Calculating Aerodynamic Coefficients of Fixed Wing Aircrafts Using DATCOM Software with Special Focus on Rudderless Flying-wing UAVs

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Abstract

In recent years, fixed-wing unmanned aerial vehicles (UAVs) have gained widespread attention in various civilian and military applications which require accurate control and guidance systems, enhanced maneuvering capabilities, and high stealth specifications. In order to design a robust control system to enable different tracking and path-following purposes, it is desired to establish a comprehensive and precise aerodynamic model. So, an accurate and straightforward approach is required for calculating the aerodynamic coefficients which are used to derive aerodynamic forces and moments. This research develops a procedure to calculate the required aerodynamic coefficients of fixed-wing aircrafts using Digital DATCOM software, which is used to establish an aerodynamic model, with a special study on rudderless flying-wing UAVs. The data input card is prepared with respect to the design and physical characteristics of the considered UAV model and related airfoil structure. By calling the input card of the given UAV model in DATCOM software, the static longitudinal/lateral stability, dynamic stability, and control coefficients and their derivatives are calculated. A 3D model is also established. Finally, the output file is imported into MATLAB environment for further analysis and implementation in dynamic modeling for control system design.

Keywords: *Fixed-wing aircraft-flying wing UAV-aerodynamic coefficients- DATCOM.*

1. Introduction

Fixed-wing UAVs have gained growing applications in recent years, because of their considerable features in terms of efficient performance in different maneuvers, even when carrying payloads [1-3]. The desired tracking behavior for performing different maneuvers may be achieved only by designing a robust control system. Accordingly, an accurate aerodynamic model is essential in the control system design process [4, 5].

Obtaining the equations of motion and building the aerodynamic model based on the presented data by the UAV manufacturer is a fundamental step in control system design. The aerodynamic coefficients are used to calculate the stability derivatives of the aerodynamic forces and moments [6]. The drag, side, and lift forces and also the pitch, roll, and yaw aerodynamic moments are related to flight parameters and states by associated aerodynamic coefficients and derivatives, which may be calculated by pre-processed real flight data, wind tunnel tests, computational fluid dynamic analysis, and other practical and semi-practical methods [7-9].

In preliminary design operations, fast and optimal estimation of aerodynamic coefficients is a prerequisite. Empirical data obtained by the real flight or wind tunnel tests are time and cost consuming which require significant man-hours and computer calculations. In this paper, step-by-step aerodynamic modeling with DATCOM software is introduced in order to calculate the aerodynamic coefficients. In summary, the airplane’s physical dimensions and design parameters are fed into DATCOM software in an input data card file. The software calculates the aerodynamic coefficients and other parameters which are stored in an output file. A 3D representation is also provided for identifying the correct input card data. The output statistics are further imported into MATLAB environment for aerodynamic modeling and control system design purposes.

2. Materials and Methods

DATCOM software is originally developed based on the United States Air Force stability and control DATCOM [10] for estimating aerodynamic parameters and flight analysis of fixed-wing aircrafts [11]. DATCOM+Pro is also an improved version [12] which allows to plot the airplane coefficients and running a 3D 6-DOF flight dynamic model. The overall procedure of the DATCOM modeling method is shown in Fig. 1.

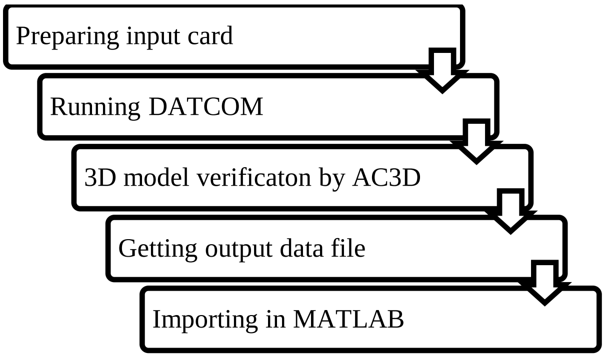

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Fig. 1: Overall process of the DATCOM method

First of all, it is necessary to create the input data card (*.f, *.inp, *.dat) based on the geometrical body shape data, airfoil type, flight condition, and other information obtained from the manufacturer data sheet with the structure defined in the next sections. The program starts by changing the input file extension to *.dcm and running it thereafter or calling the input card path address in DATCOM.exe software. A 3D model is demonstrated and an output file (*.out) is created in the same folder which contains the aerodynamic parameters estimated by DATCOM.

The output file may be used as an input in the MATLAB environment in order to carry out aerodynamic analysis, calculate the aerodynamic coefficients and derivatives, obtain aerodynamic forces and moments, and last but not least construct an aerodynamic model for a control system design. The modeling procedure by the proposed method is represented for a typical rudderless flying-wing UAV for better demonstration.

