DEVELOPMENT OF A COMPUTER PROGRAM FOR ROCKET AERODYNMIC COEFFICIENTS ESTIMATION

Md. Nizam Dahalan*, Su Vin Cent, Mohd. Shariff Ammoo

Department of Aeronautical Engineering
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 Skudai, Johor Bahru

ABSTRACT

A computational method has been developed to realize an efficient and accurate user friendly computational program called RocketCalculator, which integrates carefully assessed methodologies and offer flexibilities of the rocket configurations and velocities up to Mach number 3.0 and angle of attack of 25 degrees. The RocketCalculator is capable of analyzing the configurations of wing-alone, body-alone, wing-body combination, and wing-body-tail combination of rocket. USAF Datcom Method has been chosen as the analysis method and the programming language is Microsoft Visual Basic. The result would be displayed in form of the corresponding lift (C_L), normal force (C_N) and drag (C_D) coefficients at certain Mach number and angle of attack. Experimented data for several models have been taken out from available sources to validate the program output. Comparisons of the program output and experimental results generally show good agreement with average error of less than 10%.

Keywords : *Aerodynamic coefficients, normal force, lift, drag , rocket.*

1.0   INTRODUCTION

Aerodynamics is required throughout the design process of any flight vehicle. These aerodynamics are used for flight performance estimates, including range, maneuverability, distance and stability analysis. In addition, they are used for structural analysis especially for flight vehicle loading [1]. Classical methods such as wind tunnel testing and computational fluid dynamics (CFD) still play important roles in the aerodynamic design process of the flight vehicles. However, such time consuming methods are driving forces to the use of a more convenient and faster method to obtain desired aerodynamic coefficients [2].

It is pointed out that preliminary design programs have one advantage: they do not have to rely on benchmark data (aerodynamics, propulsion efficiencies, certified performance, flight testing) [3]. Preliminary design calculation should be fast but

_____
*Corresponding author : nizam@fkm.utm.my

reasonably accurate for first estimation, which may be based on combined theory and empirical information. As such, tedious and time-consuming computational methods may be bypassed by less tedious but sufficiently accurate one. Therefore, the present method is developed with the above objectives in mind and to serve as an alternative solution to existing less-tedious and time-consuming design method such as the well established Datcom method and software. By taking advantage of the latter method, the present work is intended to provide in-house and user-friendly software appropriate for academic and educational purposes in a university environment.

To obtain a quick but fairly accurate estimate of the aerodynamic coefficients for preliminary design purposes, a computer program has been developed which has been based on theoretical foundations as well as well established semi-empirical data, and by reference to USAF Stability and Control Datcom [4]. The program should require some basic geometry input and the environmental condition to calculate the desired parameter. In this case for aerodynamic characteristics such as lift (C_L), normal force (CN), drag (C_D), pitching moment (C_M) and center of pressure (X_{cp}) coefficients and their trend towards some changing factors like Mach number and angle of attack would be the final output. The computer program will be able to estimate the coefficients for different wing, body, wing-body, and wing-body-tail combinations of rocket. Lastly, to determine the accuracy of each code of the computer program, the program's output such as normal force, lift and drag coefficients were compared with experimental results.

2.0 METHODOLOGY AND ANALYSIS

The USAF Stability and Control Datcom has been chosen as the main reference guide to compute the aerodynamic characteristics for wing alone, body alone, wing-body combination, and wing-body-tail combination. The fundamental purpose of the USAF Stability and Control Datcom is to provide a systematic summary of methods for estimating stability and control characteristics [5]. The program Digital Datcom is a computer program based on the handbook methods contained in the USAF Datcom. It is a Fortran program available to Langley Research Center users for computing static and dynamic stability derivatives as well as high lift and control power coefficients [6]. In preliminary design applications, in spite of advances in computational fluid dynamics, it is pointed out that the approach followed by Digital Datcom is accurate enough for several applications, in particular missiles or rockets at supersonic speeds [7].

2.1 Lift Coefficient, C_L
At low angles of attack, certain mutual interference effects may arise between the components when a lifting panel is added to a body. The mutual interference effects as: (a) the effect of body upwash or cross flow on the local angle of attack of the are classified lifting panel; (b) the effect of local body flow properties such as Mach number and dynamic pressure on the panel characteristics; (c) the effect of the lift carryover from the panel onto the body; (d) the effect of panel upwash on the panel body ahead of the panel (at subsonic only), and; (e) the effect of the panel lifting vortices on the body behind the wing [4].

For the case at higher angle-of-attack that the effects of the shed vortices are somewhat more involved [4]. For high-aspect-ratio, unswept subsonic configurations, the flow remains attached over the lifting panels up to angles of attack approaching the stall. Therefore, rockets with such configurations tend to have a larger value of linear lift, and as a result, stall occurs quicker as a function of angle of attack. For swept and low-aspect-ratio configurations, the trailing vortices are shed at progressively more inboard stations as the angle of attack is increased. The effect appears in the downwash field and hence in the lift generated by the aft panel. The nonlinear cross-flow contribution to body lift is also sizable at higher angles. This cross-flow lift is caused by a pair of body vortices that can also strongly affect the lift contributions from the panels.

