“Interactive Aircraft Design for Undergraduate Teaching”

Omran Al-Shamma, Dr. Rashid Ali

University of Hertfordshire

Abstract: This paper presents new software package developed for Aircraft Design. It is intended primarily to be used for undergraduate teaching. The software does everything that is needed in preliminary design environment. It is able to predict the empty and maximum takeoff weights to an accuracy of better than 5%. The performance data computed by the software agrees very favourably with the published data of Airbus and Boeing aircraft, for a wide range of flight conditions. An interactive interface to the USAF DATCOM has also been developed to provide estimation of aircraft stability derivatives which can be used in flight simulation work to investigate the dynamic behaviour of the aircraft design under consideration.

Introduction

Aircraft design process can be divided into three design phases: *a- Conceptual, b- Preliminary, c- Detail.* They can be summarized as follows:

a- Conceptual design phase: The main objective of this phase is to determine the configuration layout (conventional or novel) which are technically feasible and commercially viable.

b- Preliminary design phase: The aim of this phase is to find the best optimum configuration geometry for the aircraft that achieves commercial operational requirements. This design is done in parallel with the parametric studies to allow any desirable changes to the layout to be made. This phase is iterative in nature and the design changes are made until all specifications are met.

c- Detail design phase: It consists of two parts. The purpose of the first part is to verify and refine the design to a greater level of detail and to produce data necessary for the manufacture of the aircraft. The second part is sometimes called production design where the specialists determine how the aircraft will be fabricated, starting with the smallest and simplest subassemblies and building up to the final assembly process. Detail design phase ends with fabricating and testing the first prototype aircraft.

Teaching Aircraft design

Many universities in UK, follow the Problem Based Learning (PBL) approach in teaching aircraft design. PBL is a concept used to enhance multidisciplinary skills using planned problem scenarios. It is an active way of learning that teaches students problem-solving skills while at the same time allowing them to acquire basic knowledge in aircraft design. In PBL approach, students work in small collaborative groups and learn what they need to know in order to solve a problem. The benefits of PBL have been explained by Duch (1). Since, the aircraft design process is iterative, one or two semesters of study is not enough time to fully cover the concepts of the aircraft design. Most universities present preliminary design projects as coursework for this reason. It should be noted that these projects are not meant to provide a "*fill in the blank*" template to be used by current and future students working on similar design problems, but to provide insight into the process itself (2). The aircraft design projects are undertaken students working in a group size comprising of 6-8 in number, and working to prescribed specifications as set by the academics. The broad subject areas include Wing and Aerodynamics, Fuselage, Undercarriage, Systems, Propulsion & Performance, Project Management, Materials and Manufacture and Stability and Control. The students work through a classical process of preliminary design based largely on textbook methods. Therefore, the need for a preliminary design tool (software) that helps the students to understand and analyze their design process is necessary.

Aircraft Design Software

Many software programs have been developed in the last fifty years ago, subsequent to the first optimized program (SYNAC II) coded by Lee, V. & et al (3) in 1967. In the early nineties, the AAA (Advanced Aircraft Analysis) (4) program started out as a computerized version of Roskam's eight-volume text: *Airplane Design*, Parts I-VIII (5), featuring a user-friendly interface. Kroo (6) developed a system for aircraft design utilizing a unique analysis architecture, graphical interface, and suite of numerical optimization methods. In 1996, Raymer released his software package RDS (7) which implements the approach described in his book. Piano (8) is another complete aircraft design program developed by Simos. It is geared towards the design of commercial aircraft. Finally, CEASIOM (9) (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods) is meant to support engineers in the conceptual design process of the aircraft.

Limitations and Shortages

- Although some of the packages are used for teaching purposes, the students need to know the philosophy of aircraft design and the influence of each variable. They need to understand principles of aircraft design before the packages can be used.
- Many assumptions need to be made in order to achieve the objectives.
- Many programs are not truly interactive which makes them unsuitable for teaching purposes.
- One of the important aspects in aircraft design is the dynamic stability. Most of these programs lack it in their synthesis process.

