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DIPARTIMENTO DI INGEGNERIA INDUSTRIALE**

**CORSO DI LAUREA IN INGEGNERIA AEROSPAZIALE
CLASSE DELLE LAUREE IN INGEGNERIA INDUSTRIALE (L-9)**

Elaborato di laurea in Meccanica del Volo
**Geometric modelling and analysis of performance,
stability, and control of the Boeing 777 aircraft
family**

**Relatore:
Prof. Danilo Ciliberti**

**Candidato:
Gennaro Novità
Matr. N35003977**

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*Ai miei nonni
A zia Giustina*

“Nessuno muore finchè vive nel cuore di chi resta”

Abstract

The objective of this project is the modeling of Boeing 777 series aircraft using the JPAD software. Subsequently, a performance analysis will be conducted using MATLAB code, while stability and control will be evaluated through the use of the OpenVSP program. JPAD, which stands for "Java toolchain of Programs for Aircraft Design", represents a comprehensive and integrated software designed to support the entire aircraft design process. This software provides specialized guidance to assist the designer in all phases. On the other hand, OpenVSP is a parametric open-source tool originally developed by NASA, allowing the creation of three-dimensional aircraft models and providing the necessary support for detailed engineering analysis on these models. In addition, VSPAERO is also used, a fast, linear, vortex-lattice-based solver used for aircraft stability analysis, applying discrete vortices to each panel generated in the aircraft geometry file and using these vortices to obtain a pressure distribution and consequently calculate the aerodynamic forces involved.

Sommario

L'obiettivo di questo progetto consiste nella modellazione dei velivoli della serie Boeing 777, sfruttando il software JPAD. In seguito, verrà condotta un'analisi delle prestazioni attraverso l'utilizzo di un codice MATLAB, mentre la stabilità e il controllo saranno valutati tramite l'uso del programma OpenVSP. JPAD, acronimo di "Java toolchain of Programs for Aircraft Design," rappresenta un software completo e integrato, progettato per supportare l'intero processo di progettazione di aeromobili. Questo software offre una guida pensata appositamente per assistere il progettista in tutte le fasi. OpenVSP, d'altra parte, è uno strumento parametrico open source originariamente sviluppato dalla NASA, che consente di creare modelli tridimensionali di aeromobili e fornisce il supporto necessario per condurre analisi ingegneristiche dettagliate su tali modelli. In aggiunta, viene utilizzato anche VSPAERO, un solutore veloce, lineare e basato su reticolo di vortici, utilizzato per l'analisi della stabilità dell'aeromobile, applicando vortici discreti a ciascun pannello generato nel file di geometria del velivolo e tramite questi vortici ottiene una distribuzione della pressione e, di conseguenza, calcolare le forze aerodinamiche coinvolte.

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1. Introduction

1.1 Objectives

The aim of this project is to conduct geometric modeling and assess the stability and control aspects of the Boeing 777 aircraft family.

1.2 Boeing 777 Aircraft family

The Boeing 777 is a long-range wide-body airliner produced by the American aerospace company Boeing since the mid-1990s. Its distinctive features include large engine nacelles under the wings, six wheels on each of the two main landing gear assemblies, and a wide circular-section fuselage. The 777 was the first airliner built by Boeing with fly-by-wire controls, meaning it is operated through computer and electronic servo-controls.

The purpose behind designing the jetliner was to fill the space between Boeing's other wide-body aircraft, namely the twin-engine 767 and the four-engine 747. Additionally, it aimed to serve as a replacement for older DC-10s and L-1011 trijets. The Triple Seven can accommodate a ten-abreast seating layout and has a typical 3-class capacity of 301 to 368 passengers, with a range of 9,700 to 15,840 km.

The 777 was the pioneering commercial aircraft developed entirely using a computer-aided design (CAD) process, known as "CATIA". This groundbreaking approach enabled engineers to virtually assemble the 777 aircraft on a computer system, allowing them to check for any interference and ensure that the thousands of parts fit together correctly before the physical assembly process began. As a result, this approach significantly reduced the need for costly rework. The precision of this CAD-based design was so remarkable that the 777 became the first Boeing jetliner where intricate details didn't need to be refined on an expensive physical aircraft mock-up.

There are two fundamental types: the Boeing 777-200 and the Boeing 777-300.



Figure 1.1 – Example of Boeing 777-200

The main difference lies in the length of the fuselage, with the 777-200 variant having a length of 209.1 feet, while the 777-300 variant is 242.4 feet long. This difference in fuselage length impacts the number of passengers and the cargo-carrying capacity of the aircraft.



Figure 1.2 – Example of Boeing 777-300

1.3 Software

This project is based on the use of software called JPAD, developed by SmartUp Engineering s.r.l., it allows me to create a highly realistic 3D model using data related to the aircraft's main components. Furthermore, this software enables the export of this created model in various formats, including OPENVSP, which is crucial for conducting stability analyses with the help of the OPENVSP-VSPAERO software, an open-source application developed by NASA. Finally, to conduct performance studies, we use MATLAB code, employing specific functions found in the 'Aerospace Toolbox' add-on.

2. Geometric model creation

The software used for geometric modeling is JPAD, below we can see an example of the main interface.

