Flight Test Academy v16

A Series of Aerospace STEM Projects Exploring Flight Test Engineering using X-Plane.

Study Guide for Units 1 and 2

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Preface

After a rewarding and exciting flight test career and when planning for my retirement from Boeing, I embarked on obtaining a master's in teaching from Seattle Pacific University in their night program, which allowed me to continue working. For my student teaching internship, Raisbeck Aviation HS offered to host me where my mentor teacher was the science teacher I had worked with and helped many years before, Scott McComb.

It was during this internship in 2012 that the initial flight test project was conceived and developed. That project encompasses the first two units of Flight Test Academy, but in a traditional 'in-person' delivery and has been included in his science class ever since. Over the years, I have enjoyed assisting students with their data review and by offering suggestions as to why their flight test data made sense or not and as a coach for their final presentations, which were made to flight test engineers and pilots from the Seattle Chapter of SFTE.

The Covid breakout in 2020 forced schools to go to a 'remote learning' model provided an opportunity to convert the slide lectures of the flight test project into video lectures, thus allowing teachers, parents and students not familiar with airplanes or flying to successfully deliver and take this class. The result being the Flight Test Academy web site.

I've always held the notion that engineers can play an important role in the classroom by providing context to the scientific principles students are learning by demonstrating industry examples of how science is used in engineering new solutions to real-world technical issues.

I'm deeply indebted to Scott McComb, an award winning and National Board-Certified Teacher for his assistance and the opportunity to utilize some of this material in his classrooms. He has been a source of inspiration on how to do the teaching job right, with enthusiasm, care and concern for his students on a daily basis.

I'm also grateful for the support from my flight test colleagues both the flight test engineers and pilots from the Society of Flight Test Engineers, Seattle Chapter. They have enthusiastically supported my efforts with both encouragement, technical assistance and participation.

For all my students, past and present, I appreciated their patience as I learned my pedagogy trade. For it was through them that I learned the most and only hoped they learned half as much of what I learned from them.

Dan Hrehov 2021

Endorsements

The Society of Flight Test Engineers' Flight Test Academy casts students in the role of flight test engineers. Working through a thoughtful progression of activities on an engineering-grade flight simulator, students learn about and apply knowledge of force and motion to conduct their first flight and then a series of takeoff tests, climb tests, and cruise tests. The data they collect and analyze provides an authentic reason to describe motion, to apply vectors and the laws of motion to real situations, and to deeply understand the forces of flight. And, it gives participants a real taste of the world of flight test.

Extensively tested and refined over the last ten years, the Flight Test Academy curriculum is intended for people whose eyes look up when planes fly overhead, for students who are looking to connect their study of physics to the world beyond classroom walls, and for teachers who are ready to engage their students in authentic processes in the creation of meaningful products.

As a classroom teacher for over 20 years, I am pleased to have been able to field test Flight Test Academy in my high-school physics classroom. With Dan's expert guidance and crisp self-paced instruction, my students finished the process clearer about the role of physics in making predictions about and strategies for shaping the engineered world, and confident in their ability to be a contributing part of that world.

Scott McComb
NBCT, MEd, AIAA Distinguished Educator, A. Scott Crossfield Educator of the Year, NCASE Crown Awardee
Raisbeck Aviation High School

From a Test Pilot,
Yes, I fully endorse this course, what a great project, it is a great and challenging way to introduce high school students to flight testing,

Capt. Rod Huete
AF Test Pilot School Graduate, Air Force and FAA Test Pilot, President of *FlightTestSafety.com*

The following are comments from ninth graders who completed the flight test project and then presented their results to flight test engineers and test pilots in the spring of 2019 at Raisbeck Aviation High School in Seattle WA.

"It was a great experience to present to professional pilots and engineers. I learned a lot about calculating distance and presenting has helped a lot to understanding the calculations."

"The mathematical relationships and how they tie in with the real world and not just some random word problem, it deepened my understanding of the math since it put it in a more tangible form."

"Dealing with the data was my favorite part of the project. I learned the most during the project after failing multiple flight tests and started using the plane's cockpit controls."

"I don't plan on becoming a flight tester, but I liked how much insight it gave me on how much has to be done to effectively test a plane and collect data. I know what we have done in class was on a smaller scale, yet it does give us at least some experiences as what it would be like."

"I liked the independent feeling of the flight testing because it made the testing feel a bit more important because of the stakes that were placed onto it."

"I especially liked the amount of mathematical relationships and the solutions to each of them. They helped me learn the physics the most by quantifying them, which makes them understandable."

