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Prediction of Aerodynamic Characteristics of Missiles with Circular and Noncircular Cross Sections

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Abstract

In this study, an engineering method is presented for computing the aerodynamic characteristics of missiles with circular, square, rectangular and elliptical cross sections. To predict the normal force coefficient values for a rectangular body, a formula was developed to modify C_{dn} values for noncircular cross sections. This semi-empirical method was applied to predict viscous separation cross flow and potential cross flow terms for the body alone. The geometric variable considered in this study was the body cross section. The aerodynamic characteristics of missiles for the bodies alone were computed for different Mach numbers. The predicted aerodynamic characteristics were in good agreement with the results in the literature.

Key Words: missile, aerodynamics, normal force, center of pressure

Dairesel ve Dairesel Kesitli Olmayan Füzelerin Aerodinamik Karakteristiklerinin Hesaplanması

Özet

Bu çalışmada dairesel, kare, dikdörtgen ve elips kesitli füzelerin aerodinamik karakteristiklerinin hesaplanması için bir metod sunuldu. Çalışmada, dikdörtgen kesitli füzelerin normal kuvvet katsayılarının hesabı için Newtonian teori kullanılarak bir formülasyon türetildi ve dairesel kesitli olmayan füzeler için C_{dn} değerlerinin daha doğru hesaplanmasını sağlayacak şekilde bir düzeltme faktörü geliştirildi. Bu yarı ampirik metod kullanılarak kanatsız füzeler için sürtünmeli çapraz akış ve potansiyel çapraz akış terimleri hesaplandı. Bu çalışmada değişken olarak füzelerin kesit şekli kullanıldı. Kanatçık içermeyen füzelerin aerodinamik karakteristikleri değişik Mach sayıları için hesaplandı. Hesaplanan aerodinamik karakteristik değerlerinin literatürden elde edilen deneysel sonuçlar ile oldukca uyumlu olduğu görüldü.

Anahtar Sözcükler: füze, aerodinamik, normal kuvvet, basınç merkezi

1. Introduction

The use of rectangular, square or elliptical cross sections as bodies for missiles or submunition dispensers, called stores, has increased in recent years. The main idea is to increase the available internal volume of a store relative to the store with a circular cross section.

Publications concerning the aerodynamic characteristics of stores with noncircular cross sections are limited. The fast aerodynamic prediction algorithms for missile configurations were written in the past to help designers to obtain quick estimates of the aerodynamic coefficients of particular configurations. Bodies with circular and elliptical cross sections have generally been considered in these studies.

The geometry of a cross section of a body strongly affects flow separation, reattachment point and vortex structure especially in subsonic and transonic regimes. The flow is dependent on the Reynolds number in the sub-critical region (Barth, 1979). The flow around sharp-edged bodies is largely independent of Reynolds number in the range of velocity and incidence considered. As the edges become rounded-off, the transition from turbulent to laminar flow separation occurs with the angle of incidence.

The present study describes a semi-empirical method to predict the aerodynamic characteristics of bodies having noncircular cross sections without wings. The predicted results are compared with the previously published theoretical and experimental results.

2. Analysis

There are many methods to calculate the aerodynamic characteristics of slender bodies. The fast prediction methods are generally based on the "component buildup method" developed by Pitts et al (1951). Jorgenson (1978) generated a semi-empirical method to predict C_N, C_m and x_{ac} for circular and elliptical bodies with and without wings. DATCOM (1963) is another method related to this subject. Sigal (1989) experimented on bodies with circular, square and rectangular cross sections, with and without delta wings.

Jorgensen (1978) applied Allen's cross flow (Pitts et al., 1951) analogy to calculate C_N and C_m characteristics for bodies with noncircular cross sections and applied it to circular and elliptical cross-sectional bodies. C_N and C_m for a body with similar cross-sectional shape along the whole length is given in the work of Jorgensen (1978) as follows;

$$C_N = \left[\frac{A_b}{A_r}\sin 2a\cos\frac{a}{2}\right]\langle\frac{C_n}{C_{n_o}}\rangle_{SB} + \left[hC_{dn}\frac{A_b}{A_r}\sin^2 a\right]\langle\frac{C_n}{C_{n_o}}\rangle_{newt} \quad (1)$$

