Estimation of aerodynamic characteristics of un-symmetrically finned bodies of revolutions

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An existing semi-empirical steady state model of a finned axisymmetric body is suitably modified to account for un-symmetrical fin arrangements such as inverted 'Y' and 'V' fins. The modified method is applied to two aerostat configurations, and the results obtained are compared with wind tunnel data and panel method calculations. Good agreement is seen, with minor variations due to certain effects, which are not taken into account by the semi-empirical method. The method was then applied to estimate the position of neutral point.

KEYWORDS: Airship, Stability, Wind Tunnel, Panel Method, Semi Empirical

Nomenclature

$\overline{C}$	Vehicle reference length = total hull length
D	Drag Force
I_1, I_3, J_1, J_2	Geometrical integrals defined in text
N	Normal force
M_{nose}	Pitch moment at nose
S	Vehicle reference area = (hull volume) $^{2/3}$
k_1, k_3	Axial and lateral apparent mass coefficients
q_0	Steady state dynamic pressure = $\rho U_0^2 / 2$
η_k	hull efficiency factor accounting for the effect of fins on hull
η_f	fin-efficiency factor accounting for the effect of hull on the fins
$(Cd_c)_f$	Fin cross flow drag coefficient referenced to S_f
$(Cd_c)_h$	Hull cross flow drag coefficient referenced to J_1
$(Cd_h)_0$	Hull zero angle axial drag coefficient, referenced to S_h
$(Cd_f)_0$	Fin zero angle axial drag coefficient, referenced to S_f
$(Cn_\alpha^*)_f$	Fin lift curve slope at $\alpha = 0$
$(Ct)_f$	Fin leading edge suction coefficient referenced to S_f
$(l_f)_h$	Distance from nose to beginning of hull fin intersection
$(l_f)_1$	Distance from the hull nose to fin aerodynamic centre
$(l_f)_2$	Distance from the hull nose to fin cross flow drag centre

Introduction

This work is based on the cross flow analytic model for prediction of aerodynamic forces on airships, proposed by Jones & DeLaurier [1]. The schematics of the analytic model are represented in Fig. 1. This method applies to the low speed regime, when the flow is attached and no flow separation has occurred over the airship hull.

Estimation of Aerodynamic Coefficients

The equation for the normal force is given as

$$N = q_0\{(k_3 - k_1)\eta_k I_1\}\sin(2\alpha)\cos(\alpha/2) + (Cd_c)_h \sin(\alpha)\sin(|\alpha|)J_1 + S_f[(Cn^*_\alpha)_f \eta_f(\sin(2\alpha)/2) + (Cd_c)_f \sin(\alpha)\sin(|\alpha|)]\}$$

. . . (1)

Axial force can be estimated using

$$D = q_0\{\,[(Cd_h)_0 S_h + (Cd_f)_0 S_f]\cos^2(\alpha) - (k_3 - k_1)I_1\sin(2\alpha)\sin(\alpha/2) - (Ct)_f S_f\}$$

. . . (2)

Moment about nose is estimated using

$$M_{nose} = -q_0[(k_3 - k_1)\eta_k I_3\sin(2\alpha)\cos(\alpha/2) + (Cd_c)_h J_2\sin(\alpha)\sin(|\alpha|) + S_f\eta_f(l_f)_1(Cn^*_\alpha)_f(\sin(2\alpha)/2) + S_f(l_f)_2(Cd_c)_f\sin(\alpha)\sin(|\alpha|)]$$

. . . (3)

The integrals appearing in these equations are defined as

$$I_1 = \int_0^{l_h}\frac{dA}{d\xi}d\xi \qquad I_3 = \int_0^{l_h}\xi\frac{dA}{d\xi}d\xi$$

$$J_1 = \int_0^{l_h}2r\,d\xi \qquad J_2 = \int_0^{l_h}2r\xi\,d\xi$$

. . . (4)