Flight Test Academy
Part 1

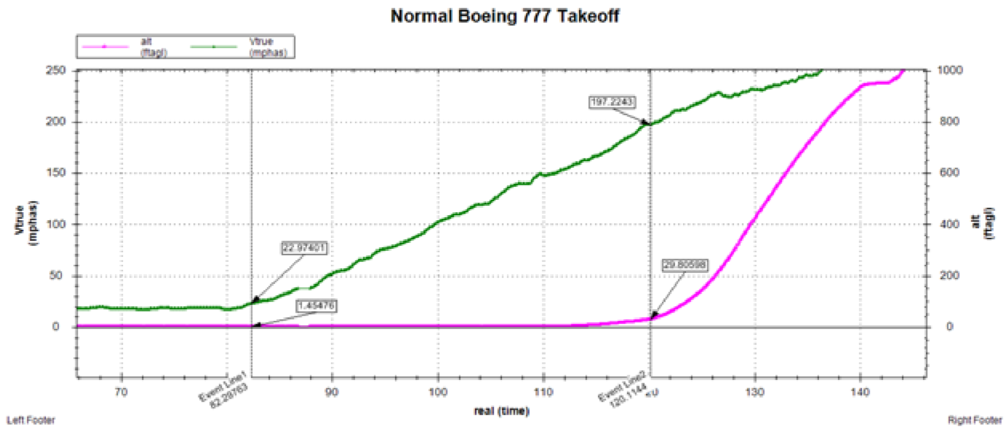
Curriculum

Flight Test Academy - Introduction and Description

Welcome to Flight Test Academy, an all-inclusive series of instructional videos in the field of flight test engineering for students and teachers. Flight Test Academy is a web-based source of authentic aerospace STEM projects for students. It includes the video instruction and other resources to guide teachers, parents and students through the projects and can be used for in-person instruction as well as remote learning or home school classes. Flight Test Academy starts off with a airplane fundamentals, a basic takeoff project and then progresses to more advanced topics and is scalable to suit both Jr High and High school students and for a variety of time durations. No flying or airplane experience expected or required for either the teacher or student.

The foundational element of flight test academy is when students use an engineering grade desktop flight simulator to perform airplane takeoff testing with varying parameters and determining the runway distance required to lift off. They will then make inferences as to what variables effect takeoff distance and why.

The activities students will perform is to; plan and conduct takeoff flight tests, create time history data plots where they obtain speed and time data points (as in the example below), use kinematic equations to calculate runway distance needed for takeoff and then infer factors that either lengthen or shorten takeoff distance.



The following topics are to bring students with little or no airplane knowledge and include; anatomy of an airplane, reading of flight instruments, forces in general and forces of flight in particular, test planning activities, a discussion of lift using the lift equation, using data plotting tools for data analysis, units and unit conversions, distance equations using either average velocity or acceleration and then other advanced topics.

This project can be scaled up or down and can accommodate a variety of grades and time durations. Junior high students can complete the initial takeoff testing by adjusting the total weight of the airplane and comparing distances, letting X-Plane graphically calculate the distance in Unit 1. High school students will accomplish that as well but in Unit 2, will also conduct advanced takeoff tests and calculate distances themselves using kinematic equations using either average velocity or acceleration. They will vary flap settings, airport altitude and temperature to see their effects on takeoff distances. The duration for these two units is approximately a ten-week quarter.

Other advanced project includes climb testing to determine the best speed for the maximum rate of climb for an airplane and cruise testing to determine the best speed for the highest lift/drag ratio for maximum range. Students will then calculate that range. A capstone project called the ‘Apple Challenge’ is presented as a real-world cargo flight planning mission.

There can be a design element to this project as well. X-Plane contains PlaneMaker software that students can use to modify the airplane such as changing the shape of the wing and its dimensions. For example, adding winglets or changing the aspect ratio of the wing and then retesting the airplane for takeoff, climb and cruise. Students can then compare their results to the baseline configuration and determine if the change was beneficial. All of this is 'real world' aerospace engineering activities that professional engineers currently perform and will recognize.

Flight Test Academy addresses the current (April 2013) Next Generation Science Standards for Science and Engineering Practices in the following areas; planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking and constructing explanations and design solutions. All of these activities reinforces the scientific tenet of making observations and using mathematical tools to develop theories that attempt to explain the observed behavior.

There are other skills that are developed with these projects as well. Skills such as test planning to understand the goal of the test and developing test plans that support that; test discipline of following a test plan, keeping track of test configuration, and data recording and management; data recovery skills in plotting and data manipulation along with data analysis and reporting skills in the areas of developing conclusions and reporting test results.

Many connections to mathematics are developed in these projects, such as relationships between velocity, time and distance; units and unit conversions; distance calculations using either average velocity or acceleration. Opportunities to explore deeper subjects such as Newton's Laws can easily be incorporated.

Flight Test Academy Syllabus

Flight Test Academy video instruction comprises six units with up to four lessons in each unit. Each lesson can take several classroom periods. Below is the breakdown of the units and lessons that includes the topics covered. Lesson plans and videos are available for each of the lessons and can be downloaded from the Seattle SFTE site Flight Test Academy – Seattle SFTE . The lesson plan outlines will provide information as to the specific activities and approximate duration for each of the lessons as an aid to planning.