$$C_M = \left[\frac{V - A_b(1-x_m)}{A_r x}\sin 2a\cos\frac{a}{2}\right]\langle\frac{C_n}{C_{n_o}}\rangle_{SB} + \left[hC_{dn}\frac{A_b}{A_r}\langle\frac{x_m - x_c}{x}\rangle\sin^2 a\right]\langle\frac{C_n}{C_{n_o}}\rangle_{newt}$$

where $0 \leq \alpha \leq 90°$. The potential cross flow term $(C_n/C_{no})_{SB}$ is the ratio of the local normal-force coefficient per unit length, C_n for the desired cross-sectional shape to the similar coefficient, C_{no} for the equivalent circular shape having the same cross-sectional area. The necessary ratios can be determined from apparent mass coefficients (slender-body theory) for many cross-sectional shapes. The viscous cross flow term $(C_n/C_{no})_{Newt}$ is given by the Newtonian impact theory. C_{dn} remains the cross-flow drag coefficients for the equivalent circular cylinder section. In these equations, η is the cross flow drag proportionality factor which is the ratio of the cross flow drag coefficients for a finite length cylinder to that of an infinite length cylinder.

C_{dn} values are given experimentally as a function of the Mach number and Reynolds number. (C_n/C_{no}) can be found in the work of Jorgensen (1978) for bodies with cicular and elliptical cross sections. η and C_{dn} for a circular cylinder as a function of Mach number and Reynolds number are given in the work of Jorgensen (1978). Chan (1981) developed a computer program to make use of Jorgensen's method for predicting C_N and C_m of bodies alone with circular and elliptical cross sections.

The peresent method is based on experessions 1 and 2. These formulae are applicable when the arbitrary cross section is transformed to an equivalent circular cross section. The general cross section of a body is given in Fig. 1. For a rectangular cros section shown in Fig. 1, $(C_n/C_{no})_{Newt}$ was calculated by means of Newtonian impact theory (Akçay, 1983). This ratio for a body with a rectangular cross section was modified in this study as follows:

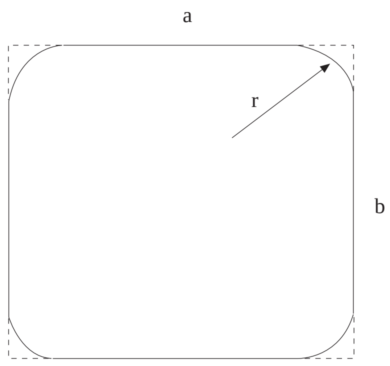

Figure 1. General cross sectional geometry of a missile

$$\langle \frac{C_n}{C_{no}} \rangle_{Newt} = \frac{(1.5a - r)}{D} \quad (2)$$

Here D is the equivalent diameter expressed as

$$D = \frac{2}{\sqrt{\pi}} \sqrt{ab + (\pi - 4) r^2} \quad (3)$$

and for a circular cross section, C_n equals C_{no} and the raito is reduced to unity and Equation (3) gives $(C_n/C_{no})_{Newt}$=1. When Jorgensen's method was applied with the above expressions it underpredicted the C_N for bodies alone with rectangular cross sections approximately by 29% and overpredicted by 12% for 90 degrees rolled rectangular bodies. C_m values were overpredicted for both of the configurations. The results are shown in Fig. 2.b ad Fig. 2.c. This inconvenience is also shown in Fig. 4.b and Fig. 4.c. for bodies with elliptical cross sections. Thus, to remedy this inconvenience an empirical correction factor K was developed as