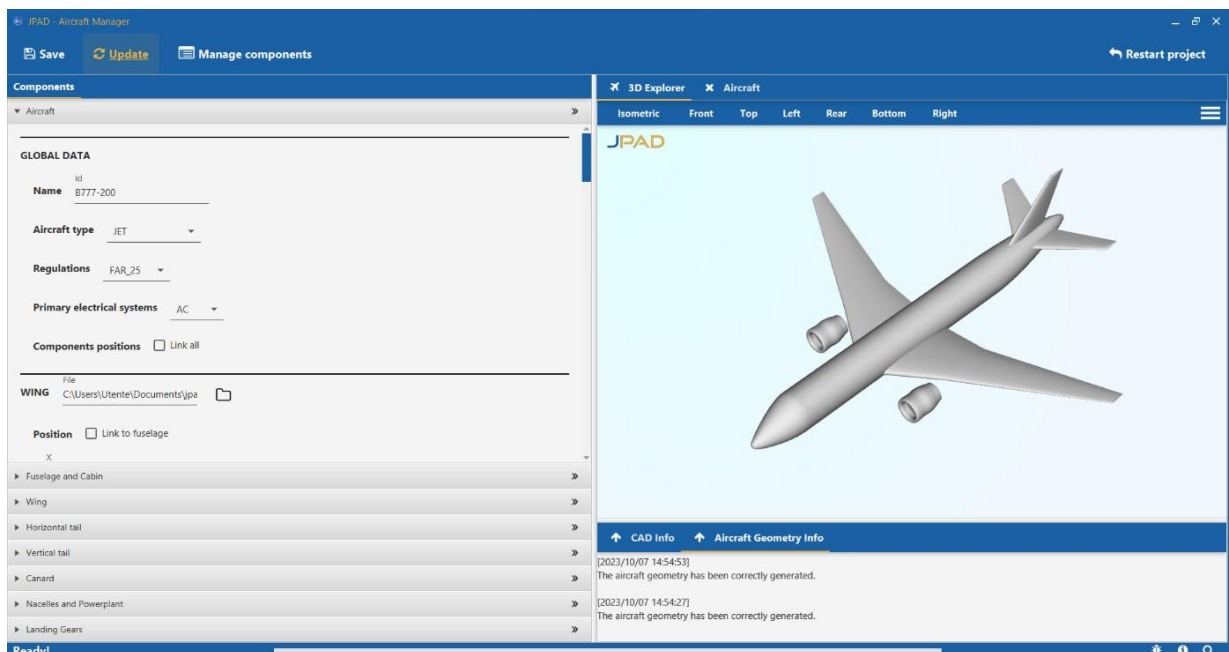


Figure 2.1 – User interface of JPAD

The first step to initiate the geometric modeling phase is to search for all the geometric data related to the aircraft so that they can be entered into JPAD. These data can be obtained from reliable sources, such as the area, aspect ratio, and length of the main aircraft components. However, all other geometric parameters are derived from the views of the models in the Boeing 777 manual by manually measuring them and maintaining their proportions. Once these data are found, they should be entered into a dedicated section of the software.

The software has an interface divided into two sections. On the right side, you can view the 3D model of the aircraft from various perspectives (top view, frontal view, and side view). On the left side, there are several subsections where data for various aircraft components will be entered.

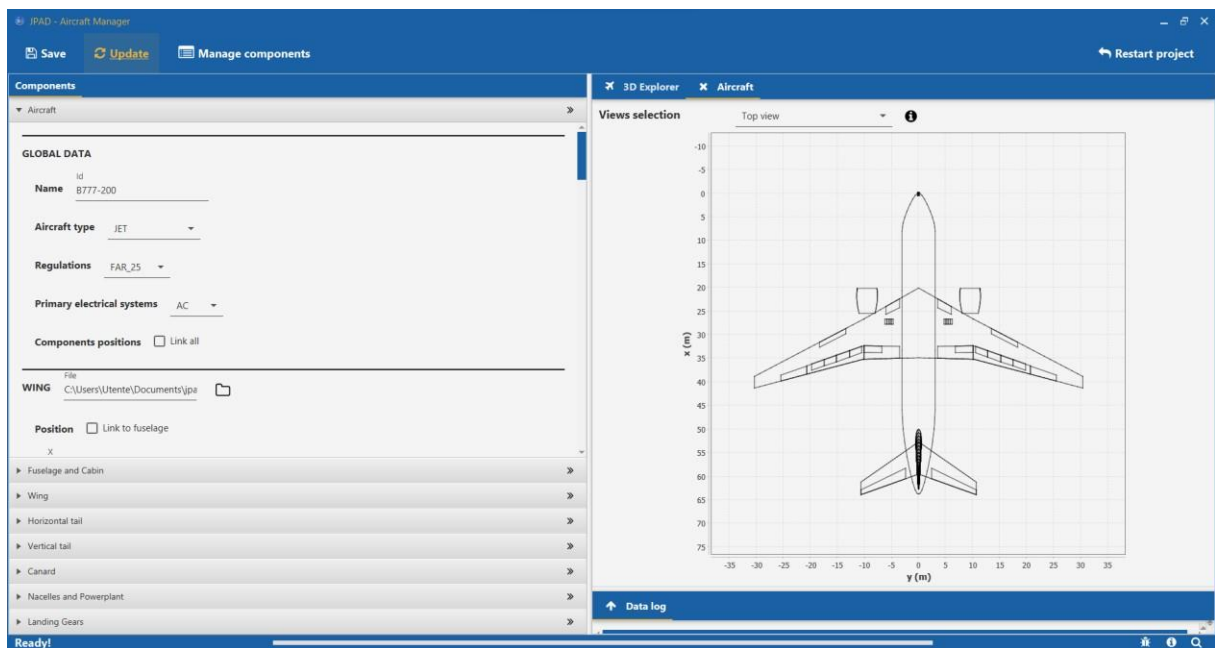


Figure 2.2 – Top view of the model

The latter is divided into the following subsections:

- Aircraft: this is where we set the (X, Y, Z) coordinates for each major component to position them correctly.
- Fuselage and Cabin: here we can define the external shape of the fuselage and the passenger accommodation cabin. As you can clearly see, the fuselage is actually divided into three parts (nose, central cylinder, tail), and for each of them, coefficients can be defined.
- Wing: there are parameters available that allow me to define the external shape of the wing. Additionally, it is possible to incorporate movable surfaces such as slats, flaps, and ailerons.
- Horizontal Tail: it is possible to define the outer part of the horizontal plane, and among the various components, there is also the elevator.
- Vertical Tail: here we can characterize the outer part of the vertical plane.
- Powerplant and nacelle: in this subsection, you will find all the parameters that define the engines and all their geometric characteristics, such as length or engine type (whether it is a Turbofan, Turboprop, etc.).

2.1 Model of Boeing 777-200

The 777-200 was the initial version for the aviation market. With a maximum range of 9,695 km, a fuselage length of 209.1 ft, and a maximum capacity of 440 passengers, it was primarily intended for airlines operating domestic flights within the USA.

