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Aircraft Aerodynamics Analysis in JAVA

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Contents:

Preface

The goal of this thesis has been developing a JAVA software tool for aerodynamic analysis of stability parameters for subsonic aircraft.
Goals of the tool were:

- Provide the tool with a fairly general analysis of unsteady derivates for longitudinal stability parameters
- Provide the tool with a fairly general analysis of lateral-directional parameters
- Correct a few inconsistencies in calculations

Engineering relations and formulas are based on the book by Napolitano and USAF DATCOM.Software used mainly consists of Eclipse Mars , Microsoft Office Excel 2010 and a Hierarchical Data Format (HDF) database. A more in-depth description of these particular applications and of software tool structure and algorithms as a whole is provided in the following chapter

Chapter 1: Short descrition of software used

1.1 Microsoft Excel

Microsoft Excel is a Microsoft Corporation's Software. It's one of the most spread software, even because it can be found inside all Office Suite versions. The majority of users takes advantage of an infinitesimal portion of its potentiality, confining themselves to use it like a huge electronic page capable of automatically execute some operations, such as the sum of some cells. Even like this, it has got a remarkable utility: even without using its advanced features, it's possible to create sheets able to accomplish many different tasks, from simple mathematic operations to more or less complex statistical analysis. Futhermore Excel is a development platform, provided with an efficient programmation language: VBA, Visual Basic for Applications, with whom highly complicated applications can be created. In this work Excel has been used like a data container, that will be utilised by the software at run time.

1.2 Eclipse

Eclipse is an open source, multi language, multi platform integrated development environment. It has been developed by IT colossus like IBM, Intel and HP in JAVA. Eclipse is provided with such a modularity that the software itself can be extended. These are the main points that lead to the creation of a huge community, assuring an heavy support to the IDE.
In fig. 1.1 we can see the usual Eclipse's interface, in which we can find the text editor, several buttons to switch between tabs and projects and the console, that can emulate the execution of softwares, futhermore it can warn about error's cause.

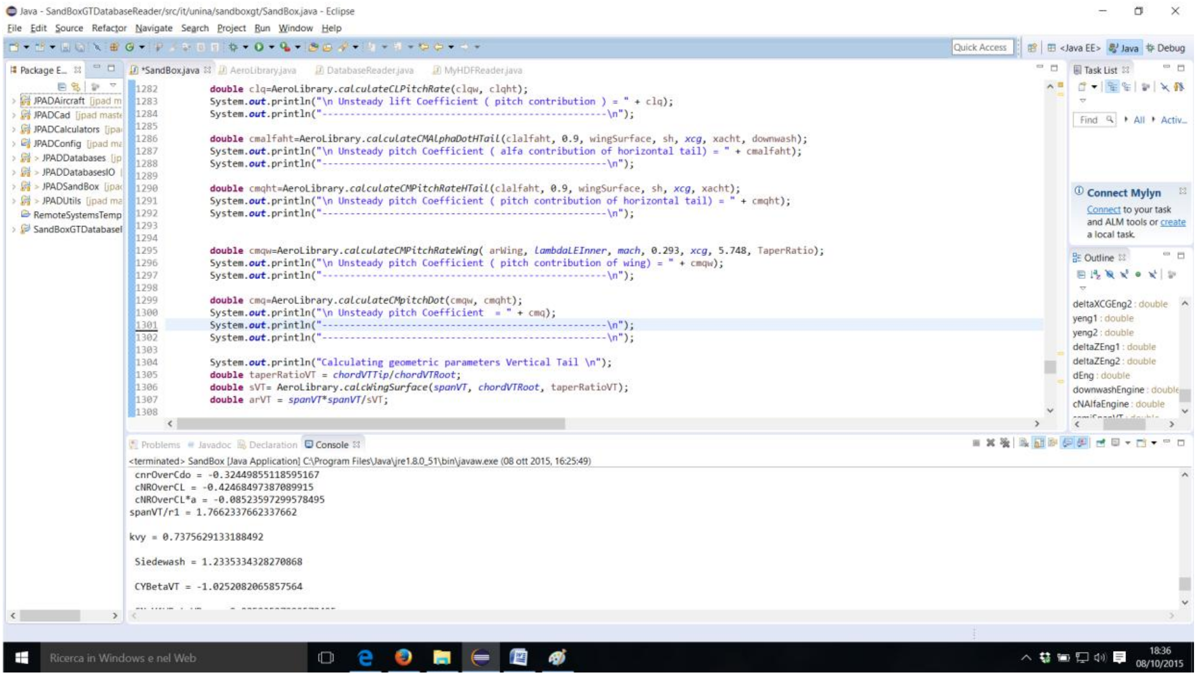


Figure 1.1: Eclipse' GUI Mars version

This work has been developed with the latest version of the IDE, Eclipse Mars.

1.3 HDFVIEW

HDFView is a Java-based tool for browsing and editing HDF4 and HDF5 files. HDFView allows users to browse through any HDF4 and HDF5 file, starting with a tree view of all top-level objects in an HDF file's hierarchy. HDFView allows a user to descend through the hierarchy and navigate among the file's data objects, as we can see in fig 1.3. The content of a data object is loaded only when the object is selected, providing interactive and efficient access to HDF4 and HDF5 files. HDFView editing features allow a user to create, delete and modify the value of HDF objects and attributes.

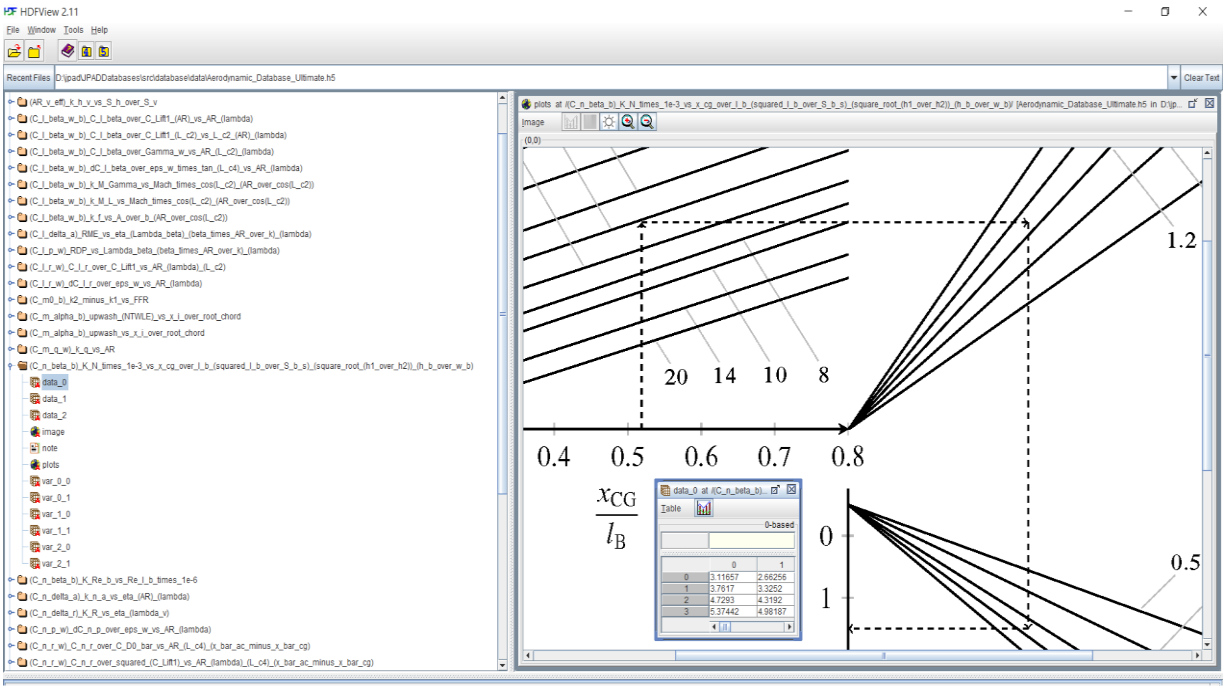


Figure 1.2: HDFVIEW GUI with plot and dataset of an object displayed

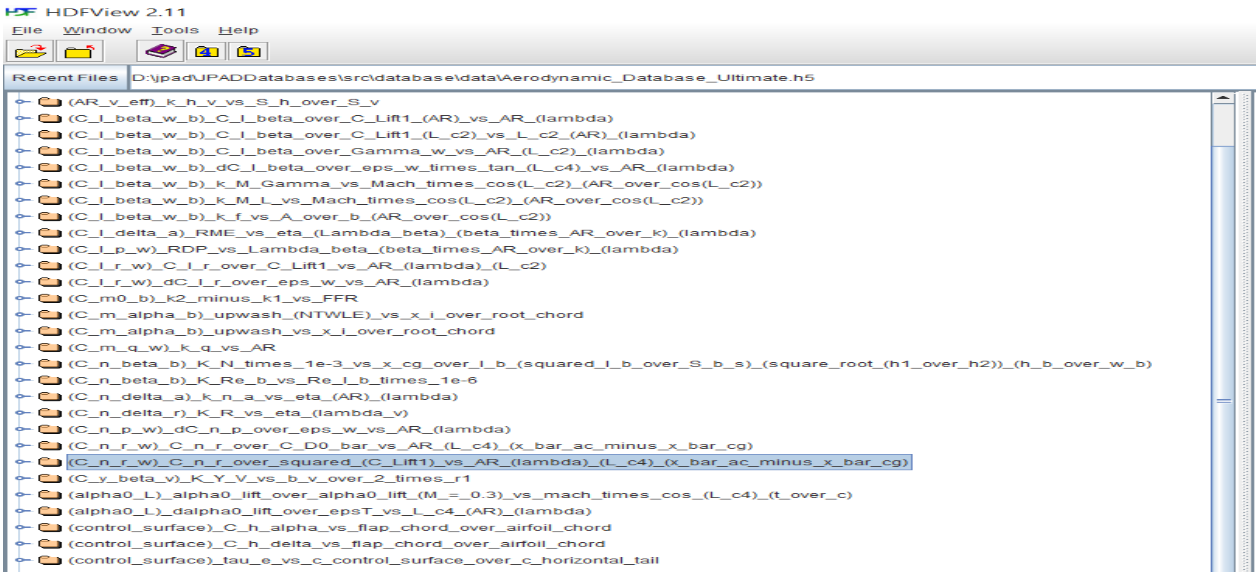


Figure 1.3: Tree view of all the top object

The HDFView graphic user interface (GUI) is simple and easy-to-use. First, HDFView was implemented by using the JavaTM 2 Platform, which is machine-independent. The GUI components have the same look-and-feel for all machines. Second, HDFView uses conventional folders and icons to display groups and datasets in a tree structure. Users can easily expand or collapse folders to navigate the hierarchical structure of an HDF file. Third, HDFView shows data content as text (table or plain text) or as an image as seen in figure 1.2.

1.4 Hierarchical Data Format HDF5

The Hierarchical Data Format (HDF) implements a model for managing and storing data. The model includes an abstract data model and an abstract storage model (the data format), and libraries to implement the abstract model and to map the storage model to different storage mechanisms. The HDF5 library provides a concrete implementation of the abstract models to programming interface. The library also implements a model of data transfer, i.e., efficient movement of data from one stored representation to another stored representation. The figure 1.4 illustrates the relationships between the models and the implementations. HDF work with primary type of object:

- Dataset : multidimensional (rectangular) array of data elements;
- Group : structure for grouping objects.

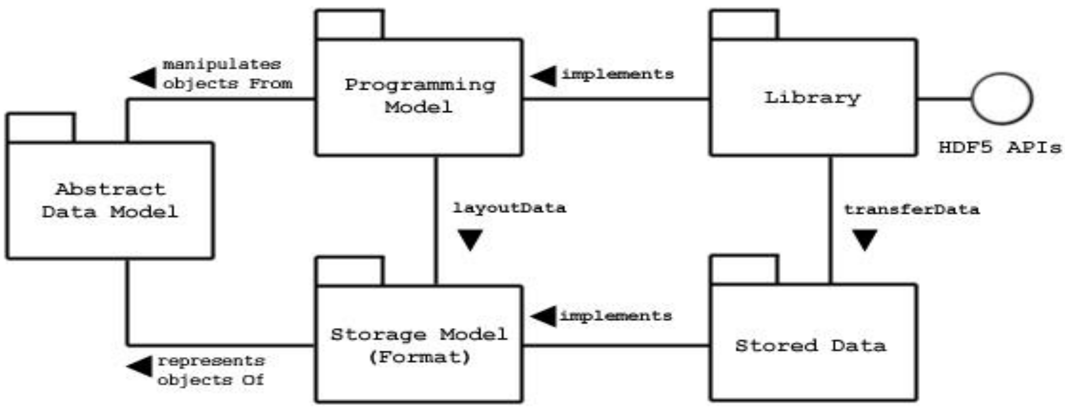


Figure 1.4: HDF5 models and implementations

With HDF we can:

- A versatile data model that can represent very complex data objects and a wide variety of metadata;
- A completely portable format with no limits on the number or size of data objects in the collection;
- A rich set of integrated performance features that guarantee access time and storage space optimizations;

- Tools and applications for managing, manipulating, viewing, and analyzing the data in the collection.

1.5 JAVA

The initial version of the Java platform was released by Sun Microsystems (part of Oracle Corporation since January 2010) in 1995. Development of the Java programming language was started in 1991. One of the most important features for its popularity is its “write once, run anywhere” (WORA) feature. This feature lets you write a Java program once and run it on any platform. For example, you can write and compile a Java program on UNIX and run it on Windows, Macintosh, or UNIX machine without any modifications to the source code. WORA is achieved by compiling a Java program into an intermediate language called bytecode. A virtual machine, called the Java Virtual Machine (JVM), is used to run the bytecode on each platform. Note that JVM is a program implemented in software.This feature makes Java programs platform-independent. The following are a few characteristics behind Java’s popularity and acceptance in the software industry:

- Simplicity;
- Wide variety of usage environments;
- Robustness.

It has features to support programming based on the object-oriented,in fact JAVA is addressed as an object-oriented programming language. The object-oriented paradigm supports four major principles: abstraction, encapsulation, inheritance, and polymorphism. Abstraction is the process of exposing the essential details of an entity, while ignoring the irrelevant details, in order to reduce the complexity for the users. Encapsulation is the process of bundling data and operations on the data together in an entity. Inheritance is used to derive a new type from an existing type, thereby establishing a parent-child relationship. Polymorphism lets an entity take on different meanings in different contexts.

Advatage of the object-oriented programming language are:

- **Modularity**: classes are parts of the software;

- **Module's coesion**: a class is a software's component well coated because it is a rappresentation of an single entity;

- **Module's decoupling**: objects have an high decoupling grade because they work on the object's internal data struct. All the system is built by operation on the objects;

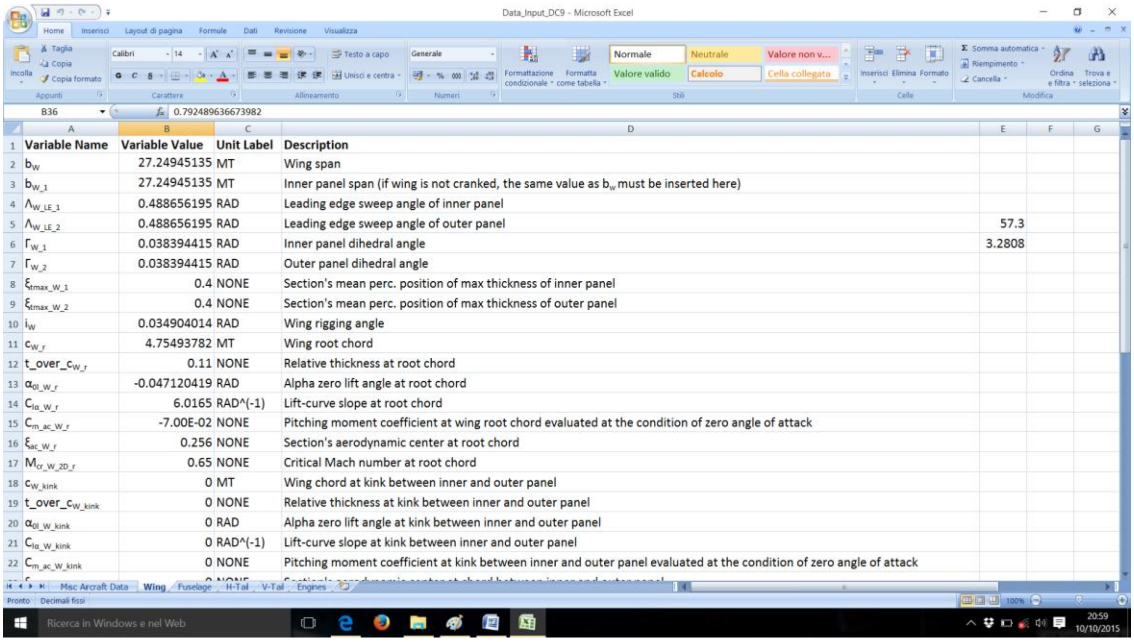
- **Information hiding**: both data struct and algorithms can be hidden outside objects;

- **Reuse**: thanks to the inheritance we can reuse a class' definition in a new class' definition subclass). Furthermore we can build libraries of classes sorted for application's type;

- **Extensibility**: thanks to the polymorfism we can add new feature with few changes to system.

1.6 Example of calculation

We start the software from the main class SandBoxGT. First, it reads an excel file (figure1.5) where aircraft data are stored, so that all the input variables are initialized (Figure 1.6).