2.2   Drag Coefficient, C_D

Drag is the most difficult aerodynamic force to predict. There are several components that have a combined effect on the total drag; they are skin friction drag, wave drag, and base drag. These components are affected by factors including configuration geometry, Mach number, Reynolds number, angle of attack and body roughness [7]. The total drag is defined as the sum of zero-lift drag and induced drag [8].

$$\text{Total Drag} = \text{Zero-lift Drag} + \text{Induced Drag} \tag{1}$$

Drag break down method is used in analyzing the drag of an aircraft, by braking down the drag of an aircraft into those caused by its components. Therefore, the total vehicle drag at angle-of-attack given by the USAF Datcom can be slightly modified to suit the rocket with cruciform tail.

$$\text{Total Drag} = \text{wing-body zero-lift drag} + \text{wing-body induced drag}$$

$$+ \text{vertical tail zero-lift drag} + \text{horizontal-tail zero-lift drag}$$
$$+ \text{horizontal-tail induced drag} \tag{2}$$

2.3   Wing Maximum Lift, $C_{L_{max}}$

At subsonic speeds, Shrenk's Method has been used in the program to estimate the wing maximum lift. The approximated spanwise location where the stall will first occur can be calculated for an untwisted tapered wing by

$$\eta_{stall} = 1 - \lambda \tag{3}$$

where λ is the wing taper ratio [4].

At supersonic speeds the lift is limited by the wing geometric considerations rather than by flow separation [4]. The semi empirical method presented in the Datcom has been used in the program to estimate the wing maximum lift at supersonic speeds.
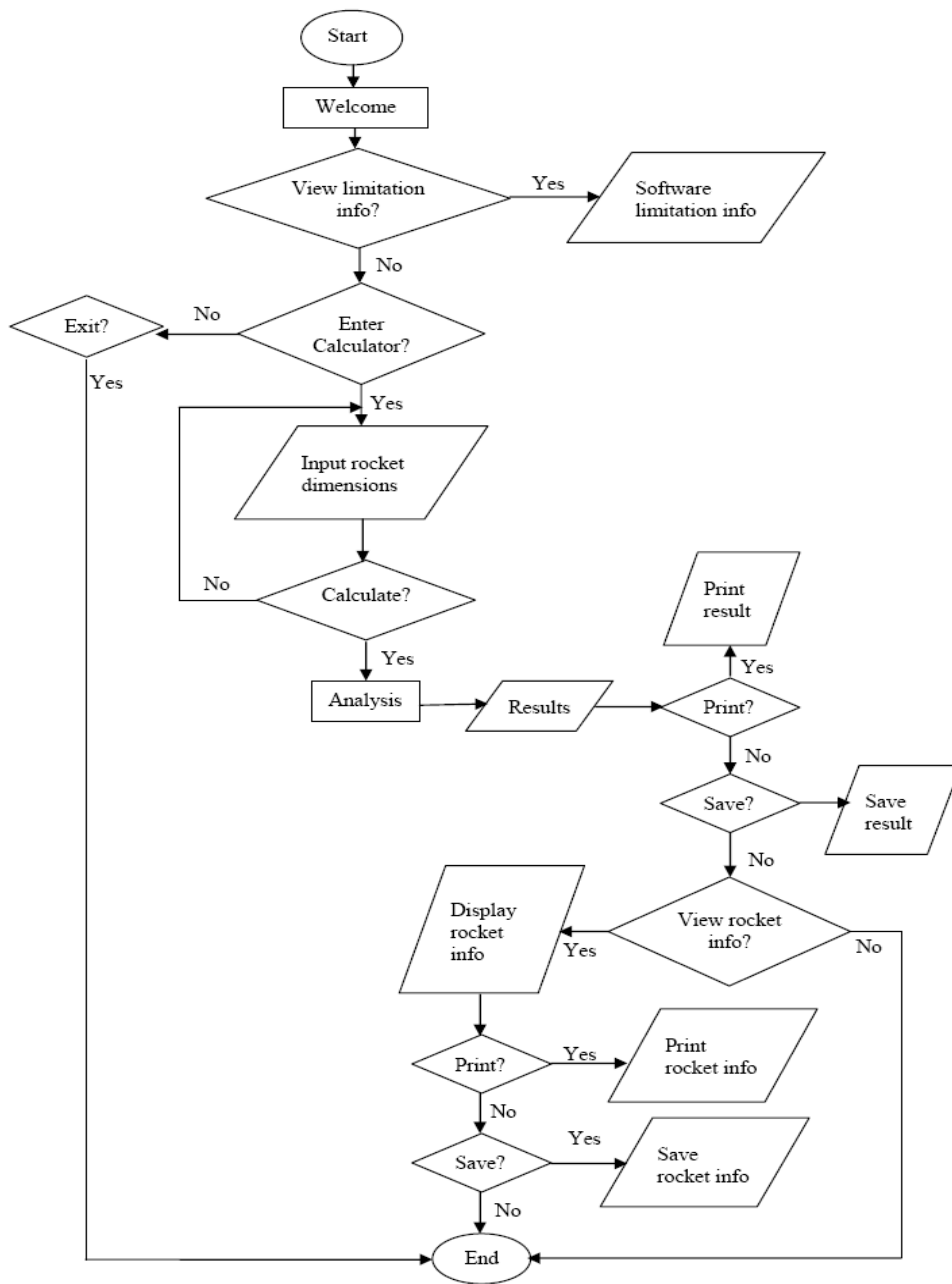
Figure 1: Basic Structure of *RocketCalculator*.

3.0   SOFTWARE METHODOLOGY AND IMPLEMENTATION

Microsoft Visual Basic .NET (VB.NET) has been chosen to develop the *RocketCalculator* because it is easy-to-learn and user-friendly. Visual Basic .NET is the next generation of Visual Basic, but it has also a significant departure from previous generations [9]. Despite all appearances Visual Basic is really very easy to use, since the complexity of the language is hidden in tools provided to developers by Microsoft [10]. All the rapid application development (RAD) tools that developers have come to expect from Microsoft are found in Visual Basic .NET, including drag-and-drop design and code behind forms. In addition, new features such as automatic control resizing eliminate the need for complex resize code. New controls such as the in-place menu editor deliver visual authoring of menus directly within the Windows Forms Designer. Flow Chart in Figure 1 shows the basic structure of the *RocketCalculator*.

3.1 Welcome Screen
The first screen when the program is loaded is the welcome screen. This can be shown in Figure 2. The screen serves as the 'cover' of the program. It gives the general information on where the program is developed, who have credits on it and what the program is.