The equations may be made dimensionless by the following relations:

$$N, D = (Cn, Cd)q_0 S$$

$$M = Cm q_0 S\overline{C}$$

$$I_1, J_1, S_f, S_h = (\hat{I}_1, \hat{J}_1, \hat{S}_f, \hat{S}_h)S$$

$$I_3, J_2 = (\hat{I}_3, \hat{J}_2)S\overline{C}$$

$$(l_f)_1, (l_f)_2 = ((\hat{l}_f)_1, (\hat{l}_f)_2)\overline{C}$$

The dimensionless coefficients as derived from Equations 1-3, assuming low α for attached flow are given as:

Lift coefficient:

$$Cn = [(Cd_c)_h J_1 + (Cd_c)_f\hat{S}_f]\sin(\alpha)\sin|\alpha| + [(k_3 - k_1)\eta_k\hat{I}_1\} + 0.5\hat{S}_f(Cn^*_\alpha)_f\eta_f]\sin(2\alpha)$$

. . . (5)

Moment Coefficient:

$$Cm = [\,(Cd_c)_h\hat{J}_2 + \hat{S}_f(\hat{l}_f)_2(Cd_c)_f]\sin(\alpha)\sin|\alpha| - [(k_3 - k_1)\eta_k\hat{I}_3 + 0.5\hat{S}_f\eta_f(\hat{l}_f)_1(Cn^*_\alpha)_f]\sin(2\alpha)$$

. . . (6)

Drag Coefficient:

$$Cd = [(Cd_h)_0\hat{S}_h + (Cd_f)_0\hat{S}_f]\cos^2(\alpha) - (k_3 - k_1)\hat{I}_1\sin(2\alpha)\sin(\alpha/2) - (Ct)_f\hat{S}_f$$

. . . (7)

Care should be taken to ensure that proper reference parameters are chosen to non-dimensionalize the geometrical parameters. For example for calculation of moment coefficient, one can use mean aerodynamic chord of the fin or the total hull length. Similarly vehicle reference area is differently taken as hull surface area or (hull volume)$^{2/3}$.

Evaluation of the aerodynamic coefficients discussed above requires knowledge of the accompanying unknowns in the respective equations. The next section describes how the values of these unknowns can be obtained.

Estimation of Unknowns Involved in Aerodynamic Coefficients

Coefficients related to broad categories of lift, drag and interference are discussed individually in following subsections. Their sources and related assumptions to estimate their values are also stated.

Fin Lift Curve Slope (Cn^*_α)

(Cn^*_α) is calculated as per the formula mentioned in Raymer [2], wherein lift curve slope for a fin is

$$C_{l\alpha} = \frac{2\pi}{2 + \sqrt{4 + \dfrac{AR^2}{\beta^2\eta^2}\left(1 + \tan^2\Lambda_{\frac{1}{2}c}\right)}}$$

. . . (8)

It must be noted that in above formula lift curve slope is for a fin which has zero dihedral angle. If the fin has a substantial dihedral, then the lift curve slope will change on two accounts. Firstly for the fact that the projected area of the fin is reduced by $\cos(\Gamma)$ and secondly since the angle of attack faced by the wing doesn't remain the same. For small α, the effective angle of attack becomes $\alpha\cos(\Gamma)$. Therefore (Cn^*_α) is given as $C_{l\alpha}\cos^2(\Gamma)$, if the entire fin area is used. If, however, the projected area is taken into consideration, than one cosine term can be dropped.

Apparent Mass Coefficient $(k_3 - k_1)$

The apparent mass term as a function of l/d for streamline bodies is given in Perkins & Hage [3], the graph is regenerated here, for the range of values relevant to the available wind tunnel results.

Curve fitting was done to do away with manual entry of these coefficients.

Hull Zero Angle Cross Flow Drag Coefficient $(Cd_h)_0$

$(Cd_h)_{wet}$ is calculated using formula provided by Hoerner [5] as

$$(Cd_h)_{wet} = 1 + \frac{3}{2}\left(\frac{d}{l}\right)^{\frac{3}{2}} + 7\left(\frac{d}{l}\right)^3$$

. . . (9)

Here *d/l* is the ratio of maximum diameter of hull to its length. This is used

$$(Cd_h)_0 = (Cd_h)_{wet}\frac{S_{wet}}{S_{ref}}C_f$$

. . . (10)

C_f, is available as a function of Reynolds number in Hoerner [5].