We can see the main components in the table below:

Fuselage and Cabin data	Length [m] 62.78	Height [m] 6.20	Length tail [m] 17.78	Length nose [m] 7.96	Cabin Length [m] 37.98
Wing	Area [m²] 427.8	Span [m] 60.90	Aspect Ratio 8.67	Dihedral Angle [deg] 6.0°	Sweep angle [deg] 33.0°
Horizontal Tail	Area [m²] 101.26	Span [m] 21.35	Aspect Ratio 4.50	Dihedral Angle [deg] 6.0°	Sweep angle [deg] 38.6°
Vertical Tail	Area [m²] 53.23	Span [m] 9.24	Aspect Ratio 1.60	Dihedral Angle [deg] 0°	Sweep angle [deg] 46.5°
Nacelles and Powerplants	Engine Type PW4077	Engine number 2	Length [m] 5.24	Nacelle diameter [m] 12.575	

Table 2.1 – Boeing 777-200 data

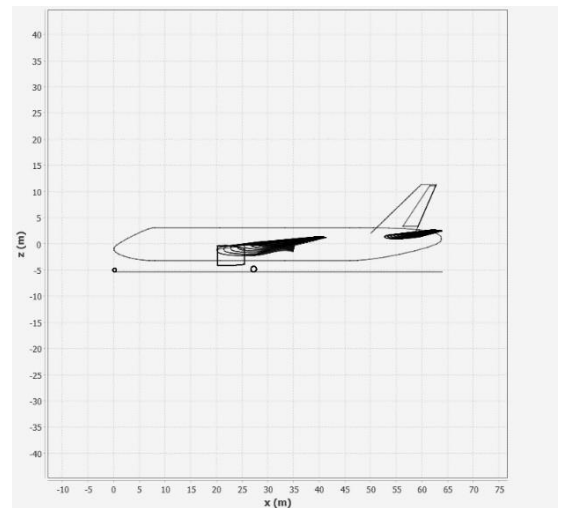
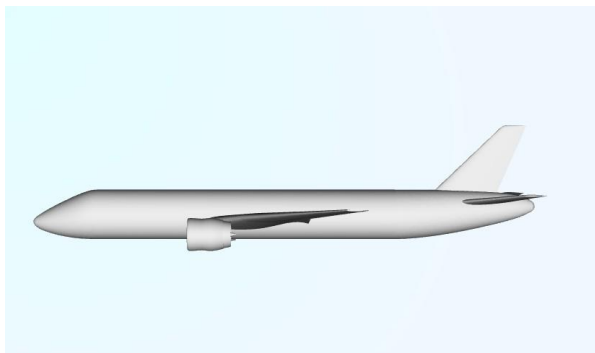
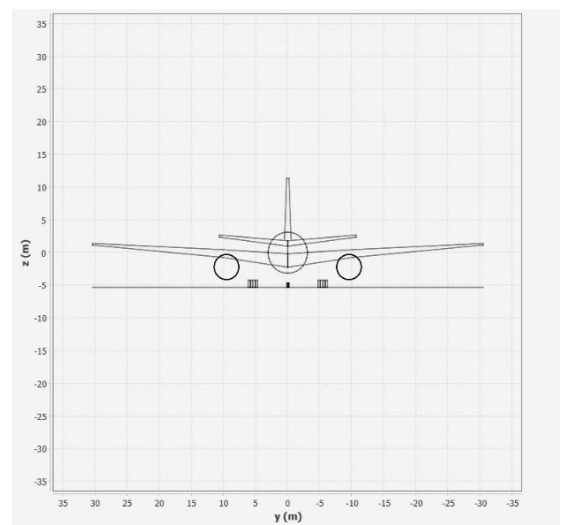
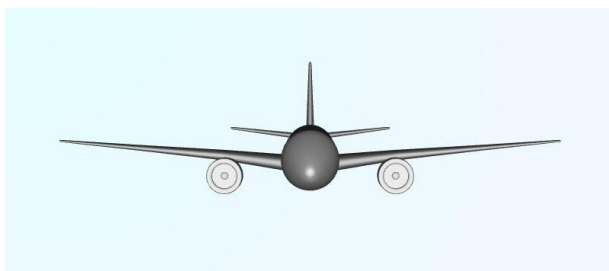
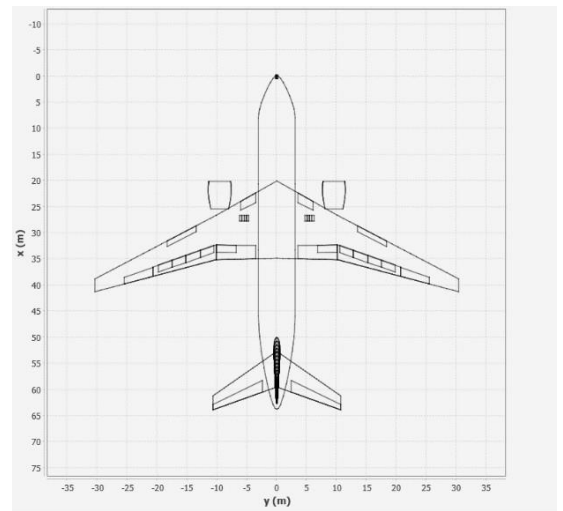
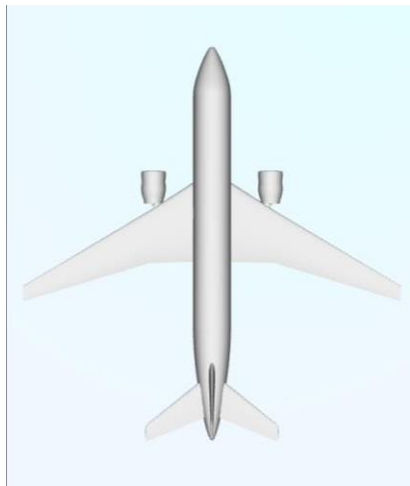


Figure 2.3 – Boeing 777-200 Analysis of different perspectives

The final model obtained is:

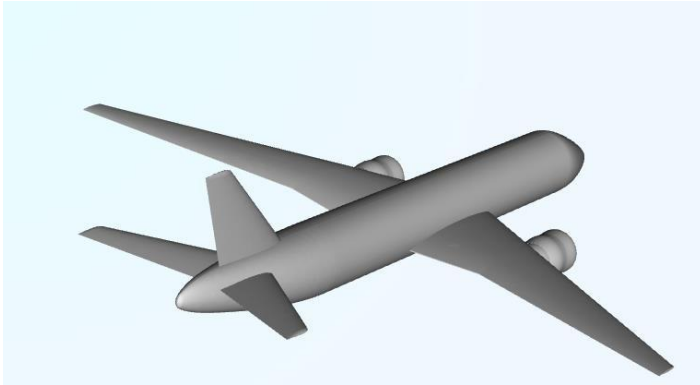


Figure 2.4 – Boeing 777-200 British Airways

2.2 Model of Boeing 777-300

The Boeing 777-300 variant has been specifically designed to increase its passenger-carrying capacity by utilizing a significantly longer fuselage compared to the model 200. With a fuselage extending by 10.1 meters (equivalent to 33.3 feet), this version can accommodate a significantly larger number of passengers, especially when configured with a single high-density class. In this configuration, it can accommodate up to 550 passengers. This adaptation is particularly useful on high-demand routes, such as those in Japan, where high-density configurations are commonly employed.

Due to its greater length, the 777-300 variant is equipped with a tail skid, also known as a "tail skid," which serves as a protective device for the lower and rear part of the aircraft in situations where the landing might be too abrupt or vertical. Furthermore, to facilitate ground

maneuvers, the aircraft is usually equipped with a camera system to provide a detailed view of the surrounding area, thereby making it easier for the pilots to control the aircraft during taxiing and parking.

We can see the main components in the table below:

Fuselage and Cabin data	Length [m]	Height [m]	Length tail [m]	Length nose [m]	Cabin Length [m]
	72.88	6.20	20.61	9.23	44.03
Wing	Area [m²]	Span [m]	Aspect Ratio	Dihedral Angle [deg]	Sweep angle [deg]
	427.8	60.90	8.67	6.0°	33.0°
Horizontal Tail	Area [m²]	Span [m]	Aspect Ratio	Dihedral Angle [deg]	Sweep angle [deg]
	101.26	21.35	4.50	6.0°	38.6°
Vertical Tail	Area [m²]	Span [m]	Aspect Ratio	Dihedral Angle [deg]	Sweep angle [deg]
	53.23	9.24	1.60	0°	46.5°
Nacelles and Powerplants	Engine Type	Engine number	Length [m]	Nacelle diameter [m]	
	PW4090	2	17.2	12.575	

Table 2.2 – Boeing 777-300 data

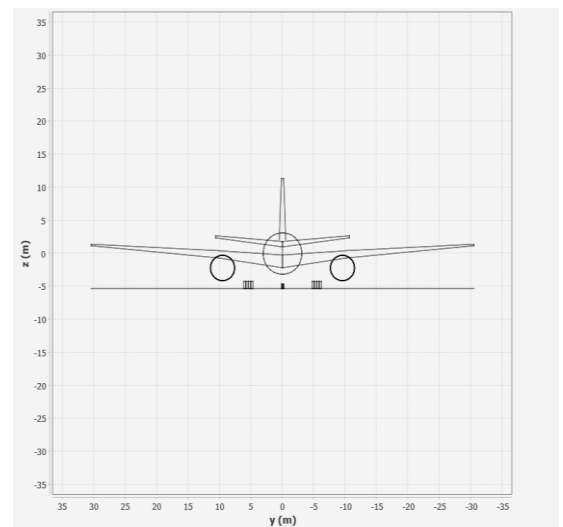
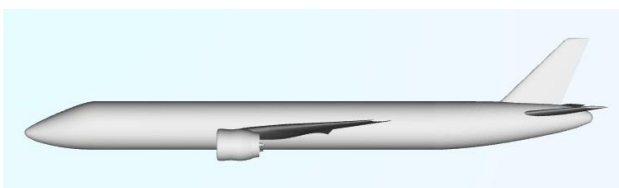
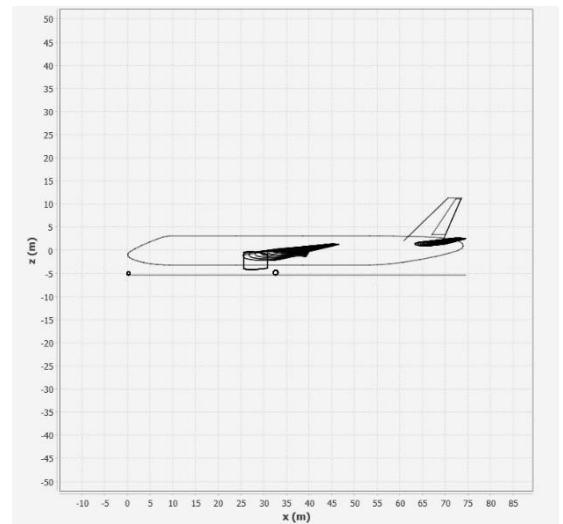
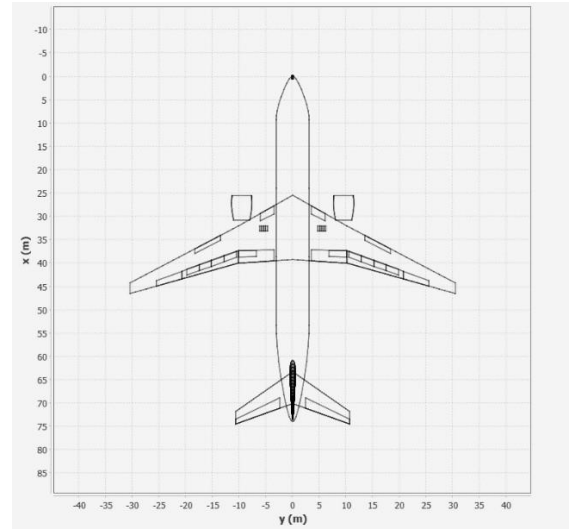
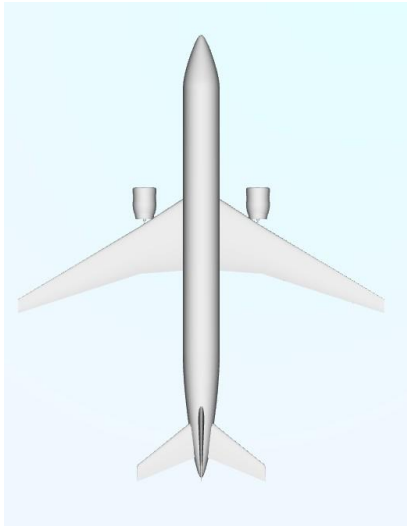
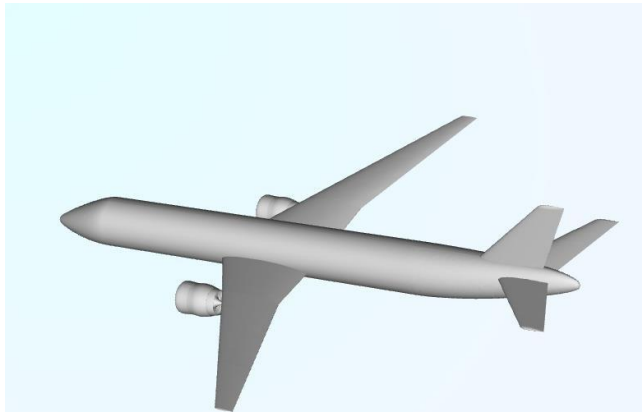