Figure 2 : Welcome Screen

3.2 Calculator Screen

The calculator screen is the most important part of this program. Figure 3 shows the interface of the calculator screen. It serves as the input data collector. It is designed as simple as possible to be user friendly. A reference figure is given for dimensioning guidance. Only dimensions in length are needed to be keyed in for dimensioning input, while other data such as leading-edge angle, taper ratio and aspect ratio will be generated automatically. A 'Reset' button is placed besides the 'Calculate' button. It is useful if the user wishes to erase the entire data keyed in previously.
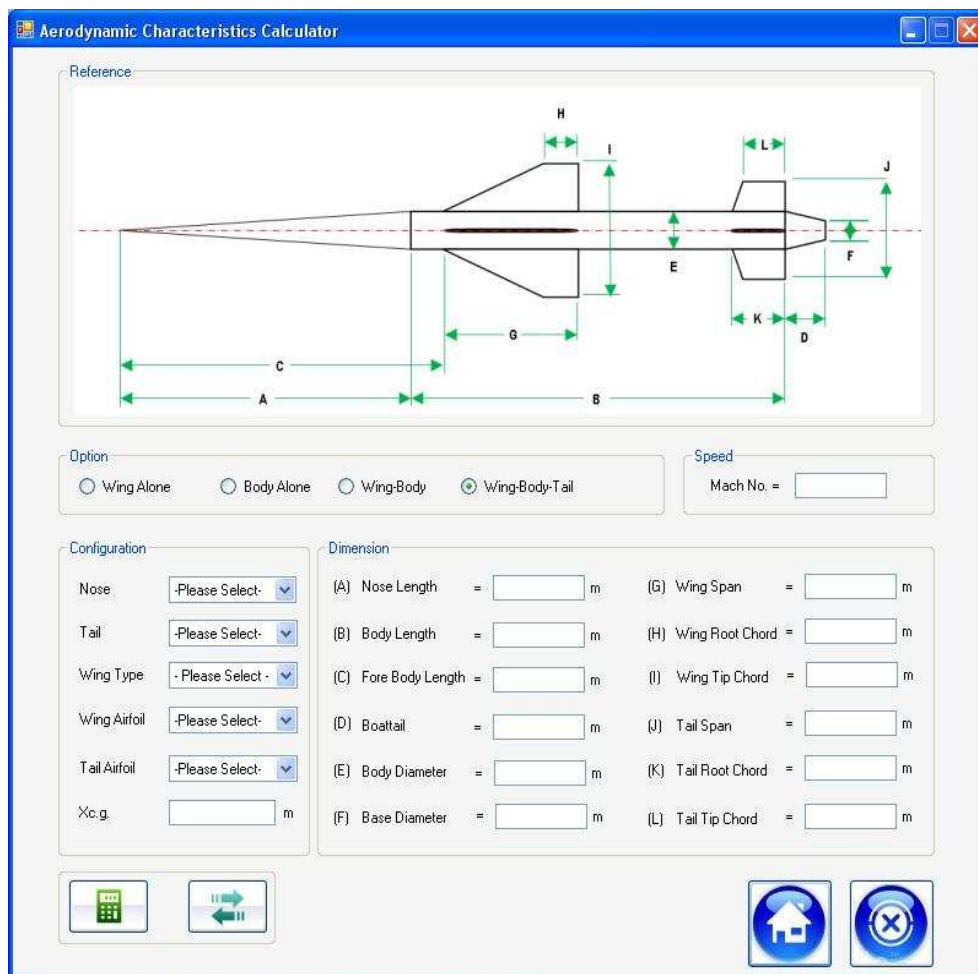

Figure 3: The interface of the calculator screen

3.3 Result Screen

Result screen will pop up if the 'Calculate' button of the calculator screen is clicked. It presents the results data in both the graphical and table form. Example of results

screen is illustrated in Figure 4 that shows the graph of normal-force and drag coefficients versus angle of attack for body alone configuration at Mach Number 2.
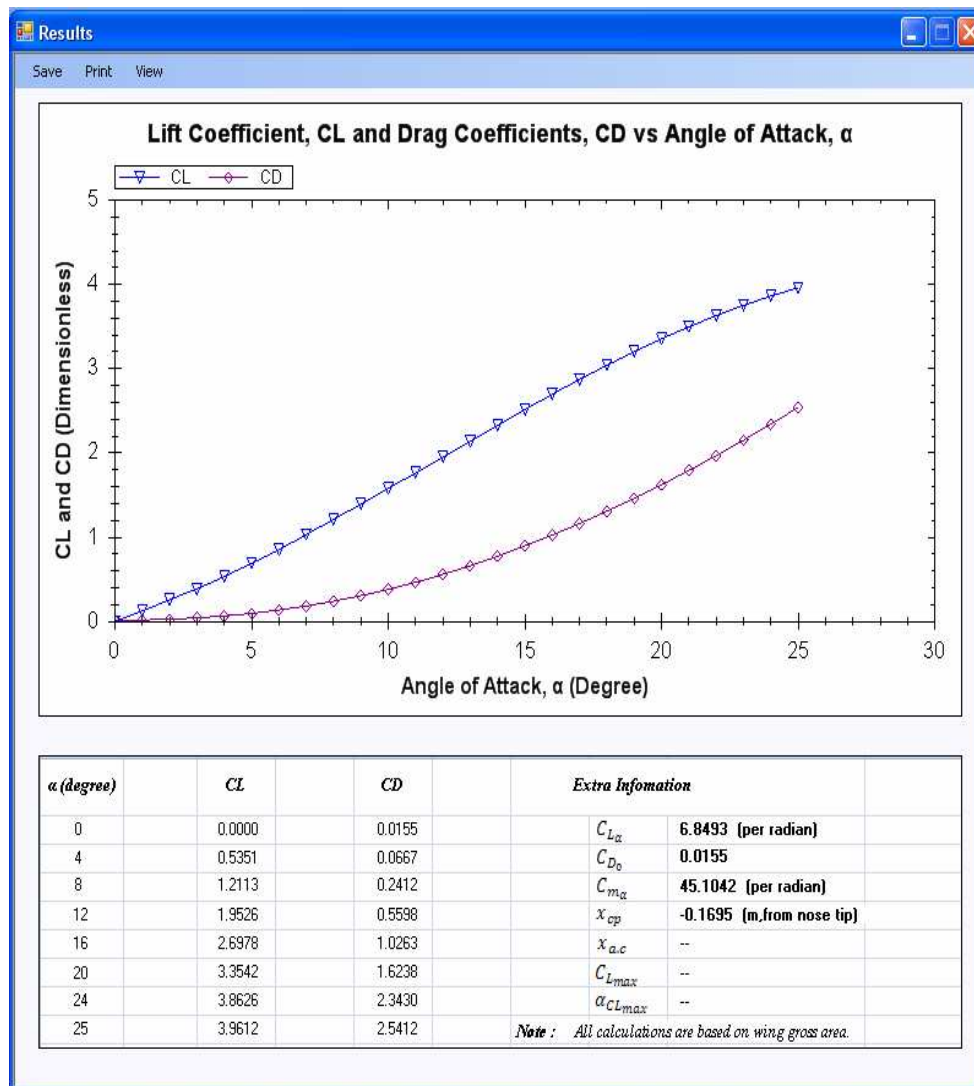