Fin Zero Angle Cross Flow Drag Coefficient $(Cd_f)_0$

Fin axial drag coefficient is calculated as

$$(Cd_f)_0 = C_{fw}(Cd_f)_{wet}\frac{S_{wet}}{S_{ref}}$$

. . . (11)

Where C_{fw} is obtained from Hoerner [5], and

$$(Cd_f)_{wet} = 1 + \frac{6}{5}\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4$$

. . . (12)

Hull Cross Flow Drag Coefficient, $(Cd_c)_h$

From Hoerner [5], $(Cd_c)_h$ for the regime of operation of airship is fairly independent of hull shape and is taken as 0.32.

Fin Cross Flow Drag Coefficient, $(Cd_c)_f$

$(Cd_c)_f$ is a function of the aspect ratio and the taper ratio of the fin. It is provided in Wardlaw [4], as a graph for various taper ratios.
For intermediate values of taper ratio, Λ the linear interpolation is used to get approximate value of $(Cd_c)_f$.

Fin and Hull Efficiency Factors, (η_f, η_k)

The value of η_k and η_f can be obtained by curve fitting the available values of hull efficiency factors of known airships as suggested by Jones and DeLaurier [1].

Comparison of Results

Experimental results and panel method predictions were available for two aerostat configurations under development at ADRDE (Aerial Delivery Research and Development Establishment), Agra. Data regarding fin arrangement and hull shape was also available which made it possible to validate the above methodology.

Both the aerostats were equipped with an inverted 'Y' fin arrangement. Hence some minor adjustments were required in Jones and De Laurier's method to account for such nonsymmetrical fin arrangement. One of the shapes was proposed by Prof. G.N.V. Rao of IISc, Bangalore and is hence named as GNVR shape. The other shape (named SAC), was developed by Space Application Centre ISRO, Ahmedabad.

Figure 8-10 show the comparison amongst the semi empirical method, wind tunnel testing and panel method for the SAC configuration.

Aerodynamic coefficients for the SAC shape were available both through wind tunnel testing, Sundaram [6], and panel method, Narayana [7]. For the GNVR shape however the wind tunnel results were not available.
Figure 11 & 12 shows comparison of semi empirical method and panel method for the GNVR configuration.

It can be seen that results obtained by the modified semi-empirical method results in good co-relation with the panel method calculations for the lift, drag and moment curve for the SAC shape. As far as comparison with the wind-tunnel data is concerned, only the trends are similar, but the values, especially for the Drag curve are not matching well. The drag curve is unsymmetrical due to the shielding of two fins at negative angle of attacks, while at positive angle of attacks only one fin is shielded. Further at low angle of attacks the drag value is higher as the wind tunnel model had corrugated fins. Reasonably good co-relation is also seen for lift and moment coefficient with the panel method for GNVR shape.

Calculation of Neutral Point

From the C_m vs C_L curve the pitch stability coefficient dC_m / dC_L can be obtained. Once the slope of C_m vs C_L curve is known, it is possible to estimate the position of the neutral point using the following equation from Perkins and Hage [3].

$$\frac{dC_m}{dC_L} = \frac{X_{nose} - X_{NP}}{L} \quad \text{. . . (13)}$$

Neutral point location helps in deciding aft c.g. limits, and hence governs location of various structures like ballonet, gondola and power plant. Figure 14 & 15 present travel of neutral point as a function of stabiliser area for the SAC and GNVR shapes. It can be observed from the graphs that for low stabiliser area the neutral point shifts quickly to aft positions with small increase in area. However, this fast shift is not sustained for long. A saturation of neutral point position around 55% is observed at stabiliser area approaching 25% of hull-wetted area.

Conclusions

It can be concluded that the modified semi-empirical method can be a useful tool for quick estimation of the aerodynamics characteristics of bodies of revolution with un-symmetrical fin geometries, for which the original method cannot be directly applied.
The method can also be applied to determine the rear limit of the location of center of gravity, by estimating the position of the neutral point.