Software Scope

The objective goal of the software is to develop a tool that can be used for teaching aircraft design. Therefore, it had to be highly interactive with friendly graphical user interface and easy to use. Addition of parametric study Capabilities. in the software enables the students to learn and understand the influences of the various design variables. Therefore, the task becomes for the students to learn the processes which will take them from the first principles and concepts, through to the conceptual design and to the point where our software begins to guide them into interactive step-by-step approach enabling them to estimate, choose, and calculate the design variables, helping them to analyse, optimize, and evaluate the proposed design in less iterations.

User Interface

Aircraft design involves a large number of design variables for a variety of calculations. These variables are required for the estimation of aircraft mass, aerodynamics, stability and control, propulsion, and aircraft performance. Many design software packages use pre-configured input data files to define the design variables. Alteration to the input data is done through modification of these files. This configuration is very tedious and is not intended for teaching. Thus, the need for a user friendly graphical-user-interface (GUI) becomes necessary. In the scope of this project an object-oriented-programming (OOP) is used to create the GUI environment. The benefits of OOP are encapsulation, polymorphism, and reuse (or so-called inheritance).

The software uses more than 150 design variables organised into eleven groups. These groups are: Wing, Fuselage, Tail, Aerofoils, Flaps, Propulsion, Weights, Speeds, Stages, Weights, and Cost. This simplified configuration helps the students to specify, alter and examine the effects of the changes efficiently. Also, the software uses a graphical user interface conforming standard software for teaching (10).

Figure 1 is a screen shot of a typical interaction form that allows the user to make the changes to the variables associated with the wing design, and in keeping with the interface requirements presented in (10).

Synthesis Program

The main synthesis program consists of many modules. These modules include: geometry, weight, aerodynamics, static stability, flight performance, cost estimation, and dynamic stability. The aircraft geometry module calculates the major geometries pertinent to aircraft components such as wing, fuselage, empennage, flaps, and nacelles. In the weight module, which is one of the most significant module due to the fact that accurate weight estimation at early stages is a hard and difficult process. The aerodynamics module evaluates: zero-lift drag, aircraft lift, lift induced drag, compressibility effects, total aircraft drag, and effects of flaps. In static stability module, static margin constraint is evaluated and static margin in the datum CG position for the proposed aircraft is also calculated. The dynamic stability module computes all the longitudinal and lateral stability derivatives and computes the properties of the modes of motion. The flight performance module is used for flight profile analysis and field performance, in the climb, cruise, and descent phases. Detail changes in aircraft mass, air density, speeds, and time are calculated at the mid-segment position. Time and fuel are calculated using linear interpolation in each stage. In the climb stage the engines are at the maximum continuous climb rating, whilst for the cruise segment engine thrust is at a min fuel condition. The descent phase calculations are performed at flight idle setting. The field performance is assessed using step-integration analysis of the equation of the motion of the aircraft presented by Torenbeek(11) to determine the balanced field length (BFL) requirements, whereas Loftin(12) analysis is used to find the landing field length (LFL). Finally, the cost estimation module evaluates the aircraft cost, engine cost, and direct operating cost (DOC). DOC is the most significant parameter for commercial aircraft. Therefore, three common standard methods are developed in the cost module, American Transport Association (ATA), NASA, and Association of European Airlines (AEA) (13, 14, & 15). The student is free to choose any method in his analysis. All these methods are based on up-to-date data published by ATA and MIT (year 2010) which is based on operational data averaged from many airlines and gives a reasonable estimate of the average DOC.

Take-off Module

Although the BFL is calculated in the performance module, an additional module is used to synthesise the take-off stage in a more accurate analysis. The module is based on the approach proposed by Krenkel & Salzman(16). It is organized into two parts. Each part defines different aspects of take-off analysis. These parts are:

a- Normal Take-off, i.e. from stop to liftoff to passage over a 35 ft (11m) obstacle.

b- Balance Field Length calculation, i.e. Iterative solution to find where the engine can fail so that the distance to perform an OEI take-off is equal to the accelerate stop distance available (ASDA).

Parametric Studies Module

A key feature that helps in understanding the philosophy of aircraft design is the interrelationship of variables. This module consists of two options, either 1-to-1 or 2-to1 i.e. changing one independent (design) variable to one dependent (calculated) variable, or changing two independent variables to one dependent variable. The user is allowed to set the lower and upper limits of the allowable changing band for the selected design parameters. The resulting data are plotted as 2D graphs.

