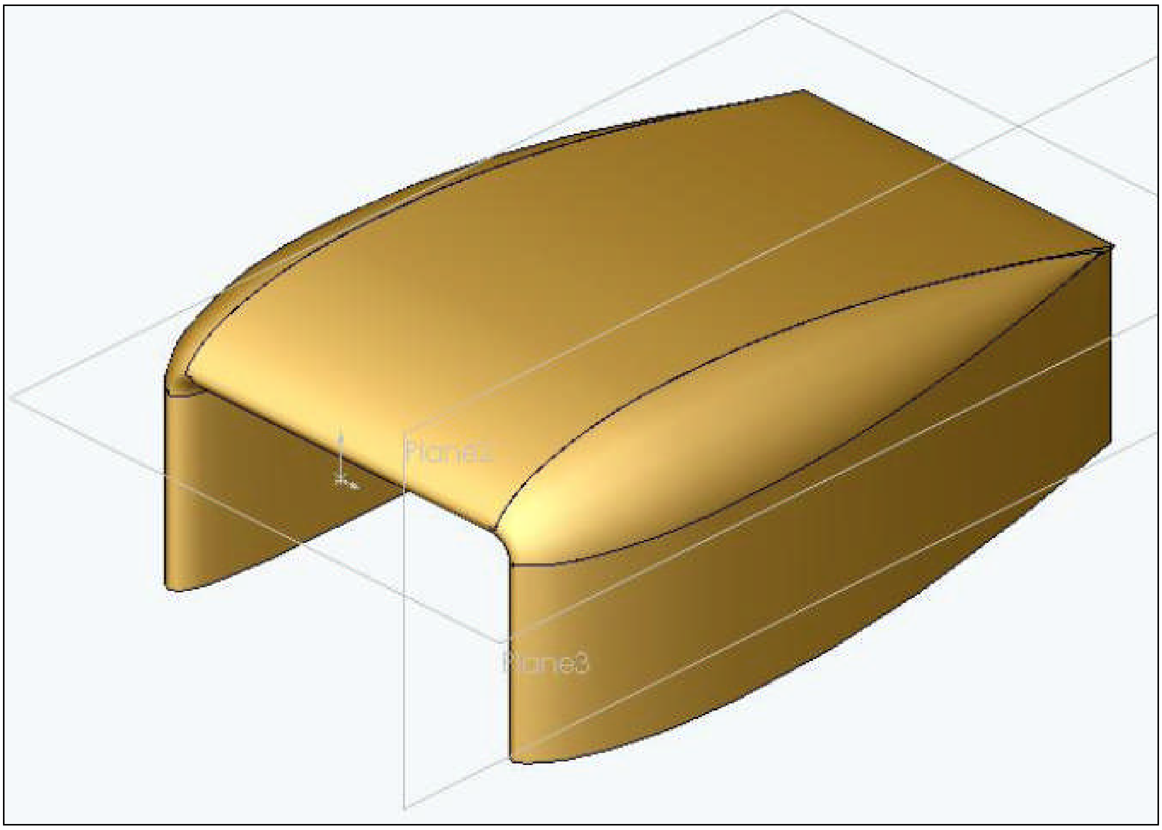

Figure 5: AAMV configuration analyzed, above waterline section, from [27]