The rudderless flying-wing UAV is a fixed-wing type UAV equipped with elevons that play the role of elevators and ailerons simultaneously, the special design of which improves flight efficiency, stealth performance, structural strength, and integrity [13]. However, it faces challenges in designing a robust control system due to the lack of control surfaces and design characteristics. So, it is required to establish a comprehensive nonlinear aerodynamic model with accurate aerodynamic calculations [14]. The proposed procedure in this paper is implemented in order to get aerodynamic coefficients for the rudderless flying-wing UAV model demonstrated in Fig. 2 (Freya, Smart Planes) [15-17].

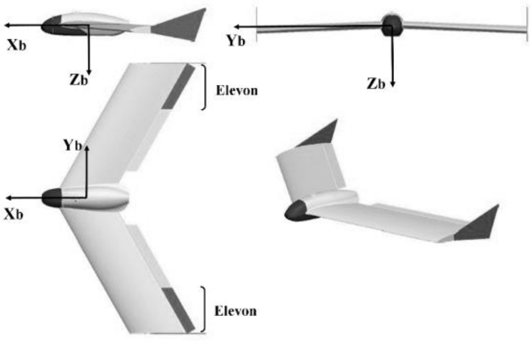


Fig. 2: Schematic view of the Freya UAV [15]

2.1. Preparing data input card

The data input card must be prepared in a text or FORTRAN code file. An input card consists of many control cards and statements which form one or more cases. The namelists which are preceded by a “$” sign (ex. $FLTCON) are used to define the flight conditions and body shape dimensions. The statements inside the namelist are terminated with a “$” sign. The main control cards and namelists used to create the input card structure are defined in the next subsections [11].

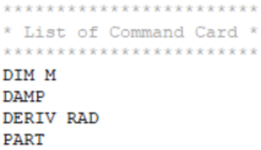
2.1.1. Command card

The command card is used to demonstrate different commands (Table 1).

Table 1: Command card

Command	Definition
DIM	System of units
DAMP	Presence of the dynamic derivatives
DERIV	Dimension of the derivatives
PART	Provide auxiliary and partial outputs in each Mach number

The command DIM M shows that the dimensions must be in the metric unit system. Other unit systems are also available for analysis (DIM FT, DIM IN). A command card for the considered UAV model is presented in Fig. 3. DERIV RAD also causes the static and dynamic derivatives to be measured in terms of radians.



```
************************
* List of Command Card *
************************
DIM M
DAMP
DERIV RAD
PART
```

Fig. 3: Command card example

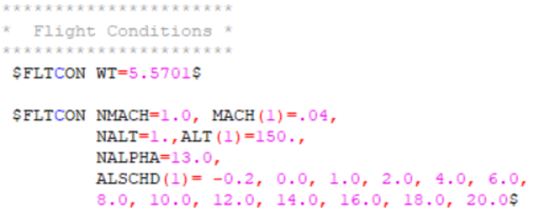
2.1.2. Flight condition (FLTCON namelist)

The namelist $FLTCON defines the flight conditions such as Mach number, vehicle weight, altitude, and values of the angle of attacks which are described in Table 2.

Table 2: FLTCON namelist

Variable	Definition
WT	Vehicle weight
NMACH	Number of the velocities to be run
MACH	Mach number
NALT	Number of atmospheric conditions or altitudes to be run
ALT	Altitude
NALPHA	Number of the angle of attacks to be tested
ALPHA	Angle of attack

Note that MACH, ALT, and ALPHA are arrays with NMACH, NALT, and NALPHA dimensions respectively. FLTCON namelist for the considered UAV model is represented in Fig.4.



```
**********************
*  Flight Conditions *
**********************
 $FLTCON WT=5.5701$

 $FLTCON NMACH=1.0, MACH(1)=.04,
         NALT=1.,ALT(1)=150.,
         NALPHA=13.0,
         ALSCHD(1)= -0.2, 0.0, 1.0, 2.0, 4.0, 6.0,
         8.0, 10.0, 12.0, 14.0, 16.0, 18.0, 20.0$
```

Fig. 4: FLTCON namelist example

2.1.3. Reference parameters (OPTINS namelist)

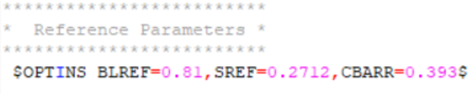
The namelist $OPTINS describes the reference parameters such as wing area, wing span, and mean chord length (Table 3).

Table 3: OPTINS namelist

Variable	Definition
SREF	Wing area
CBARR	Mean chord

BLREF	Wing span

A typical input block for the OPTINS namelist of the considered UAV model is presented in Fig. 5.



```
*************************
*  Reference Parameters *
*************************
 $OPTINS BLREF=0.81,SREF=0.2712,CBARR=0.393$
```

Fig. 5: OPTINS namelist example

2.1.4. Synthesis parameters (SYNTHS namelist)

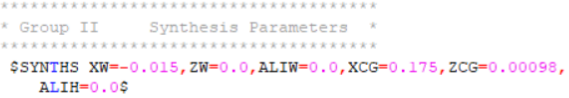
The $SYNTHS namelist defines the center of gravity, location of the wing, stabilizers, and fin (Table 4, Fig.6).