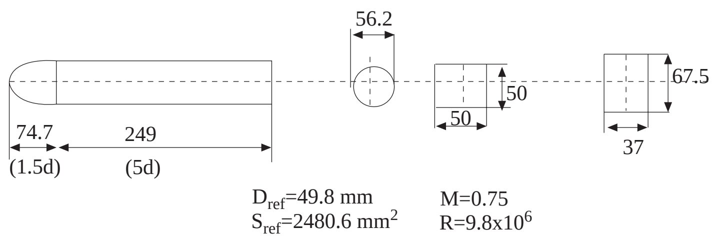

Figure 2a. Dimensions of models with rectangular, square and circular bodies

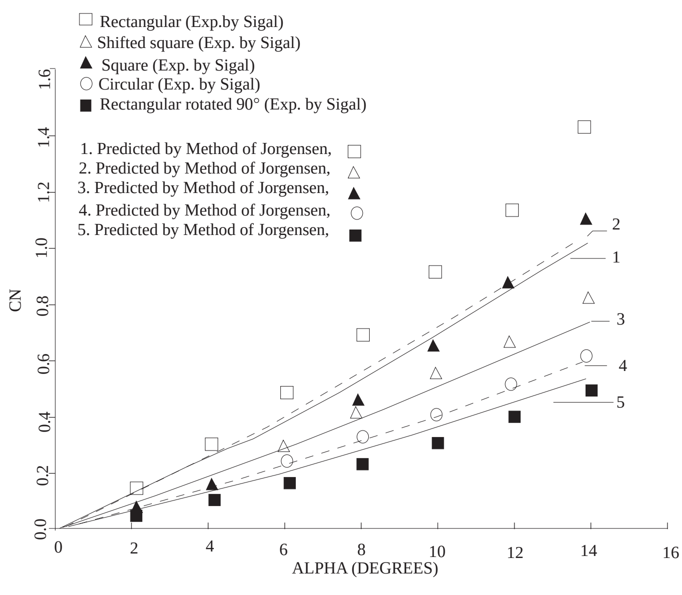

Figure 2b. Comparison of computed normal force coefficients obtained by Jorgensen's method with the measured data of Ref.6 of rectangular, square and circular bodies. Ma=0.75

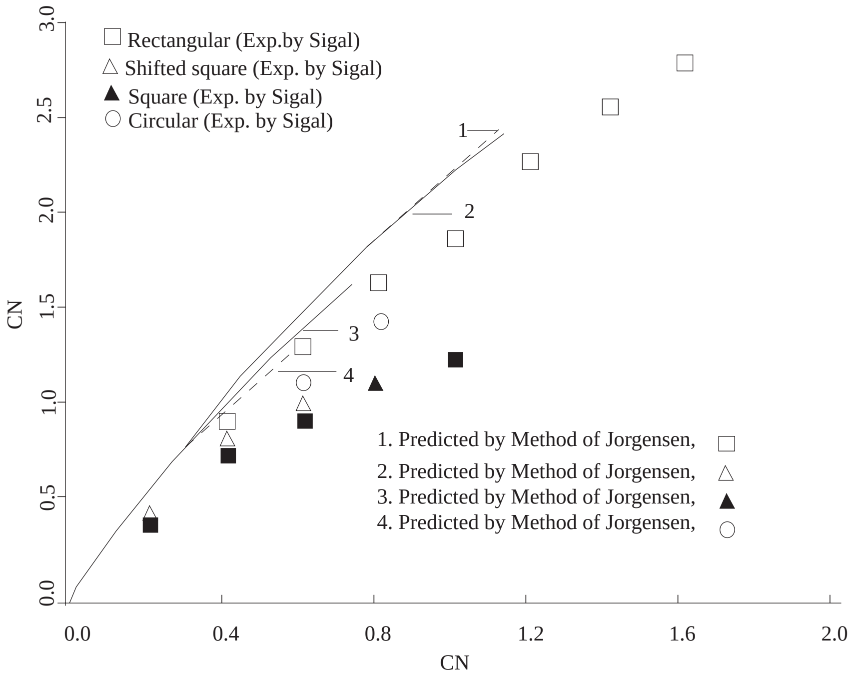

Figure 2c. Comparison of computed pitching moment coefficients obtained by Jorgensen's method with the measured data of Ref.6 of rectangular, square and circular bodies. Ma=0.75