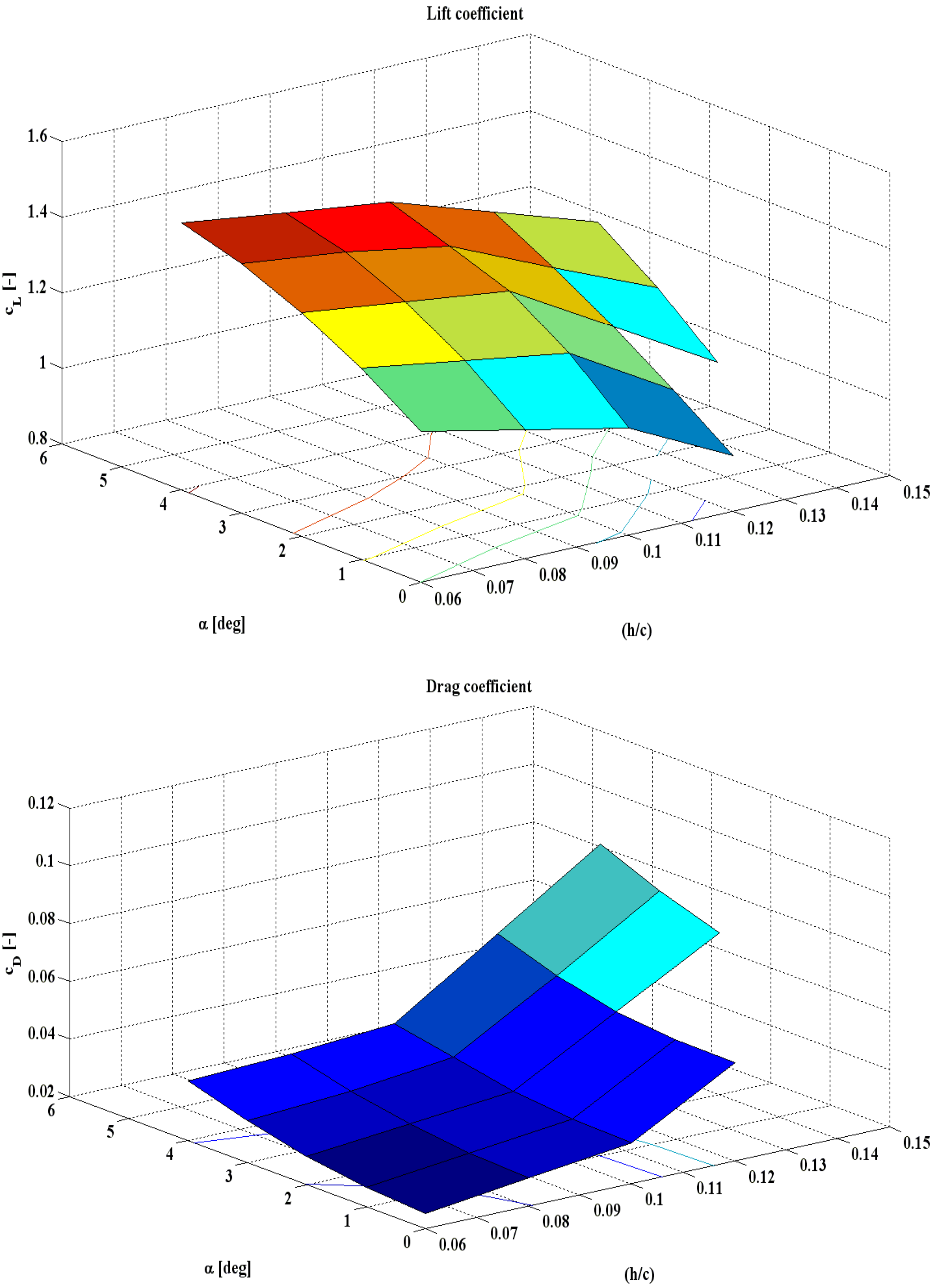

Figure 6: AAMV-01 lift and drag coefficients, function of angle of attack (α) and dimensionless height above the surface (h/c)