Unit	Unit Title	Lesson	Lesson Title	Topics
0	Administrative	0	Project Introduction	FT Academy Administration
1	Basic Takeoff Testing	1-1	Introduction to FT Engineering	Flight Test Engineering
		1-2	Airplane Anatomy	Parts of an Airplane Airplane Axis Cockpit Familiarization
		1-3	Airplane Forces	Balanced and Unbalanced Forces Forces of Flight Units
		1-4	Xplane Basics	Xplane Demo/Setup First takeoff tests varying gross weight Data Analysis – graphical runway length determination
2	Advanced Takeoff Testing	2-1	Kinematic Equations	Displacement, Velocity, Distance

		2-2 2-3 2-4	Forces of Flight -Lift Takeoff Test Planning Data Recover and Analysis	Lift equation Angle of Attack B777 Takeoff tests varying Flaps, airport temperature and/or altitude Data recovery DatPlot demonstration Data Analysis – runway length determination Extensions – Change airport winds setting or make design changes to wing and repeat tests
3	Climb Testing	3-1 3-2	Climb Testing Data Recovery and Analysis	Induced and Parasitic Drag Drag equation Climb testing of C172 Develop speeds for best rate of climb Extensions – Change flap setting or make design changes to wing and repeat tests
4	Cruise Testing	4-1 4-2	Cruise Testing Data Recovery and Analysis	Lift over Drag ratio, Range Cruise Test planning Cruise testing of C172 Determine speeds for maximum L/D ratio, best range and duration Extensions – Change flap setting or make design changes to wing and repeat tests
5	Apple Challenge	5-1	Cargo Flight Planning	Plan an optimized flight plan to carry the maximum payload and minimum fuel based on student's cruise drag testing results.
6	Extensions	6-1	Modify airplane wing in PlaneMaker	Repeat takeoff, climb and cruise testing and compare results

Administration

This section included information needed to conduct these series of classes and contains the required supplies, example schedules, education standards, connections to math and a list of abbreviations. What is not included are homework assignments, practice problems, assessments and other extensions.

Supplies Needed

Tools needed for this work are: Laptop with X-Plane, Fly-to-Learn v9 loaded, DatPlot program loaded, mouse and/or joystick, calculator, balsa glider, wind vane materials, notepad and writing instrument. Additionally, basic computer skills such as; creating and finding directories, renaming and copying files and using Word and Excel, is required. The following describes in more detail the supplies needed. All the software can be downloaded for free.

- X-Plane version 9 demo for free at http://www.x-plane.com/desktop/try-it/older/ (Depending on internet connection it will take some time to download.) This free demo version will stop running after 10 minutes and requires a program restart, but it runs long enough to conduct the takeoff testing. The version 9 is recommended if it is to be run on older, less powerful laptops with the built-in integrated graphics card.

- Alternatively, there is a commercial course called *Fly to Learn* that includes v9 X-Plane software, lesson plans and other resources for both teachers and students to conduct the basic testing. The cost to purchase X-Plane Fly to Learn is approximately $15 per computer which eliminates the 10 minute restriction and can be found at http://flytolearn.com/
- Laptop (PC) or desktop computer with mouse, joystick is desired but not required.
- Excel spreadsheet software or graph paper to plot the data.
- Word processing software.
- Stripchart data plotting program such as DatPlot (http://www.datplot.com/) PC only.
- Balsa wood glider such as

https://www.guillow.com/images/products/detail/No.35Starfire.jpg

- Wind vane materials of pencil with eraser, push pin, scissors, index card and drinking straw.

Other On-line References

Flight Test Academy – Seattle SFTE for instructional videos, lesson plans and study guide.

- *NASA Beginners Guide to Aeronautics* page https://www.grc.nasa.gov/WWW/k-12/airplane/index.html
- *NASA What is Aeronautics* page https://www.grc.nasa.gov/WWW/k-12/UEET/StudentSite/aeronautics.html

Education Standards

Research into the Common Core Standards for math and science revealed a new series of standards adopted by Washington State for science called Next Generation Science Standards, NGSS. The following Science standards apply to this project.

Planning and Carrying Out Investigations
Analyzing and Interpreting Data
Using Mathematics and Computational Thinking
Engaging in Argument from Evidence
Obtaining, Evaluating and Communicating Information

Reference: Appendix F Science and Engineering Practices in the NGSS - FINAL 060513.pdf (nextgenscience.org) April 2013

Student Learning Outcomes

Student Learning Outcomes (SLO's) are important for educators to be able to identify the important concepts of the lessons as well as provide a method for assessing student learning. Listed below are the SLO's for each of the units.

Unit 1 Basic Takeoff Testing

At the conclusion of Unit 1, students will be able to:

- Define the role of the flight test engineer and pilot and identify their specific tasks and responsibilities in their role in testing and evaluating an airplane.
- List the major parts of the airplane.
- Identify the four major forces of flight.
- Explain the aircrafts flight controls and the airplane axis they rotate about.
- Understand and read flight instruments of airspeed, altimeter, rate of climb, heading and engine tachometer.
- Set up X-Plane to record the correct test data, configure the airplane with the proper payload and runway location, conduct consistent takeoff tests and determine the runway distance required for takeoff using the graphical feature of X-Plane.