	Variable Name	Variable Value	Unit Label	Description	
2	b_W	27.24945135	MT	Wing span	
3	b_{W_1}	27.24945135	MT	Inner panel span (if wing is not cranked, the same value as b_w must be inserted here)	
4	$\Lambda_{W\_LE\_1}$	0.488656195	RAD	Leading edge sweep angle of inner panel	
5	$\Lambda_{W\_LE\_2}$	0.488656195	RAD	Leading edge sweep angle of outer panel	57.3
6	Γ_{W_1}	0.038394415	RAD	Inner panel dihedral angle	3.2808
7	Γ_{W_2}	0.038394415	RAD	Outer panel dihedral angle	
8	$\xi_{tmax\_W\_1}$	0.4	NONE	Section's mean perc. position of max thickness of inner panel	
9	$\xi_{tmax\_W\_2}$	0.4	NONE	Section's mean perc. position of max thickness of outer panel	
10	i_W	0.034904014	RAD	Wing rigging angle	
11	c_{W_r}	4.75493782	MT	Wing root chord	
12	t_over_c_{W_r}	0.11	NONE	Relative thickness at root chord	
13	$\alpha_{0l\_W\_r}$	-0.047120419	RAD	Alpha zero lift angle at root chord	
14	$C_{l\alpha\_W\_r}$	6.0165	RAD^(-1)	Lift-curve slope at root chord	
15	$C_{m\_ac\_W\_r}$	-7.00E-02	NONE	Pitching moment coefficient at wing root chord evaluated at the condition of zero angle of attack	
16	$\xi_{ac\_W\_r}$	0.256	NONE	Section's aerodynamic center at root chord	
17	$M_{cr\_W\_2D\_r}$	0.65	NONE	Critical Mach number at root chord	
18	c_{W_kink}	0	MT	Wing chord at kink between inner and outer panel	
19	t_over_c_{W_kink}	0	NONE	Relative thickness at kink between inner and outer panel	
20	$\alpha_{0l\_W\_kink}$	0	RAD	Alpha zero lift angle at kink between inner and outer panel	
21	$C_{l\alpha\_W\_kink}$	0	RAD^(-1)	Lift-curve slope at kink between inner and outer panel	
22	$C_{m\_ac\_W\_kink}$	0	NONE	Pitching moment coefficient at kink between inner and outer panel evaluated at the condition of zero angle of attack	

Figura 1.5: Excel GUI with data (sheet relative to wing)

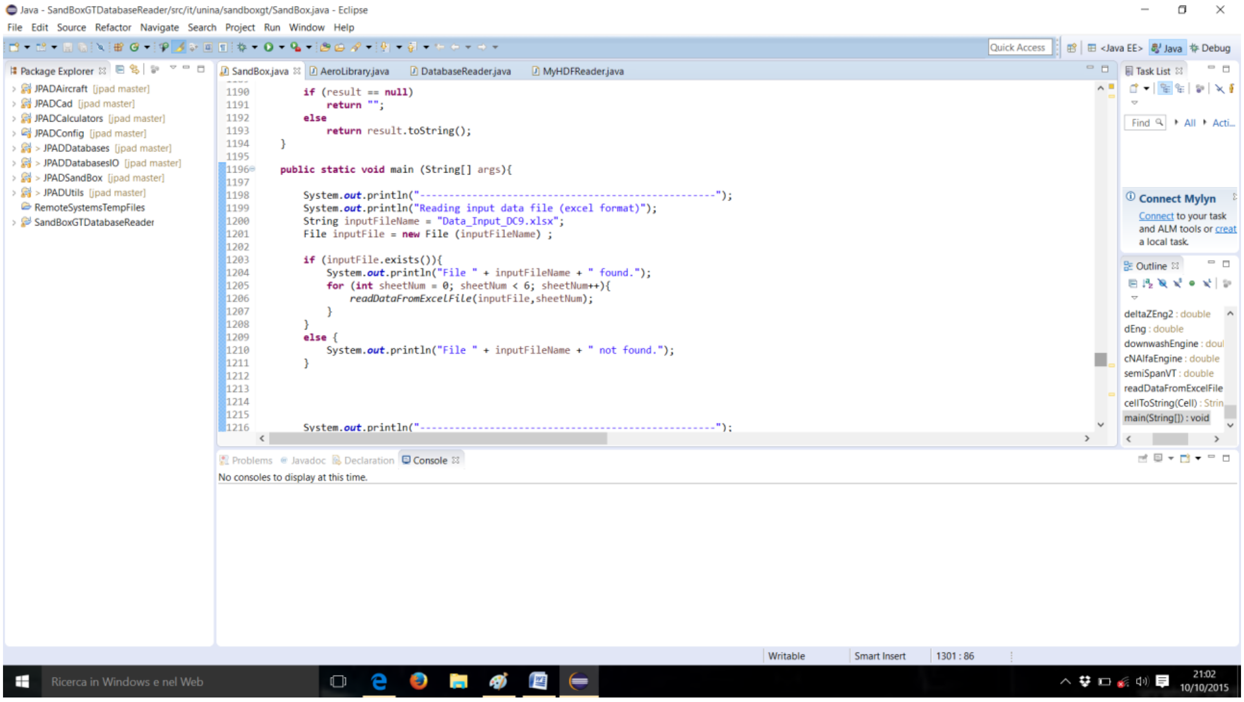


Figura 1.6: Call to read Excel file and to assign variables

After the file reads and assigns all variables value and it starts to calculate the value of aerodynamic coefficient.All the relationships of aerodynamic coefficient are stored in the the class AeroLibrary. In Figure 1.7 we can see how the main SandBoxGT calls the class AeroLibrary,in particular the function calculateCNRollRateWB.

```
double cNRollRateWB = AeroLibrary.calculateCNRollRateWB(arWing, lambdaquarterWing, xcg, xacw, mach, cl,TaperRatio,TwistAngleWingTip*57.3);
System.out.println("\n CN_RollRateWB  = " + cNRollRateWB  );
System.out.println("---------------------------------------------------\n");
```

Figura 1.7: Call to a function stored in another class

In figure 1.8 we can see how the function calculateCNRollRateWB is built

```java
         * @param ar wing aspect ratio
         * @param lambdaquarter sweep angle at quarter of chord of mean aerodynamics chord of wing
         * @param xgc center of gravity expressed as a percentage of the mean aerodynamics chord
         * @param xacw aerodynamic center of wing-body expressed as a percentage of the mean aerodynamics chord
         * @param mach mach number
         * @param cl lift coefficient
         * @return wing-body contribution to yawing moment due to the roll rate
         * @see Napolitano_Aircraft_Dynamics_Wiley_2012 page from 183
         */
public static double  calculateCNRollRateWB(double ar, double lambdaquarter, double xcg, double xacw, double mach, double cl,double taperRatio,double twist) {

            double a = calculateCNpOverCLCoefficient(ar, lambdaquarter, xcg, xacw);

            System.out.println("\n CNpOverCL = "+ a);
            double b = calculateCoefficientCRollRate(ar, mach, lambdaquarter);
            System.out.println("\n CoefficientCRollRate = "+ b);

            double delta = DatabaseReader.get_DeltaCnpOverTwist(ar, taperRatio);

            System.out.println("Delta = "+delta+" twist = "+twist);

            return a*b*cl+delta*twist;
        }
```

Figura 1.8: Body of the function calculateCNRollRateWB

In this function we can see the call to another class: DatabaseReader. In this class all function that read the HDF5 database relative to DATCOM graph (Appendix A) are stored .This function made an interpolation of the HDF5 database's data as shown in figure 1.9 In picture 1.10 we can see the plot of HDF5 database's data.

```java
private static final MyInterpolatingFunction get_DeltacpOverTwistAngle = aeroDatabase.interpolate2DFromDatasetFunction("(C_n_p_w)_dC_n_p_over_eps_w_vs_AR_(lambda)");
```

```java
public static double get_DeltaCnpOverTwist(double ar,double taperRatio) {
    return get_DeltacpOverTwistAngle.value(ar,taperRatio);
}
```

Figura 1.9: Function that allows interpolation and extract the value of the interpolation

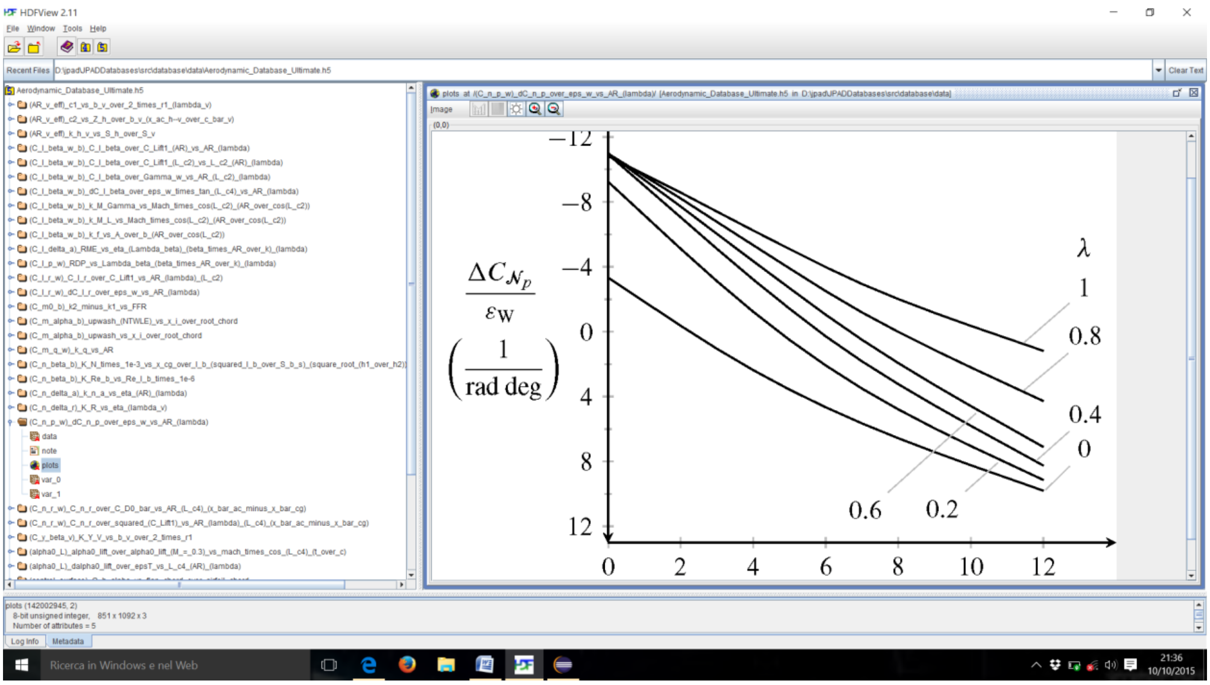


Figura 1.10: Plot of the function interpolated from function calculateCNRollRateWB

Chapter 2:Calculation formulas

The aircraft during its flight is susceptible to a system of forces and moments. The knowlodge of elements' value of this system is very important during the aircraft design. The software has been developed in order to give a preliminary value of some longitudinal and all lateral-directional coefficient knowing the geometric aircraft data.

2.1 Geometrical and aerodynamics parameters of wing

The wing is the most important part of an aircraft, indeed all the lift that enables an aircraft to fly is generated by wing. Starting from some basic geometrical data we can define the parameters for a 3D wing. Basic geometrical parameters for a wing are surface,taper ratio, aspect ratio and mean aerodynamic chord (MAC) , which are evaluated by the following relationship, respectively:

$$S_W = \frac{b_W}{2} c_{W_{Root}} (1 + \lambda_W) \tag{2.1}$$

$$\lambda_W = \frac{c_{w_{Tip}}}{c_{W_{Root}}} \tag{2.2}$$

$$AR_w = \frac{b^2}{S_W} \tag{2.3}$$

$$\bar{c}_W = \frac{2}{3} c_{W_{Root}} \frac{1+\lambda_W{}^2+\lambda_W}{1+\lambda_W} \tag{2.3}$$

Position of the mean aerodynamic chord leading edge on x-axis is evalueted with the following equation:

$$X_{\bar{c}_{W,LE}} = \frac{2}{3} b_W \frac{1+2\lambda_W}{1+\lambda_W} tan\Lambda_{LE} \quad (2.4)$$

Where Λ_{LE} is sweep angle at wing leading edge. The wing sweep angle can be estimated at different point, which are expressed in percentage of the chord by the term x, as shown in the following relationship:

$$tan\Lambda_X = tan\Lambda_{LE} - \frac{4x(1-\lambda_W)}{1+\lambda_W} \quad (2.5)$$

At subsonic condition the lift-curve slop can be evalueted with the empirical relationship of Polhamus. The condition to apply Polhamus's relationship are:

(i) $M\infty < M_{CR,3D}$

(ii) $\Lambda_{LE} < 32$ deg

(iii) $0.4 < \lambda_W < 1$

(iv) $3 < AR_w < 8$

If this condition are fulfilled, the expression of $C_{L_\alpha,W}$ is :

$$C_{L_\alpha,W} = \frac{2\pi AR_w}{2+\sqrt{\{\left[\frac{AR_w{}^2(1-Mach^2)}{K_p{}^2}\left(1+\frac{tan^2(\Lambda_{0.5})}{1-Mach^2}\right)\right]+4\}}} \quad (2.6)$$

The constant K_p is a function of wing's geometrical characteristics, in particolular of AR_w :

for $AR_w < 4$ $\quad K_p = 1 + \frac{AR_w(1.87-0.000233\,\Lambda_{LE})}{100}$ (2.7)

for $AR_w \geq 4$ $\quad K_p = 1 + \frac{[(8.2-2.3\lambda_{LE})-AR_w(0.22-0.153\Lambda_{LE})]}{100}$ (2.8)

In 2.7 and 2.8 Λ_{LE} is expressed in radiants.

2.2 Geometrical and aerodynamics parameters of horizontal tail

The horizontal tail's tasks in subsonic aircraft are to help ensuring stability of the aircraft to pitch moment. To compute all parameters needed with regard to the Horizontal Tail, see Section 2.1. Please notice that in this case the root profile related parameters are always referred to the fuselage centre line.

2.3 Geometrical and aerodynamics parameters of vertical tail

The vertical tail's tasks in subsonic aircraft are to help ensuring stability of the aircraft to lateral-directional force and moments(yaw and roll). To compute all parameters needed with regard to the Horizontal Tail, see Section 2.1. Please notice, that in this case the root profile related parameters are always referred to the fuselage centre line.

2.4 Longitudinal Unsteady-state coefficients

We start from modeling the small perturbation components of the lift and drag forces and the pitching moment. The origin of these components is associated with the perturbation terms in all the components of the linear and angular velocities.

2.4.1 Rate of change in the angle of attack

The contributions from the fuselage and the wing can be neglected, therefore for $C_{L_{\dot{\alpha}}}$ we have the approximation $C_{L_{\dot{\alpha}}} \approx C_{L_{\dot{\alpha}},HT}$. A closed-form expression for $C_{L_{\dot{\alpha}}}$ is given by:

$$C_{L_{\dot{\alpha}},HT} = 2C_{L_{\dot{\alpha}},HT}\eta_{HT}\frac{S_{HT}}{S_W}(\bar{X}_{AC_{HT}} - \bar{X}_{CG})\frac{d\varepsilon}{d\alpha} \qquad (2.9)$$

Also for the coefficient $C_{M_{\dot{\alpha}}}$ the contributions from the fuselage and the wing can be neglected, so we have $C_{M_{\dot{\alpha}}} \approx C_{M_{\dot{\alpha}},HT}$. A closed-form relationship is given by:

$$C_{M_{\dot{\alpha}},HT} = -2C_{L_{\dot{\alpha}},HT}\eta_{HT}\frac{S_{HT}}{S_W}(\bar{X}_{AC_{HT}} - \bar{X}_{CG})^2\frac{d\varepsilon}{d\alpha} \qquad (2.10)$$

The drag coefficient $C_{D_{\dot{\alpha}}}$ is always negligible.