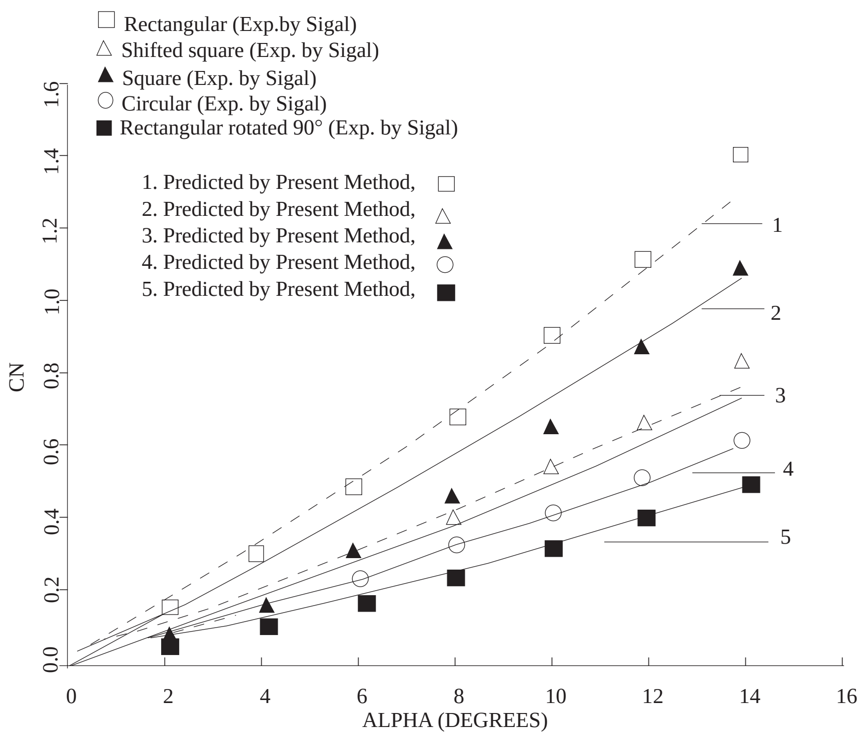

Figure 3a. Comparison of computed normal force coefficients obtained by the present method with the measured data of Ref.6 of rectangular, square and circular bodies. Ma=0.75

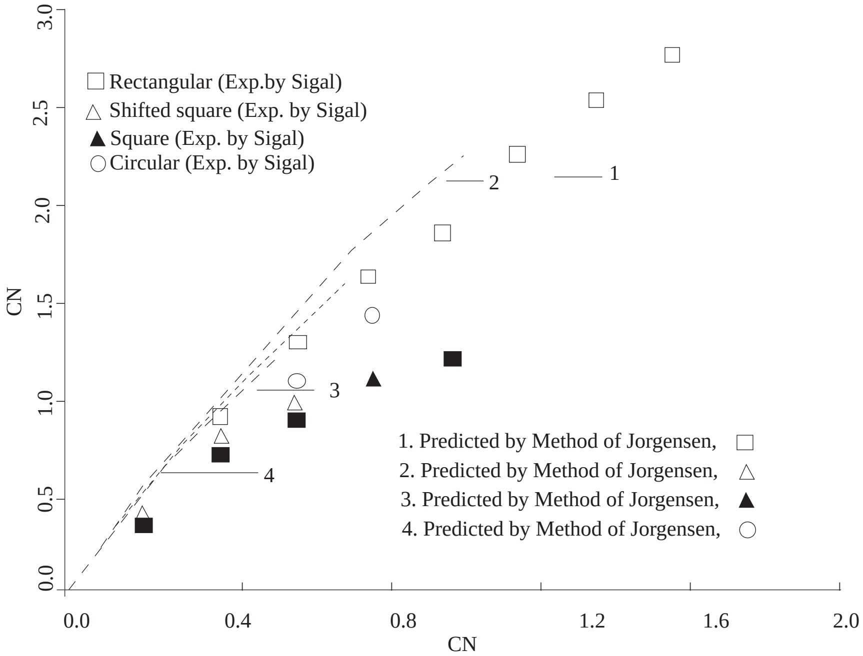

Figure 3b. Comparison of computed pitching moment coefficients obtained by the present method with the measured data of Ref.6 of rectangular, square and circular bodies. Ma=0.75

$$K = \langle \frac{H}{D}\frac{b}{a} \rangle^{0.2998} \quad (4)$$

where

$$H = \sqrt{(a^2 + b^2)} - 0.818r \quad (5)$$

K depeds on the geometry of the configuration. K is 1 or a circular body and greater than 1 for rectangular and elliptical bodies and less than 1 for 90 degrees rolled rectangular and elliptical bodies. Equation 3 is general expression for bodies with circular, square , rectangular and elliptical cross sections. To calculate C_N of a body alone, C_{dn} obtained from the work of Jorgensen (1978) has to be multiplied by K as

$$C_d = C_{dn}K \quad (6)$$

3. Geometry of the Models

Four kinds of body with circular, rectangular, square and elliptical cross sections were considered in this study. Rectangular and square cross-sectional bodies had different corner radii. Each of thesee bodies are described separately.

4. Normal Force, Pitching Moment and Center of Pressure

For the first model, the dimensions are presented in Fig. 2.a. The radius of corners had a 0.1 reference length. The total fineness ratio was 6.5, ad the tangent give noses had a fineness ratio of 1.5. The reference area and length in the definition of the aerodynamic coefficient were the centerbody cross-sectional area and its square root respectively. These quantities were independent of the configuration. For the first type of model, it was considered that the center of moment was located 3.5 reference lengths from the tips of the boides. All calculations were carried out at Mach number 0.75 and Re=9.8×10^6 for angles of attack $0\leq \alpha \leq14$ degrees.