Optimiser

An optimiser from RAE(17) has been incorporated that allows a great flexibility in selecting objective functions and in exploring the optimized design to changes in specifications or constraints. Main objective functions include total fuel weight, take-off weight, direct operating cost, and weight of the wing. Fourteen equality and/or in-equality constraints, which include fuel weight, total take-off weight, balanced and landing field lengths, static margin, stage length, etc, can be set by the students. Other feature of the optimizer is that it allows the student to decide on which of the variable are fixed and which the optimiser can optimise.

Output Module

The software outputs all the necessary design data in alphanumeric and graphical format. This includes weight, geometric, aerodynamic, and takeoff stage analysis, aspects of flight performance and static and dynamic stability. The output module allows data to be saved or exported to EXCEL for further analysis if required. The key feature is the software's ability to draw the 2-D aircraft geometry that alters in real time as any of the design parameters are changed.

Case Study

Many case studies have been performed for current Airbus and Boeing aircraft. The performance data computed by the software agrees very favourably with the published data of Airbus and Boeing aircraft, in all conditions. In particular, a full case study for Boeing 777-200ER is presented here. Initially, the published data used as design variables are shown in Table 1. The software evaluates the aircraft components weights as in Table 2. The software predicts the operating empty weight and maximum takeoff weight to an accuracy of better than 4%. This is considered to be satisfactory in the early stages of the design. In aerodynamic module, zero-lift drag coefficient of aircraft components, lift coefficient of the aerofoil section, wing, and trimmed aircraft are calculated, for takeoff and landing stages. A polar plot (C_L vs. C_D of the aircraft is shown as Figure. 2. Table 3 shows the output data of the flight performance for the main stage. Notional and diversion stage data in a similar manner to the main stage are also available. The Direct Operating Cost (DOC) elements which in turn are based on up-to-date data published by ATA and MIT (18 & 19) are evaluated according to the selected method as shown in Table 4. Also, static stability, balanced field length, and landing field length are calculated. Table 5 shows the detail analysis output data for the takeoff stage.

Table 6 shows the typical output produced by the dynamic stability module, and includes all the stability derivatives for the lateral and longitudinal dynamics. properties of all the modes of motion (not shown) and summarises the data in a state space format which can be exported for control system design in MATLAB (20).

Presented in Table 7 is the published and predicted operation empty weights of the Airbus and the Boeing family of aircraft, note that the OEW prediction is fairly accurate, except for a couple of cases where the discrepancy is due to the lack of information regarding usage of composite materials. The program has adjustment factors that can allow this to be corrected.

Conclusion

New software package has been developed for teaching undergraduate Aircraft Design students. It performs weight analysis, geometric aerodynamic performance estimates, aspects of flight performance, and dynamic stability. Many case studies have been performed for the current Airbus and Boeing aircraft. A full case study for the Boeing 777 aircraft is presented.

References

1. Duch, B. J., et al, "The Power of Problem Based Learning", *Stylus Publishing*, Virginia, USA, 2001.

2. Jenkinson, L., & Marchman III, J., *"Aircraft Design Projects"*, Elsevier science Ltd, UK, 2003.

3. Lee, V. A., & et at, "Computerized Aircraft Synthesis", *Journal of Aircraft*, Vol. 4, No. 5, September 1967.

4. Roskam, J., and Malwaek, S., "Automated Aircraft Configuration Design and Analysis", *SAE* paper 891072, April 1989.

5. Roskam, J., *"Airplane Design"*, vol. I-VIII, DAR Corporation, USA, 1985-2007.

6. Kroo, I., "An Interactive System for Aircraft Design and Optimization", *AIAA* paper 92-1190, February 1992.

7. Raymer, D., "RDS-Professional in Action: Aircraft Design on a Personal Computer", *SAE/AIAA*, paper 5567, October 1996.

8. Simos, S., "Piano", *Lissys Limited*, UK.

9. Kaenel, R., et al, "CEASIOM: Simulating Stability and Control with CFD/CSM in Aircraft Conceptual Design", *26th ICAS*, 2008.

10. Jayaram, S., et al, "ACSYNT – A Standards-Based System for Parametric Computer Aided Conceptual Design of Aircraft", *AIAA* paper 92-1268, Feb. 1992.