2.4.2 Modeling roll rate contribution

For C_{L_q} we have that only the contribution from the fuselage is negligible. Therefore, we can consider $C_{L_q} \approx C_{L_q,W} + C_{L_q,HT}$. A closed-form relationship for the evaluation of $C_{L_q,W}$ is given by:

$$C_{L_{q},\mathrm{W}} = \frac{\mathcal{R}_{\mathrm{W}} + 2\cos\Lambda_{c/4}}{\mathcal{R}_{\mathrm{W}}B + 2\cos\Lambda_{c/4}} C_{L_{q},\mathrm{W}}\Big|_{M=0}$$

(2.11)

Where :

$$B = \sqrt{1 - M^2\left(\cos\Lambda_{c/4}\right)^2}$$

(2.12)

$$C_{L_{q},\mathrm{W}}\Big|_{M=0} = \left(\frac{1}{2} + 2\left|\xi_{\mathrm{AC,W}} - \xi_{\mathrm{CG}}\right|\right) C_{L_{\alpha},\mathrm{W}}\Big|_{M=0} \qquad (2.13)$$

The contribution from the horizontal tail is given by the following relationship:

$$C_{L_{q,\mathrm{H}}} = 2C_{L_{\alpha,\mathrm{H}}}\eta_{\mathrm{H}}\frac{S_{\mathrm{H}}}{S_{\mathrm{W}}}\left(\xi_{\mathrm{AC,H}} - \xi_{\mathrm{CG}}\right) \tag{2.14}$$

Considering both the equations 2.11 and 2.14 we have for C_{L_q} the following expression:

$$C_{L_q} = \frac{\mathcal{R}_{\mathrm{W}} + 2\cos\Lambda_{c/4}}{\mathcal{R}_{\mathrm{W}}\sqrt{1 - M^2\left(\cos\Lambda_{c/4}\right)^2} + 2\cos\Lambda_{c/4}}\left(\frac{1}{2} + 2\left|\xi_{\mathrm{AC,W}} - \xi_{\mathrm{CG}}\right|\right)C_{L_{\alpha,\mathrm{w}}}\Big|_{M=0} + 2C_{L_{\alpha,\mathrm{H}}}\eta_{\mathrm{H}}\frac{S_{\mathrm{H}}}{S_{\mathrm{W}}}\left(\xi_{\mathrm{AC,H}} - \xi_{\mathrm{CG}}\right) \tag{2.15}$$

For the coefficient C_{M_q} the contribution from the fuselage can be typically negligible. Therefore, we have $C_{M_q} \approx C_{M_{q,W}} + C_{M_{q,HT}}$. A closed-form relationship for the wing contribution is given by:

$$C_{\mathcal{M}_{q,\mathrm{w}}} = \frac{\frac{\mathcal{R}_{\mathrm{W}}^3\tan^2\Lambda_{c/4}}{\mathcal{R}_{\mathrm{W}}+6\cos\Lambda_{c/4}} + \frac{3}{B}}{\frac{\mathcal{R}_{\mathrm{W}}^3\tan^2\Lambda_{c/4}}{\mathcal{R}_{\mathrm{W}}+6\cos\Lambda_{c/4}} + 3}C_{\mathcal{M}_{q,\mathrm{w}}}\Big|_{M=0} \tag{2.16}$$

Where:

B = 2.11

$$C_{\mathcal{M}_{q,\mathrm{w}}}\Big|_{M=0} = -K_q C_{L_{\alpha,\mathrm{w}}}\Big|_{M=0}\cos\Lambda_{c/4}C \tag{2.17}$$

$$C = \frac{\mathcal{R}_{\mathrm{W}}\left(0.5\left|\xi_{\mathrm{AC,W}} - \xi_{\mathrm{CG}}\right| + 2\left|\xi_{\mathrm{AC,W}} - \xi_{\mathrm{CG}}\right|^2\right)}{\mathcal{R}_{\mathrm{W}} + 2\cos\Lambda_{c/4}} + \frac{1}{24}\frac{\mathcal{R}_{\mathrm{W}}^3\tan^2(\Lambda_{c/4})}{\mathcal{R}_{\mathrm{W}} + 6\cos\Lambda_{c/4}} + \frac{1}{8} \tag{2.18}$$

Horizontal tail contribution is given by:

$$C_{\mathcal{M}_{q,\mathrm{H}}} = -2C_{L_{\alpha,\mathrm{H}}}\eta_{\mathrm{H}}\frac{S_{\mathrm{H}}}{S_{\mathrm{W}}}\left(\xi_{\mathrm{AC,H}} - \xi_{\mathrm{CG}}\right)^2$$

(2.19)

Considering both the equations 2.11 and 2.14 we have for C_{L_q} the following expression:

$$C_{\mathcal{M}_q} = \frac{\frac{\mathit{AR}_{\mathrm{W}}^3 \tan^2\Lambda_{c/4}}{\mathit{AR}_{\mathrm{W}}+6\cos\Lambda_{c/4}} + \frac{3}{\sqrt{1-M^2\left(\cos\Lambda_{c/4}\right)^2}}}{\frac{\mathit{AR}_{\mathrm{W}}^3 \tan^2\Lambda_{c/4}}{\mathit{AR}_{\mathrm{W}}+6\cos\Lambda_{c/4}} + 3}\left[-K_q C_{L_{\alpha,\mathrm{W}}}\Big|_{M=0}\cos\Lambda_{c/4}\right] \cdot$$
$$\cdot \frac{\mathit{AR}_{\mathrm{W}}\left(0.5\left|\xi_{\mathrm{AC,W}} - \xi_{\mathrm{CG}}\right| + 2\left|\xi_{\mathrm{AC,W}} - \xi_{\mathrm{CG}}\right|^2\right)}{\mathit{AR}_{\mathrm{W}} + 2\cos\Lambda_{c/4}} + \frac{1}{24}\frac{\mathit{AR}_{\mathrm{W}}^3\tan^2\Lambda_{c/4}}{\mathit{AR}_{\mathrm{W}} + 6\cos\Lambda_{c/4}} + \frac{1}{8} +$$
$$- 2C_{L_{\alpha,\mathrm{H}}}\eta_{\mathrm{H}}\frac{S_{\mathrm{H}}}{S_{\mathrm{W}}}\left(\xi_{\mathrm{AC,H}} - \xi_{\mathrm{CG}}\right)^2 \qquad (2.20)$$

As $C_{D_{\dot{\alpha}}}$ also C_{D_q} value is always negligible.

2.5 Lateral-Directional aerodynamic coefficients

Now we have to model the system of aerodynamic lateral directional force and moments at steady-state and perturbed condition. Toward this model we define the effect of wing, vertical tail, horizontal tail, body and the deflection of control surface as rudder and ailerons. In this system of force and moments is very important the lateral angle of attack β that has the same role of α in the for modeling of the longitudinal forces and moments. The steady-state rolling and yawing moments and the lateral force are shown in Figure 2.1.

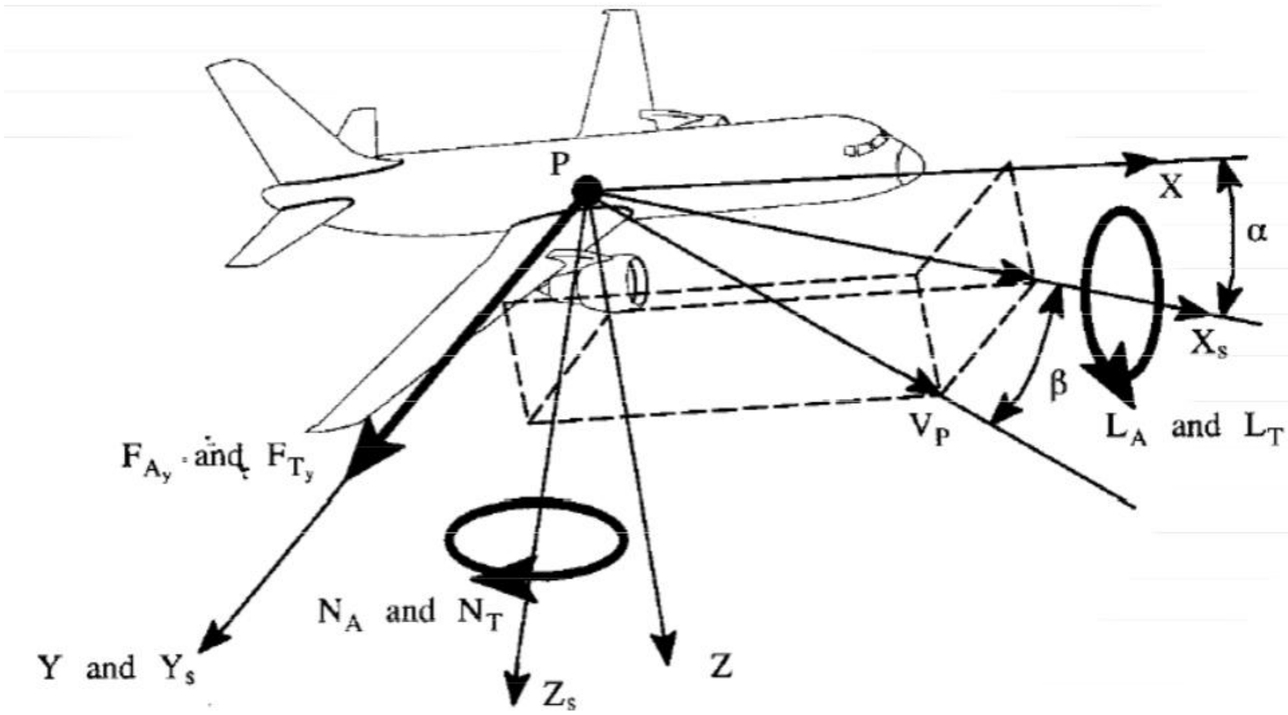


Figura 2.1 Steady-state lateral directional force and moments

2.5.1 Steady-state coefficients of side force

The modeling of the steady-state lateral force starts from the basic relationship:

Y = $c_y S\bar{q}$

Lateral force coefficienti is a function of: lateral angle of attack, rudder deflection and ailerons deflection:

$c_y = f(\beta, \delta_A, \delta_R)$

By use of first order approximation of Taylor we obtain:

$c_y = c_{y0} + c_{Y_\beta}\beta + c_{Y_{\delta_A}}\delta_A + c_{Y_{\delta_R}}\delta_R$

Due to aircraft symmetry respect to XZ axis $c_{y0} = 0$. So we have to find a way to model the aircraft coefficient c_{Y_β}, $c_{Y_{\delta_A}}$, $c_{Y_{\delta_R}}$.

2.5.1.1 Modeling of c_{Y_β}

Contribution to side force is given by wing-body configuration, vertical tail and horizontal tail. So we obtain the relationship :

$$c_{Y_\beta} = c_{Y_{\beta,WB}} + c_{Y_{\beta,HT}} + c_{Y_{\beta,VT}} \qquad (2.21)$$

Contribution to side force given by horizontal tail is negligible, unless the aircraft has horizontal tail with large dihedral angle, instead the contribution of fuselage can be divided from wing contribution.

A relationship for $c_{Y_{\beta,W}}$ is given by :

$$c_{Y_{\beta,W}} = -0.0001\Gamma_w * 57.3 \qquad (2.22)$$

A relationship for $c_{Y_{\beta,B}}$ instead is given by :

$$c_{Y_{\beta,B}} = -2K_{int}\,\frac{S_{P\rightarrow V}}{S_W} \qquad (2.23)$$

K_{int} is an interference factor associated with the wing-fuselage interface, it is entracted from figure A.1 in the appendix A

$S_{P\rightarrow V}$ is the cross section at the location of the fuselage where the flow ceases to be potentian

The contribution of vertical tail, instead is given by :

$$c_{Y_{\beta,VT}} = -k_{V_y}\left|c_{L_{\alpha,VT}}\right|\eta_{VT}\left(1+\frac{\mathrm{d}\sigma}{\mathrm{d}\alpha}\right)\frac{S_{VT}}{S_W} \qquad (2.24)$$

k_{V_y} is an empirical factor due to β, it is evalueted from figure A.2 in appendix A

$\eta_{VT}\left(1+\frac{\mathrm{d}\sigma}{\mathrm{d}\alpha}\right)$ is the effect of sidewash, an empirical relatioship is

$$\eta_{VT}\left(1+\frac{\mathrm{d}\sigma}{\mathrm{d}\alpha}\right) = 0.724 + 3.06\,\frac{S_{VT}/S_W}{1+\cos\Lambda_{0.25}} + 0.4\frac{Z_W}{d} + 0.0009\mathrm{AR}_w \qquad (2.25)$$

$\left|c_{L_{\alpha,VT}}\right|$ can be found with Polhamus relation, but we can't use AR_{VT}, due to the interference of horizontal tail, fuselage. So to evaluated $\left|c_{L_{\alpha,VT}}\right|$ we use $\mathrm{AR}_{Effective\ ,VT}$, given by :

$$\mathrm{AR}_{Effective\ ,VT} = c_1 \mathrm{AR}_{VT}(1 + K_{HV}(c_2 - 1)) \tag{2.26}$$

Where:

c_1 is a factor due to fuselage interference, it is evalueted from figure A.3 in appendix A

c_2 is a factor due to horizontal tail interference, it is evalueted from figure A.4 in appendix A

K_{HV} is a factor accouting for the relative size accounting for the relative size of the horizontal and vertical tail, it is evalueted from figure A.5 in appendix A

2.5.1.2 Modeling of $c_{Y_{\delta_R}}$

Rudder is a control surface, its contribution to side force is due to a deflection of the rudder that generated a lateral lift. The relationship of $c_{Y_{\delta_R}}$ is:

$$c_{Y_{\delta_R}} = \left|c_{L_{\alpha,VT}}\right| \eta_{VT} \frac{S_{VT}}{S_W} \tau_R \Delta(K_R) \tag{2.27}$$

τ_R is a control surface effectiveness, it is evalueted from figure A.6 in appendix A

$\Delta(K_R)$ correction factor associated with span of rudder within vertical tail span, it is evalueted from figure A.7 in appendix A

2.5.1.3 Modeling of $c_{Y_{\delta_A}}$

Ailerons are an asymmetric surface control   A positive deflection of the ailerons implies a trailing edge down deflection of the left aileron and a trailing edge up deflection of the right aileron. Contribution to sideforce of the ailerons is always negligible,so : $c_{Y_{\delta_A}} \approx 0$

2.5.2 Unsteady-state coefficients of side force

We starts from modeling the small perturbation components of the side force. The origin of these components is associated with the perturbation terms in all the components of the linear and angular velocities:

- roll rate→ c_{Y_p};
- yaw rate → c_{Y_q}.

2.5.2.1 Modeling of c_{Y_p}

Contribution to c_{Y_p} of the aircraft is given only by the vertical tail. A relationship of c_{Y_p} is :

$$c_{Y_p} = 2 * c_{Y_{\beta,VT}} * \frac{(Z_V cos\alpha_1 - X_V sin\alpha_1)}{b} \qquad (2.28)$$

Where:

Z_V e X_V are shown in figure 2.2

$c_{Y_{\beta,VT}}$ is modeled in par 2.4.1

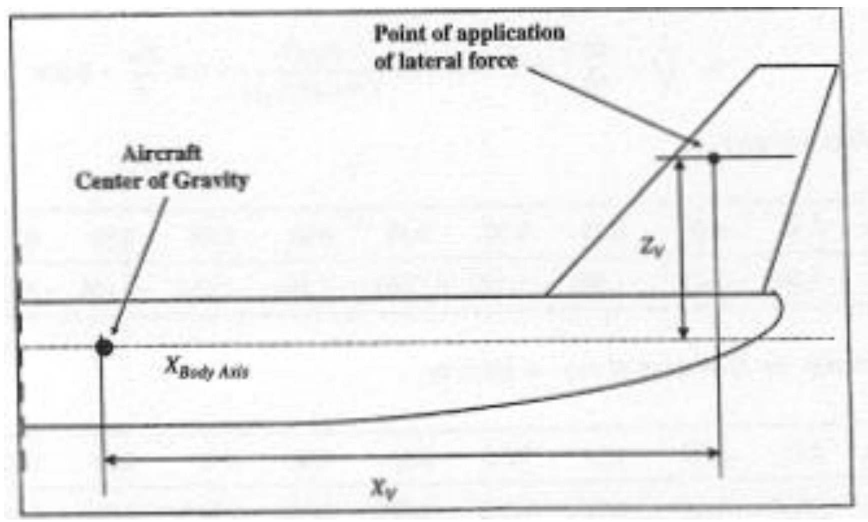


Figura 2.2: Geometric parameters of the vertical tail.

2.5.2.2 Modeling of c_{Y_q}

Contribution to c_{Y_q} of the aircraft is given only by the vertical tail. A relationship of c_{Y_q} is :

$$c_{Y_q} = -2 * c_{Y_{\beta,VT}} * \frac{(X_V cos\alpha_1 + Z_V sin\alpha_1)}{b} \qquad (2.29)$$

Where:

Z_V e X_V are shown in figure 2.2

$c_{Y_{\beta,VT}}$ is modeled in par 2.4.1.

2.5.3 Steady-state coefficients of rolling moments

The modeling of the steady-state rolling moments starts from the basic relationship:

$\mathcal{L} = c_L S b \bar{q}$

Rolling moments coefficients are a function of: lateral angle of attack, rudder deflection and ailerons deflection :

$c_{\mathcal{L}} = f(\beta, \delta_A, \delta_R)$

By use of first order approximation of Taylor we obtain :

$$c_{\mathcal{L}} = c_{\mathcal{L}0} + c_{\mathcal{L}_\beta}\beta + c_{\mathcal{L}_{\delta_A}}\delta_A + c_{\mathcal{L}_{\delta_R}}\delta_R$$

Due to aircraft symmetry respect to XZ axis $c_{\mathcal{L}0} = 0$. So we have to find a way to model the aircraft coefficient c_{L_β}, $c_{\mathcal{L}_{\delta_A}}$, $c_{\mathcal{L}_{\delta_R}}$.

2.5.3.1 Modeling of $c_{\mathcal{L}_\beta}$

The coefficient c_{L_β} is also called dihedral effect. Contribution to dihedral effect is given by wing-body configuration, vertical tail and horizontal tail. So we obtain the relationship :

$c_{\mathcal{L}_\beta} = c_{\mathcal{L}_{\beta,WB}} + c_{\mathcal{L}L_{\beta,HT}} + c_{\mathcal{L}L_{\beta,VT}}$

Contribution to dihedral effect given by horizontal tail is negligible, unless the aircraft has horizontal tail with large dihedral angle. Instead the contribution of the wing-body configuration is a function of many parameters such wing's sweep angle, wing's dihedral angle , wing's position ecc.

A relationship of $c_{\mathcal{L}_\beta}$ that considered all this parameters is given by:

$$C_{\mathcal{L}_{\beta,\mathrm{WB}}} = 57.3 C_L \left[\left(\frac{C_{\mathcal{L}_\beta}}{C_L} \right)_{\Lambda_{c/2}} K_{M_\Lambda} K_f + \left(\frac{C_{\mathcal{L}_\beta}}{C_L} \right)_{AR} \right] + 57.3 \left\{ \Gamma_W \left[\frac{C_{\mathcal{L}_\beta}}{\Gamma_W} K_{M_\Gamma} + \frac{\Delta C_{\mathcal{L}_\beta}}{\Gamma_W} \right] + \left(\Delta C_{\mathcal{L}_\beta} \right)_{Z_W} + \varepsilon_W \tan \Lambda_{c/4} \left(\frac{\Delta C_{\mathcal{L}_\beta}}{\varepsilon_W \tan \Lambda_{c/4}} \right) \right\} \quad (2.30)$$

Where:

- $(\frac{c_{\mathcal{L}_\beta}}{c_L})_{\Lambda/2} =$ contribution to $c_{\mathcal{L}_{\beta,WB}}$ due to wing sweep angle;
- $K_{\mathcal{M}_\Lambda} =$ compressibility correction factor;
- K_f = fuselage correction factor due to wing seep angle;
- $(\frac{c_{\mathcal{L}_\beta}}{c_L})_{AR} =$ contribution to $c_{\mathcal{L}_{\beta,WB}}$ due to wing aspect ratio;
- $\frac{c_{\mathcal{L}_\beta}}{\Gamma_W} =$ contribution to $c_{\mathcal{L}_{\beta,WB}}$ due to wing dihedral angle;
- $K_{\mathcal{M}_{\Gamma_W}}$ = compressibility correction factor;
- $\frac{\Delta c_{\mathcal{L}_\beta}}{\varepsilon - \tan(\Lambda/2)} =$ contribution to $c_{\mathcal{L}_{\beta,WB}}$ due to wing twist angle;

All these coefficients are evaluated from figure A.8 to A.14 in appendix 1.