Unit 2 Advanced Takeoff Testing

At the conclusion of Unit 2, students will be able to:

- Describe and differentiate between displacement, velocity and distance.
- Be able to compute velocity, distance or time, knowing any two of the three variables.
- Differentiate between speed in knots and miles per hour and be able to convert both to feet per second.
- Understand and utilize the kinematic equations to calculate distance needed for takeoff using either the average velocity or acceleration method.
- Understand and describe the Lift equation in general, and specifically describe each parameter along with its corresponding units.
- Describe and differentiate between airplane pitch, flight path angle and angle of attack.

- Prepare a flight test plan to include; Title, Test Purpose, Data Required, Airplane Configuration and Test Procedure.
- Set up X-Plane to conduct advanced takeoff testing varying parameters associated with the lift equation.
- Predict the required runway length, in general terms, based on changes to takeoff parameters.
- Utilize the software DatPlot to create properly formatted time history strip charts of their takeoff tests.
- Analyze time history data of their tests for reasonableness and consistency.
- Prepare summary charts that plot runway distance vs. manipulated variable.
- Compare the predicted distance with the actual takeoff distance and make inferences as to the accuracy of the prediction.
- Identify possible issues with the test data and determine if it can be used or needs to be re-flown.
- Prepare a Flight Test Report that includes: Title, Test Purpose, Data Required, Airplane Configuration, Test Procedure, Test Results summary, Summary data plots and Conclusion.

Unit 3 Climb Testing

At the conclusion of Unit 3, students will be able to:

- Understand and describe the Drag equation in general, and specifically describe each parameter along with its corresponding units.
- Describe and differentiate between the two types of drag, induced and parasitic as it relates to angle of attack.
- Develop a climb test flight test plan.
- Conduct a series of climb tests to determine the airspeeds to fly for optimum rate of climb and best flight path angle.
- Recover flight test data and create time history strip charts.
- Identify possible issues with the test data and determine if it can be used or needs to be re-flown.
- Plot summary results of climb performance and airspeed.
- Analyze results and draw conclusions from the data.
- Prepare a climb test flight test report that identifies the airspeeds to fly for optimum rate of climb and best flight path angle.

Unit 4 Cruise Testing

At the conclusion of Unit 4, students will be able to:

- Develop a cruise test flight test plan.
- Conduct a cruise flight test to determine airspeeds to fly for maximum duration and range.
- Recover flight test data and create time history strip charts.
- Identify possible issues with the test data and determine if it can be used or needs to be re-flown.
- Plot the summary results of cruise performance and airspeed.
- Plot a Lift/Drag curve vs. airspeed curve.
- Analyze results and draw conclusions from the data.
- Prepare a cruise test flight test report and include L/D curve and identify airspeeds to fly for maximum duration and range.

Unit 5 Apple Challenge

At the conclusion of Unit 5, students will be able to:

- Measure distance between two cities by referring to either paper or digital maps (charts).
- Develop a flight plan that uses flight test data for the optimum climb and cruise speeds.
- Determine the amount of fuel to be used for the desired route.
- Determine the correct aircraft loading to include fuel and reserves, pilot and apple payload.
- Fly the flight plan and evaluate how close their estimate of fuel usage matched predictions.
- Recover flight test data and create time history strip charts.
- Identify possible issues with the test data and determine if it can be used or needs to be re-flown.
- Plot the summary results of the Apple Challenge.
- Prepare a Flight Test Report of the Apple Challenge testing.

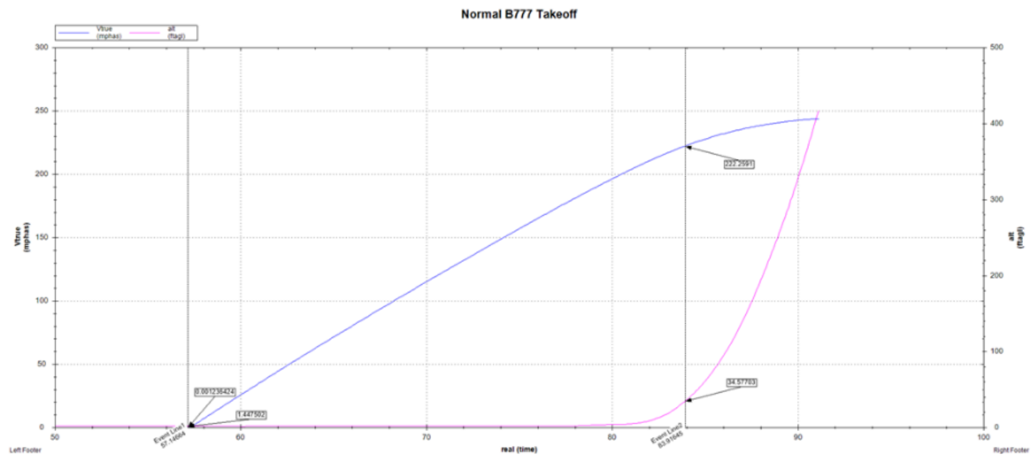
Math Connections

The connections to math concepts associated with these projects is important, not only just for practice in calculations, but primarily in the validating of the test results against the theory. Here are some other specific examples.