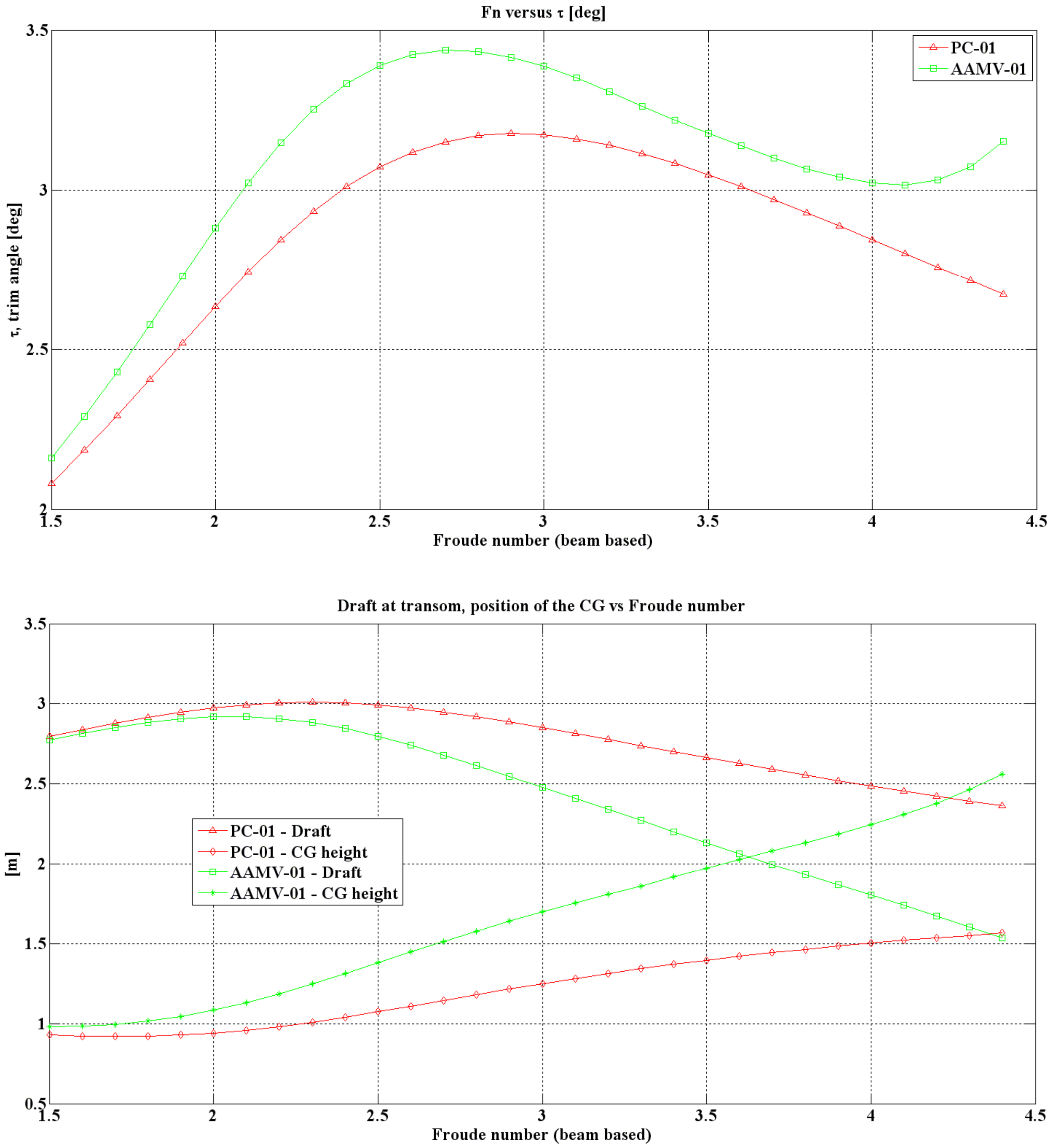

Figure 7 AAMV-01 vs. PC-01: trim angle, draft and CG height above the surface