Figure 4:   Result screen

3.4 Rocket data Screen

Rocket data screen will be shown when the 'view' menu of the result screen in selected. This screen (Figure 5) contains all the geometric information of the rocket model used in the program calculation. This is particularly useful for user to keep record and or to verify the geometrics of the rocket designed.

Some other additional functions are contained in the program such as 'Print' and 'Save' function. These two functions only occur in the result screen and rocket data screen.
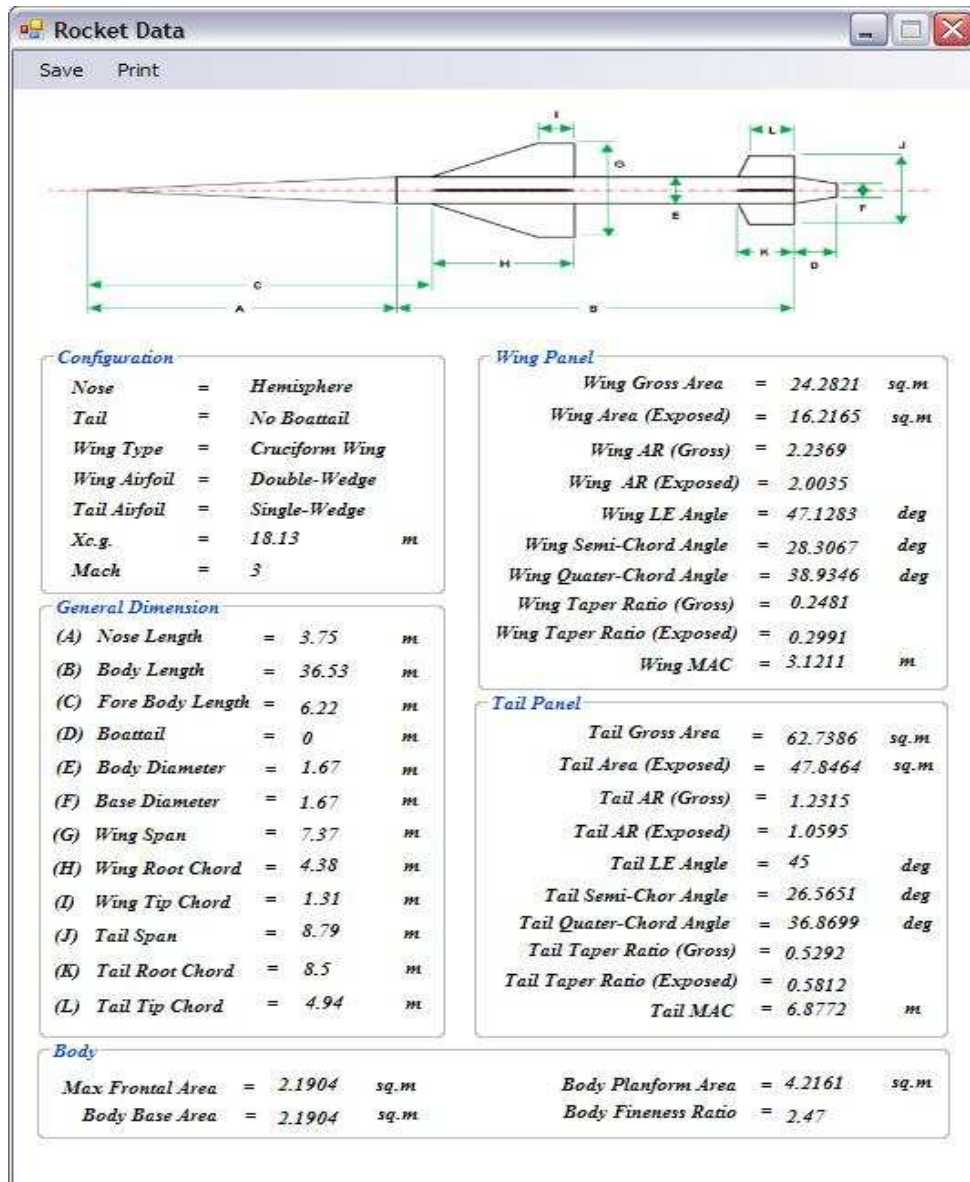
Figure 5:   Rocket data screen.