11. Torenbeek, E., *"Synthesis of Subsonic Airplane Design"*, Delft Univ. Press, Delft, The Netherlands, 1982.

12. Loftin, L. K., "Subsonic Aircraft: Evolution and the Matching of Size to Performance", *NASA* RP 1060, 1980.

13. ATA, "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes", *ATA*, December 1967.

14. Liebeck, R.H., et al, "Advanced Subsonic Airplane Design and Economic Studies", *NASA* CR-195443, April 1995.

15. AEA, "Short-Medium Range Aircraft – AEA Requirements", December 1989.

16. Krenkel, A.R., Salzman, A., "Take-Off Performance of Jet-Propelled Conventional and Vectored Thrust STOL Aircraft", *Journal of aircraft*, Vol. 5, No. 5, pp. 429, 1968.

17. Strobanski, J. J., *"User Guide for RQPMIN (a program for constrained optimisation)"*, also, *"A Method for Solving the Non-Linearity Constrained Optimisation Problem"*, Royal Aircraft Establishment, Technical Reports, 1984.

18. Air Transportation Association: www.air-transport.org / (click on economics and energy, in drop-down menu click on jobs and labour, at bottom of page under "inside this section" click on airline cost index, which puts you on the page "Quarterly Cost Index : U.S. Passenger Airlines" where links to tables and charts are given).

19. MIT Global Airline Industry program: http://web.mit.edu/airlinedata/www/default.html

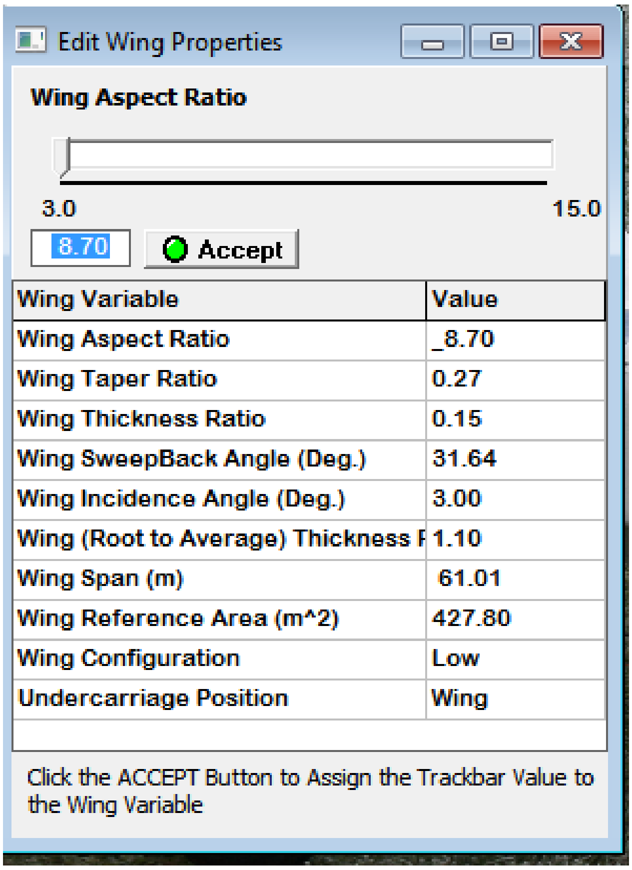
20. http://www.mathworks.com.

Design Variables		Value
Maximum Takeoff Weight	**(kg)**	297555
Operating Empty Weight	**(kg)**	145015
Maximum Takeoff Thrust / Engine (lb)		93700
Number of Passengers	**(1-Class)**	440
Dive Velocity	**(m/s)**	317
Range	**(km)**	14310
Fuel Weight	**(kg)**	98000
Fuselage Length	**(m)**	63.73
Fuselage Diameter	**(m)**	6.2
Wing Area	**(m^2)**	427.8
Wing Aspect Ratio		8.7
Wing Sweepback Angle	**(deg.)**	31.64