Contribution of vertical tail to dihedral effect is given by :

$$c_{\mathcal{L}L_{\beta,VT}} = c_{Y_{\beta,VT}} * \frac{(Z_V \cos\alpha_1 - X_V \sin\alpha_1)}{b} \quad (2.31)$$

Where :

Z_V e X_V are shown in figure 2.2

$c_{Y_{\beta,VT}}$ is modeled in par 2.4.1.1

2.5.3.2 Modeling of $c_{\mathcal{L}_{\delta_A}}$

Ailerons are an asymmetric surface control. A positive deflection of the ailerons implies a trailing edge down deflection of the left aileron and a trailing edge up deflection of the right aileron, this deflection produces a positive rolling moment. Although ailerons effect has a simple origin, its determination is quite complex, because ailerons effect is due to many factor as wing aspect ratio, wings sweep angle, wings lift-curve slop, Mach number, position of ailerons (inner and outer position). To find ailerons effect to rolling moments we follow a step-by-step procedure:

1) Find inner and outer position of ailerons:

$$\eta_{inner} = \frac{y_{inner}}{b/2} \qquad \eta_{outer} = \frac{y_{outer}}{b/2}$$

2) Evaluate empirical coefficient K_M and Λ_β given by:

$$K_M = \frac{C_{L_{\alpha},W}\,\beta}{2\pi} \quad (2.32)$$

$$\Lambda_\beta = tan^{-1}\left(\frac{\Lambda/4}{\beta}\right) \quad (2.33)$$

Where

$$\beta = \sqrt{1 - Mach^2} \quad (2.34)$$

With AR, K_M, Λ_β and λ we can find rhe value of rolling moments effectiviness (RME) coefficient at inner and outer panel of ailerons from figure A.15. At the end we find $\Delta($RME).

3) $c_{\mathcal{L}_{\delta_A}}$ is given by:

$$c_{\mathcal{L}_{\delta_A}} = \frac{\tau_R \, \Delta(\mathrm{RME})}{\beta} \tag{2.35}$$

τ_A is a control surface effectiveness, it is evalueted from figure A.6 in appendix A

2.5.3.1 Modeling of $c_{\mathcal{L}_{\delta_R}}$

Rudder is a control surface,its contribution to rolling moments is due to a deflection of the rudder, that generated a lateral lift, assocciated with a moments arm(figure 2.2). The relationship is given by :

$$c_{\mathcal{L}_{\delta_R}} = c_{Y_{\delta_R}} \frac{(Z_V cos\alpha_1 - X_V sin\alpha_1)}{b} \tag{2.36}$$

$c_{\mathcal{L}_{\delta_R}}$ is modeled in par 2.4.1.2

2.5.4 Unsteady-state coefficients of rolling moments

As for unsteady-state side force coefficient, the contribution to rolling moments due to small perbutation comes from:

- yaw rate → $c_{\mathcal{L}_q}$
- roll rate → $c_{\mathcal{L}_p}$

2.5.4.1 Modeling of $c_{\mathcal{L}_p}$

The coefficient $c_{\mathcal{L}_p}$ models the contribution of the rolling moment coefficient due to roll rate. The mathematical relationship is given by:

$$C_{\mathcal{L}_p} = C_{\mathcal{L}_{p,\mathrm{WB}}} + C_{\mathcal{L}_{p,\mathrm{H}}} + C_{\mathcal{L}_{p,\mathrm{V}}} \tag{2.37}$$

The contribution from the fuselage is negligible, so $c_{\mathcal{L}_{p,WB}} \approx c_{\mathcal{L}_{p,W}}$ and the relationship for this coefficient is given by:

$$c_{\mathcal{L}_{p,W}} = \mathrm{RDP}\,\frac{k}{\beta} \tag{2.38}$$

RDP is the rolling damping parameter, evalueted from figure A.16 in appendix A
k can be find with (2.32), β can be find with (2.34)

$c_{\mathcal{L}_{p,H}}$ value istead is always negligible.

The contricution of vertical tail is given by :

$$c_{\mathcal{L}_{p,V}} = 2c_{Y_{\beta,VT}} \left(\frac{Z_{VT}}{b}\right)^2 \tag{2.39}$$

2.5.4.2 Modeling of $c_{\mathcal{L}_r}$

The coefficient $c_{\mathcal{L}_r}$ models the contribution of the rolling moment coefficient due to yaw rate. The mathematical relationship is given by:

$$C_{\mathcal{L}_r} = C_{\mathcal{L}_{r,\mathrm{WB}}} + C_{\mathcal{L}_{r,\mathrm{H}}} + C_{\mathcal{L}_{r,\mathrm{V}}} \tag{2.40}$$

Tipically fuselage and horizontal tail contribution are negligible, so we have to find only Vertical tail and wings contribution.

The modeling of $c_{\mathcal{L}_{r,W}}$ is quite complex, a semi-empirical relationship is given by:

$$C_{\mathcal{L}_{r,\mathrm{W}}} = \left(\frac{C_{\mathcal{L}_r}}{C_L}\right)\bigg|_{M,C_L=0} C_L + \left(\frac{\Delta C_{\mathcal{L}_r}}{\Gamma_W}\right)\Gamma_W + \left(\frac{\Delta C_{\mathcal{L}_r}}{\varepsilon}\right)\varepsilon \tag{2.41}$$

Where:

$$\left(\frac{C_{\mathcal{L}_r}}{C_L}\right)\bigg|_{M,C_L=0} = D\left(\frac{C_{\mathcal{L}_r}}{C_L}\right)\bigg|_{M=0,C_L=0} \qquad (2.42)$$

The coefficient of the relationship (2.42) are given by:

$$D = \frac{1 + \frac{AR_W(1-B^2)}{2B[AR_W \cdot B+2\cos\Lambda_{c/4}]} + \frac{AR_W B+2\cos\Lambda_{c/4}}{AR_W B+4\cos\Lambda_{c/4}} \frac{\tan^2\Lambda_{c/4}}{8}}{1 + \frac{AR_W+2\cos\Lambda_{c/4}}{AR_W+4\cos\Lambda_{c/4}} \frac{\tan^2\Lambda_{c/4}}{8}}$$

β can be find with (2.34).

$\frac{c_{\mathcal{L}_r,}}{c_L}\Big|_{M=0,c_L,=0}$ is evacuate from figure A.17 in appendix A.

The effect of the wing dihedral angle to rolling moment due to yaw rate is given by:

$$\frac{\Delta C_{\mathcal{L}_r}}{\Gamma_W} = \frac{1}{12} \frac{\pi AR_W \sin\Lambda_{c/4}}{AR_W + 4\cos\Lambda_{c/4}}$$

Instead the coefficient $\left(\frac{\Delta c_{\mathcal{L}_r}}{\varepsilon}\right)$ is found from figure A.18.

$$c_{\mathcal{L}_p,V} = c_{Y_V} \frac{(X_V \cos\alpha_1 - Z_V \sin\alpha_1)}{b} \frac{(Z_V \cos\alpha_1 - X_V \sin\alpha_1 - Z_V)}{b} \quad (2.43)$$

2.5.5 Steady-state coefficients of yawing moments

The modeling of the steady-state yawing moments starts from the basic relationship:

$\mathcal{N} = c_{\mathcal{N}} S b \bar{q}$

rolling moments coefficients is a function of: lateral angle of attack, rudder deflection and ailerons deflection :

$c_{\mathcal{N}} = f(\beta, \delta_A, \delta_R)$

By the use of first order approximation of Taylor we obtain:

$$c_{\mathcal{N}} = c_{\mathcal{N}0} + c_{\mathcal{N}_\beta}\beta + c_{\mathcal{N}_{\delta_A}}\delta_A + c_{\mathcal{N}_{\delta_R}}\delta_R$$

Due to aircraft symmetry respect to XZ axis $c_{\mathcal{N}0} = 0$. So we have to find a way to model the aircraft coefficient $c_{\mathcal{N}_\beta}$, $c_{\mathcal{N}_{\delta_A}}$, $c_{\mathcal{N}_{\delta_R}}$.

2.5.5.1 Modeling of $c_{\mathcal{N}_\beta}$

The coefficient $c_{\mathcal{N}_\beta}$ is also called weathercock effect. Contribution to weathercock effect is given by wing-body configuration, vertical tail and horizontal tail. So we obtain the relationship :

$$c_{\mathcal{N}_\beta} = c_{\mathcal{N}_{\beta,WB}} + c_{\mathcal{N}_{\beta,HT}} + c_{\mathcal{N}_{\beta,VT}}$$

Contribution to weathercock effect due to wing and horzontal tail is often negligible, so we have only contribution of fuselage and vertical tail.

$$C_{\mathcal{N}_{\beta,\mathrm{B}}} = -57.3 K_N K_{Re_B} \frac{S_{\mathrm{B,side}}}{S_{\mathrm{W}}} \frac{l_{\mathrm{B}}}{b_{\mathrm{W}}} \qquad (2.44)$$

where the coefficient KN is an empirical factor, estimated graphically (figure A.19), related to the geometric coefficients of the axial cross section of the fuselage and the coefficient KReB, evaluated graphically (figure A.20), is related to the Reynolds number.

The most significant contribution to $c_{\mathcal{N}_\beta}$ is provided by the vertical tail. This contribution is evaluated by:

$$C_{\mathcal{N}_{\beta,\mathrm{V}}} = k_{Y_\mathrm{V}} |C_{L_{\alpha,\mathrm{V}}}| \eta_{\mathrm{V}} \left(1 + \frac{d\sigma}{d\beta}\right) \frac{S_{\mathrm{V}}}{S_{\mathrm{W}}} \frac{X_V \cos\alpha_{\mathrm{W}} + Z_V \sin\alpha_{\mathrm{W}}}{b_{\mathrm{W}}} \qquad (2.45)$$

2.5.5.2 Modeling of $c_{\mathcal{N}_{\delta_A}}$

The asymmetric deflection of left and right ailerons also generate small but not negligible drag force leading to a small negative yawing moment. A relationship for $c_{\mathcal{N}_{\delta_A}}$ is given by :

$$C_{\mathcal{N}_{\delta_a}} = \Delta(K_{n_a}) C_L C_{\mathcal{L}_{\delta_a}} \qquad (2.46)$$

Where :
Δk_{n_a} is evacuate from figure A.21.
c_L is lift coefficient.
$c_{\mathcal{L}_r}$ is yawing moments coefficient.

2.5.5.3 Modeling of $c_{\mathcal{N}_{\delta_R}}$

Rudder is a control surface, its contribution to rolling moments is due to a deflection of the rudder, that generated a lateral lift, assocciated with a moments arm(figure 2.2). The relationship is given by :

$$C_{\mathcal{N}_{\delta_r}} = -|C_{L_{\alpha,\mathrm{V}}}| \eta_{\mathrm{V}} \frac{S_{\mathrm{V}}}{S_{\mathrm{W}}} K_r \tau_r \frac{X_r \cos\alpha_{\mathrm{W}} + Z_r \sin\alpha_{\mathrm{W}}}{b_{\mathrm{W}}} \qquad (2.47)$$

2.5.6 Unsteady-state coefficients of yawing moments

As for unsteady-state side force coefficient, the contribution to rolling moments due to small perbutation comes from:

- yaw rate → $c_{\mathcal{N}_r}$
- roll rate → $c_{\mathcal{N}_p}$

2.5.6.1 Modeling of $c_{\mathcal{N}_p}$

The coefficient $c_{\mathcal{N}_p}$ gives the effect of roll rate to yawing moments. We can stars its modeling from equation :

$$c_{\mathcal{N}_p} = c_{\mathcal{N}_p,WB} + c_{\mathcal{N}_p,H} + c_{\mathcal{N}_p,V} \tag{2.48}$$

But contribution of horizontal tail and fuselage can be neglected. The modeling of $c_{\mathcal{N}_r,W}$ is quite complex, a semi-empirical relationship is given by:

$$\left(\frac{c_{\mathcal{N}_p}}{c_L}\right)\Big|_{Mach,C_L=0} c_L + \left(\frac{\Delta c_{\mathcal{N}_p}}{\varepsilon_W}\right)\varepsilon_W \tag{2.49}$$

The coefficient $\left(\frac{c_{\mathcal{N}_p}}{c_L}\right)\Big|_{Mach,C_L=0}$ is given by:

$$\left(\frac{c_{\mathcal{N}_p}}{c_L}\right)\Big|_{Mach,C_L=0} = C\left(\frac{c_{\mathcal{N}_p}}{c_L}\right)\Big|_{Mach=0,C_L=0}$$

Where:

$$C = \frac{AR_W + 4\cos\Lambda_{c/4}}{AR_W B + 4\cos\Lambda_{c/4}} \frac{AR_W B + \frac{1}{2}[AR_W B + 4\cos\Lambda_{c/4}]\tan^2\Lambda_{c/4}}{AR_W + \frac{1}{2}[AR_W + 4\cos\Lambda_{c/4}]\tan^2\Lambda_{c/4}} \tag{2.50}$$

With

$$B = \sqrt{1 - Mach^2 cos\Lambda_{c/4}}$$

$$\left(\frac{c_{\mathcal{N}_p}}{c_L}\right)\Big|_{Mach=0,C_L=0} = -\frac{1}{6}\frac{AR_W + 6(AR_W + \cos\Lambda_{c/4})\left[(\xi_{CG} - \xi_{AC})\frac{\tan\Lambda_{c/4}}{AR_W} + \frac{\tan^2\Lambda_{c/4}}{12}\right]}{AR_W + \cos\Lambda_{c/4}} \tag{2.51}$$

The coefficient $\left(\frac{\Delta c_{\mathcal{N}_p}}{\varepsilon_W}\right)$ is evacuate from figure A.22

Vertical tail contribution istead is given by

$$c_{\mathcal{N}_p,V} = c_{Y_V} \frac{(X_V cos\alpha_1 - Z_V sin\alpha_1)}{b} \frac{(Z_V cos\alpha_1 - X_V sin\alpha_1 - Z_V)}{b} \tag{2.52}$$

2.5.6.2 Modeling of $c_{\mathcal{N}_r}$

The coefficient $c_{\mathcal{N}_r}$ models the contribution to the yawing moments due to yaw rate. As for $c_{\mathcal{N}_r}$ the modeling of this equation starts from :

$$c_{\mathcal{N}_r} = c_{\mathcal{N}_r,WB} + c_{\mathcal{N}_r,H} + c_{\mathcal{N}_r,V} \qquad (2.53)$$

But contribution of horizontal tail and fuselage can be neglected .A relationship for $c_{\mathcal{N}_r,W}$ is :

$$c_{\mathcal{N}_r,W} = \left(\frac{c_{\mathcal{N}_r}}{c_L{}^2}\right) c_L{}^2 + \left(\frac{c_{\mathcal{N}_r}}{c_{D0}}\right) c_{D0}$$

The coefficient $\left(\frac{c_{\mathcal{N}_r}}{c_L{}^2}\right)$ can be evacuate from figure A.23.
The coefficient $\left(\frac{c_{\mathcal{N}_r}}{c_{D0}}\right)$ can be evacuate from figure A.24.
Vertical tail contribution is:

$$c_{nr_V} \approx 2 \cdot c_{Y_{\beta_V}} \cdot \frac{(X_V \cos\alpha_1 + Z_V \sin\alpha_1)^2}{b^2} \qquad (2.54)$$