The normal force coefficients and pitching moment coefficients calculated by Jorgensen's are presented in Fig. 2.b and Fig. 2.c. The normal force coefficients and pitching moment coefficients calculated in our study are presented in Fig. 3.a. and Fig. 3.b. The normal force was largest for the rectangular body and smallest for the same body rolled 90 degrees.

The normal force coefficient values calculated by Jorgensen's method were 29% less than the experimental values for a body with a rectangular cross section and were % 12 greater than the experimental values for a 90 degress rolled rectangular body. Jorgensen's medhod gave good results for both circular and square cross-sectional bodies. All values were 14 % overpredicted for both of the rectangular configurations. The agreement between the predict data in our method and the experimental data of Sigal (1989) was quite satisfactory. The bodies with square and rectangular cross sections had greater C_N values than the bodies with circular cross sections with the same cross-sectional area. The rectangular body had the greatest C_M values among these three configurations. The present method predicted the C_m values well for rectangular bodies, overpredicting 12% for square and circular bodies.

Jorgensen (1978) preticted C_N and X_{ac}/D for circular and elliptical cross-sectional bodies. The circular cross-sectional body had a diameter of 6.6 cm and a total fineness ratio of 3. The elliptical cross sections had the same area as the circular cross section. The center of moment was located 37.32 cm from tips of the bodiy . The dimensions of these models are shown in Fig. 4.a. The calculations were carried out with Mach number 0.6 and $Re = 6.5 \times 10^6$ for angle of attack $0 \leq \alpha \leq 60$ degrees.

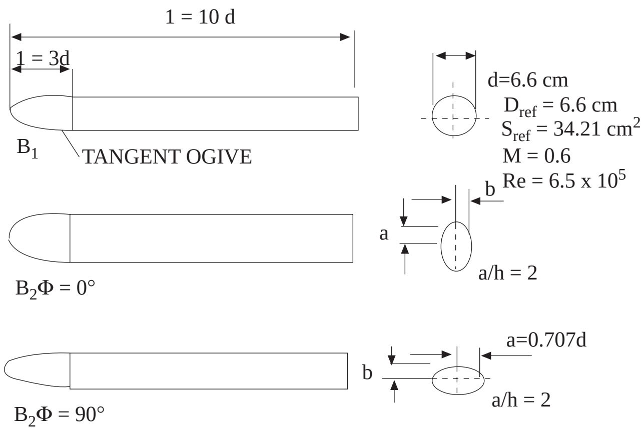

Figure 4a. Dimensions of models with circular and ellipsoidal bodies

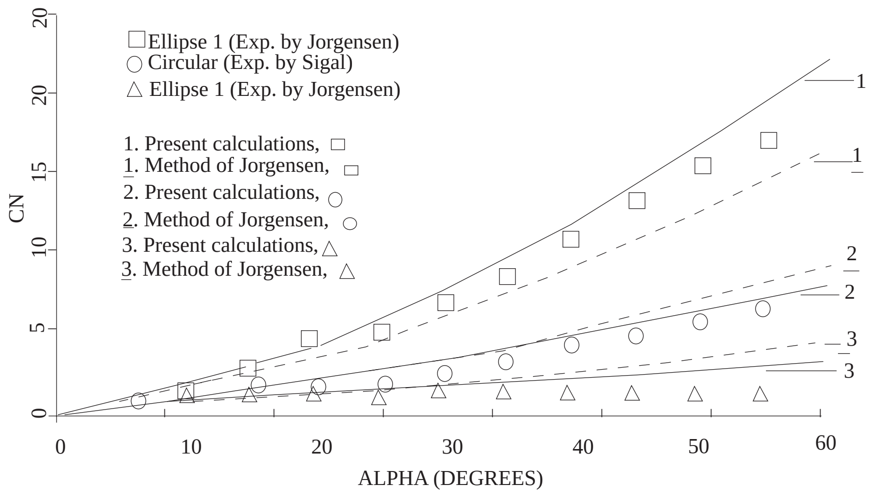

Figure 4b. Comparison of computed normal force coefficients obtained by the present method and Jorgensen's method with the measured data of Ref.4 of circular and ellipsoidal bodies. Ma=0.6