Table 1 – Design variables for Boeing 777-200ER aircraft

```
@@@@@@@@@@@ Mass calculation @@@@@@@@@@@@@@@@@@@@
Wing includes flaps (kg) =  35437.0
Fuselage            (kg) =  30772.9
Empennage           (kg) =   8185.1
Nacelles            (kg) =   4670.0
Propulsion System   (kg) =  24206.9
Propulsion Group    (kg) =  19536.9
Undercarriage       (kg) =  11045.3
Surface Controls    (kg) =   2838.1

Auxiliary power unit                 (kg) =   2194.8
Paint & Oxygen system                (kg) =   2235.3
Electrical system                    (kg) =   2217.6
Avionics & Instruments iclud AoPilot (kg) =   2738.8
Air conditioning & Anti-icing system (kg) =   1630.2
Hydraulic system                     (kg) =   2368.7
Systems (Total)     (kg) =  13385.5

Furnishings         (kg) =  11966.1
Empty Mass          (kg) = 137836.9

Operation Items     (kg) =   6586.8
Crew mass           (kg) =    186.0
Flight attendants   (kg) =    952.0
Op. empty mass      (kg) = 145561.7

Passsenger Load     (kg) =  48897.8
Zero Fuel mass      (kg) = 194459.5
Total Fuel          (kg) =  98000.0

Maximum TakeOff     (kg) = 292459.5
#############################################
```

Table 2 – Calculated Component Weights for Boeing 777-200ER



Wing Variable	Value
Wing Aspect Ratio	_8.70
Wing Taper Ratio	0.27
Wing Thickness Ratio	0.15
Wing SweepBack Angle (Deg.)	31.64
Wing Incidence Angle (Deg.)	3.00
Wing (Root to Average) Thickness F	1.10
Wing Span (m)	61.01
Wing Reference Area (m^2)	427.80
Wing Configuration	Low
Undercarriage Position	Wing

Click the ACCEPT Button to Assign the Trackbar Value to the Wing Variable

Figure 1 – Wing Design Variables Form

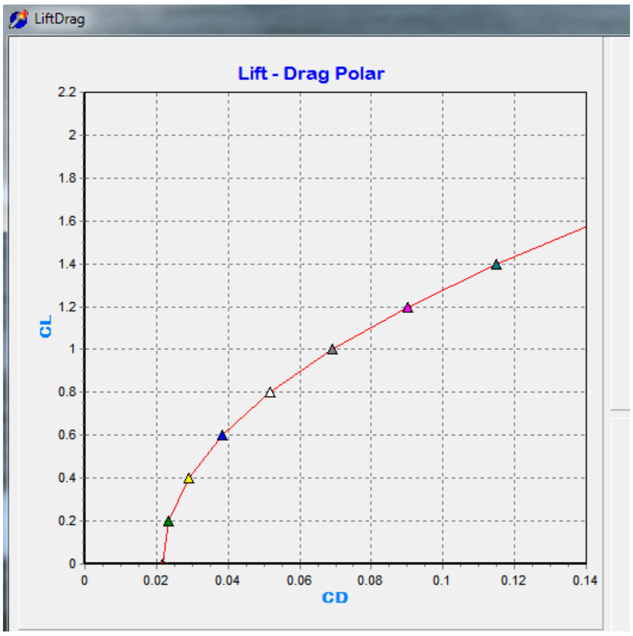
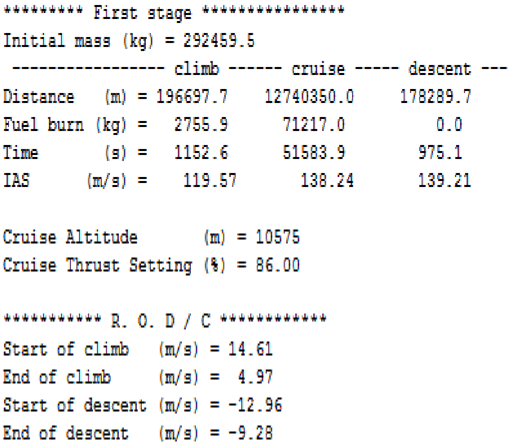
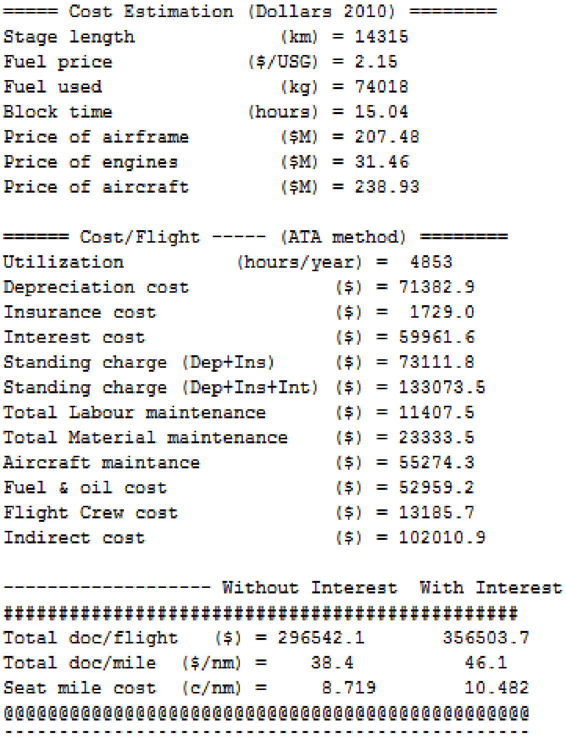