Figure 2.4 - Boeing 777-300 Analysis of different perspectives

The final model obtained is:



3. Evaluation of performance

After completing the modeling process using JPAD, it became possible to focus on the performance aspects of the considered aircraft family. This was achieved with the use of MATLAB code, where input data for the specific aircraft were inputted and subsequently processed to obtain propulsive characteristics, technical polar data, various flight profiles, endurance, takeoff, and landing data. Finally, these pieces of information are analyzed for each aircraft model.

3.1 Data input

The input data is available in the following tables:

VERSION	WEIGHT DATA	
AIRPLANE	W_{TO} [kg]	W_f [kg]
Boeing 777-200	242670	94240
Boeing 777-300	299370	94240

Table 3.1 - Weight Data

POWERPLANT DATA			
VERSION	T_0 [kgf]	$TSFC$ [lb/(lb · hr)]	n °
AIRPLANE			
Boeing 777-200	34964	0.545	2
Boeing 777-300	44852.2	0.545	2

Table 3.2 – Powerplant Data

VERSION	GEOMETRY DATA	
AIRPLANE	S [m ²]	b [m]
Boeing 777-200	427.8	60.93
Boeing 777-300	427.8	60.93

Table 3.3 – Geometry Data

AERODYNAMIC DATA							
VERSION	C_{D0}	C_{LMAX}	e	$C_{LMAX,TO}$	$C_{LMAX,L}$	C_{Lg}	M_{dd}
AIRPLANE							
Boeing 777-200	<i>0.019</i>	<i>1.50</i>	<i>0.8</i>	<i>2.20</i>	<i>2.80</i>	<i>0.60</i>	<i>0.82</i>
Boeing 777-300	<i>0.019</i>	<i>1.50</i>	<i>0.8</i>	<i>2.20</i>	<i>2.80</i>	<i>0.60</i>	<i>0.82</i>

Table 3.4 – Aerodynamic Data

3.2 Output Data

Thanks to the program executed in MATLAB, we are able to obtain the outputs shown below, such as technical charts, etc.

3.21 Technical polar

The characteristic points of the drag curve are as follows:

- Point E: the point of maximum efficiency, and simultaneously, it is the point where drag is at a minimum.

- Point P: Point of minimum power in level flight. It is also a critical point for fuel efficiency and resistance.
- Point A: The point where the distance covered is maximum.
- Point S: The point of minimum aircraft speed. That is, the minimum stall speed or safe flight speed.

SEA LEVEL

POINT E

VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	0.64	0.040	16.9	118.83	14060	16706.9	0.35
Boeing 777-300	0.64	0.040	16.9	131.98	17345	22892.1	0.39

Table 3.5 – Point E at Sea Level

SEA LEVEL

POINT P

VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	1.11	0.080	14.6	116.48	16235	14658.4	0.27
Boeing 777-300	1.11	0.080	14.6	100.29	20028	20085.1	0.29

Table 3.6 – Point P at Sea Level

SEA LEVEL

POINT A							
VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	0.37	0.030	14.6	156.4	16235	25389.1	0.46
Boeing 777-300	0.37	0.030	14.6	173.7	20028	34788.5	0.51

Table 3.7 – Point A at Sea Level

SEA LEVEL

POINT S							
VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	1.50	0.12	12.3	100.4	19404	15101.3	0.23
Boeing 777-300	1.50	0.12	12.3	86.4	23938	20692.1	0.25

Table 3.8 – Point S at Sea Level

CRUISE ALTITUDE

POINT E							
VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	0.64	0.040	16.9	204.7	14060	28783.6	0.68
Boeing 777-300	0.64	0.040	16.9	227.4	17345	39439.6	0.76

Table 3.9 – Point E at Cruise Altitude

CRUISE ALTITUDE

POINT P							
VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	1.11	0.080	14.6	155.56	16235	25254.2	0.52
Boeing 777-300	1.11	0.080	14.6	224.1	20028	44877.7	0.58

*Table 3.10 – Point P at Cruise Altitude*CRUISE ALTITUDE

POINT A							
VERSION	C_L	C_D	E	$V [m/s]$	$T [N]$	$P [kW]$	M
Boeing 777-200	0.37	0.030	14.6	201.7	16235	43741.6	0.90
Boeing 777-300	0.37	0.030	14.6	148.9	20028	35649.3	1.00

Table 3.11 – Point A at Cruise Altitude

CRUISE ALTITUDE

POINT S

VERSION	C_L	C_D	E	V [m/s]	T [N]	P [kW]	M
Boeing 777-200	1.50	0.12	12.3	134.1	19404	26017.4	0.45
Boeing 777-300	1.50	0.12	12.3	148.9	23938	35649.3	0.50