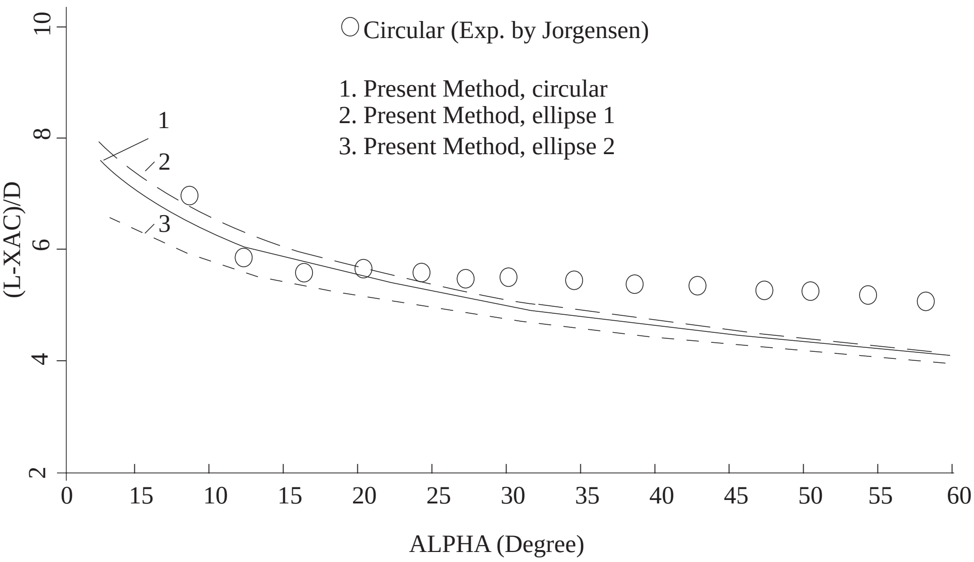

Figure 4c. Comparison of computed center of pressure obtained by the present method and Jorgensen's method with the measured data of Ref.4 of circular and ellipsoidal bodies. Ma=0.6

As seen in Fig. 4.b, the normal froce coefficients calculated by Jorgensen's method were 18 % less than the experimental values for an elliptical cross section a/b=2, and two times greater than that of the bodies of 90 degrees rotated elliptical cross sections a/b=0.5 and fitted well with experimental values for the bodies with circular scross sections. Although the present method calculated C_N values well for the elliptical cross section a/b=2 and circular cross section, it still overpredicted C_N values for the 90 degrees rotated elliptical cross section a/b=0.5. The agreement between the present calculatinos and experimental data was better than Jorgensen's results even in this case. As seen in Fig. 4.c., the predictions of the centre of pressure (1-X_{ac})/L were good for elliptical and circular cross section up to 25 degrees but there was underprediction up to 60 degrees. The peresent method underpredicted the center of pressure for the 90 degrees rotated elliptical cross section.

In Fig. 5.b and Fig. 5.c, C_N and center of pressure predicted by the present method and Jorgensen's method are compared with the experimental data for Mach number 0.7 with a subcritical Reynolds number. Jorgensen's method predicted C_N well up to 65 degrees but underpredicted for angles of attack greater than this values. Although the peresent method overestimated the C_N values, the trend followed the experimental trend up to angles of attack of 90 degress. The prediction of the centre of pressure with the peresent method was in good agreement with that of the experimental values. To be sure that the peresent method worked for transonic and supersonic flow conditions, the experimental data obtained from the work of Jorgensen (1978) was compared with the calculated data for the circular cross-sectional bodies with a fineness ratio of 2.5. The related geometry is shown in Figure 6.a. The experimental and calculated normal force coefficients C_N and center of pressure for Mach number of 0.6, 0.9, 1.2 and 2 with a sub-critical Reynolds number of 4.3×10^5 are given in Fig. 6.b and Fig. 6.c. The predicted and measured data were in good agreement for both normal force coefficient and center of pressure for all Mach number ranges. Calculations were not repeated for Jorgensen's method which worked well for circular cross-sectional bodies with supersonic Mach numbers. In the supersonic flow regime, the cross flow drag coefficient C_{dn} was independent of the Reynolds number and was only a function of the Mach number. C_{dn} calculated with Newtonian theory and measured values of C_{dn} were very close in this flow regime as shown in the work of Jorgensen (1978).