Figure 2 – Polar Plot for Boeing777-200ER



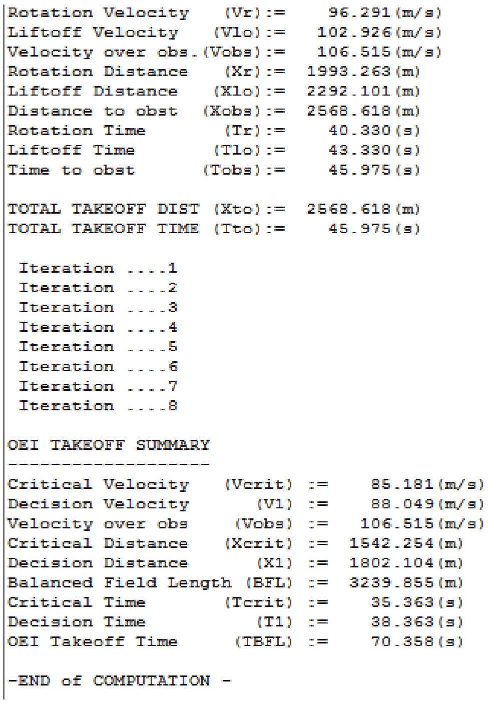
```
********* First stage ****************
Initial mass (kg) = 292459.5
 ----------------- climb ------ cruise ----- descent ---
Distance   (m) = 196697.7    12740350.0     178289.7
Fuel burn (kg) =   2755.9      71217.0          0.0
Time       (s) =   1152.6      51583.9        975.1
IAS      (m/s) =    119.57       138.24       139.21

Cruise Altitude       (m) = 10575
Cruise Thrust Setting (%) = 86.00

*********** R. O. D / C ************
Start of climb   (m/s) = 14.61
End of climb     (m/s) =  4.97
Start of descent (m/s) = -12.96
End of descent   (m/s) = -9.28
```

Table 3 – Main Stage Performance for Boeing 777-200ER



```
===== Cost Estimation (Dollars 2010) ========
Stage length                (km) = 14315
Fuel price               ($/USG) = 2.15
Fuel used                   (kg) = 74018
Block time               (hours) = 15.04
Price of airframe          ($M) = 207.48
Price of engines           ($M) = 31.46
Price of aircraft          ($M) = 238.93

====== Cost/Flight ----- (ATA method) ========
Utilization           (hours/year) =  4853
Depreciation cost              ($) = 71382.9
Insurance cost                 ($) =  1729.0
Interest cost                  ($) = 59961.6
Standing charge (Dep+Ins)      ($) = 73111.8
Standing charge (Dep+Ins+Int)  ($) = 133073.5
Total Labour maintenance       ($) = 11407.5
Total Material maintenance     ($) = 23333.5
Aircraft maintance             ($) = 55274.3
Fuel & oil cost                ($) = 52959.2
Flight Crew cost               ($) = 13185.7
Indirect cost                  ($) = 102010.9

------------------- Without Interest  With Interest
################################################
Total doc/flight   ($) = 296542.1       356503.7
Total doc/mile  ($/nm) =    38.4           46.1
Seat mile cost  (c/nm) =     8.719         10.482
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
------------------------------------------------
```