Table 4: SYNTHS namelist

Variable	Definition
XCG, ZCG	Center of gravity
XW, ZW	Location of the wing
XV, ZV	Location of the vertical stabilizer
XH, ZH	Location of the horizontal stabilizer
XVF, ZVF	Location of the fin
ALIW, ALIH	Incident angle for the wing and horizontal stabilizer
VERTUP	Vertical panel orientation

The location of the C.G., wing, or stabilizers is measured from an arbitrary datum axis which must be constant during all of the measurements.

The command VERTUP=.TRUE. shows that the vertical stabilizer points up. Its value must change to FALSE if the vertical stabilizer has a downward configuration.



```
*************************************
* Group II      Synthesis Parameters  *
*************************************
 $SYNTHS XW=-0.015,ZW=0.0,ALIW=0.0,XCG=0.175,ZCG=0.00098,
    ALIH=0.0$
```

Fig. 6: SYNTHS namelist example

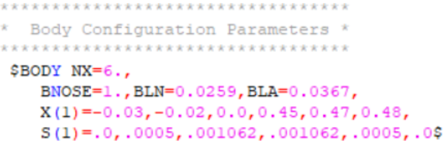
2.1.5. Body configuration (BODY namelist)

The $BODY namelist expresses the fuselage geometry (Table 5, Fig. 7). Fuselage body cross-section may be circular, elliptical, or in other shapes. By defining the cross-section area S, DATCOM will calculate the radius and periphery. Other methods for defining the fuselage shape are also present [11].

Table 5: BODY namelist

Variable	Definition
NX, X	Number and location of the stations
S	Cross-section area of the fuselage
BLA	Length of cylindrical afterbody
BLN	Length of nose
BNOSE, BTAIL	Nose and tail shape parameters

X is a vector that shows the location of NX stations defined to enter fuselage characteristics such as area. The station locations are measured from the datum line. Note that, S is an array that gets the fuselage cross-section area calculated in each station; so, its dimension is NX. BNOSE and BTAIL values are set to 1.0 for conical type and set to 2.0 for sharp point type nose or tail.



```
**********************************
*  Body Configuration Parameters *
**********************************
 $BODY NX=6.,
    BNOSE=1.,BLN=0.0259,BLA=0.0367,
    X(1)=-0.03,-0.02,0.0,0.45,0.47,0.48,
    S(1)=.0,.0005,.001062,.001062,.0005,.0$
```

Fig. 7: BODY namelist example

2.1.6. Wing, horizontal tail, vertical tail, and vertical fin planform (PLNF namelists)

The namelists WGPLNF, HTPLNF, VTPLNF, and VFPLNF are included to describe wing, horizontal tail, vertical tail, and vertical fin planforms, respectively. The variables defined in Table 6 are identical for each surface considered, which are typically demonstrated for the wing planform in Fig. 8 [12].

Table 6: PLNF namelist

Variable	Definition
CHRDR, CHRDTP	Airfoil chord at the root, and tip
CHRDBP	Chord length at the wing breakpoint
SSPN	Semi-span of the surface from the aircraft centerline to the tip.
SSPNE	Exposed distance from the fuselage to the tip
SAVSI, SAVSO	Sweep of the inboard, and outboard panels
DHDADI, DHDADO	Dihedral angles of the inboard, and outboard panels
TWISTA	Twist angle of the surface
TYPE	Planform type

Note that the root chord is measured from the centerline of the aircraft. The type of the surface defines TYPE value (straight tapered:1, Double delta: 2, Cranked: 3). As an example, the wing planform characteristics are given as the command card in Fig. 9 for the considered UAV model.

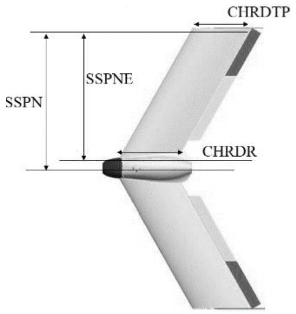
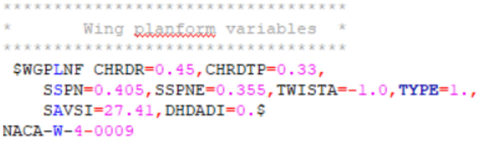


Fig. 8: BODY variables of wing planform (WGPLNF) [12]



```
**********************************
*        Wing planform variables  *
**********************************
 $WGPLNF CHRDR=0.45,CHRDTP=0.33,
    SSPN=0.405,SSPNE=0.355,TWISTA=-1.0,TYPE=1.,
    SAVSI=27.41,DHDADI=0.$
NACA-W-4-0009
```

Fig. 9: WGPLNF namelist example

The UAV model under study is a rudderless flying-wing UAV that lacks conventional horizontal and vertical stabilizers, so only WGPLNF is entered in PLNF namelist.