5. Summary and Conclusions

An engineering method is presented for computing the normal force, pitching moment and center of pressure for slender bodies of circular, square, rectangular and elliptical cross sections. A semi-empirical method was applied to predict vicosu separation cross flow and potential cros flow terms for a body alone. The geometric variable considered in this study was the body cross section. C_N, C_m and X_{ac} values obtained for the body were in good agreement with the results. The following conclusions can be made.

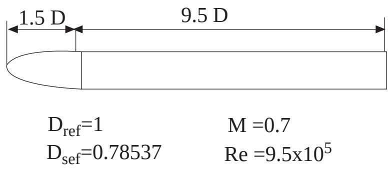

Figure 5a. Dimensions of model with circular body

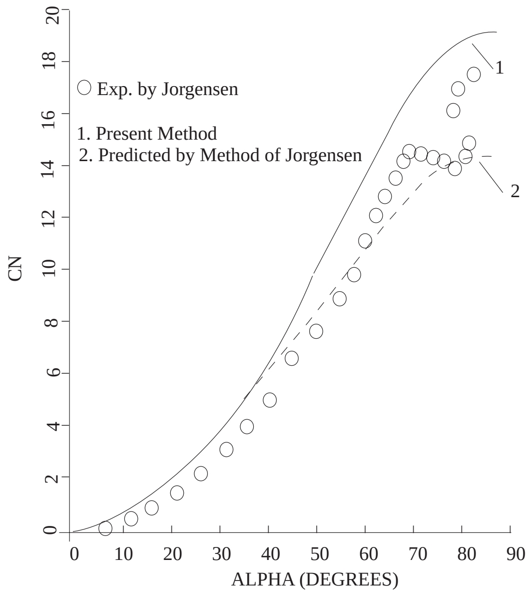

Figure 5b. Comparison of computed normal force coefficients obtained by the peresent metod and Jorgensen's method with the measured data of Ref.4 of circular body Ma=0.7

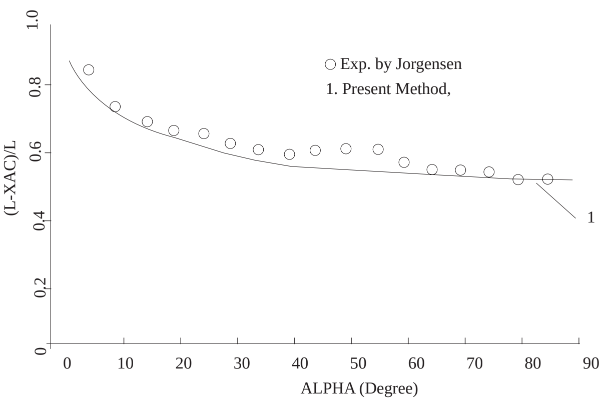

Figure 5c. Comparison of computed center of pressure obtained by the peresent metod and Jorgensen's method with the measured data of Ref.4 of circular body Ma=0.7

a- Jorgensen's method based on Allen's cross flow analogy underpredicts the normal force coefficients C_N versus angles of attack for noncircular cross-sectional bodies in sub-critical flow conditions where M≤1. To predict $(C_n/C_{no})_{Newt}$ values for a rectangular body, a formulation was generated by means of Newtonian theory in this study. An empirical correction factor K was develoepd to modify C_{dn} values for noncircular cross sections.
K=1 for circular cross-sectional body,
K> 1 for rectangular cross-sectional body
K< 1 for rotated rectangular cross-sectional body.

b- The agreement between predicted and experimental C_N and X_{CP} data obtained versus angles of attack was quite satisfactory for circular, elliptical, square and rectangular cross-sectional bodies.

c- This study shows that a body with a square or a rectangular cross section exhibits aerodynamic advantages in addition to their logistic advantages.

d- The present method based on a semi-empirical approach requires a few seconds to calculate normal force coefficients C_N and center of pressure X_{CP} for angles of attack up to 90 degrees. It is concluded that the present method is very fast and precise enough for engineering calculations.