- The concept of velocity is introduced and used as an important factor in determining takeoff distance and in its effects on lift in the lift equation.
- The conversion of units, specifically miles per hour => feet per second is required to obtain the runway distance in the correct units of feet.
- Distance calculations can be made using average velocity where velocity can be assumed to be linear; distance equals average velocity multiplied by time: $d = V_{ave}*t$, where $V_{ave} = (V_f + V_i)/2$
- Distance can also be arrived at by using acceleration: distance, $d = ½at^2$, where a, acceleration is determined by: $a = \Delta v/\Delta t$. Coupling this with another useful concept that the slope of the velocity plot equates to acceleration is another useful method to reinforce linear equation concepts.
- Introducing the lift equation, $L = \frac{1}{2}\rho S V^2 C_L$, is important in understanding the parameters that affect lift. For example, knowing that the lift generated by the wing must equal the weight of the airplane for lift off, will illustrate to students the need to increase some variable in the equation to produce the extra needed lift for a heavier airplane. For example, increasing either velocity, wing area or the Coefficient of Lift, C_L will increase lift. In another example, adding flaps will increase both wing area, S, and C_L. Advanced students can explore how air density affects lift by testing various airport temperatures or elevations. Other factors such as headwinds and thrust settings have a direct relationship to runway distance and test results can readily illustrate that.
- Introducing the drag equation, $D = \frac{1}{2}\rho A V^2 C_D$ that includes the concepts of both induced and parasitic drag.
- Concluding with a real-life capstone project called the 'Apple Challenge' that requires detailed flight planning using students climb and cruise flight test data for use in developing that flight plan and then to flight test the transport of the maximum payload of apples between two places.

Example Calculations

The example below demonstrates the steps in reducing the flight test data from the takeoff testing into runway distance. The plot below is of just two variables, speed and altitude, against time (in seconds). From these two parameters, runway distance can be determined by selecting the times associated with the start and end of the takeoff, in this case the end was determined to be when the airplane reached an altitude of 35 feet. The example below used DatPlot as the charting software.



Average Velocity Method Example Steps:

1. Plot True Airspeed and Altitude above ground vs time in seconds
2. Add Event Markers for the takeoff start and at 35 feet to obtain numeric values of airspeed and altitude at these times. Obtain appropriate times for both start and end.

Calculate Average Velocity as follows:

a. Convert MPH to ft/s for the ending speed (assume starting speed is zero)

i. 222 MPH = 325 ft/s

ii. Determine delta velocity => Δv : (325 – 0) = 325 ft/sec

b. Determine delta time => Δt : (83.9 - 57.1) = 26.8 sec

c. Determine average velocity => (0 + 325)/2 = 162.5 ft/sec

3. Calculate distance as follows:

a. Calculate distance => d =(Ave Velocity) * delta time = (162.5 ft/sec) *(26.8 sec) = 4355 ft.

Acceleration Method Example Steps:

1. Plot 'True Airspeed' and 'Altitude above ground' vs time in seconds
2. Add Event Markers for the takeoff start and at 35 feet to obtain numeric values airspeed and altitude at these times. Obtain appropriate times for both start and end.
3. Calculate acceleration as follows:

a. Convert MPH to ft/s for the ending speed (assume starting speed is zero)

i. 222 MPH = 325 ft/s

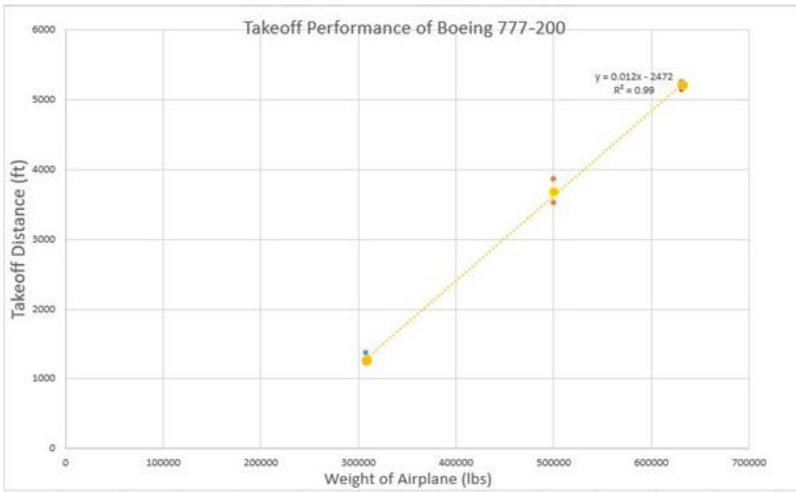
ii. Determine delta velocity => Δ *v:* (325 – 0) = 325 ft/sec

b. Determine delta time => Δ*t*: (83.9 - 57.1) = 26.8 sec

c. Determine acceleration => Δ *v*/Δ*t:* (325-0)/ (26.8) = 12.1 ft/sec^2

4. Calculate distance $d = ½at^2$ => ½* 12.1 * $(26.8)^2$ = 4345 ft.

These steps are repeated for the remaining takeoff tests and then summarized in a chart. Such an example is the one below done in Excel by a ninth-grade student. Notice that the results fit nicely with the theory that the heavier the airplane, the more runway it requires to takeoff. Other important attributes of the data points are they being in tight patterns signifying consistent testing methods and results with no significant outliers.