3.5   Software Limitations
The followings are the limitations of the program developed:

i.   Operational speeds, $M \leq 3.0$

ii.   The ratio of the wing span to tail span must be less than or equal to 1.5, $\dfrac{b'}{b''} \leq 1.5$

iii. The ratio of the body diameter to wing span is less than 0.8, $\dfrac{d}{b} \leq 0.8$

iv. Rectangular wing, cropped delta wing, and delta wing.
v. Untwisted wing only.
vi. Airfoils are limited to the following
    a. NACA0003
    b. NACA0006
    c. NACA0009
    d. Symmetrical Bi-convex airfoil.
    e. Symmetrical Double-wedge airfoil.
    f. Symmetrical Single-wedge airfoil.
vii. Nose shapes:
    a. Cone
    b. Hemisphere

viii. The calculation of aerodynamic characteristics is only limited to angle of attack up to 25 degree for supersonic speed and up to the stall angle in the subsonic speeds if the stall angle is less than 25 degree.

4.0 RESULTS AND DISCUSSION

Comparison of results of program output and experimented data for wing-alone, body-alone and wing-body configurations at various speeds are presented to show the degree of accuracy of the program *RocketCalculator*.

4.1 Wing-Alone Configuration

There are 10 wing models were tested by [11]. However, only 3 tests with different conditions are taken out for validation purpose. Table 1 shows the wing model for supersonic condition with leading-edge shock attached, and supersonic condition with leading-edge shock detached, while Table 2 shows the wing model for supersonic condition with subsonic leading-edge.

Table 1: Wing model for supersonic condition with leading-edge shock attached, and supersonic condition with leading-edge shock detached.

Span, b	30.48 cm
Root Chord, c_r	10.16 cm
Tip Chord, c_t	5.08 cm
Mean Chord, $\bar{c}$	7.90 cm
Taper Ratio, λ	0.5
Leading Edge Angle, Λ_{LE}	18.44 deg
Maximum thickness, $\left(\dfrac{t}{c}\right)_{max}$	16.0759 %c
Position of the maximum thickness from LE	29.99813 %c

All wings had planform area of 232.26 cm², a maximum thickness of 1.27 cm, and had leading edges, tips, and trailing edges consisting of sharp wedges with a total

angle 30° measured in a plane perpendicular to the edges. For wing with supersonic leading-edge shock detached condition analysis is made at Mach number 1.6. For wing with supersonic leading-edge shock attached condition, analysis is made at Mach number 2.86. For wing with subsonic leading edge condition, analysis is made at Mach number 2.0. Comparisons of the program output and experimental results by [11] generally show good agreement, and the results are shown in Figures 6 to 8.

Table 2: Wing model for supersonic with subsonic leading-edge condition

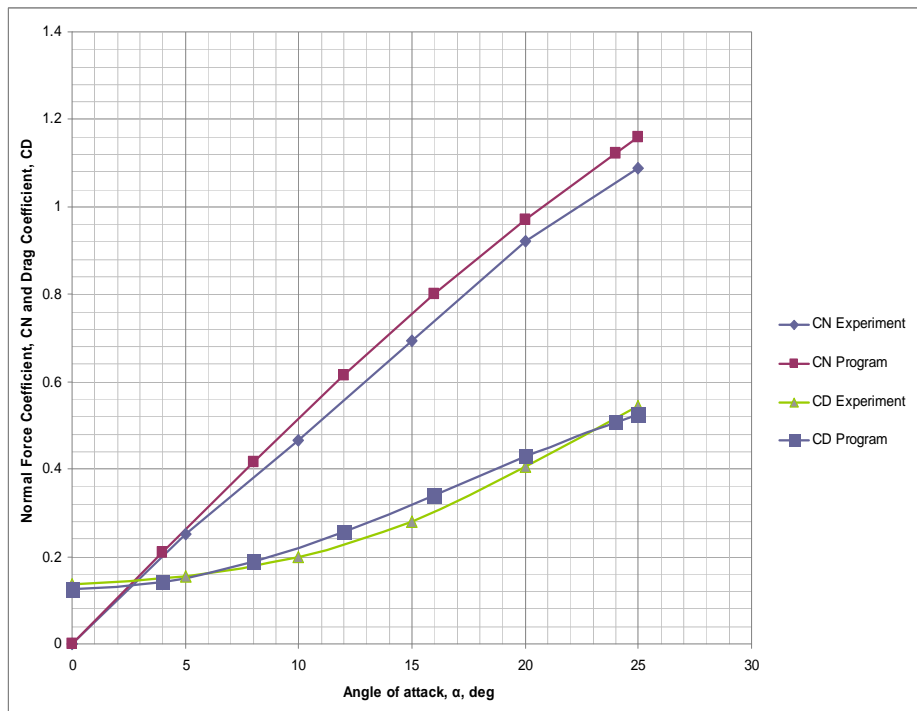| Span, b	15.24 cm
Root Chord, c_r	30.48 cm
Tip Chord, c_t	0.00 cm
Mean Chord, $\bar{c}$	20.32 cm
Taper Ratio, λ	0
Leading Edge Angle, Λ_{LE}	75.96 deg
Maximum thickness, $\left(\dfrac{t}{c}\right)_{max}$	6.25 %c
Position of the maximum thickness from LE	11.6627 %c