The NACA number denotes the airfoil type. The letter W, H, V, or F indicate wing, horizontal stabilizer, vertical stabilizer, or ventral fin respectively. The number denotes the series of the airfoil section. The wing airfoil of the Freya UAV falls into the 4-digit series NACA-0009 (Fig. 10).

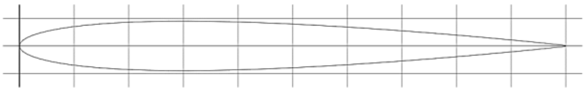


Fig. 10: NACA-0009 airfoil [18]

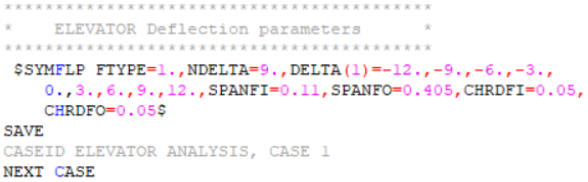
2.1.7. Symmetric flaps (SYMFLP namelist)

The input data for symmetrical control surfaces are described in $SYMFLP namelist, the variables of which are listed in Table 7.

Table 7: SYMFLP namelist

Variable	Definition
NDELTA, DELTA	Number of deflections, deflections
FTYPE	Type of flap
CHRDFI, CHRDFO	Chord of flap at the inboard, and onboard stations
SPANFI, SPANFO	Distance from the centerline for the inboard, and outboard edges of the flap surface

There are different types of symmetrical flaps (FTYPE=1.plain, 2.single slotted, 3.fowler, 4.double slotted, 5.split, 6.leading edge flaps, 7. Leading edge flaps, 8.Krueger). Elevators usually fall into plain type symmetrical flaps, FTYPE=1.0. For example, the specification for elevons in the elevator role is given in Fig. 11.



```
******************************************
*    ELEVATOR Deflection parameters      *
******************************************
 $SYMFLP FTYPE=1.,NDELTA=9.,DELTA(1)=-12.,-9.,-6.,-3.,
    0.,3.,6.,9.,12.,SPANFI=0.11,SPANFO=0.405,CHRDFI=0.05,
    CHRDFO=0.05$
SAVE
CASEID ELEVATOR ANALYSIS, CASE 1
NEXT CASE
```

Fig. 11: SYMFLP namelist example

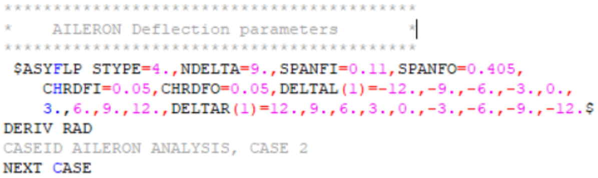
2.1.7. Asymmetric flaps (ASYFLP namelist)

The $ASYFLP namelist (Table 8) is used to define input data for asymmetric flaps which move in different directions to generate roll maneuvers. There are five flap types (STYPE=1.flap spoiler on the wing, 2.plug spoiler on the wing, 3.spoiler-slot-deflection on the wing, 4.plain flap aileron, 5.differentially deflected moveable horizontal tail). The ailerons are usually defined by STYPE=4.0.

Table 8: ASYFLP namelist

Variable	Definition
NDELTA, DELTAL, DELTAR	Number of deflections, deflections of left, and right flaps
STYPE	Type of flap
CHRDFI, CHRDFO	Chord of flap at the inboard, and onboard stations
SPANFI, SPANFO	Distance from the centerline for the inboard, and outboard edges of the flap surface

Note that DELTAR and DELTAL should have opposite signs. The specifications contributing to elevons in the aileron role for Freya UAV are described in ASYFLP namelist in Fig. 12.

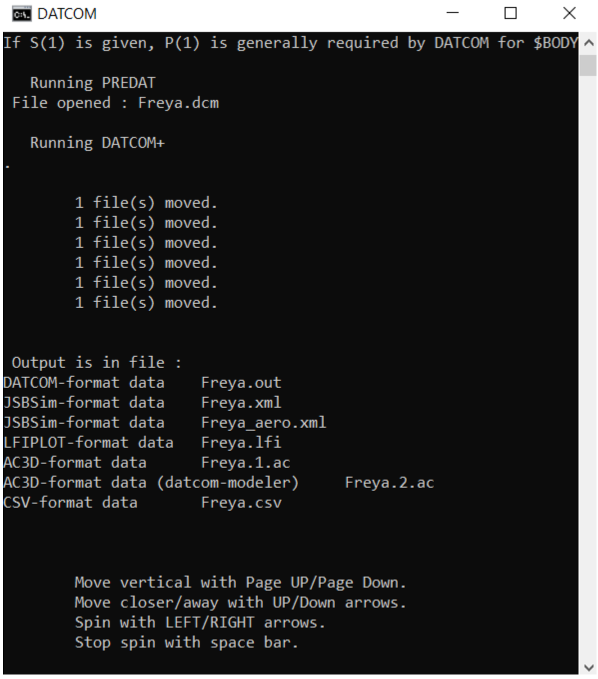


```
*****************************************
*    AILERON Deflection parameters      *
*****************************************
 $ASYFLP STYPE=4.,NDELTA=9.,SPANFI=0.11,SPANFO=0.405,
    CHRDFI=0.05,CHRDFO=0.05,DELTAL(1)=-12.,-9.,-6.,-3.,0.,
    3.,6.,9.,12.,DELTAR(1)=12.,9.,6.,3.,0.,-3.,-6.,-9.,-12.$
DERIV RAD
CASEID AILERON ANALYSIS, CASE 2
NEXT CASE
```