Abbreviations

The following abbreviations will be used throughout this study guide.

A	Reference area
AOA	Angle of Attack, degree
a	Acceleration; $a = \Delta v/\Delta t$
C_D	Coefficient of Drag, dim
C_L	Coefficient of Lift, dim
d	distance
$d = V_{ave}*t$,	distance
$d = ½at^2$,	distance
$D = \frac{1}{2}\rho A V^2 C_D$	Drag equation, force

$L = \frac{1}{2}\rho S V^2 C_L$,	Lift equation, force
S	Wing area
v	velocity
V_f	final velocity
V_i	initial velocity
$V_{ave} = (V_f + V_i)/2$,	average velocity
t	time in seconds
ρ	air density

Unit 1 - Basic Takeoff Testing

In Unit 1, students with little or no experience with airplanes, flying or X-Plane are provided with information that will allow them to conduct meaningful takeoff flight testing. There are also instructions on how to set up and use the software program X-Plane.

This Unit starts off with an introduction to the branch of engineering called flight test engineering and then introduces: Parts of the airplane, Airplane axis, Cockpit instrument familiarization, Forces of flight and X-Plane instructions and demonstrations. The simulation software, X-Plane, is introduced and steps are provided on how to set it up for a takeoff test including recording the required flight test data and reviewing the resulting X-Plane distance. Students then conduct their own takeoff tests varying the total weight (gross weight) of the airplane looking for changes in the runway distance needed for takeoff and making inferences as to why.

1-1 Flight Test Engineering

Lesson 1-1 Flight Test Engineering

Flight test engineering is a branch of aeronautical engineering that pertains to the ground and flight testing of aircraft. The following lesson plan outlines the general activities in their proper order along with an estimate of the duration.

Lesson 1-1 Title: Introduction to Flight Test Engineering

Objective: Discover the role aerospace engineers play in the testing of new airplanes

Supplies Needed: Slides, notebook

Item	Running Time (min)	Est Time (min)	Explore Engage Evaluate	Lesson Activity
1	2	2	Explore	Lesson Introduction
				Introduction to Flight Test Engineering
2	10	8	Explore	Engineers as Designers slides
3	18	8	Explore	Reasons for Flight Testing slides
4	23	5	Explore	Flight Test Video slide
6	28	5	Engage	Student Discussion

6	33	5	Explore	Activities of Flight Test Engineers and Pilots slide
7	35	2	Evaluate	**Summary**
8	50	15	Engage	**Student Activities**
9	52	2	Explore	**What's Next**
				End of Lesson

Introduction to Flight Test Engineering

Engineers use the laws of nature and by using math and science, apply them to practical applications to solve real world problems that make our lives better. They design and build what others dream of. Currently the technological issues that face society now such as cleaner energy, faster communications etc. are being addressed by engineers now.

Flight test engineering is a small branch of aeronautical engineering that tests and evaluates new airplane designs. Where most aeronautical engineers work designing new airplanes, this group is tasked with evaluating those designs. Most, but not all, flight test engineers and flight test pilots have either aeronautical or mechanical engineering degrees. Flight test engineers that design and install the instrumentation on the aircraft used in flight, generally have electrical engineering or computer science backgrounds.

In general, flight test engineers plan and conduct aircraft flight and ground tests, they record and analyze test data and compile test reports and make pass/fail decisions as to the test results.

Airplanes are designed to industry standards, but designers cannot foresee every possible situation the design could experience during a lifetime of flight. When failures occur, it could be to a variety of causes, some of which could be due to the design. Errors in the design could be due to incorrect assumptions, wrong design criteria, normal mistakes or unforeseen circumstances.

So, it is for these reasons that the design is tested in flight over a wide range of flight and environmental conditions. The testing needs to be done on a vehicle with data recording capability so that sensor data can be analyzed and reviewed both during the flight and afterward. Testing needs to be done safely with a trained flight test crew that can deal with both system design failures as well as normal flight failures. Test data is then reviewed and feedback to the design group is provided for improvements and/or changes. The cycle is then repeated.

Look at the picture below of a unique aerospace vehicle. Will this fly?

To answer this question, engineers and scientists have several tools at their disposal to use. First and foremost being their prior experience. What worked well in the past is usually a good starting point for a new design or a change in design. For example, the Boeing 737 was originally built in the 1960's but has had several re-designs over the years that have made incremental improvements that result is that the current models being produced do not have many features in common to that of the original.