References

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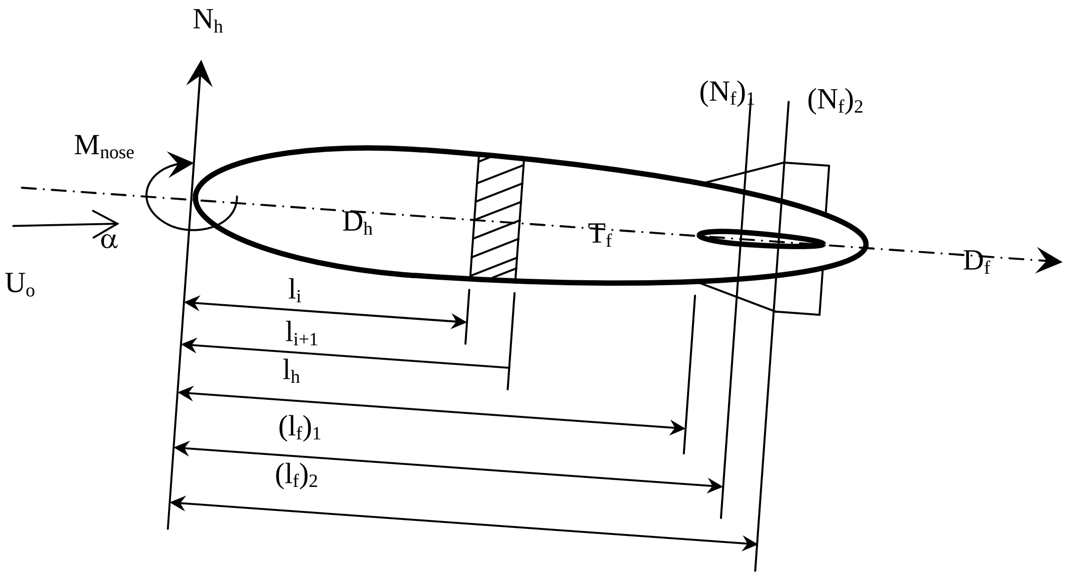