Fig. 12: ASYFLP namelist example

2.2. Running DATCOM, AC3D model

After preparing the input card in the correct format, the extension of the file is changed to *.dcm, or the input file path is called in the DATCOM software. By changing the file extension, DATCOM+PRO runs and a 3D model of the considered airplane is also demonstrated by the AC3Dview program which is used to verify whether the input data are given correctly and the desired aerial vehicle shape is established. The DATCOM.exe window after finalizing the calculations is shown in Fig. 13.

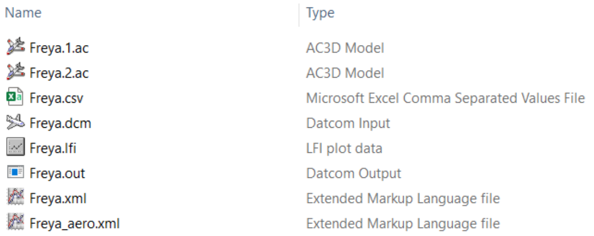


```
If S(1) is given, P(1) is generally required by DATCOM for $BODY

   Running PREDAT
 File opened : Freya.dcm

   Running DATCOM+
.

        1 file(s) moved.
        1 file(s) moved.
        1 file(s) moved.
        1 file(s) moved.
        1 file(s) moved.
        1 file(s) moved.


 Output is in file :
DATCOM-format data     Freya.out
JSBSim-format data     Freya.xml
JSBSim-format data     Freya_aero.xml
LFIPLOT-format data    Freya.lfi
AC3D-format data       Freya.1.ac
AC3D-format data (datcom-modeler)     Freya.2.ac
CSV-format data        Freya.csv



        Move vertical with Page UP/Page Down.
        Move closer/away with UP/Down arrows.
        Spin with LEFT/RIGHT arrows.
        Stop spin with space bar.
```

Fig. 13: DATCOM.exe window view

2.3. Output file

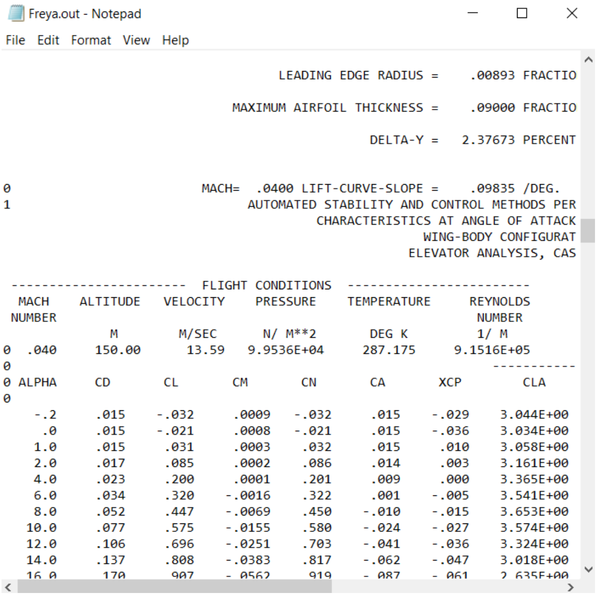
After finishing the DATCOM analysis, the output file (*.out) containing calculated aerodynamic coefficients and other information, the 3D model (*.ac), and an XML file is created by which running, some valuable figures are generated automatically. Also, a *.csv file is provided which contains the output data in an excel format (The list of created output files is shown in Fig. 14).



Name	Type
Freya.1.ac	AC3D Model
Freya.2.ac	AC3D Model
Freya.csv	Microsoft Excel Comma Separated Values File
Freya.dcm	Datcom Input
Freya.lfi	LFI plot data
Freya.out	Datcom Output
Freya.xml	Extended Markup Language file
Freya_aero.xml	Extended Markup Language file

Fig. 14: List of created output files

The output file for the considered UAV model has the structure shown in Fig. 15 which contains the calculated parameters for the given input card data.