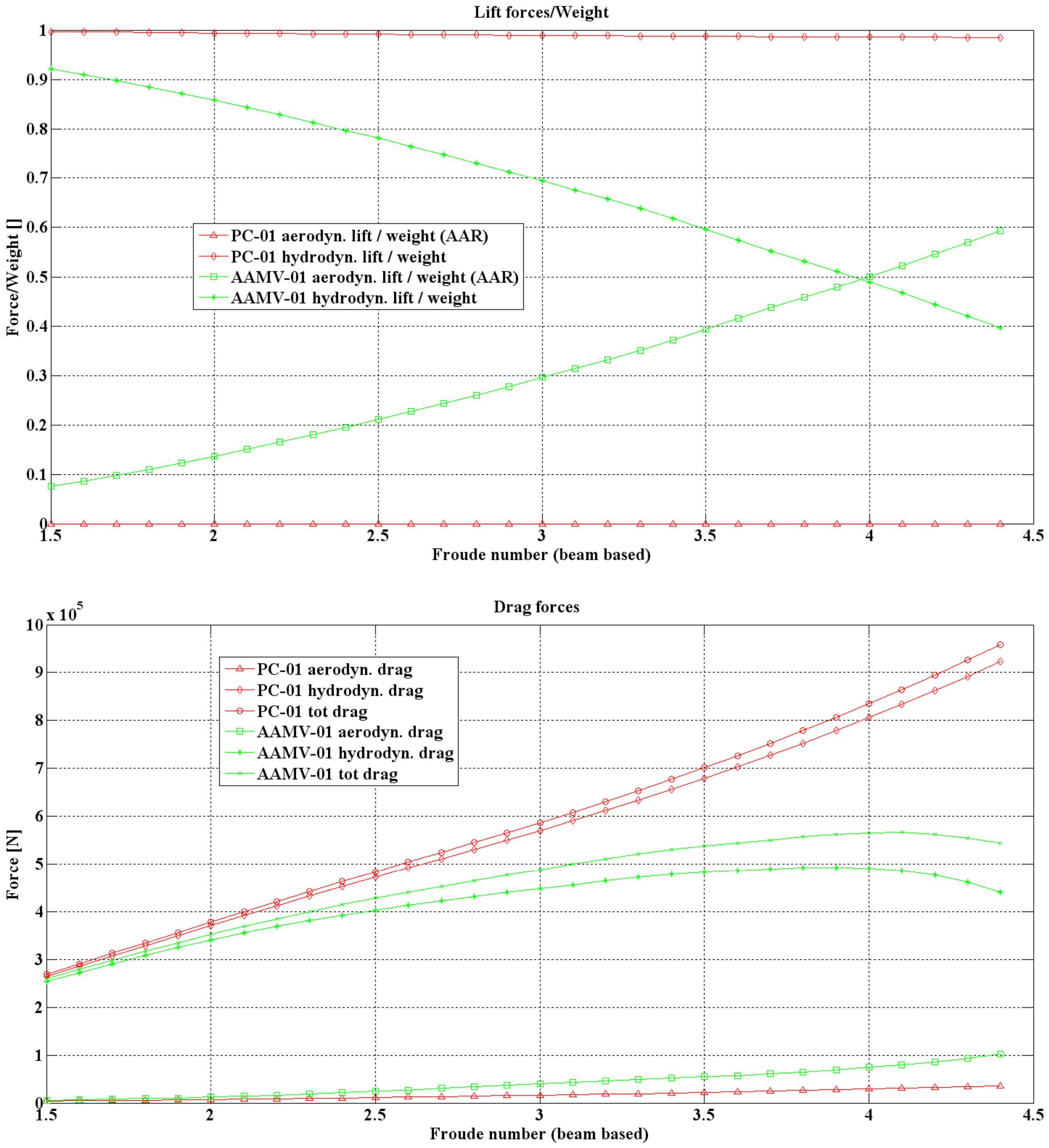

Figure 8 AAMV-01 vs. PC-01: lifts and drags, aerodynamic and hydrodynamic