Chapter 3:Example of application on Douglas DC-9-10

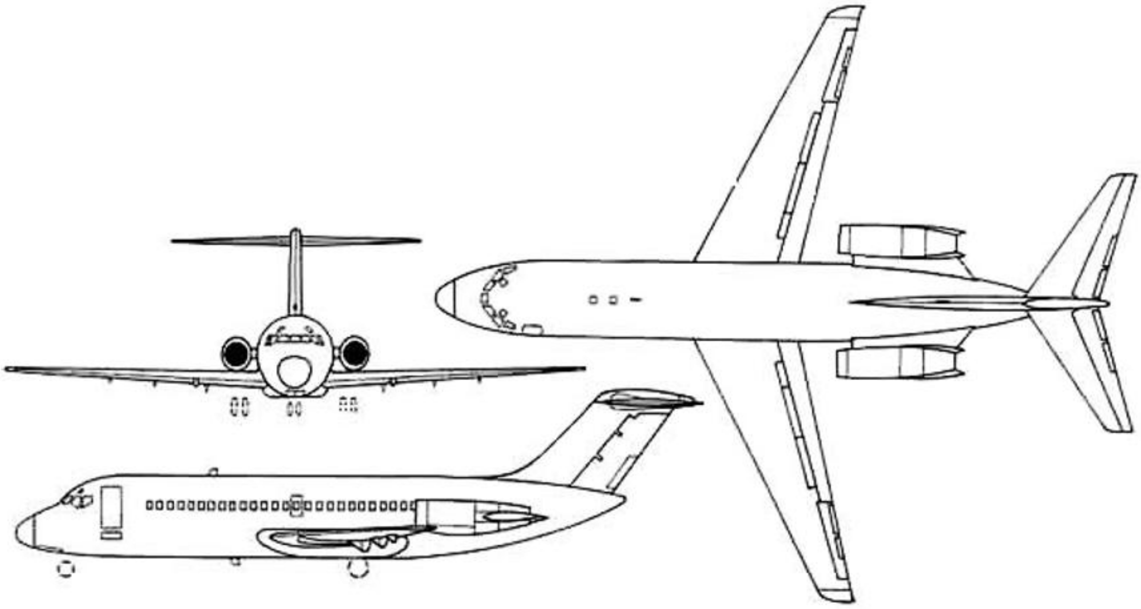


Figura 3.1: DC 9-10 three view

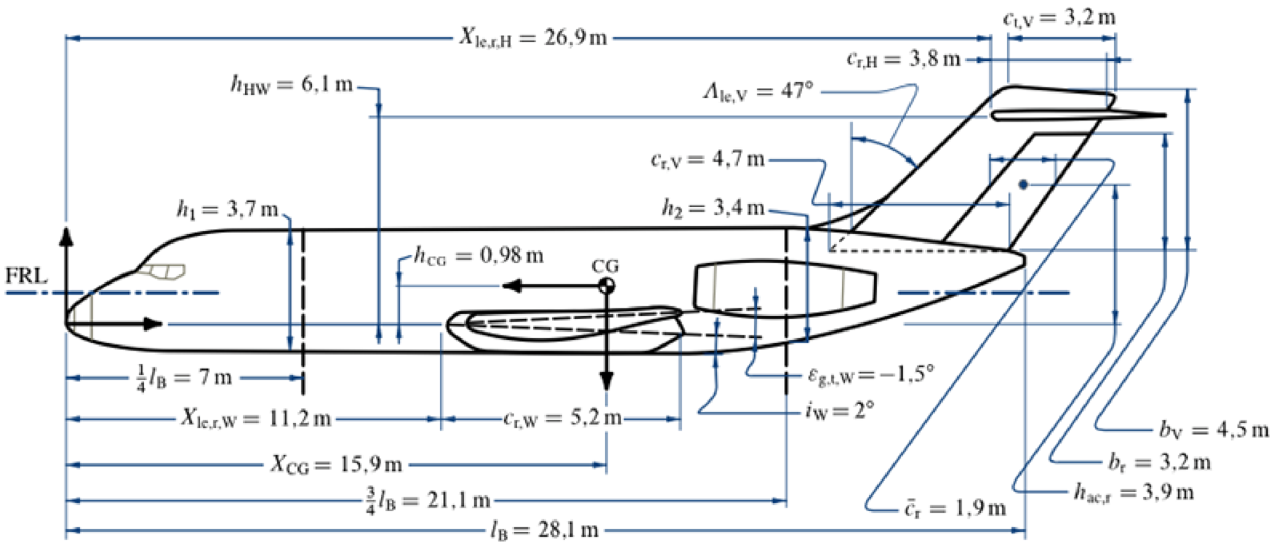


Figure 3.2: DC 9-10 side view geometrical data

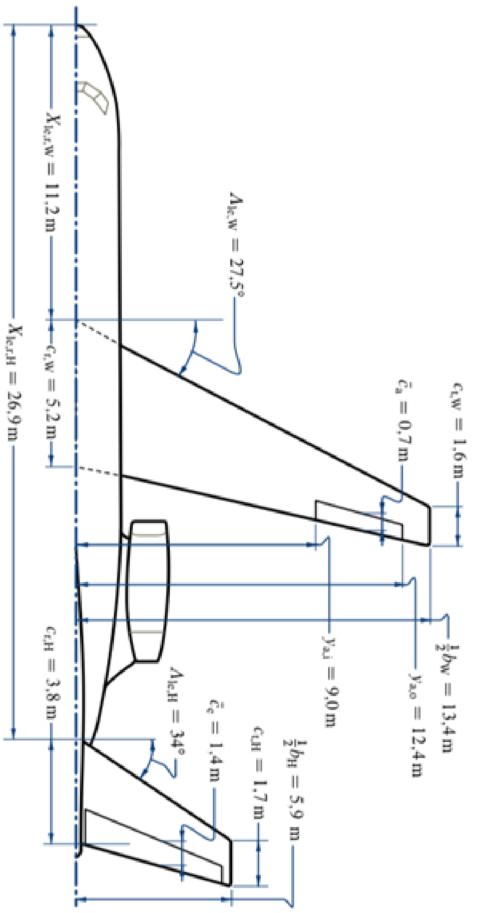


Figure 3.3: DC 9-10 top view geometrical data

$C_{L_{\dot{\alpha}},H}$	2.750835993198621	Rate of change in the angle of attack
$C_{L_q,W}$	6.069647309878318	Unsteady lift Coefficient (pitch contribution of wings)
$C_{L_q,H}$	11.182260134953744	Unsteady lift Coefficient (pitch contribution of horizontal tail)
$C_{M_{\dot{\alpha}},H}$	-10.296379122542437	Unsteady pitch Coefficient (rate of change of alfa contribution of horizontal tail)
$C_{M_q,H}$	-41.85519968513186	Unsteady pitch Coefficient (pitch contribution of horizontal tail)
$C_{M_q,W}$	-1.5508244325023455	Unsteady pitch Coefficient (pitch contribution of wing)
$c_{Y_{\beta,W}}$	-0.012606000000000001	CYBeta wing contribution
$c_{Y_{\beta,B}}$	-0.17335993319105503	CYBeta fuselage contribution
$c_{Y_{\beta,V}}$	-0.9944979203176462	CYBeta vertical tail contribution
$c_{Y_{\delta_R}}$	0.2934696566529219	Rudder contribution to side force
c_{Y_p}	-0.24173044406500085	Roll rate contribution to side force
c_{Y_q}	0.7851913657023578	Yaw rate contribution to side force
$c_{\mathcal{L}_{\beta,WB}}$	-0.08411965180160728	Dihedral effect,contribution of wing body
$c_{\mathcal{L}_{\beta,V}}$	-0.026069981422944363	Dihedral effect,Vertical tail
$c_{\mathcal{L}_{\delta_A}}$	0.0559529952273778	Ailerons effect on rolling moments
$c_{\mathcal{L}_{\delta_R}}$	0.035666515219888784	Rudder effect on rolling moments
$c_{\mathcal{L}_{p,W}}$	-0.34443657613977324	Roll pitch wing contribution to rolling moments

$C_{\mathcal{L}_{p,H}}$	-0.0008079909813196784	Roll pitch horizontal tail contribution to rolling moments
$C_{\mathcal{L}_{p,V}}$	-0.0026520316087262547	Roll pitch Vertical tail contribution to rolling moments
$C_{\mathcal{L}_r,W}$	0.12680086336152063	Yaw pitch wing contribution to rolling moments
$C_{\mathcal{L}_r,V}$	-0.037395744333626	Yaw pitch Vertical tail contribution to rolling moments
$C_{\mathcal{N}_{\beta},B}$	-0.18042090236446487	Fuselage contribution to weathercock effect
$C_{\mathcal{N}_{\beta},V}$	0.39985707886242444	Vertical tail contribution to weathercock effect
$C_{\mathcal{N}_{\delta_A}}$	5.519749901580546E-4	Ailerons effect to yawing moments
$C_{\mathcal{N}_{\delta_R}}$	-0.11428873456601799	Rudder effect to yawing moments
$C_{\mathcal{N}_p,WB}$	-0.07838443958551851	Roll rate contribution of the wing to yawing moments
$C_{\mathcal{N}_p,V}$	-0.010791654543710835	Roll rate contribution of the vertical tail to yawing moments
$C_{\mathcal{N}_r,W}$	-0.08523597299578495	Yaw rate contribution of the wing to yawing moments
$C_{\mathcal{N}_p,V}$	-0.31097287584428746	Yaw rate contribution of the vertical tail to yawing moments

Appendix A

In this Appendix are stored all plot of the interpolating function in this work.

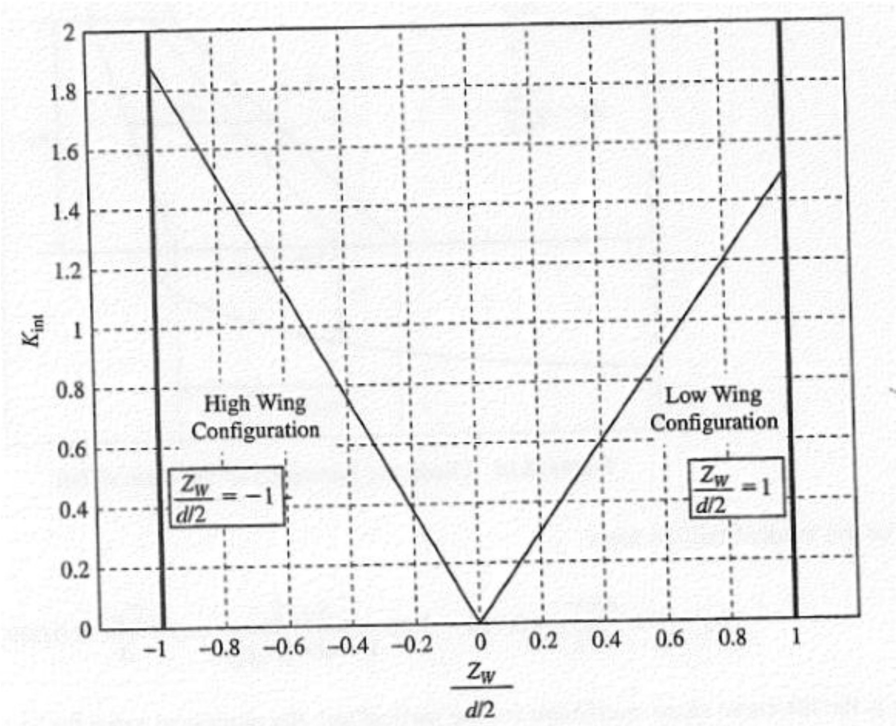


Figure A.1: Wing-Body interference factor

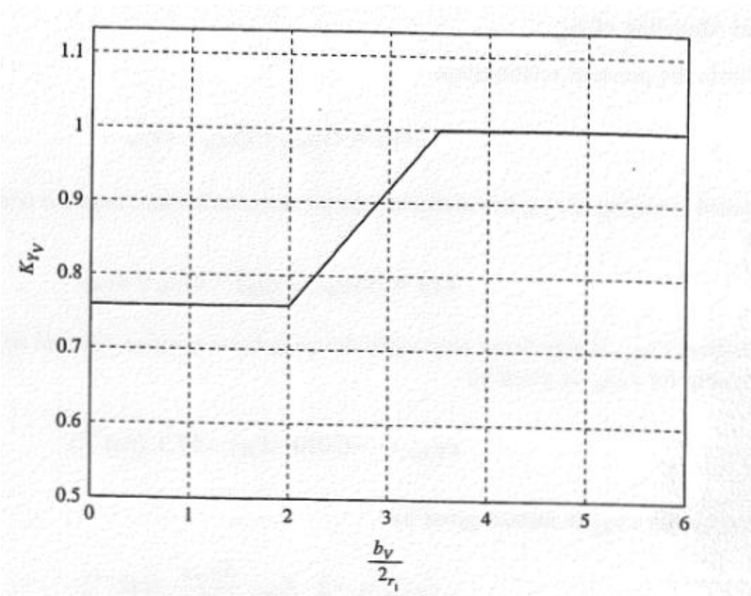


Figure A.2: Empirical factor for lateral force at the vertical tail due to β

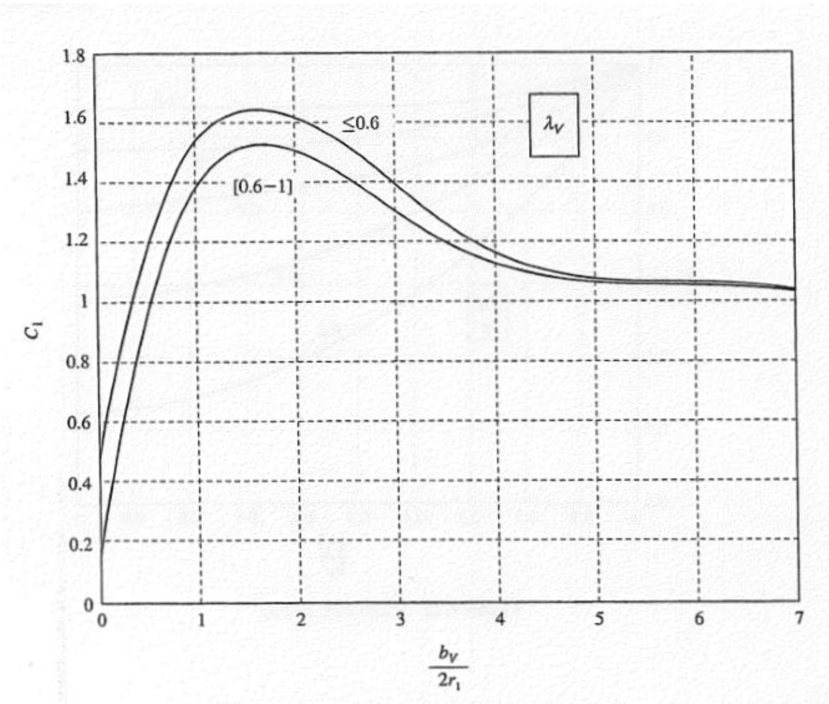


Figure A.3: c_1 for evaluation of $\mathbf{AR}_{effective}$

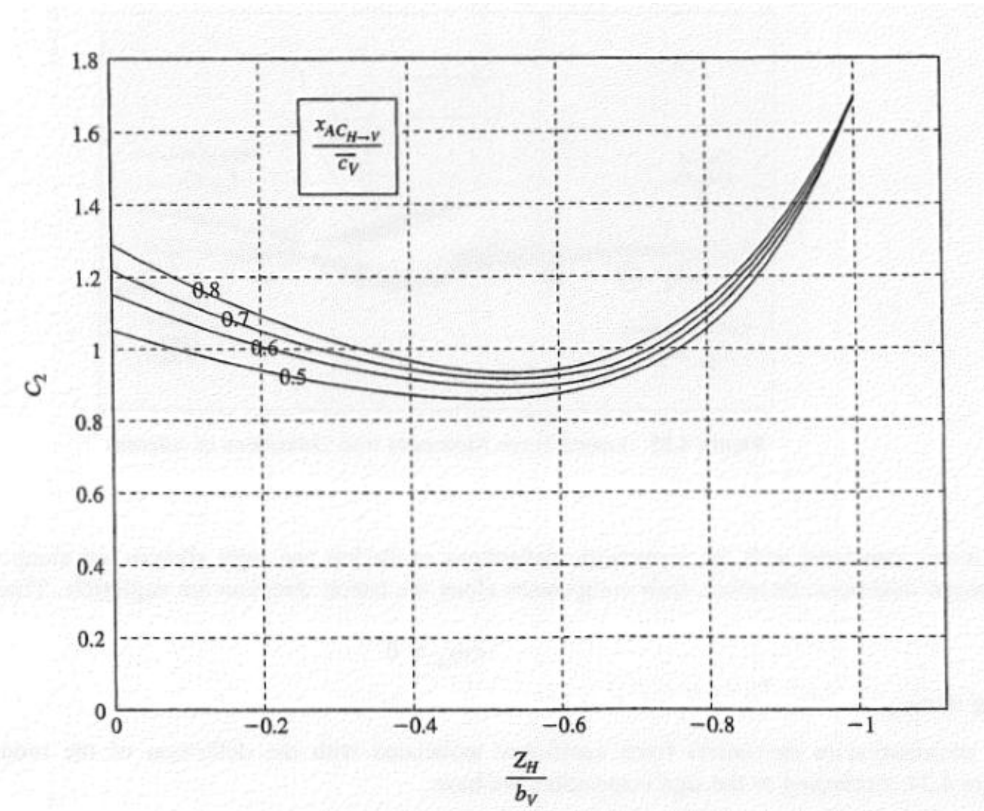


Figure A.4: c_2 for evaluation of $\mathbf{AR}_{effective}$

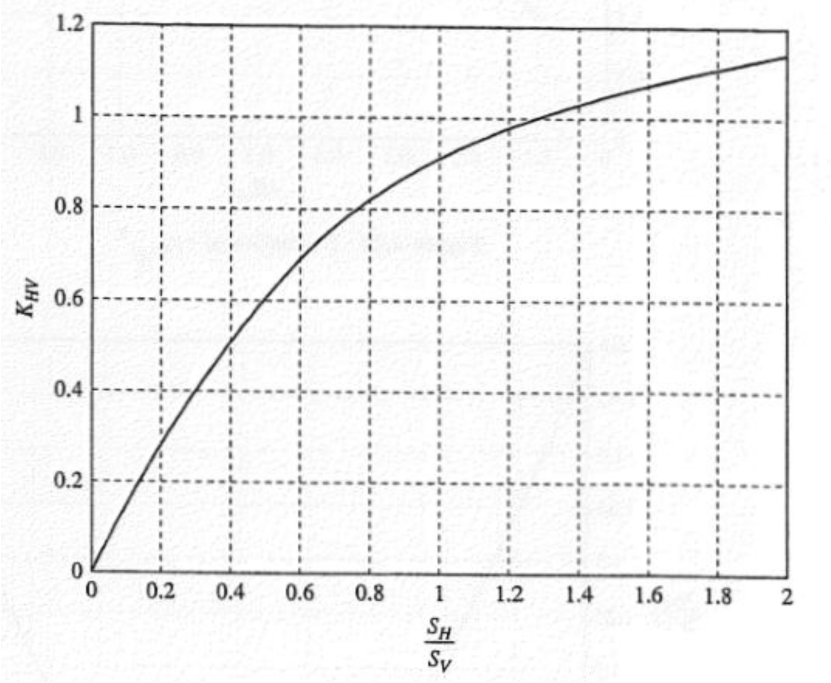


Figure A.5: Empirical factor for $\frac{S_H}{S_V}$ relative size

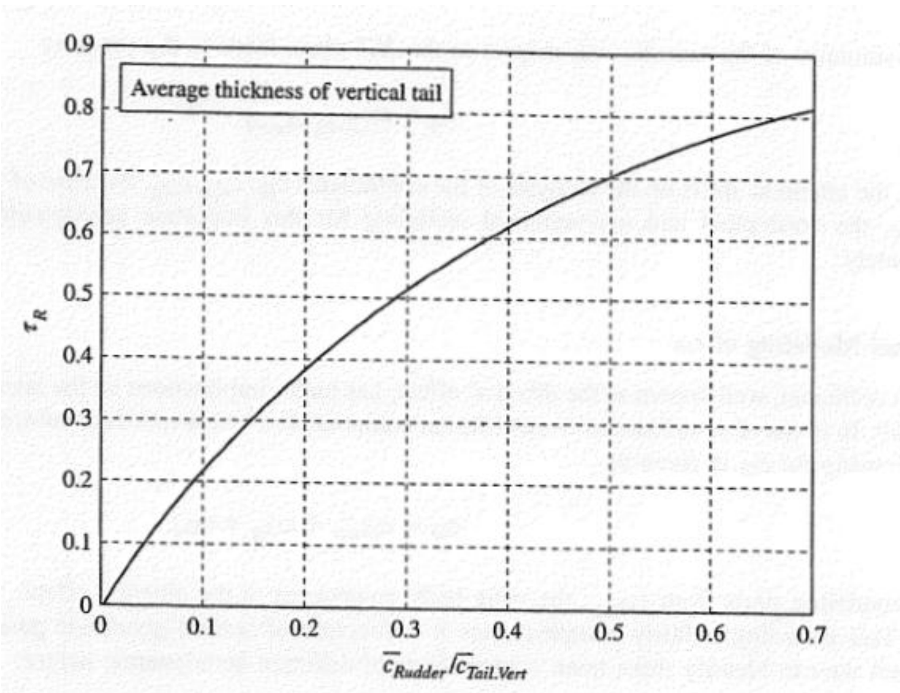


Figure A.6: Effectiveness of rudder,it can be used also for ailerons and elevator