Figure 6: Comparison of problem output with previously published data for supersonic leading-edge shock detached condition at Mach number 1.6
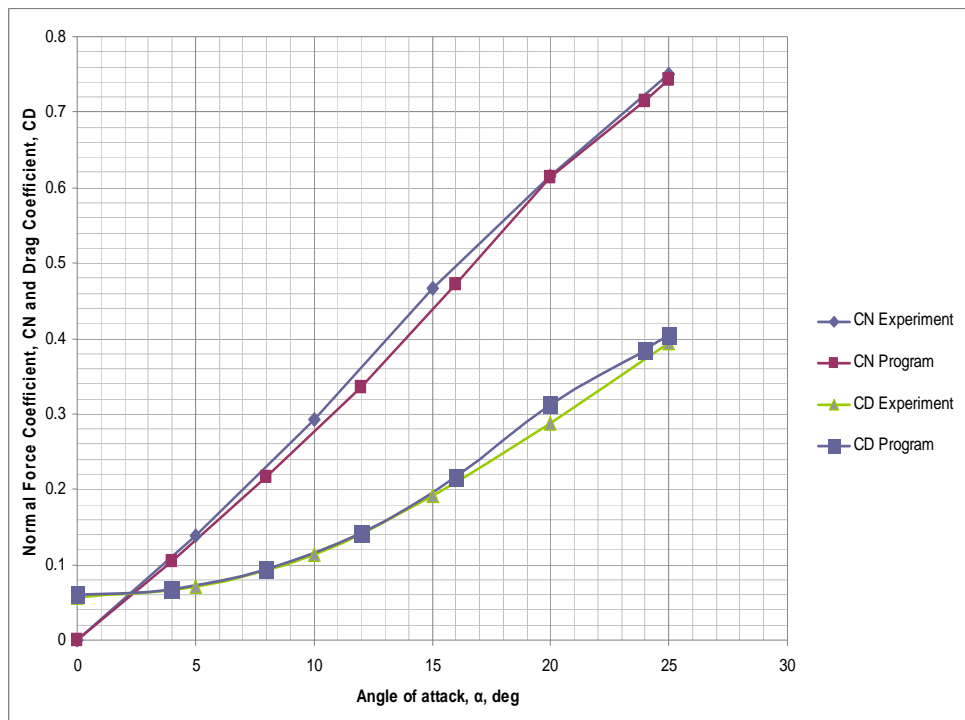
Figure 7 : Comparison of program output with previously published data for supersonic leading-edge shock attached condition at Mach number 2.86.
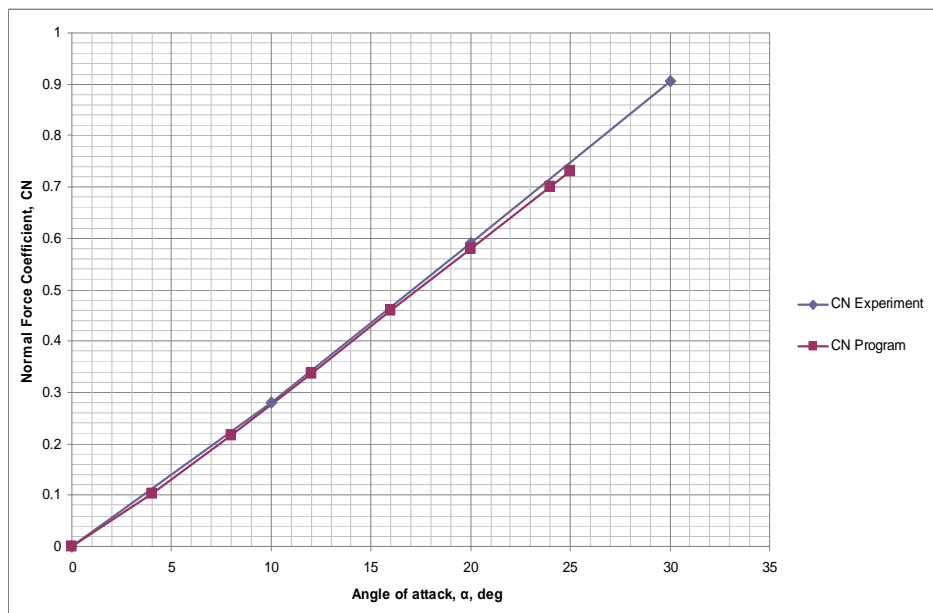

Figure 8 : Comparison of program output with previously published data for supersonic wing with subsonic leading-edge at Mach number 2.0