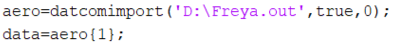


```
                                        LEADING EDGE RADIUS =    .00893 FRACTIO

                                    MAXIMUM AIRFOIL THICKNESS =    .09000 FRACTIO

                                                     DELTA-Y =   2.37673 PERCENT


0                            MACH=  .0400 LIFT-CURVE-SLOPE =    .09835 /DEG.
1                                  AUTOMATED STABILITY AND CONTROL METHODS PER
                                            CHARACTERISTICS AT ANGLE OF ATTACK
                                                          WING-BODY CONFIGURAT
                                                         ELEVATOR ANALYSIS, CAS

 ----------------------  FLIGHT CONDITIONS  ------------------------
  MACH    ALTITUDE   VELOCITY    PRESSURE    TEMPERATURE      REYNOLDS
 NUMBER                                                        NUMBER
              M        M/SEC      N/ M**2       DEG K          1/ M
0  .040    150.00      13.59   9.9536E+04     287.175     9.1516E+05
0                                                                   ----------
0 ALPHA     CD       CL       CM       CN       CA       XCP        CLA
0
    -.2     .015    -.032     .0009   -.032     .015    -.029    3.044E+00
     .0     .015    -.021     .0008   -.021     .015    -.036    3.034E+00
    1.0     .015     .031     .0003    .032     .015     .010    3.058E+00
    2.0     .017     .085     .0002    .086     .014     .003    3.161E+00
    4.0     .023     .200     .0001    .201     .009     .000    3.365E+00
    6.0     .034     .320    -.0016    .322     .001    -.005    3.541E+00
    8.0     .052     .447    -.0069    .450    -.010    -.015    3.653E+00
   10.0     .077     .575    -.0155    .580    -.024    -.027    3.574E+00
   12.0     .106     .696    -.0251    .703    -.041    -.036    3.324E+00
   14.0     .137     .808    -.0383    .817    -.062    -.047    3.018E+00
   16.0     .170     .907    -.0562    .919    -.087    -.061    2.635E+00
```

Fig. 15: DATCOM output file (*.out)

2.4. Importing in MATLAB

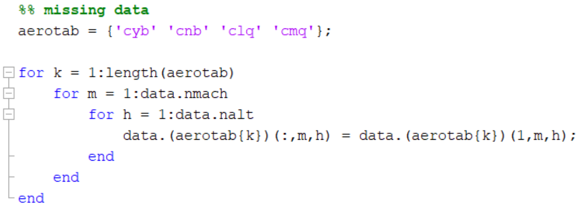
Now, the calculated aerodynamic characteristics are called in MATLAB by the “datcomimport” command shown in the proper format in Fig. 16. The output file (*.out) path address is given in parentheses.



```
aero=datcomimport('D:\Freya.out',true,0);
data=aero{1};
```

Fig. 16: Import output data in MATLAB

Some missing aerodynamic coefficients ($C_{Y\beta}, C_{N\beta}, C_{lq}, C_{Mq}$) are also called by the following command in Fig. 17.



```
%% missing data
aerotab = {'cyb' 'cnb' 'clq' 'cmq'};

for k = 1:length(aerotab)
    for m = 1:data.nmach
        for h = 1:data.nalt
            data.(aerotab{k})(:,m,h) = data.(aerotab{k})(1,m,h);
        end
    end
end
```

Fig. 17: Importing missing data in MATLAB

After importing the output data in MATLAB, the calculated aerodynamic coefficients are ready to use in aerodynamic calculations for dynamic modeling and further control system design purposes. For example, the data attributing to the drag aerodynamic coefficient C_d is listed by entering “data.cd” (Refer to MATLAB help for detailed information).

3. Simulation Results

The simulation results for the considered rudderless flying-wing Freya UAV [13, 15, 16] are presented in this section. The 3D model (Fig. 18) is first provided which is in good accordance with the real UAV shape model.

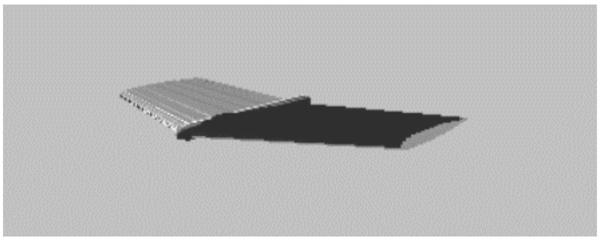


Fig. 18: AC3D model of Freya UAV

By importing the data in MATLAB, the arrays of aerodynamic coefficients for Freya UAV are obtained in the defined angles of attacks. For example, the output aerodynamic coefficients in the typical angle of attack $\alpha = 14\,\text{deg}$ are presented in Table 9. The desired mean or trim values may be also calculated based on the output data.

Table 9: Output aerodynamic coefficients for Freya UAV ($\alpha = 14\,\text{deg}$)

Longitudinal aerodynamic coefficients	**Value**	**Lateral aerodynamic coefficients**	**Value**
C_{d0}	0.029	C_{Y0}	0
$C_{d\alpha}$	0.604	$C_{Y\beta}$	-0.0075
C_{dq}	0	C_{Yp}	0.1985
$*\,C_{d\delta e}$	0.0005	$*\,C_{Y\delta a}$	0.05
C_{l0}	0.2615	C_{L0}	0
$C_{l\alpha}$	3.0180	$C_{L\beta}$	-0.2804
C_{lq}	0	C_{Lp}	-0.2357
$*\,C_{l\delta e}$	0.7448	$*\,C_{L\delta a}$	0.1422
C_{M0}	0	C_{N0}	0
$C_{M\alpha}$	-0.4445	$C_{N\beta}$	0.001005
C_{Mq}	0	C_{Np}	0.01685
$*\,C_{M\delta e}$	-0.3272	$*\,C_{N\delta a}$	-0.0013