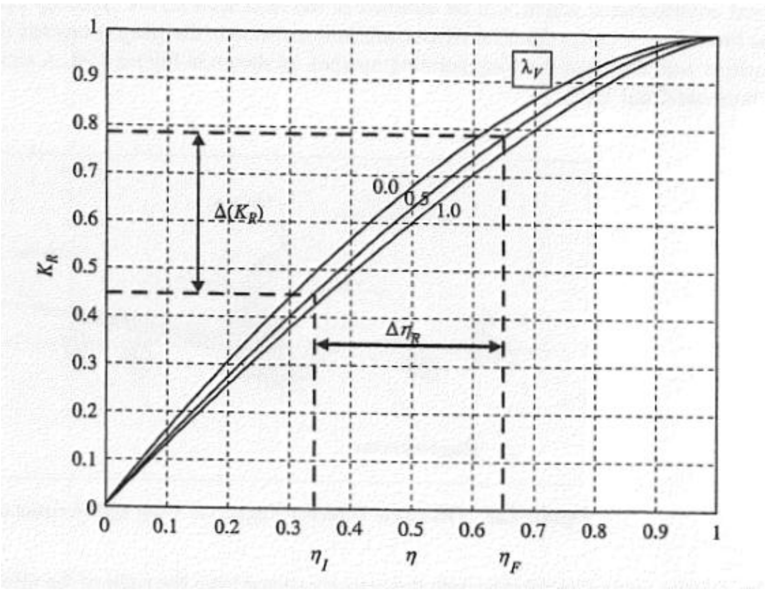


Figure A.7: Effectiveness Span factor between rudder and vertical tail

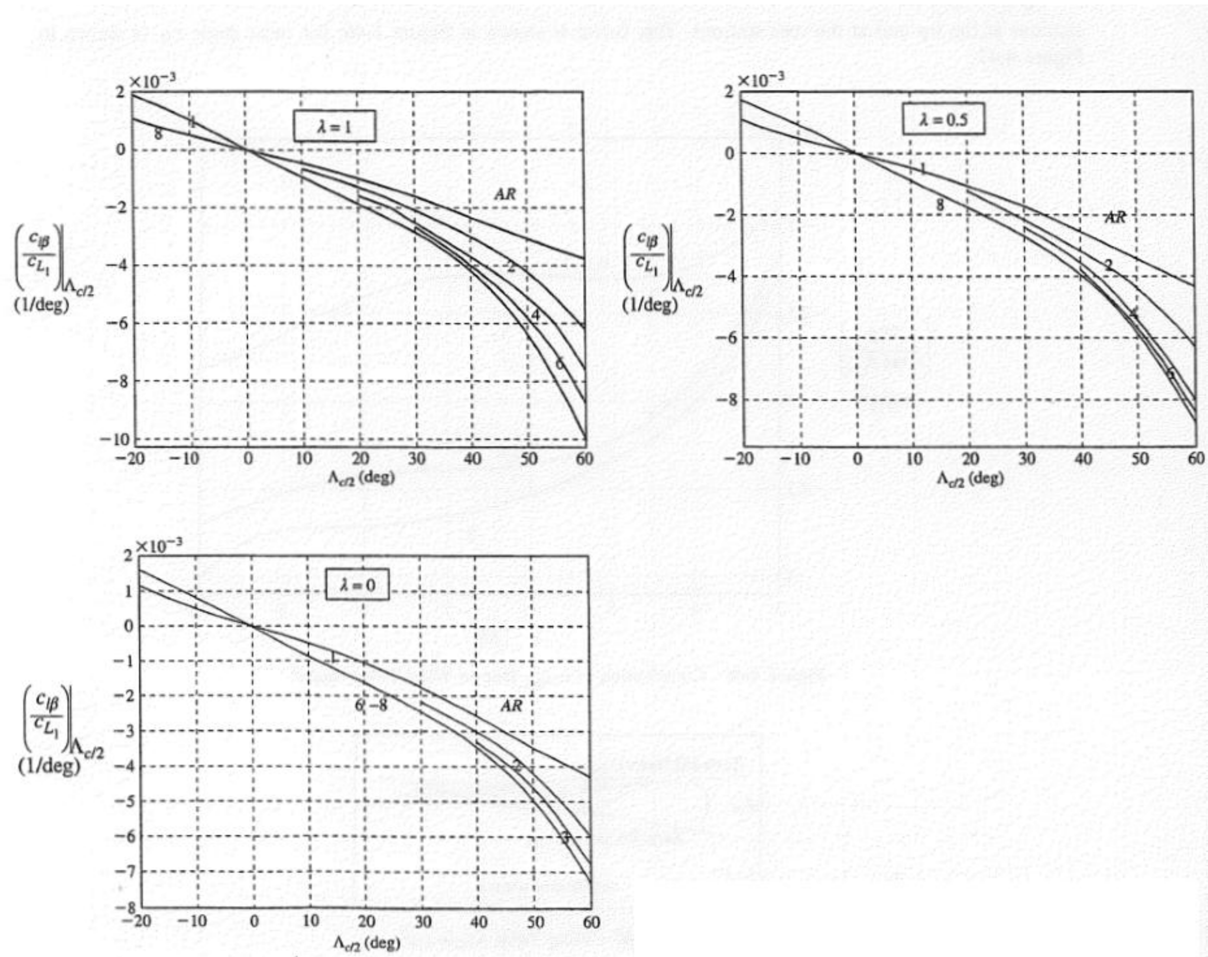


Figure A.8: Contribution to dihedral effect of the wing-body due to sweep angle

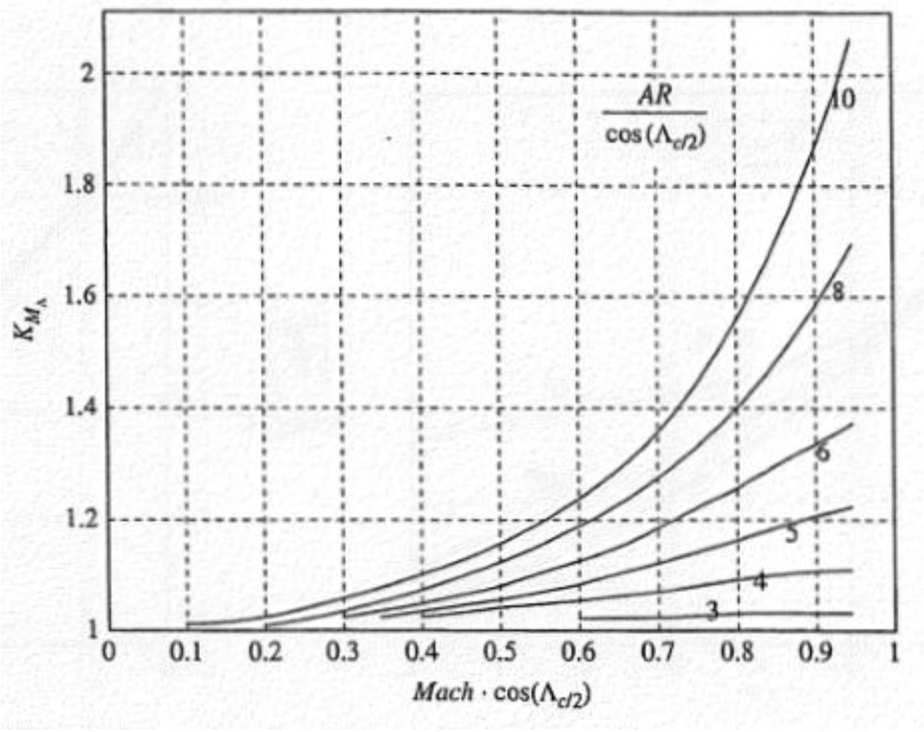


Figure A.9: Compressibility factor due to sweep angle

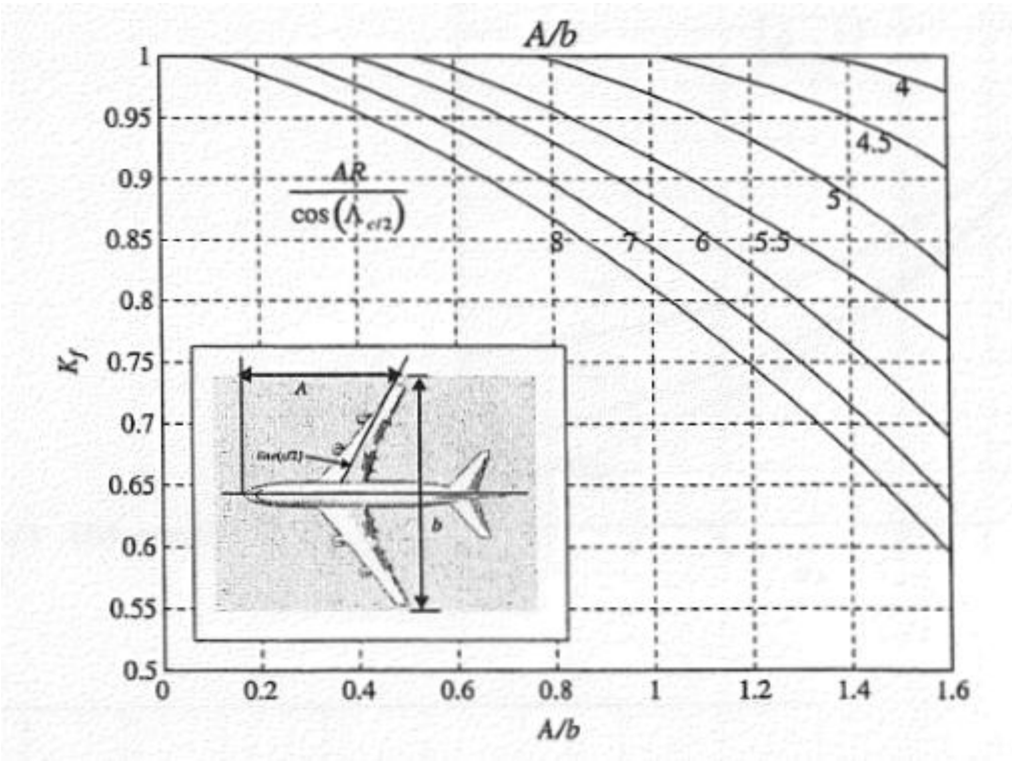


Figure A.10: Correction factor of the fuselage due to sweep angle

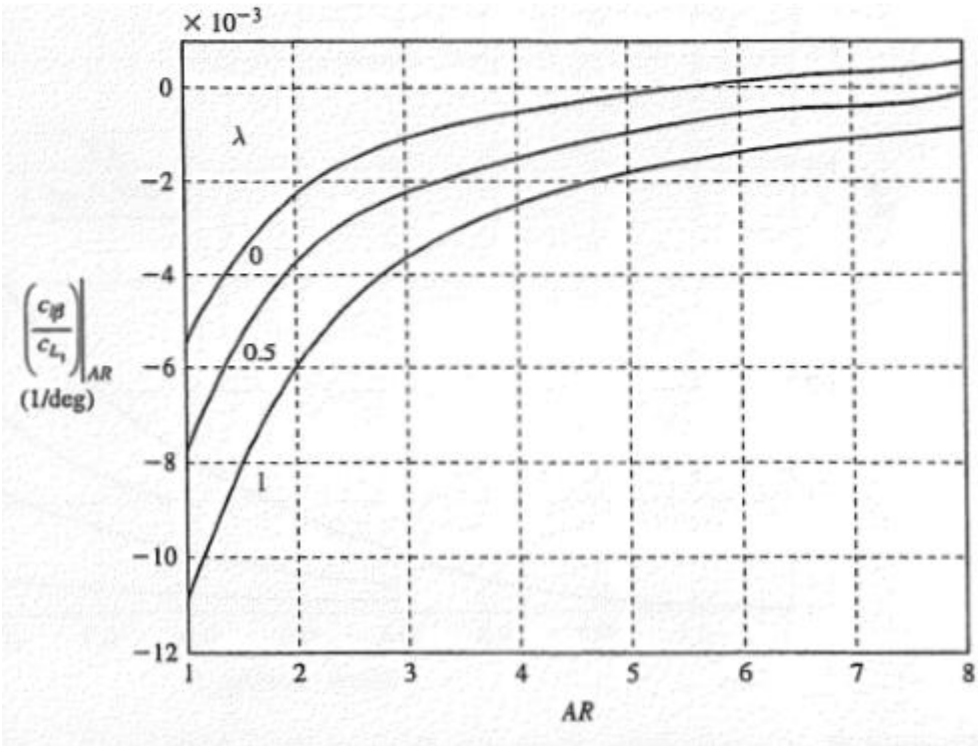


Figure A.11: Contribution to dihedral effect of the wing-body due to wing aspect ratio

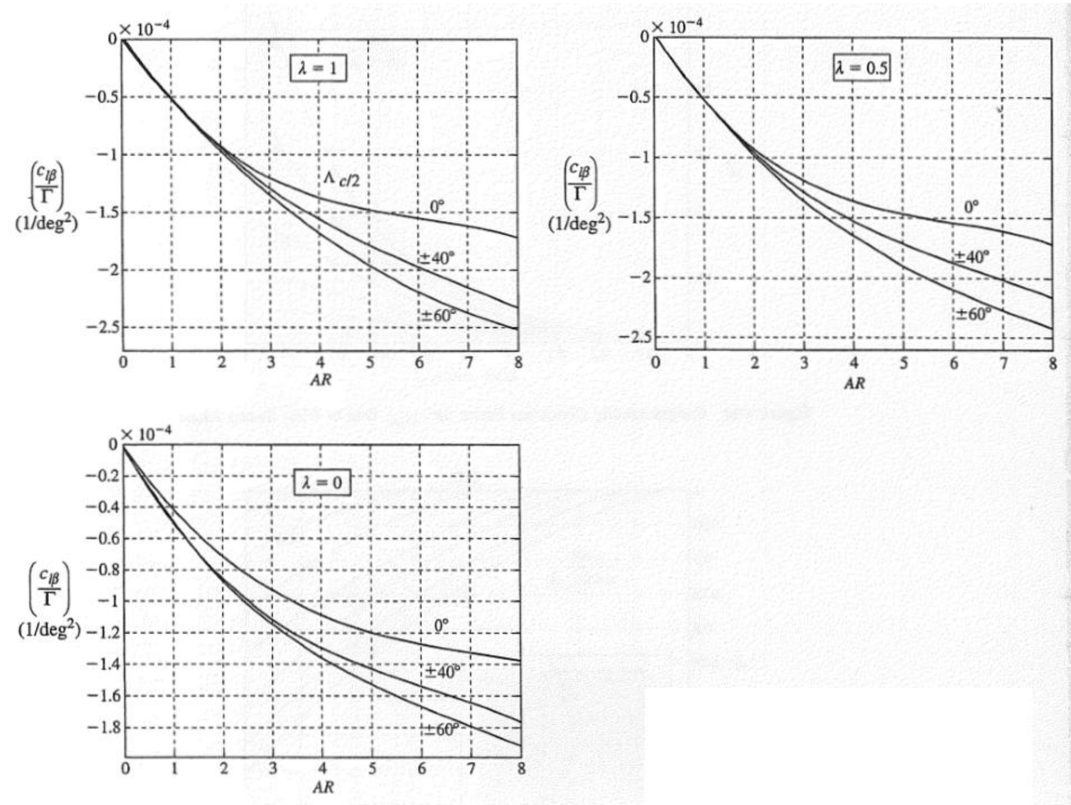


Figure A.12: Contribution to dihedral effect of the wing-body due to wing dihedral angle