4.2   Body-Alone Configuration

In figures 9 and 10 the results of the program *RocketCalculator* are compared with experimental data by [12] and [13] for body-alone configurations with body fineness ratio 10 and nose fineness ratio 2.5. The analysis is made at March numbers (M) 0.6 and 2.0 respectively. Comparisons of the program output and experimental results generally illustrate a good agreement within the range of ±10% error.
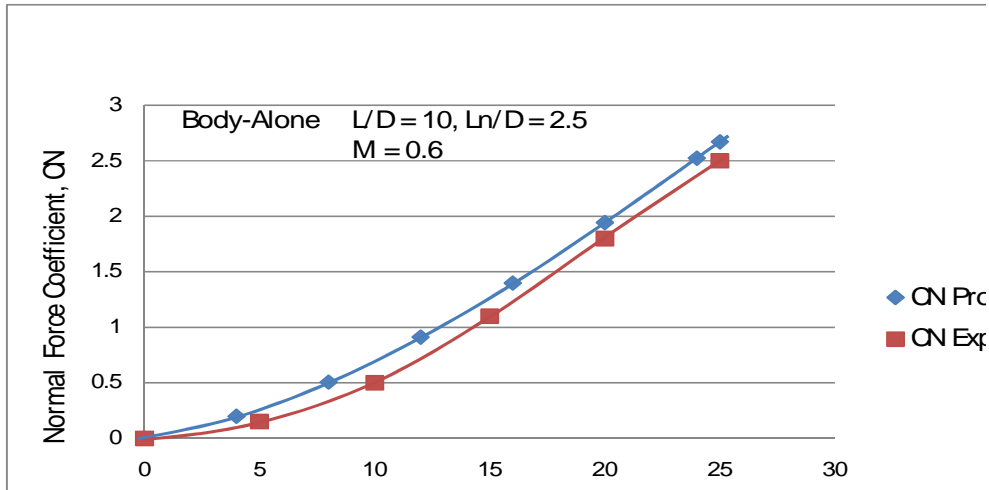
Figure 9 :   Comparison of program output with experiment for body-alone
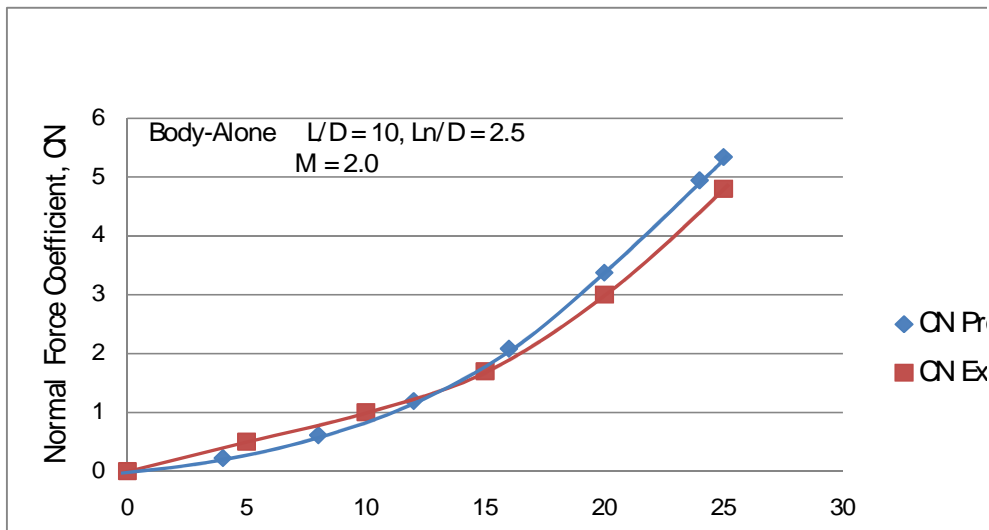   at M = 0.6

Figure 10:   Comparison of program output with experiment for body-alone
            at M = 2.0

4.3   Wing-Body Configuration

The configurations of wing-body combination of rocket model for this comparison are taken from an undergraduate thesis of Universiti Teknologi Malaysia (UTM) [14]. The orthographic drawing of the rocket model is shown in Figure 11 and the specification and configuration detail are given in Table 3.
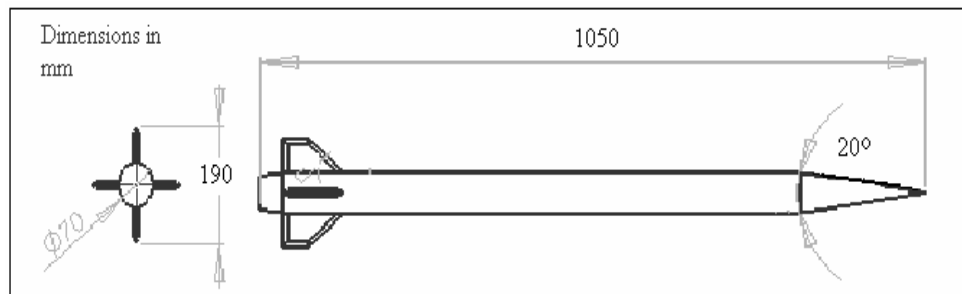

Figure 11 : Rocket Model Configuration

Table 3 : Specification and Configuration of Rocket Model

GENERAL DESCRIPTION	
Rocket Model	UTM-X1
Overall Length, L	1050 mm
Diameter, D	70 mm
Nose Type	Conical
Nose Length, l_N	198.49 mm
Afterbody Length, l_A	718.51 mm
L/D Ratio	15
Weight without warhead	68.67 N (7 kg)
Warhead	WDU-500X/B GPF
Launchers	LAU-5005
Motors	C17 (RLU-5004/B) Rocket Motor
Range	3.6 Km
WING CONFIGURATION	
Wing Platforms	Clipped Tip Delta
Wing Cross Section Shape	Modified Double-Wedge
Wing Span, b	190 mm
Wing Area	16800 mm^2
Wing Aspect Ratio, AR	1.1828
Root Chord, C_r	98 mm
Tip Chord, C_t	42 mm
Wing Thickness, t	2 mm
Wing Taper Ratio, λ	0.4286
Wing Leading Edge Sweptback Angle, Λ_{LE}	43.03^o

BOATTAIL CONFIGURATION	
Boattail Type	Conical
Boattail Length, l_b	35 mm
Base Diameter, D_b	63.88 mm
Boattail Angle, β	5°

   The rocket model was tested in wind tunnel in the Aeronautical Laboratory, Faculty of Mechanical Engineering, (UTM). The wind tunnel tests were undertaken in the 2.0m (width) x 1.5m (height) x 5.8m (length) test section and the average turbulence intensity at the centre of the working section is 0.04%. The maximum Mach number is 0.235, which corresponds to a velocity of 80 m/s (280 km/h).
   Figure 12 shows the comparison between the data of wind tunnel testing and program *RocketCalculator.* The data were taken at a velocity of 70 m/s for angle of attack up to 25 degree. The model was tested at extremely low velocities due to the limitation of wind tunnel availability. Nevertheless, the graph of lift coefficient versus angle of attack show that the agreement between the predicted data by program output and experimental data is quit satisfactory which is reliable with average error of less than 10%.
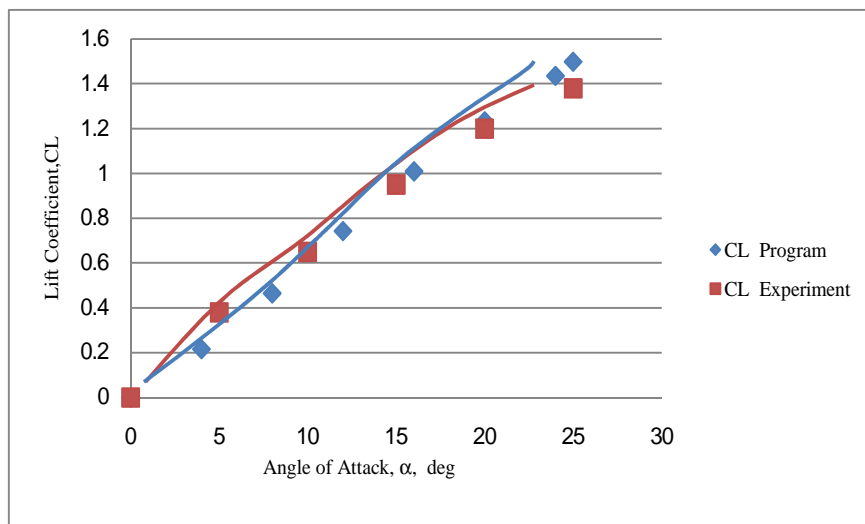