In addition to prior experience, engineers solve design problems in three basic ways. The first way, and what non-engineers generally think, is that there is an empirical formula to use for every problem and by plugging numbers into it, the correct answer will result (i.e. $F = ma$). Unfortunately, this is not often the case. Formulas are used a lot, typically for the more details of the design.

An ever increasing and important tool for evaluating is using computer modeling or simulations. This is becoming more and more prevalent due to the advancement in computing capabilities. The computer can rapidly calculate many possible outcomes in a very short time, enabling designers to evaluate their design to the criteria they have. The drawback to this method is that the mathematical or computer model needs to reflect both the actual design but also the actual environment it will operate in that includes accounting for all the inputs/outputs of the system. Any errors in the model will adversely affect the outcome of the results. Other source of errors in simulation modeling is when incorrect assumptions are made in the design of the simulation. The model needs to be properly validated, with corrections rolled back into the simulation model and re-validated. It is then that the simulation can be correctly utilized.

The third method is experimentally. Performing the 'experiment' removes many of the ambiguities and doubts from computer modeling due to the fact that the real equipment is being used in the real environment with the real input/outputs eliminating many previous assumptions. This is what happens in flight test. Flight testing is 'performing the experiment' this time with a flying airplane. In many cases, flight testing is the only method to evaluate whether the new airplane or change meets the design requirements. This is because in the lab or doing simulations doesn't account for all the variables that the airplane will experience in flight. The downside of flight testing is that it is very expensive compared to the other methods so there is much pressure on the flight test organization to reduce the amount of testing to the absolute minimum.

For companies large and small, engineers use a combination of all those methods; prior experience, empirical, modeling and flight and lab testing to evaluate their designs. But in some cases, it is easier to 'perform the experiment' than to develop a satisfactory computer model for the simulation. So, the for the airplane pictured above, it was easier to throw it and see what happened. Go ahead and try it out for yourself.

Another important reason for flight testing is that the FAA (Federal Aviation Administration) requires flight testing as the only acceptable method of compliance for some of their regulations. Although they do accept other methods such as an analysis or simulation for many of their regulations, they acknowledge that in some cases, flight testing in the actual environment as only way to prove its airworthiness and be permitted to be ‘certified’. Certification allows the new airplane or component such as new hardware or software etc. to be permitted for airline use.

Another reason for flight testing, especially for a new model airplane, is to obtain flight test data to be able to create and compile the airplane’s ‘owner’s manual’. These are called either flight manuals or pilot operating handbooks (POH). Examples of useful information contained within the POH for pilots to use are; tables that specify the length of runway needed to takeoff or landing for various airplane weights, airport temperatures and elevations. Other useful information within the POH is data on how far the airplane can fly on a tank of fuel, called range information. All this information contained in the POH was obtained through flight testing the airplane.

Flight Testing Video

The following YouTube video, published by The Boeing Company, takes you behind the scenes of a flight test organization and shows some of the more dramatic flight tests. Most of the flight tests are very routine, steady state flight conditions, like what you would experience on a commercial flight. But there are some maneuvers that tests the extreme limits of the airplane in areas such as maximum speed, minimum speed, engine and other failures etc. In fact, some of these maneuvers appear to ‘abuse’ the airplane, but they are needed to validate the airplanes performance in these specific areas as simulations alone cannot adequately determine the outcome.

There is some associated risk with all flight testing conducted on new airplanes. Before the airplane design is fully validated, flight test engineers must assume something may fail or go wrong. Much effort is expended on finding a safe way to perform these tests. An evaluation of the associated risk along with its likelihood of failure are key components to the risk analysis. Once this is determined, then appropriate alleviations can be set in place to reduce the overall risk to the test crew.

You will see several different flight tests and explanations by the test engineers.
Testing a dream: An in-depth look at Boeing 787 flight test - YouTube

Typical Activities of a Flight Test Engineer

It takes a lot of effort to conduct flight tests such as the one seen in the video. But for every hour of flight testing, many more hours were spent on the planning of those tests beforehand. Planning includes activities such as; creating the test plan that will be the ‘script’ that the pilot will follow on the flight, specifying and installing the sensors and instrumentation to record and display the test data in flight, schedule the testing in an optimized order, configure the airplane with the proper equipment, software, fuel weight, center of gravity etc., analyze data both during the flight and afterward and then compile test reports to document the tests and results.

Typical Activities of a Flight Test Pilot

Test pilots are active participants in the airplane design and are often consulted early on in the design especially when choices are to be made with respect to the human/machine interface with systems in the flight deck.

Other activities of a flight test pilot compare with those of the flight test engineer in that many more hours are required for the test planning portion then the actual flying portion. Here are some of those activities; pilots perform the airplane maneuvers as called out in the test plan to collect the required data, they verify that the airplane can be flown in both normal and non-normal conditions without exceptional skill or effort, they also 'teach' the airplane, autopilot, flight control systems to 'fly' like a pilot would, by providing feedback on the software back to the design engineers, and then trains other pilots on how to fly that new airplane.