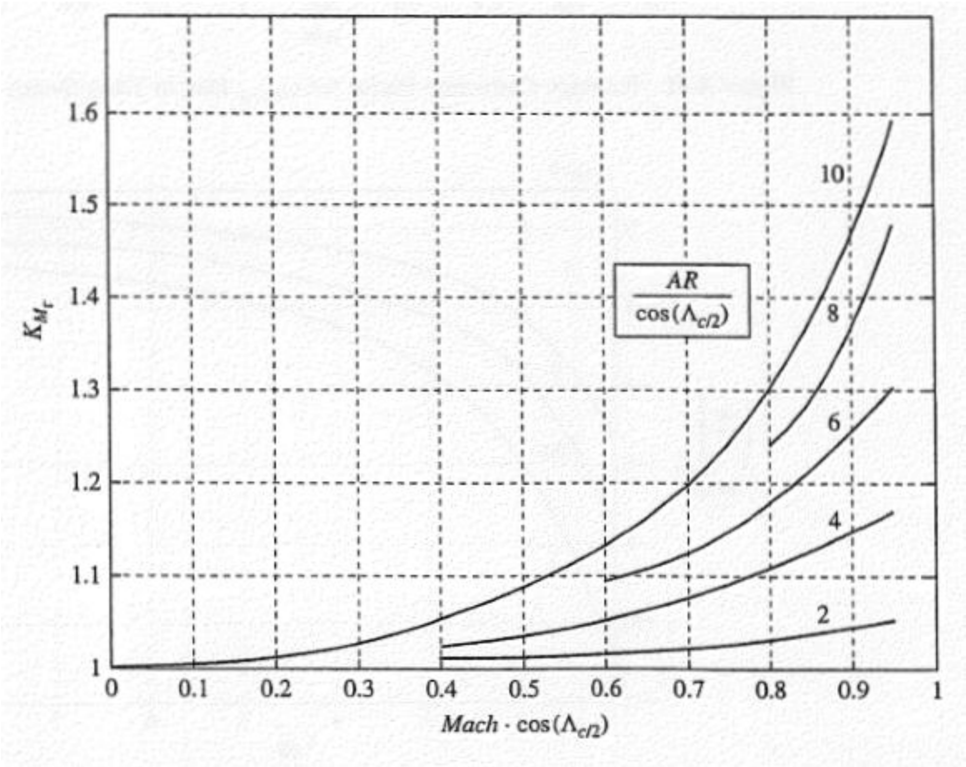


Figure A.13: Compressibility factor due to wing dihedral angle

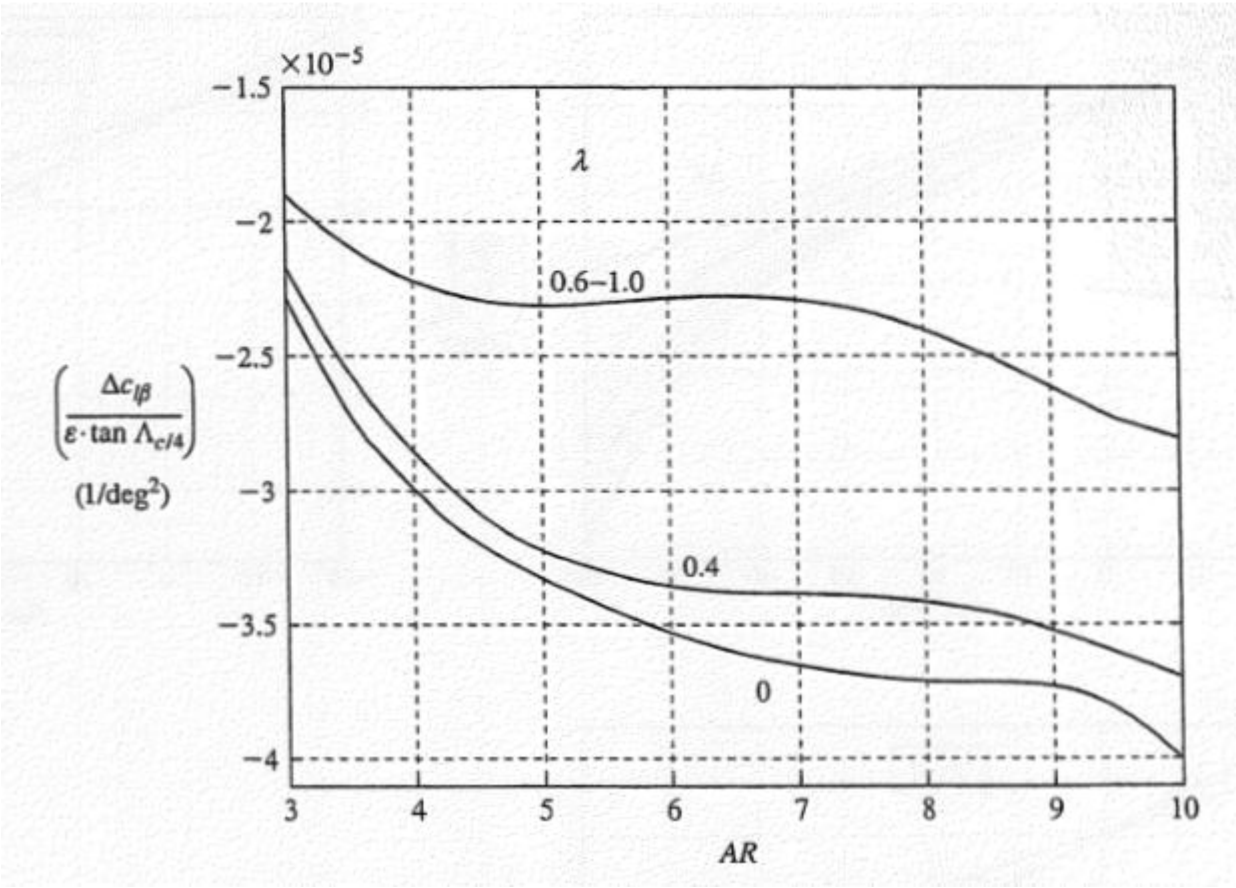


Figure A.14: Contribution to dihedral effect of the wing-body due to wing twist angle

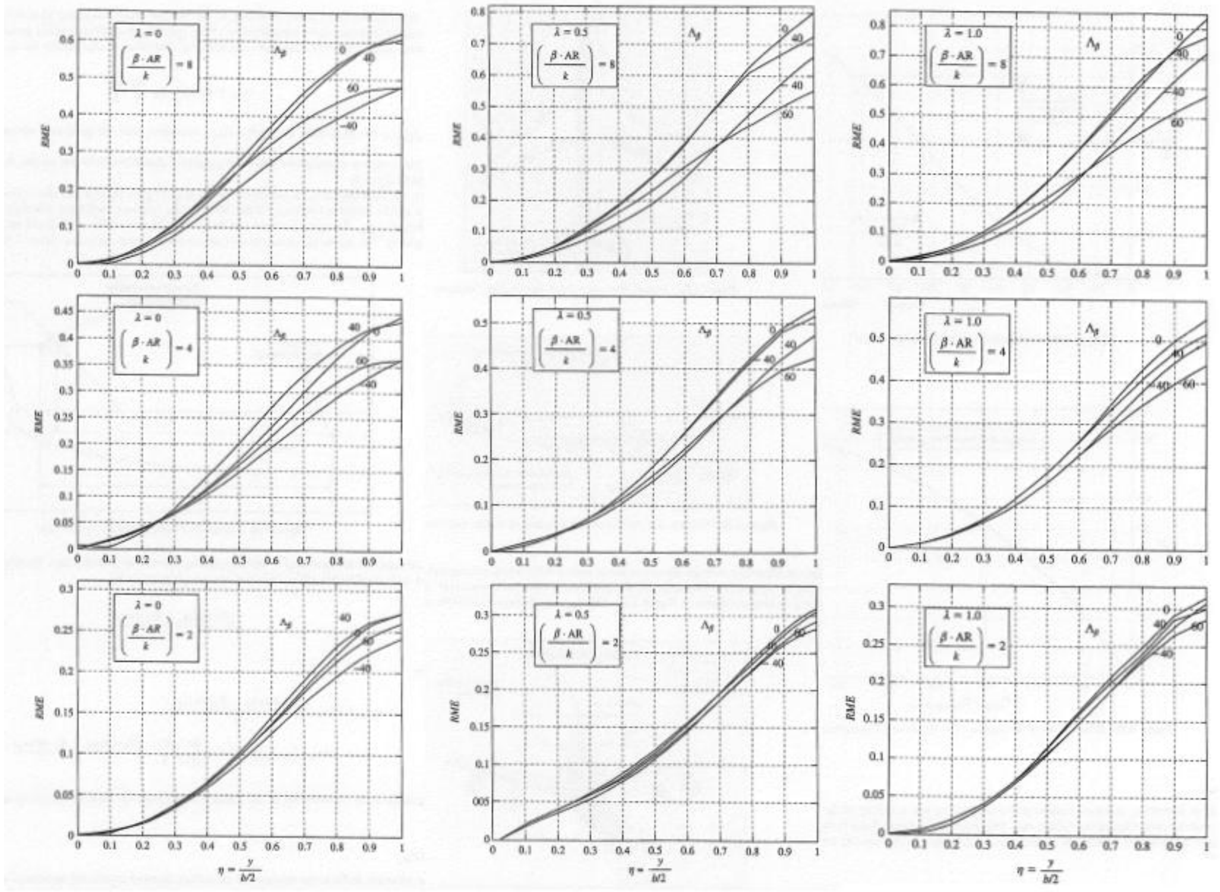


Figure A.15: Rolling moment effectiveness for different wing's geometry

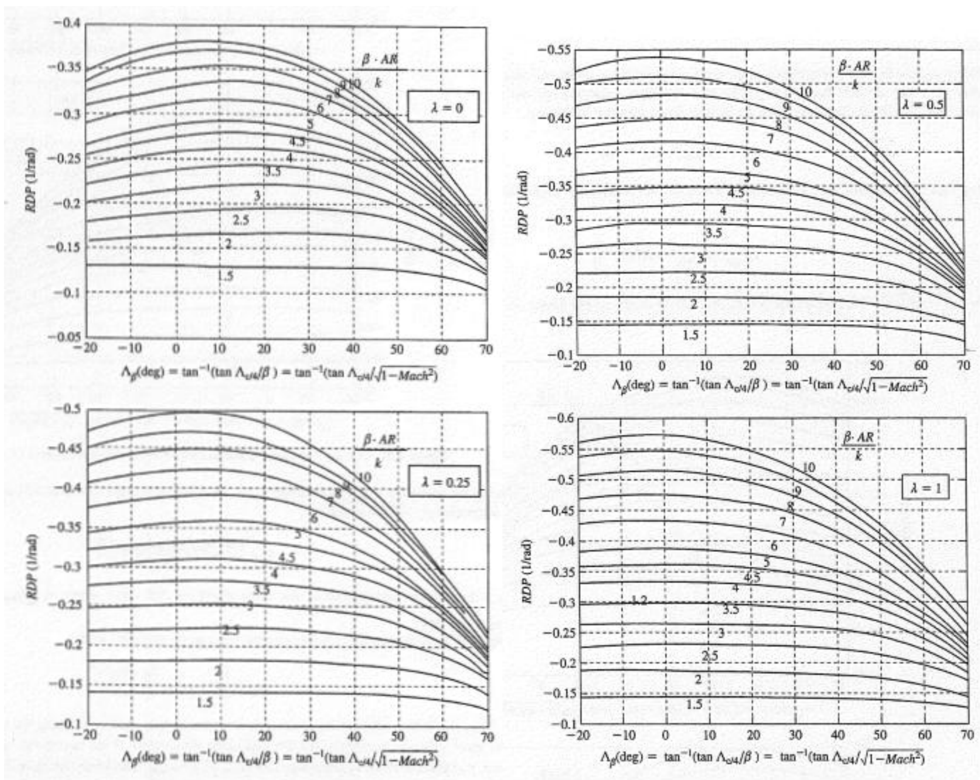


Figure A.16: Rolling damping parameters for different wing's geometry

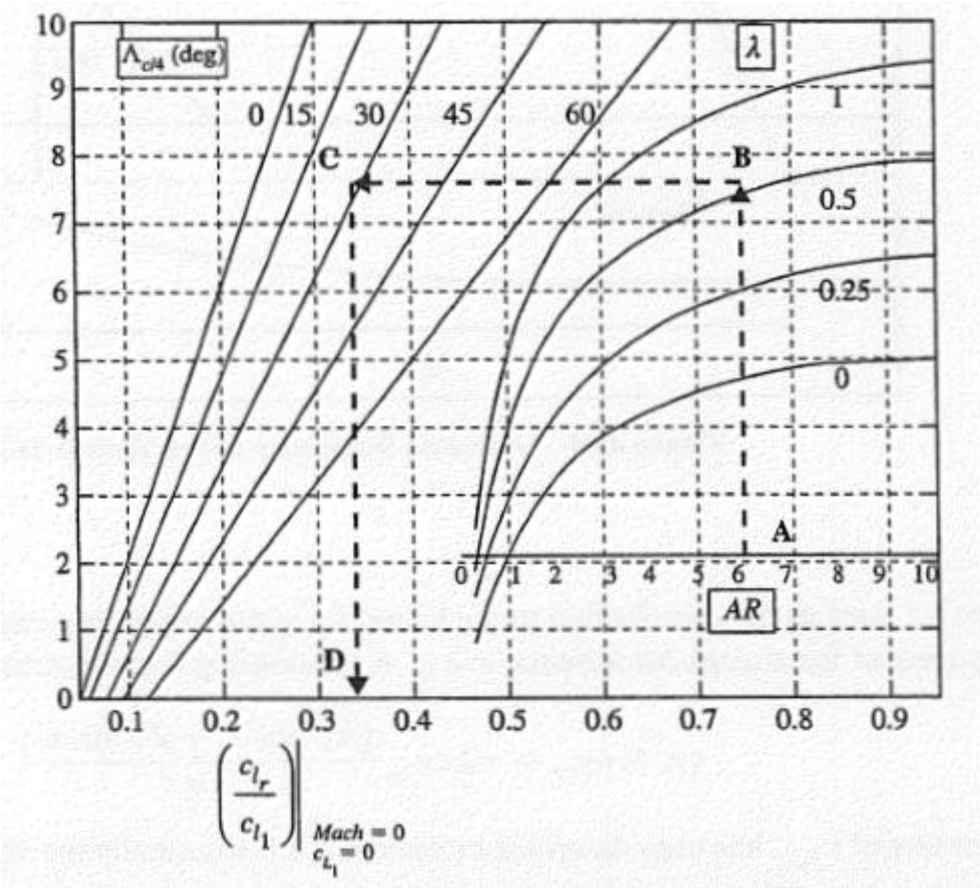


Figure A.17: Evaluation of $\frac{C_{\mathcal{L}_{r,}}}{c_L}\Big|_{M=0,c_{L,}=0}$