Figure 12 : Comparison results between program and experiment for wing-body
              combination at velocity 70 m/s

4.4   Maximum Lift

An investigation of the maximum lift of wings at supersonic speeds was carried out by [15]. Two tested results for 3 different wings were taken from their report for validation purpose. For wings at supersonic speeds, the maximum lift is determined by those geometric parameters that influence the wing lift-curve slope, i.e., aspect ratio, sweep, taper ratio, and Mach number. The comparison is shown in Table 4.

Comparison of the experimental data and program output shows that the maximum lift falls within the $\pm 8\%$ error range.

Table 4 : Comparisons of experimented maximum lift and program output for wings at supersonic speeds

Mach / Result		1.55			2.32		
		Experiment	Program	% error	Experiment	Program	% error
Triangular, $\Lambda_{LE} = 64\ deg$	$C_{L_{max}}$	1.03	1.1212	8.1341	1.00	1.0004	0.04
Triangular, $\Lambda_{LE} = 45\ deg$	$C_{L_{max}}$	1.10	1.1274	2.4304	1.05	1.0031	-4.6755
Rectangular, $AR = 1.74$	$C_{L_{max}}$	1.15	1.1395	-0.9215	--	--	--

5.0   CONCLUSION

A user friendly computer program named *RocketCalculator* has been developed by using the technology of Visual Basic.Net. USAF Datcom Method has been the main reference to develop the program's algorithm. The software developed enables users to estimate the linear and nonlinear aerodynamic coefficients of wing-alone, body-alone, wing-body and wing-body-tail combinations at speeds below Mach number 3.0 and angle of attack up to 25 degree.

For normal-force, lift, drag, and maximum lift coefficients and its corresponding angles of attack, the comparisons of the program outputs with experimental data indicate the errors within $\pm 10\%$. Generally, aerodynamic coefficients of rockets estimated by *RocketCalulator* are in good agreement with experimental results, and adequately provide data for preliminary design purposes. However, more additional data for validation purposes would be desirable.

REFERENCES

1. Frank G. Moore 2000, *Approximate Methods for Weapon Aerodynamics*, American Institute of Aeronautics and Astronautics, Inc., Danvers, Massachusetts.
2. Chia-Wei Hsu 1995, *The Use of Datcom Method and Wind Tunnel Testing for Spoonbill Unmanned Aerial Vehicle Aerodynamic Analysis*. Master Thesis. National Cheng Kung University, Taiwan.
3. Filippone A. 2008, *Comprehensive Analysis of Transport Aircraft Flight Performance*. Progress in Aerospace Sciences, Volume 44, Issue 3, Pages 192-236.

4. Hoak D.E. and Finck R.D 1978,*USAF Stability and Control Datcom*. Global Documents.
5. Williams J.E, Vukelich S.P. 1979, *The USAF stability and control digital Datcom, vol. i. Technical Report AFFDL TR-79-3032*. McDonnell- Douglas.
6. Marie-Louise Roy and Steven M. Sliwa 1983, *A Computer Program for Obtaining Airplane Configuration Plots from Digital Datcom Input Data, NASA TM 84639,* NASA Langley Research Center.
7. Thomas J. Sooy and Rebecca Z.Schmidt 2004, *Aerodynamic Predictions, Comparisons, and Validation using Missile Datcom (97) and Aeroprediction 98 (AP98)*, AIAA Paper No. 2004-1246.
8. Jan Roskam 1990, *Airplane Design Part IV: Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics*. Kansas: Roskam Aviation and Engineering Corporation.
9. Dave Grundgeiger 2002, *Programming Visual Basic .NET*, First Edition, ISBN: 0-596-00093-6: O'Reilly.
10. Bill Sempf 2006.Visual Basic 2005 for Dummies. Wiley Publishing, Inc., Indianapolis, Indiana.
11. Robert L; Stallings, Jr., and Milton Lamb 1981, *Wing-Alone Aerodynamic Characteristics for High Angles of Attack at Supersonic Speeds*, *NASA TP 1889* Langley Research Center.
12. Aiello, G.F. and Bateman, M.C. 1979 *Aerodynamic Stability Technology for Maneuverable Missiles.* Vol.1, Configuration Aerodynamic Characteristics. AFFDL-TR-76-55.
13. Daniel J. Lesieutre, John F.Love and Marnix F.E. Dillenius 1996, *High Angle of Attack Missile Aerodynamics Including Rotational Rates- Program M3HAX*, AIAA Paper No. 96-3392.
14. Muhammad Riza Abd. Rahman 2007, *Wind Tunnel Test on UTM-X1 Rocket Body*, Universiti Teknologi Malaysia : Thesis
15. Gallagher J. J. and Mueller J. N. 1955, *An Investigation of the Maximum Lift of Wings at Supersonic Speeds, NACA TR 1227,* NASA Langley Research Center.