Table 3.12 – Point S at Cruise Level

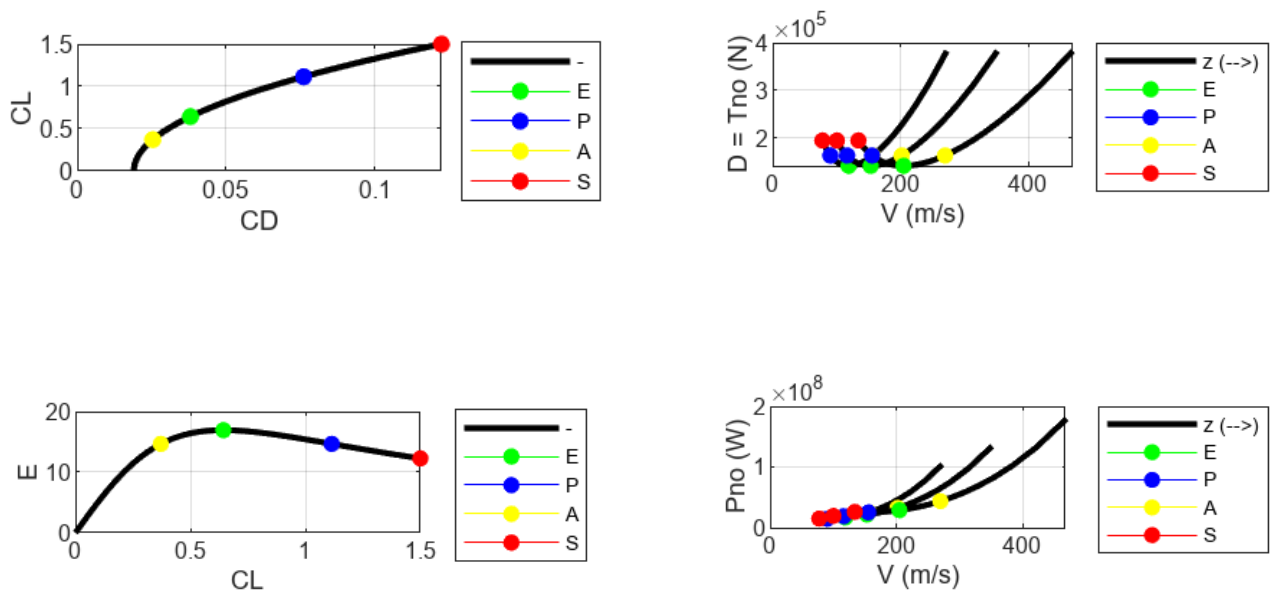


Figure 3.1 - Charts of technical polar data in climb and cruise conditions, Boeing 777-200

3.22 Propulsive characteristics

The following rating was employed for calculating the performance:

$$T = 0.71 \cdot T_0 \cdot \sigma \cdot \varphi \cdot n_{engines}$$

VERSION	<i>T</i> [kN]	<i>P</i> [kW]	<i>Fuel</i> [kg]
Boeing 777-200	<i>131.27</i>	<i>32818.1</i>	<i>58360.90</i>
Boeing 777-300	<i>168.39</i>	<i>42099.45</i>	<i>74865.99</i>

Table 3.13 – Propulsive characteristics

To find the following values, it has been set:

- *rating* “Cruise”;
- *Throttle* $\varphi = 0.8$;
- $v_{TAS} = 250 \frac{m}{s}$;
- *flight hours* = 8.

3.23 Climb, Level Flight

In the next table, you can see the values that Boeing 777 family aircraft assume in Climb and Level Flight conditions:

VERSION	RC_{max} [m/s]	V_{max} [km/h]
Boeing 777-200	10.32	235.2
Boeing 777-300	11.53	247.0

Table 3.14 – Climb and Level Flight

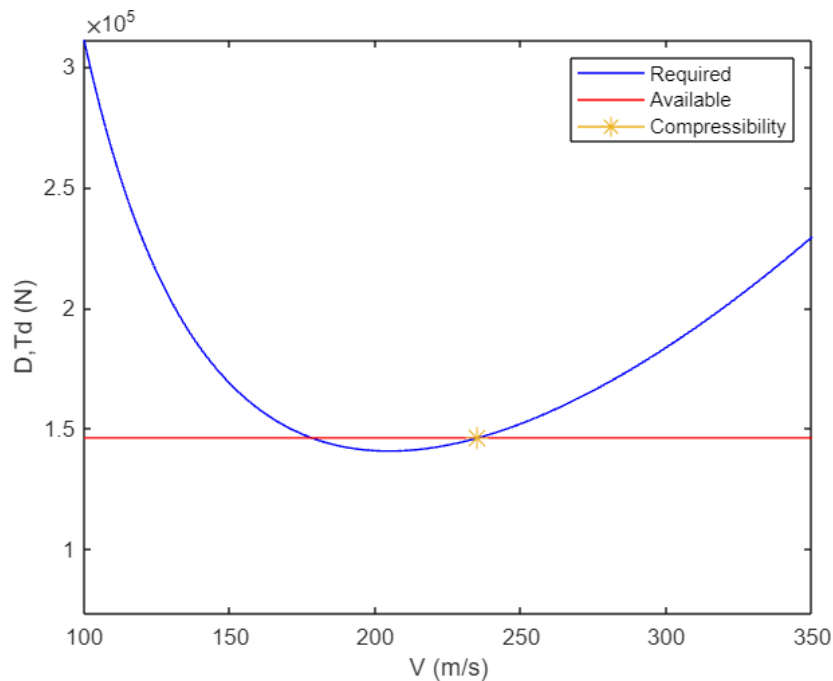


Figure 3.2 - Comparison diagram between the power requested and the power supplied

3.24 Autonomies

In the following table, you can view the range values assumed by the categories of Boeing 777 aircraft:

VERSION	R_{max} [km]	En_{max} [hr]
Boeing 777-200	11368.5	15.27
Boeing 777-300	9979.6	11.74

Table 3.15 – Autonomies

We obtain the values present in the table by considering the following formulas:

- $En_{MAX} = \frac{E_{MAX}}{TSFC} \cdot \ln\left(\frac{W_0}{W_1}\right)$
- $R_{MAX} = 11.27 \cdot \frac{2}{TSFC} \cdot \sqrt{\frac{2}{\rho S}} \cdot \left(\frac{\sqrt{C_L}}{C_D}\right)_{MAX} \cdot (\sqrt{W_0} - \sqrt{W_1})$

These are nothing more than the Breguet formulas found by assuming fixed h in altitude.