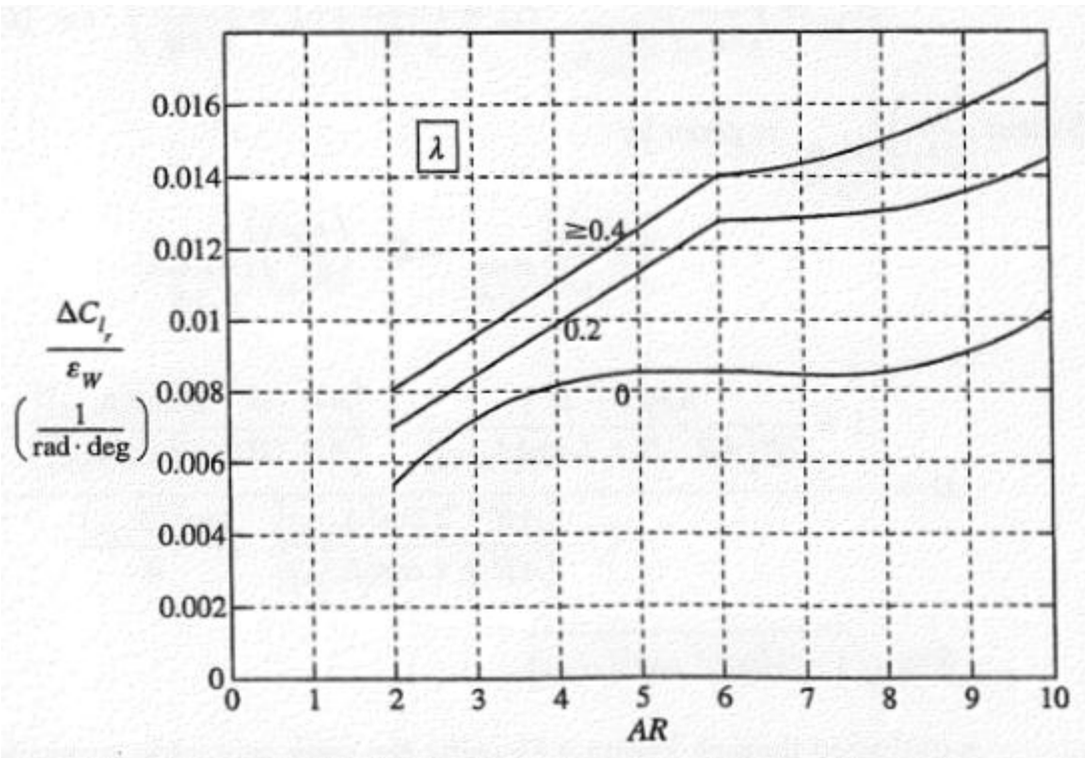


Figure A.18: Wing's twist angle effect on $C_{\mathcal{L}_{r'}}$

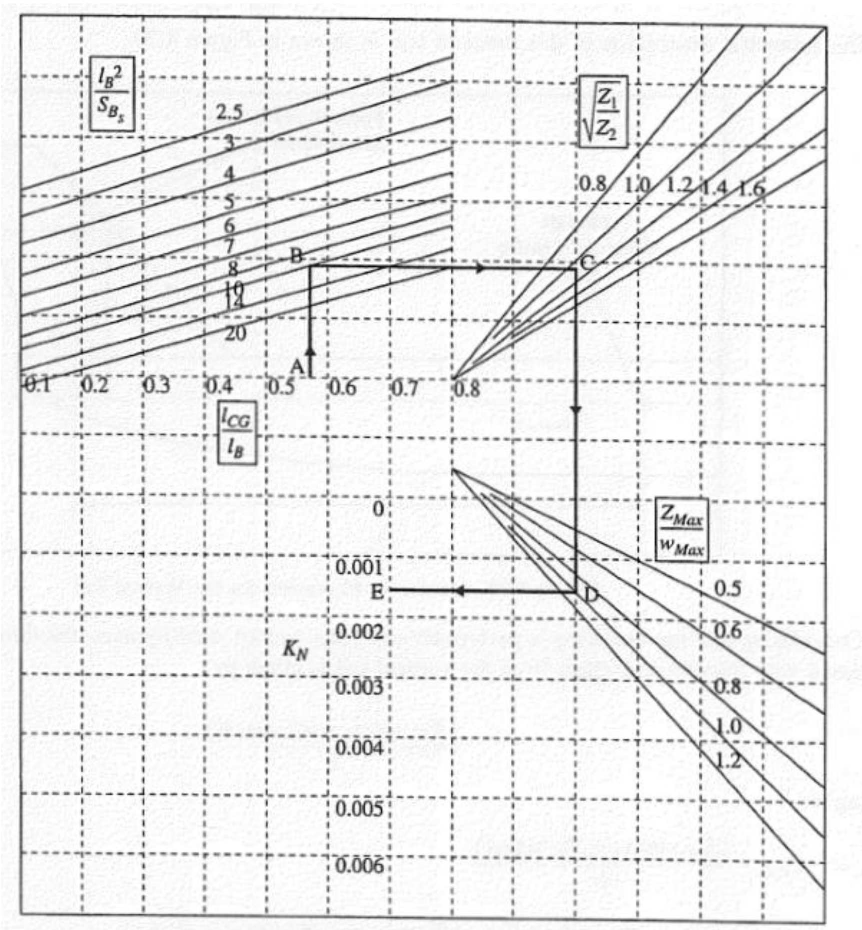


Figure A.19: Empirical factor $\boldsymbol{K_N}$ for wing-body interference

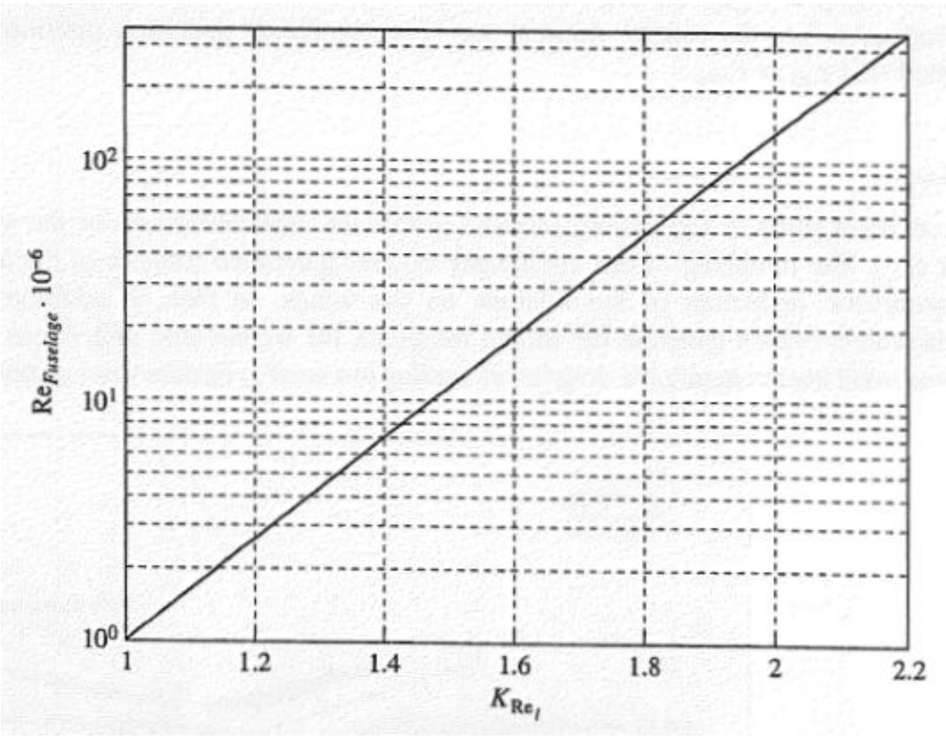


Figure A.20: Empirical factor $\boldsymbol{K_{RE}}$(Reynolds number effect) for wing-body interference

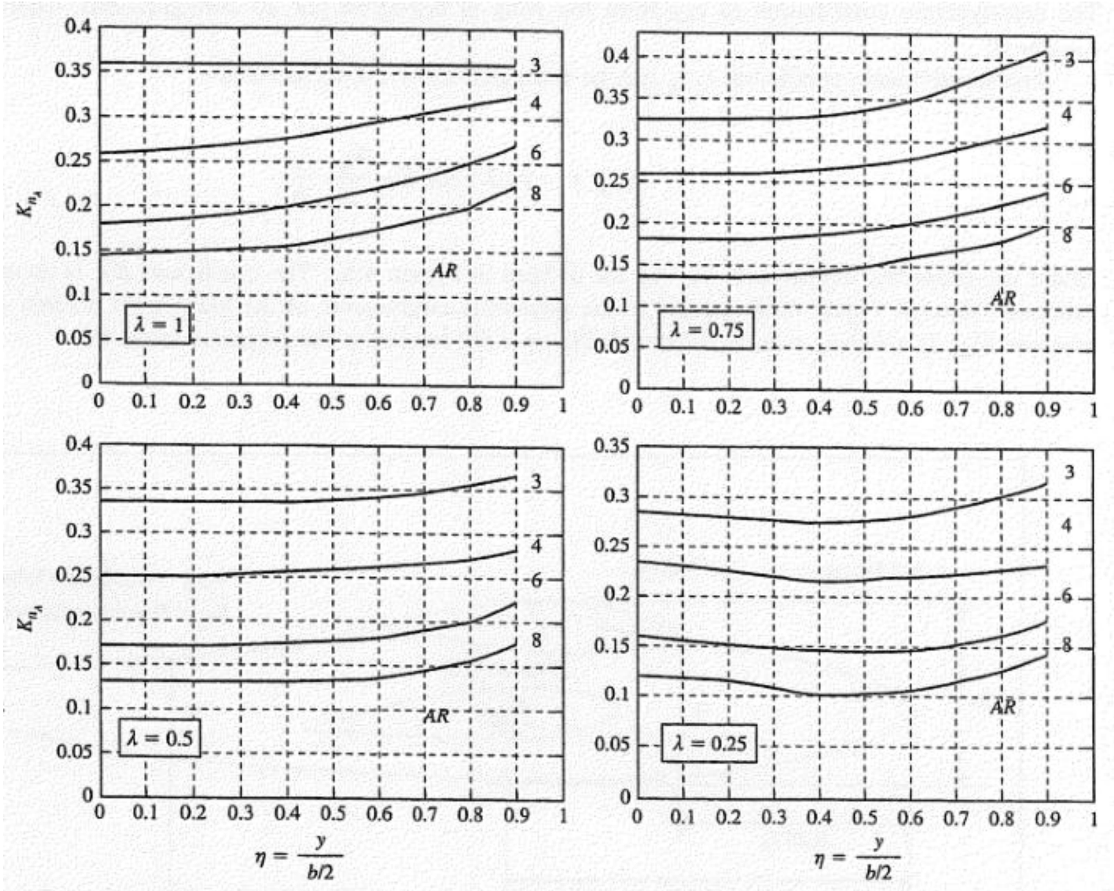


Figure A.21: Correlation to yawing moments due to ailerons deflection

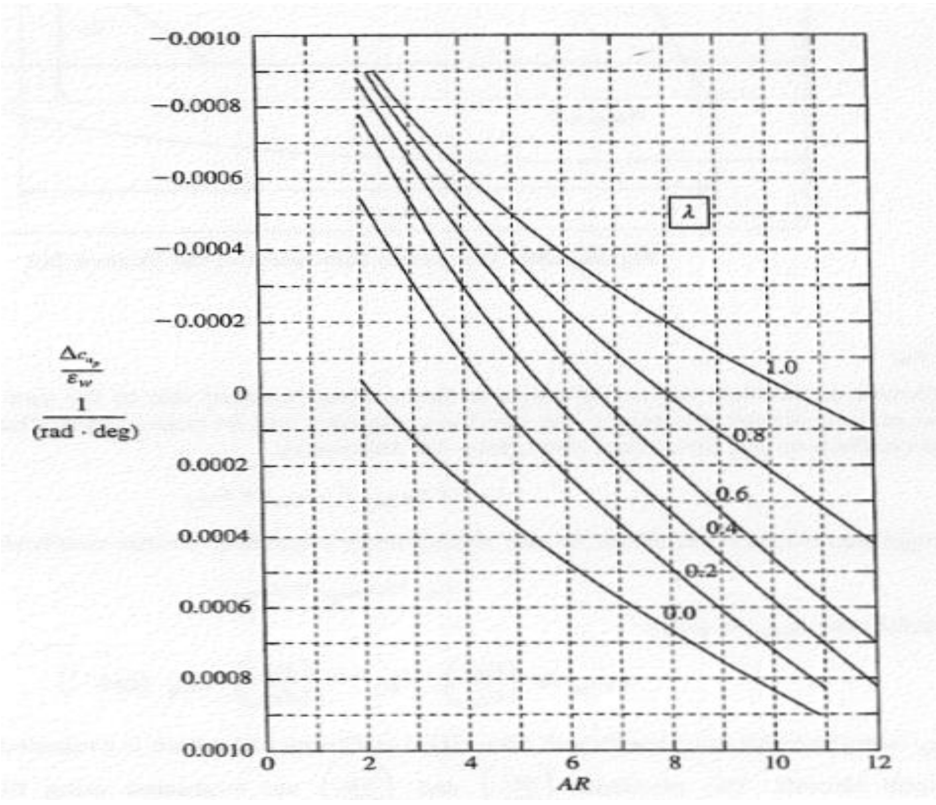


Figure A.22: Effect of wing twist to $\boldsymbol{C}_{\mathcal{N}_p}$

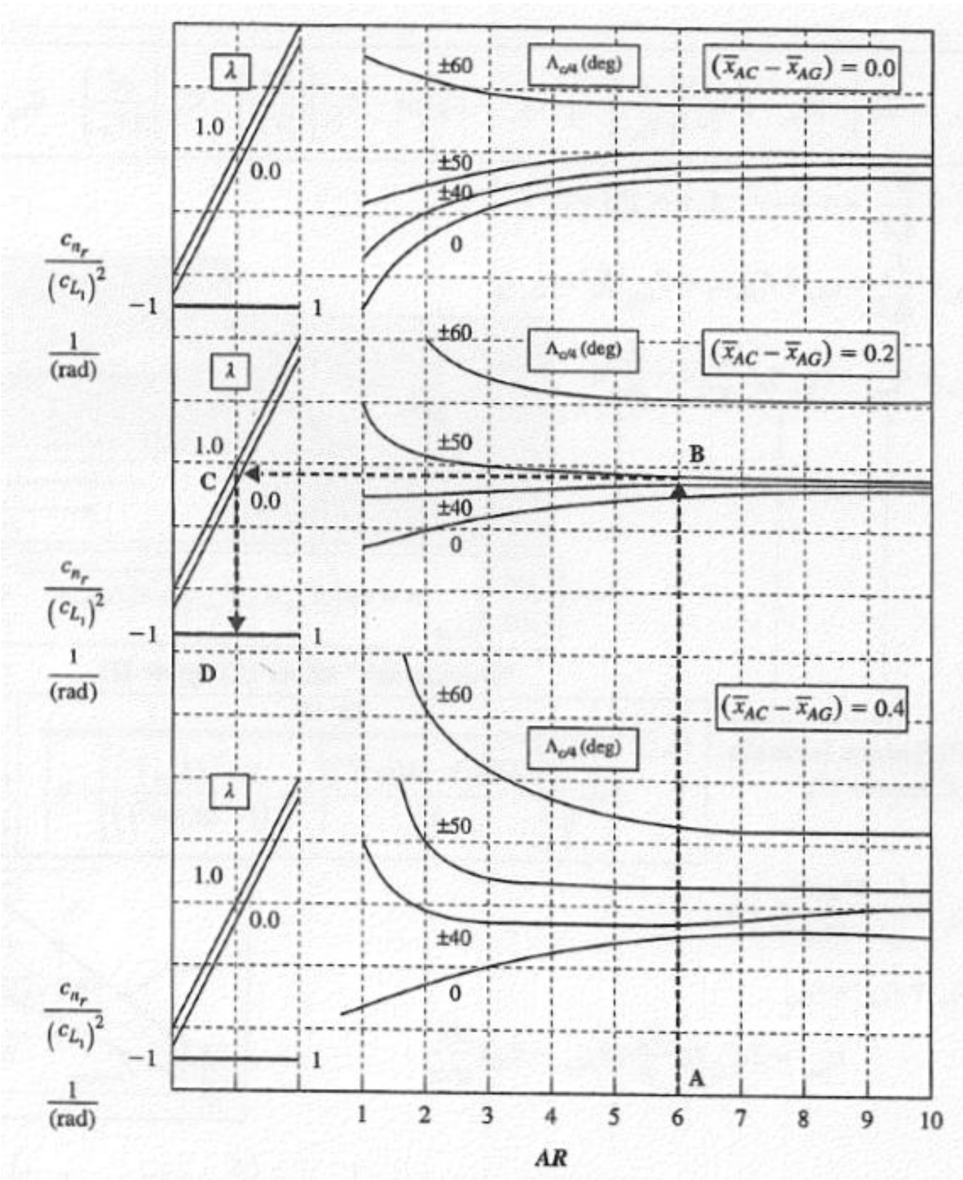


Figure A.23: Effect of lift and wing's geometric parameters to $\boldsymbol{C}_{\mathcal{N}_r}$

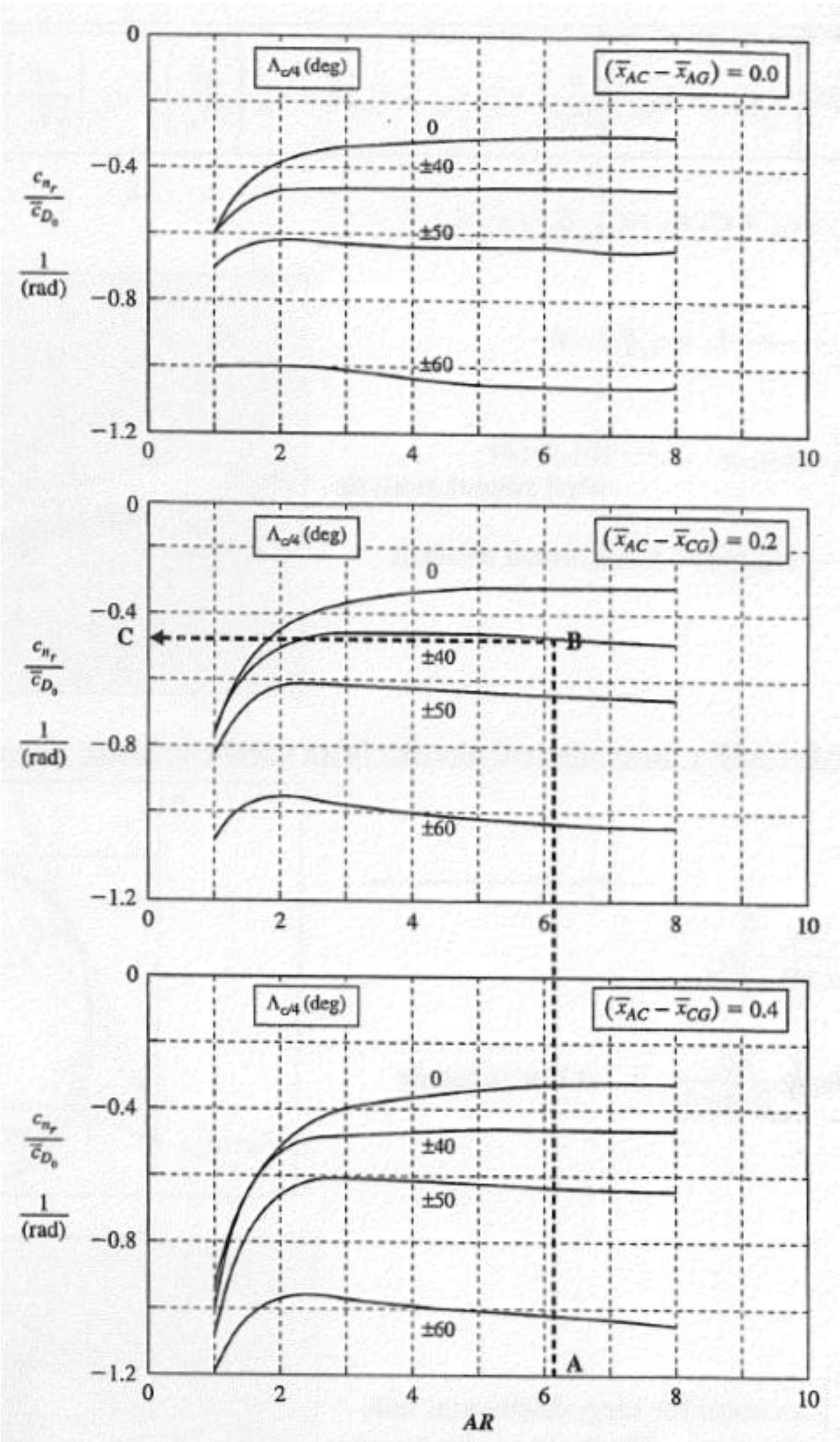


Figure A.24: Effect of parasite drag and wing's geometric parameters to $\boldsymbol{C}_{\mathcal{N}_r}$

Ringraziamenti

La parte più complicata di un progetto di tesi non è la realizzazione stessa del lavoro, bensì riuscire a ringraziare tutti nel modo corretto. Credetemi è difficile farlo usando poche parole…

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