*** Note: the aerodynamic derivatives contributing to the control surfaces, are functions of control surfaces deflection and an average slope value is calculated.**

Some representative figures plotted in MATLAB are demonstrated in Figs. (19-24). Note that by calculating the slope of the aerodynamic lift and moment coefficient with respect to the angle of attack α, the contributing aerodynamic coefficients $C_{l\alpha}$ and $C_{M\alpha}$ are obtained respectively, which are comparable to aerodynamic derivatives already calculated by DATCOM (data.cla, data.cma).

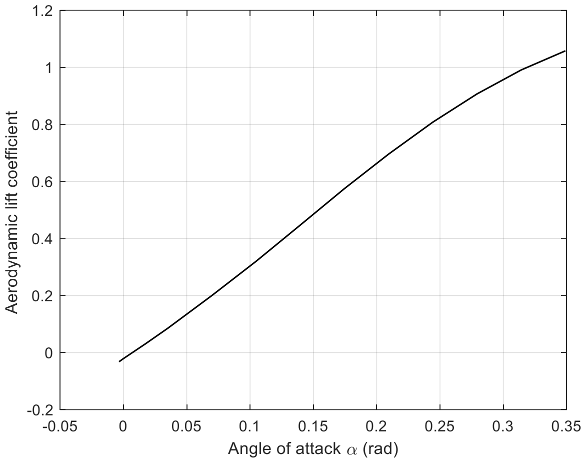


Fig. 19: Aerodynamic lift coefficient C_l vs angle of attack α

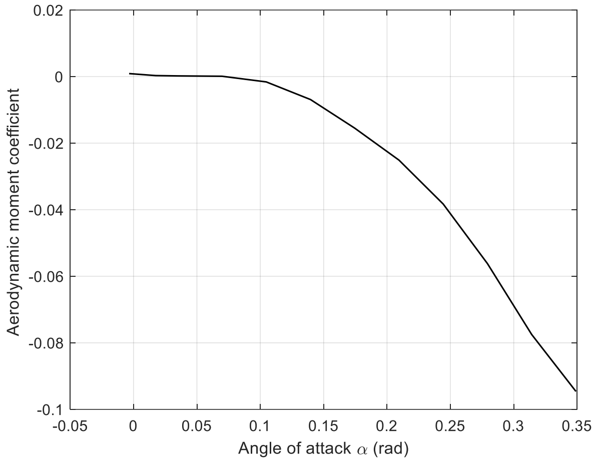


Fig. 20: Aerodynamic moment coefficient C_M vs angle of attack α

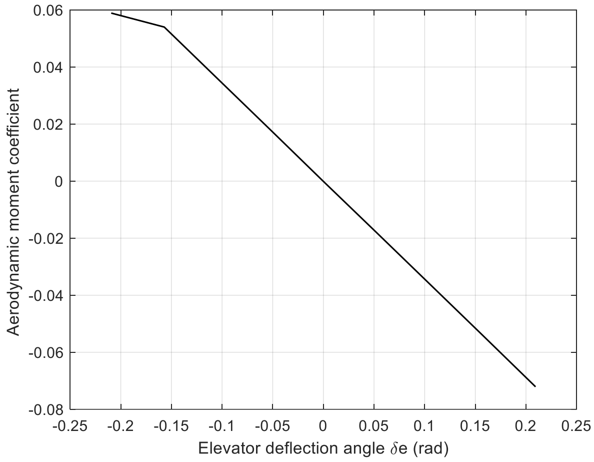


Fig. 21: Aerodynamic moment coefficient C_M vs elevator deflection angle δ_e

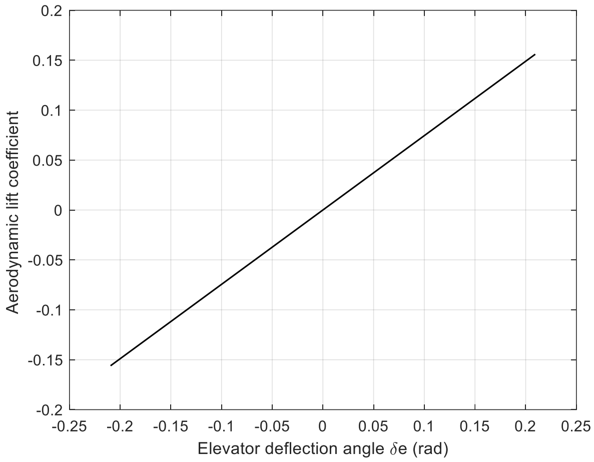


Fig. 22: Aerodynamic lift coefficient C_l vs elevator deflection angle δ_e

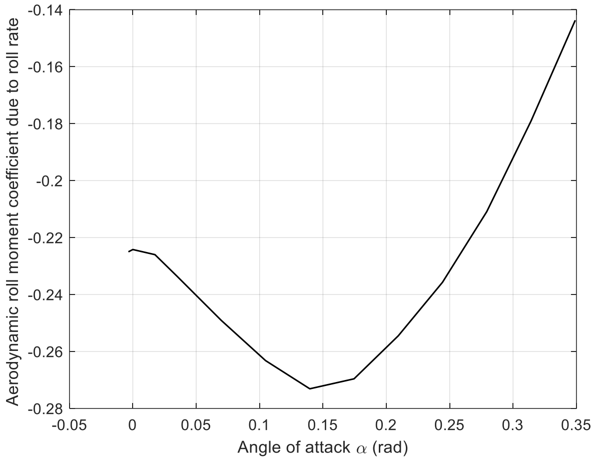


Fig. 23: Aerodynamic roll moment coefficient due to roll rate C_{Lp} vs angle of attack α

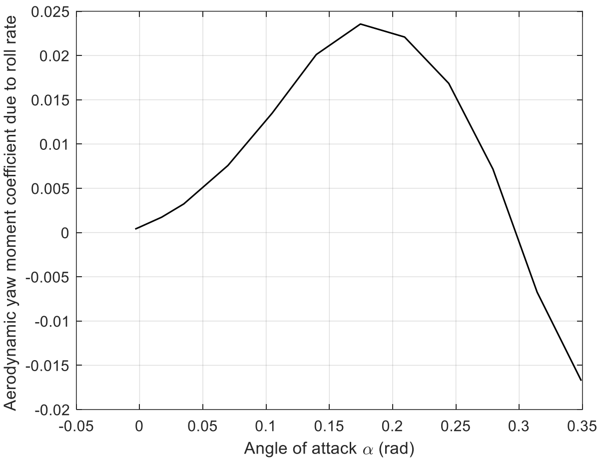
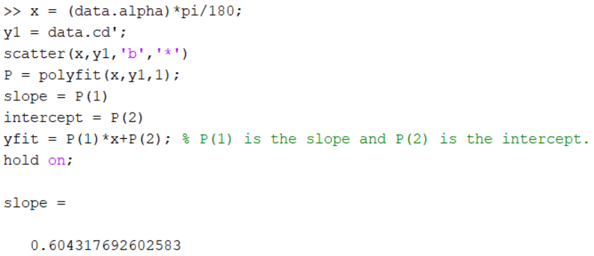


Fig. 24: Aerodynamic yaw moment coefficient due to roll rate C_{Np} vs angle of attack α

Some aerodynamic derivatives are not included directly in the output data file. For example, in order to obtain $C_{d\alpha}$, it is suggested to plot available drag coefficient data C_d against the angle of attack, and calculate the slope of the figure using “polyfit” and “slope” commands in MATLAB by curve fitting (Fig. 25). The results are compared to the figure provided by running XML file (Fig. 26).