Fig. 1 Schematics of Airship Geometry, Forces and Moments

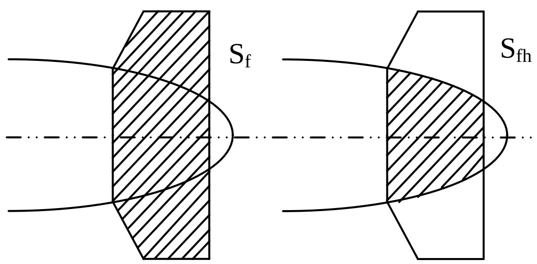

Figure 2 Definition of Fin Areas

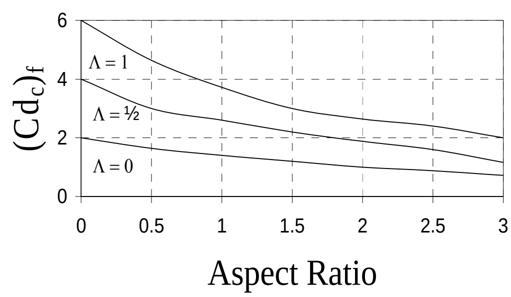

Figure 4 Fin Cross Flow Drag Coefficient

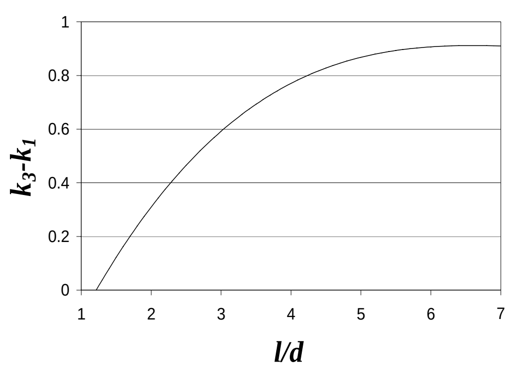

Figure 3 Lateral and Axial Apparent Mass Coefficient

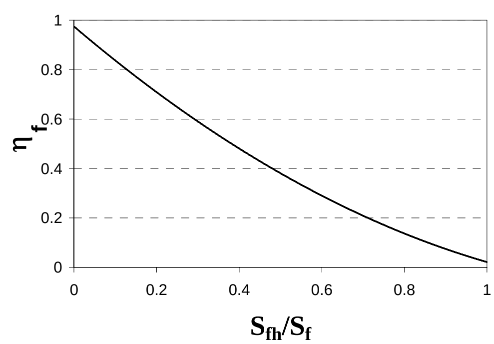

Figure 5 Fin Efficiency Factor

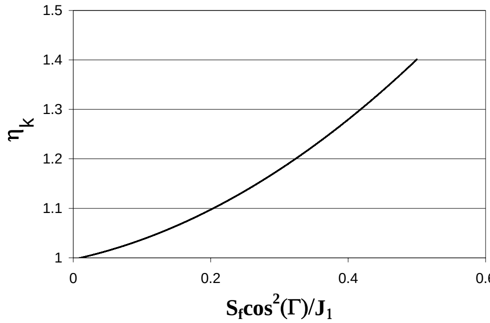

Figure 6 Hull Efficiency Factor

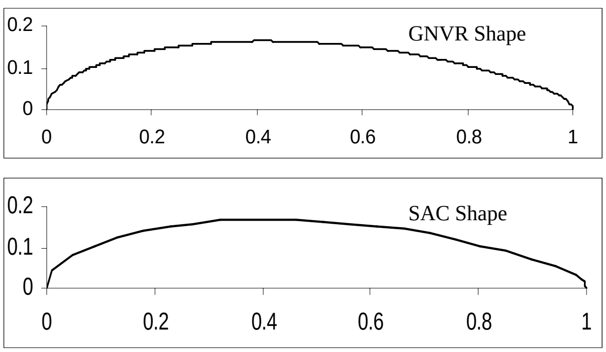

Figure 7 Hull Shapes for GNVR and SAC Configurations (only top half shown)