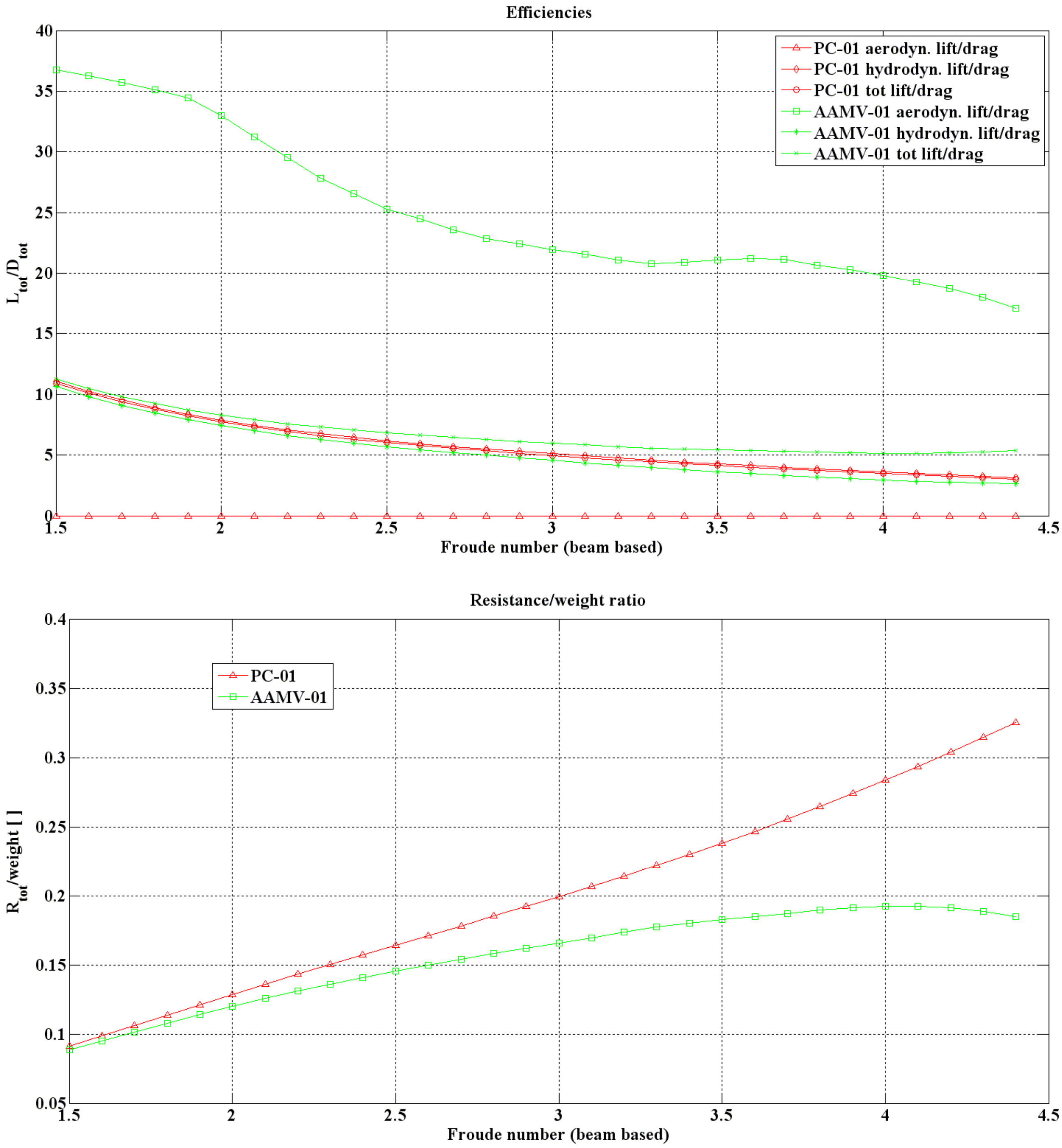

Figure 9 AAMV-01 vs. PC-01:lft/drag ratio (aero.,hydro.,tot) and Resistance/Weight ratio