```
>> x = (data.alpha)*pi/180;
y1 = data.cd';
scatter(x,y1,'b','*')
P = polyfit(x,y1,1);
slope = P(1)
intercept = P(2)
yfit = P(1)*x+P(2); % P(1) is the slope and P(2) is the intercept.
hold on;

slope =

   0.604317692602583
```

Fig. 25: Obtaining aerodynamic drag derivative $C_{d\alpha}$ in MATLAB

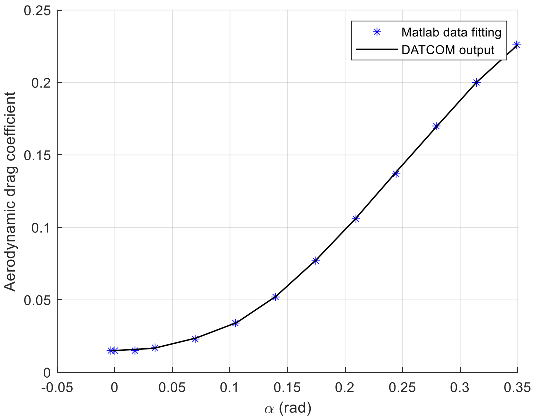


Fig. 26: Aerodynamic drag coefficient C_d vs angle of attack α

4. Conclusion

An accurate and straightforward approach for the calculation of aerodynamic coefficients based on DATCOM software is presented which is essential in any aerodynamic model design process. In this paper, step-by-step aerodynamic modeling is presented to calculate the aerodynamic coefficients using DATCOM software with a special focus on rudderless flying-wing UAVs. In summary, an input card for the DATCOM software is prepared using the physical characteristics and flight condition of the aircraft. The aerodynamic coefficients and other parameters are calculated and stored in an output file. Using the DATCOM+PRO software, a 3D representation, an excel file containing the output data, and an XML file are also created which are useful in aerodynamic modeling. The output statistics may be further imported into MATLAB for aerodynamic analysis and control system design purposes.

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