3.25 Take-off distance, Landing distance

Below in the table, we can see the values of take-off and landing distances compared for different categories of Boeing 777 aircraft:

VERSION	Take-off field length [m]	Landing length [m]
Boeing 777-200	1406	943
Boeing 777-300	1660	1088

Table 3.16 – Take-off and landing distance

3.26 Turn

VERSION	Minimum turn [m/s] speed	Max \emptyset [km/h]
Boeing 777-200	123.05	66.43
Boeing 777-300	136.68	66.43

Table 3.17 – Turn

4. Evaluation of Stability and Control

Once the performance evaluation phase was completed using the MATLAB software, the models created in JPAD were exported in OpenVSP format, thus allowing the analysis of the stability and control of the models created using the OPENVSP software, specifically through the use by VSPAERO. By stability of an aircraft we mean a fundamental aspect to guarantee safety and maneuverability during flight. It guarantees the aircraft to reposition itself in the initial equilibrium conditions, without modifying the movement characteristics. it is essential to avoid dangerous situations, such as "stall".

Below, you can see an image that shows us what the interface of this program looks like.

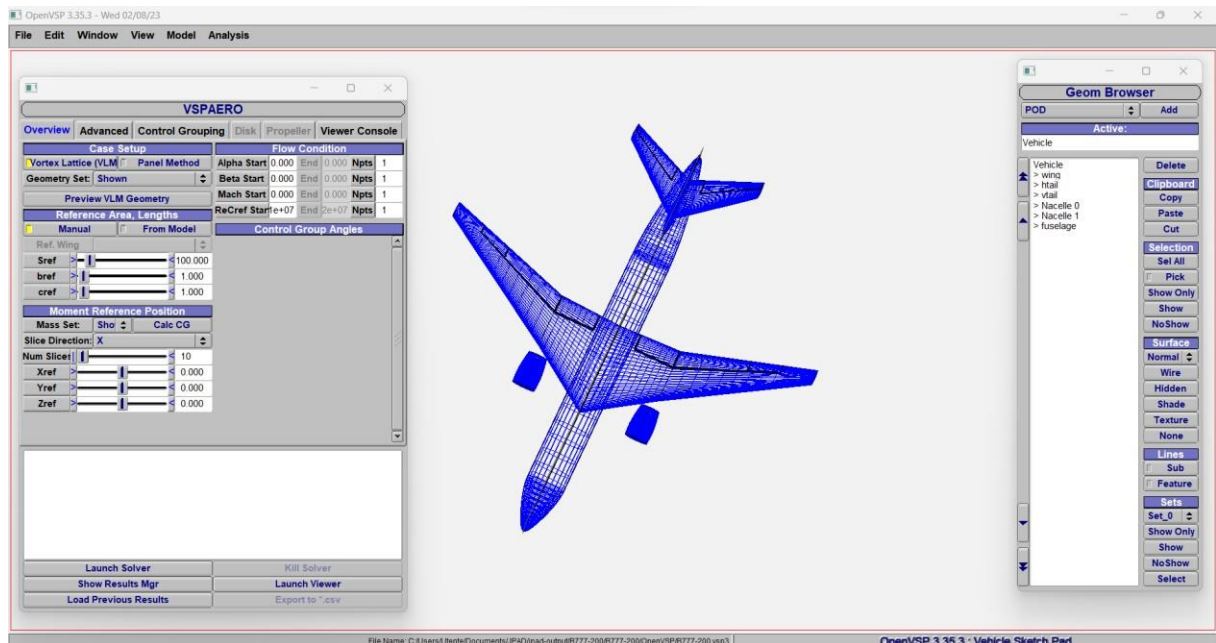


Figure 4.1 – OPENVSP interface

4.1 VSPAERO

VSPAERO is an analysis tool based on a linear vortex lattice that incorporates actuator disks. Thanks to this software, it has been possible to perform a series of calculations related to stability and control derivatives. The VSPAERO interface allows for the input of geometric information about the aircraft, including reference chord, center of gravity position, and wing area, which can be entered manually or imported from other programs like JPAD. Additional parameters, such as angle of attack and Mach number, can also be specified.

After entering all the necessary data and specifying the desired number of iterations (in this case, 3), the analysis can be initiated to obtain the desired derivatives. It is important to note that the values entered in the program must be consistent with the user's chosen measurement system, as VSPAERO does not explicitly require units of measurement to be specified.