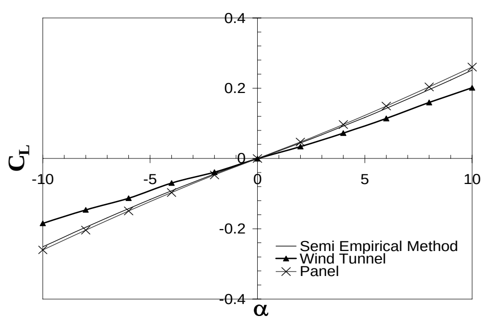

Figure 8 Lift Curve Comparison for SAC shape

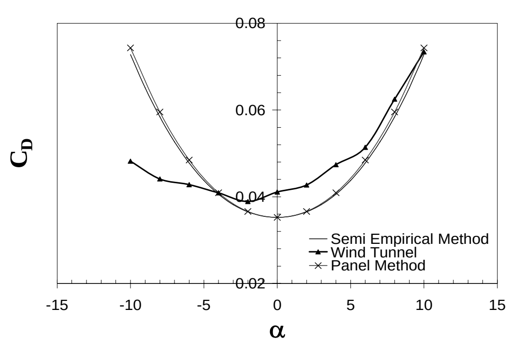

Figure 9 Drag Curve for SAC Shape

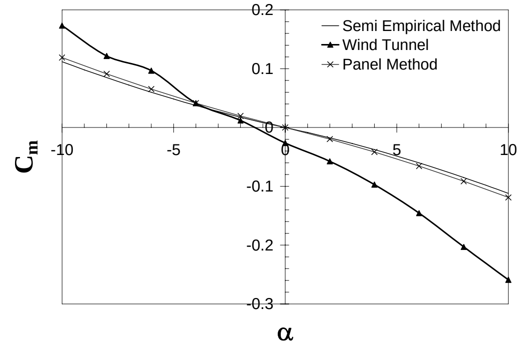

Figure 10 Moment Curve for SAC Shape

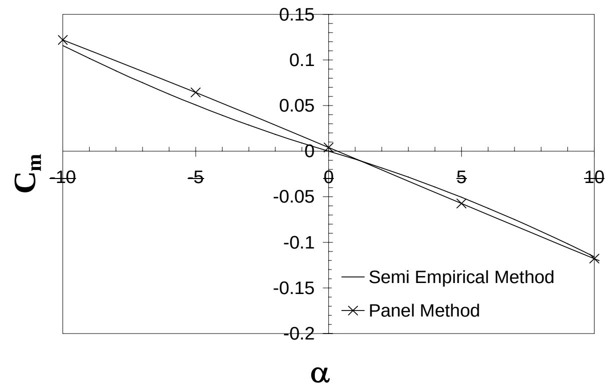

Figure 11 Moment Curve Comparison for GNVR Shape

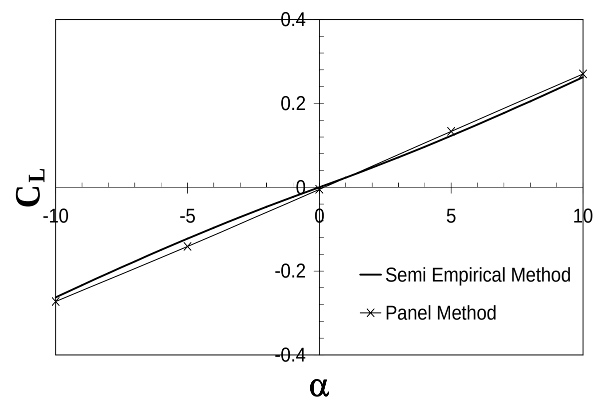

Figure 12 Lift Curve for GNVR Shape

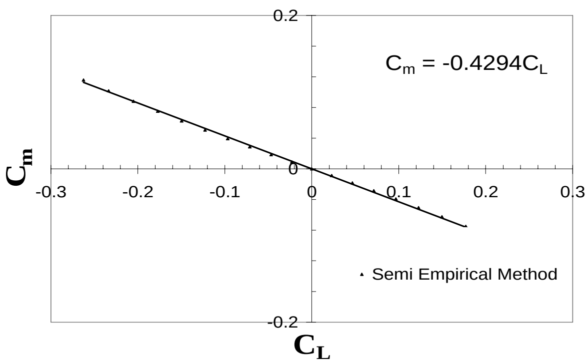

Figure 13 Pitch Stability Coefficient Calculation from Semi Empirical method results for GNVR Shape

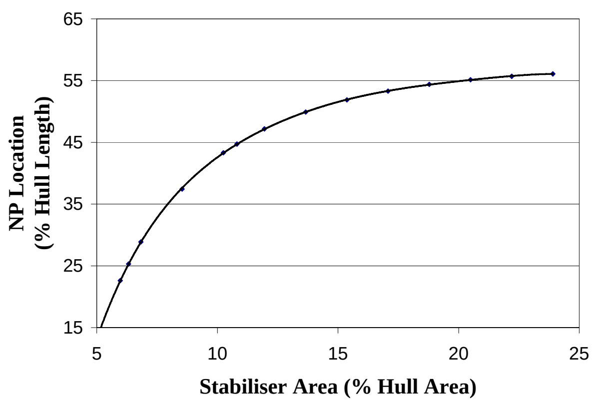

Figure 14 Neutral Point Travel Due To Change in Fin Area (For SAC Shape)

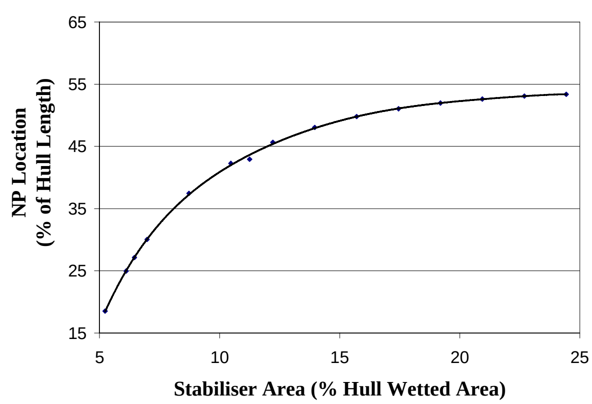

Figure 15 Neutral Point Travel Due To Change in Fin Area (For GNV Shape)