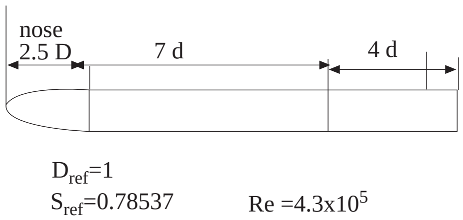

Figure 6a. Dimensions of model with circular body

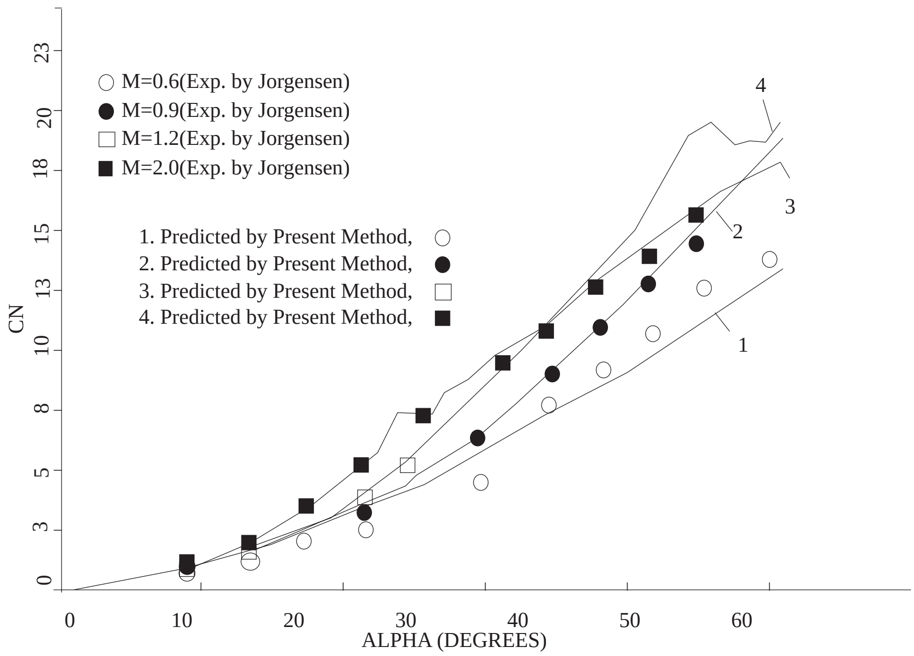

Figure 6b. Comparison of computed normal force coefficients obtained by the peresent method with the measured data of Ref.4 of circular body. Ma=0.6, Ma=0.9, Ma=1.2, Ma=2.

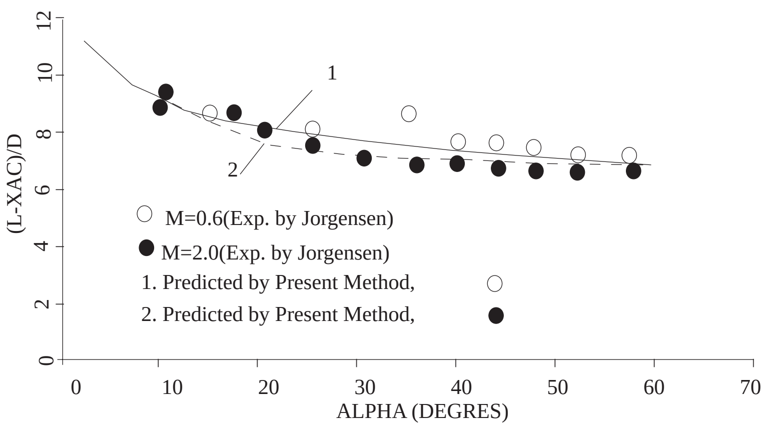

Figure 6c. Comparison of computed center of pressure obtained by the present method with the measured data of Ref.4 of circular body. Ma=0.6, Ma=0.9, Ma=1.2, Ma=2.

6. Nomenclature

A_b	Body base area (at x=1)
A_p	Planform area of a body
A_r	Reference area
a	Length of rectangle
b	Width of rectangle
C_d	Cross flow drag coefficient
C_{dn}	Cross flow drag coefficient of circular cylindrical section
C_m	Pitching moment coefficients
C_N	Normal force coefficients
C_n	Normal force coefficient per unit length
C_{no}	Normal force coefficient per unit length for the equivalent circular shape having the same cross-sectional area
D_{ref}	Reference circular body diameter
S_{ref}	Reference area, cross-sectional area of circular body
d	Reference length, $d = \sqrt{S_{ref}}$
H	Hypotenuse of rectangular body
K	Correction factor
M	Free stream Mach number
Re	Free stream Reynolds number
r	Corner radius of a cross section
V	Body volume
x_c	Axial distance from body nose to centroid of body planform area
x_{ac}	Distance of the center of pressure from the nose apex.
x_m	Center of mass
x	Axial distance from body nose
α	Angle of attack
η	Crossflow drag proportionality factor

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