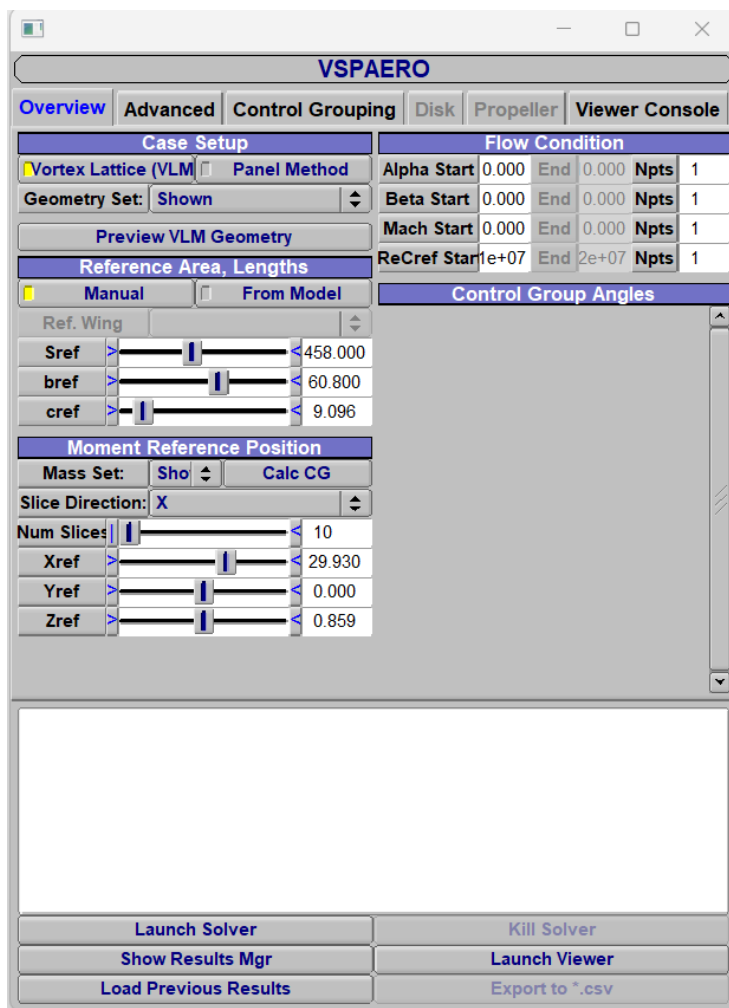


Figure 4.2 – VSPAERO Interface with Data for the Boeing 777-200

For the analysis, we will consider the following center of gravity values for the 2 aircraft under consideration:

- ✓ For the Boeing 777-200, we will have a center of gravity X-coordinate of 29.93 m.
- ✓ For the Boeing 777-300, we will have a center of gravity X-coordinate of 35.12 m.

This result is obtained from the following calculation, where the various parameters have been identified in the appropriate sections of JPAD.

$$X_{ref} = X + x + 30\% m. a. c.$$

By that, I mean:

- X is the distance relative to the origin of the axes, which is at the apex of the aircraft.
- x is the distance relative to the wingtip.
- M.A.C. is the mean aerodynamic chord.

Furthermore, in the case of the Boeing 777-200, the following values have been determined:

X=20.056 m; x=7.144 m; M.A.C.=9.096 m.

Similarly, in the case of the Boeing 777-300:

X=25.420 m; x=7.153 m; M.A.C.=8.492 m.

4.2 Aerodynamic stability derivatives

“Stability derivatives” are nothing more than aerodynamic parameters used in the analysis of the stability and control characteristics of an aircraft. These refer to the coefficients that represent the variation of aerodynamic forces and moments with respect to specific parameters, such as the angle of attack (α), the pitch angle (θ), etc.

The derivatives analyzed are listed below:

- The derivative of lift concerning the angle of attack ($dC_L/d\alpha$) shows how lift changes as the angle of attack varies.
- The derivative of pitching moment concerning the angle of attack ($dC_{M_y}/d\alpha$) indicates how the pitching moment (moment around the lateral axis) alters as the angle of attack changes.
- The derivative of rolling moment concerning the slip angle ($dC_{M_x}/d\beta$) reveals how the rolling moment (moment around the longitudinal axis) changes with different slip angles.
- The derivative of yaw moment concerning the slip angle ($dC_{M_z}/d\beta$) demonstrates how the yaw moment (moment around the vertical axis) varies with varying slip angles.
- The derivative of pitching moment concerning the elevator deflection angle ($dC_{M_y}/d\delta_e$) provides information about the pitching moment's alteration when the elevator is deflected.
- The derivative of yaw moment concerning the rudder deflection angle ($dC_{M_z}/d\delta_r$) offers insights into the change in yaw moment when the rudder is deflected.
- The derivative of the roll moment relative to the aileron deflection angle ($dC_{M_x}/d\delta_a$) allows you to calculate how quickly and efficiently an aircraft can perform a roll maneuver when the ailerons are deflected.

The first four derivatives are stability derivatives, while the other three are control derivatives.

For the following data in the tables, the parameters listed in section 4.1 were used.

VERSION	$dC_L/d\alpha$	$dC_{My}/d\alpha$	$dC_{Mx}/d\beta$	$dC_{Mz}/d\beta$
Boeing 777-200	4.913	-1.494	0.115	-0.106
Boeing 777-300	5.010	-2.046	0.123	-0.139

Table 4.1 - Stability derivates (values in rad^{-1})

VERSION	$dC_{My}/d\delta_e$	$dC_{Mz}/d\delta_r$	$dC_{Mx}/d\delta_a$
Boeing 777-200	-1.303	0.071	0.0713
Boeing 777-300	-1.781	0.092	0.0710

Table 4.2 - Control derivates (values in rad^{-1})

First, we can define the stability margin as:

$$\frac{dC_M}{dC_L} = \frac{C_{M\alpha}}{C_{L\alpha}} = (x_{Ref} - x_N) = SM$$

A stable aircraft therefore has $SM < 0$ and a negative stability derivative $C_{M\alpha} < 0$.

Now we can define the neutral point using the following equation:

$$x_N = x_{Ref} + SM$$

The "neutral point" in an aircraft represents the point where the aircraft achieves a perfect balance between load and weight. The precise position of the center of gravity is crucial to ensure both stability and maneuverability of the aircraft and can be adjusted by redistributing the load on board. If the center of gravity is not positioned correctly, it can lead to potentially dangerous configurations during flight.

VERSION	SM	x_G	x_N
Boeing 777-200	0.304	29.93	32.69
Boeing 777-300	0.408	35.12	38.59

Table 4.3 – Neutral point

5. Conclusion

This work aimed to create accurate geometric models of Boeing aircraft, particularly the Boeing 777 family, using JPAD software, studying their performance through MATLAB code, and conducting stability and control analysis using OpenVSP. The results obtained from various software tools allowed us to assess the efficiency, stability, and safety of these aircraft.

However, certain limitations in the project need to be highlighted, especially in the geometric modeling phase using JPAD. While it enables the creation of realistic geometric models, further refinements are required, particularly in modeling the windshield and vertical tail, as they do not seamlessly integrate with the fuselage, leading to minor differences in the views, especially concerning the windshield.

Additionally, some inaccuracies were identified in the performance analysis process, particularly in the calculation of propulsion characteristics, notably with regard to fuel quantity.

In conclusion, this work has made a significant contribution to understanding geometric modeling, performance analysis, stability, and control of the Boeing 777 aircraft family.

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