Table 4 – Cost Estimation Output for Boeing 777-200ER



```
Rotation Velocity    (Vr):=    96.291(m/s)
Liftoff Velocity    (Vlo):=   102.926(m/s)
Velocity over obs.(Vobs):=   106.515(m/s)
Rotation Distance    (Xr):=  1993.263(m)
Liftoff Distance    (Xlo):=  2292.101(m)
Distance to obst   (Xobs):=  2568.618(m)
Rotation Time        (Tr):=    40.330(s)
Liftoff Time        (Tlo):=    43.330(s)
Time to obst       (Tobs):=    45.975(s)

TOTAL TAKEOFF DIST  (Xto):=  2568.618(m)
TOTAL TAKEOFF TIME  (Tto):=    45.975(s)

 Iteration ....1
 Iteration ....2
 Iteration ....3
 Iteration ....4
 Iteration ....5
 Iteration ....6
 Iteration ....7
 Iteration ....8

OEI TAKEOFF SUMMARY
-------------------
Critical Velocity    (Vcrit)  :=    85.181(m/s)
Decision Velocity       (V1)  :=    88.049(m/s)
Velocity over obs     (Vobs)  :=   106.515(m/s)
Critical Distance    (Xcrit)  :=  1542.254(m)
Decision Distance       (X1)  :=  1802.104(m)
Balanced Field Length  (BFL)  :=  3239.855(m)
Critical Time        (Tcrit)  :=    35.363(s)
Decision Time           (T1)  :=    38.363(s)
OEI Takeoff Time      (TBFL)  :=    70.358(s)

-END of COMPUTATION -
```

Table 5 – Take-off Analysis for Boeing 777-200ER

LONGITUDINAL DIRECTIONAL COEFFICIENTS			
	X	M	Z
U	-0.0055	0.000	-0.0748
W	0.0374	-0.0199	-0.4433
W_dot	0.000	-0.0009	-0.0045
Alfa	6.1336	-4.9923	-111.2169
Alfa_dot	0.000	-0.2284	-1.1320
q	0.000	-0.6790	-3.3652
Delta_e	0.000	-2.8158	-13.9564
LATERAL DIRECTIONAL COEFFICIENTS			
Beta	-15.6394	2.2367	-0.0113
P	0.5543	-0.0422	-1.6706
R	1.8386	-0.2322	0.2984
Delta_r	7.8372	-1.0648	0.8709
Delta_a	0.000	-0.1083	3.9821
LONGITUDINAL A MATRIX			
-0.005	0.037	0.000	-9.810
-0.075	-0.443	250.890	0.000
0.000	-0.019	-0.907	0.000
0.000	0.000	1.000	0.000
LATERAL A MATRIX			
-0.062	0.002	0.993	0.039
-0.011	-1.671	0.298	0.000
2.237	-0.042	-0.232	0.000
0.000	-0.042	-0.232	0.000

Table 6 – Dynamic Stability Derivatives for Boeing 777-200ER

Aircraft Type	Published Data		Calculated Data		% Diff. OEW	% Diff. MTOW
	OEW	MTOW	OEW	MTOW		
A319 – 100	40800	75500	40829	75165	+ 0.07	- 0.45
A321 - 200	48500	95510	48605	94754	+ 0.22	- 0.8
A330 – 200	119600	238000	123269	235499	+ 3.07	- 1.06
A330 – 300	124500	235000	124971	235969	+ 0.38	+ 0.37
A340 – 300	130200	276500	130659	278056	+ 0.35	+ 0.56
A340 – 600	177800	368000	173148	356936	- 2.69	- 3.1
737 – 700	38147	70305	38671	70329	+ 1.37	+ 0.03
737 – 800	41145	79245	43154	80668	+ 4.88	+ 1.8
737 – 900ER	44676	79245	44038	83531	- 1.45	+ 5.41
767 – 400ER	103145	204570	104064	200638	+ 0.89	- 1.96
777 – 200ER	145015	297550	145561	292459	+ 0.03	- 1.02
777 – 300ER	167830	351500	173236	348158	+ 3.22	- 0.96

Table 7 – Comparison of the Published and Predicted Operational Empty Weights