How to Become a Flight Test Engineer or Pilot?

There are only a few colleges that teach flight test, although some flight test pilots and engineers graduate from military or civilian test pilot schools. But most FTEs learn their trade on-the-job from experienced engineers and pilots at an aircraft manufacturing company. Experience in flight testing from a large aircraft manufacturer is how most flight test engineers learn their trade. The larger the company, the larger the flight test department usually is. Smaller companies can have the test pilot do both roles.

Here are some suggested student activities

- Describe how flight testing promotes airline safety.
- Describe a flight test maneuver shown in the video and why it was conducted.
- Research career fields for flight test engineers and pilots.
- Where do they go to school and what degrees did they get?
- Where specifically can you get trained to flight test?
- What companies hire flight test engineers and pilots?
- Does the government hire flight test engineers and pilots?
- Research takeoff and landing distances in a Pilots Operating Handbook, POH, for a particular airplane and determine, for the same conditions, which takes more runway, takeoff or landing.
- Visit the following flight test engineering professional societies web sites:
  - Society of Flight Test Engineers, SFTE www.sfte.org
  - Society of Experimental Test Pilots, SETP www.setp.org
  - American Institute of Aeronautics and Astronautics, AIAA www.aiaa.org

Airplane Basics

In this series of lessons, students will learn about parts of an airplane, the three axis the airplane rotates about and how to read the cockpit instruments. An introduction to the forces of flight as well as the basics of X-Plane are presented. Students then conduct their first takeoff tests.

1-2 Airplane Anatomy

Lesson 1-2 Airplane Anatomy

In this section, you will learn about parts of an airplane, the three axis the airplane rotates about and how to read the cockpit instruments.

Flight Test Academy Lesson Plans

Lesson 1-2 **Title**: **Airplane Anatomy**

Objective: Understand the major components of the airplane and their purpose.

Supplies Needed: Slides**,** Balsa glider, paper, scissors, notebook

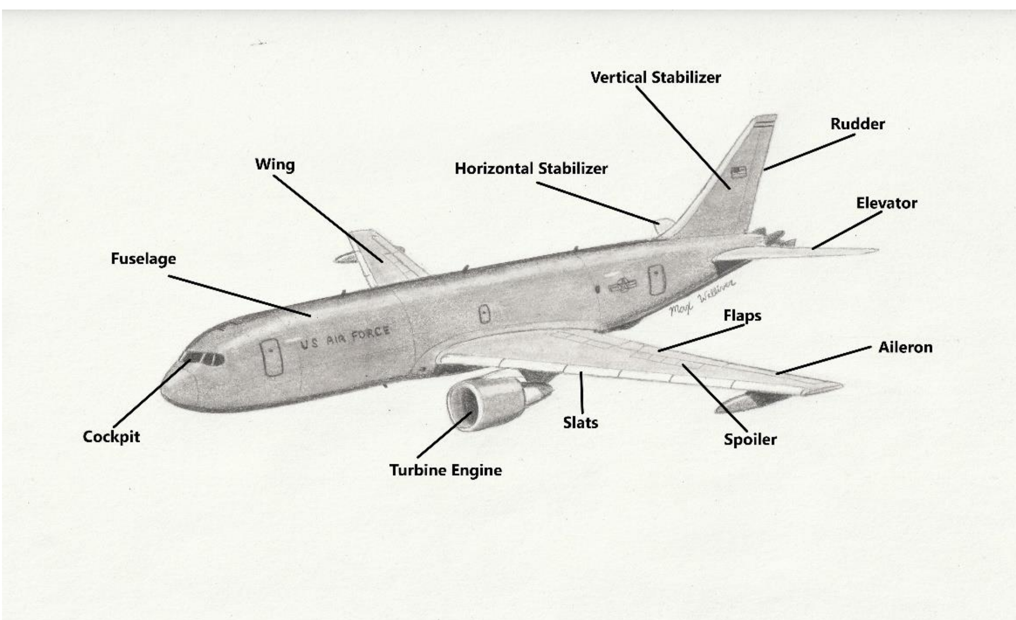
Note: Students will be building and throwing balsa and paper airplanes in this lesson. Ensure this is done in a large enough area so that it can be done safely.

Item	Running Time (min)	Est Time (min)	Explore Engage Evaluate	Lesson Activity
1	2	2	Explore	Lesson Introduction
2	4	2	Explore	Project Roadmap slide
				Parts of Airplane
3	6	2	Explore	Parts of Airplane Slides
4	21	15	Engage	Activity - Balsa Airplane Glider
5	36	15	Engage	Activity – Paper Airplane Glider
6	39	3	Explore	Flight Controls On Ground Movie slide
				Airplane Axis
7	41	2	Explore	Airplane Axis slides

8	44	3	Explore	Flight Controls Inflight Movie slide
9	47	3	Engage	Activity – Flight Controls
10	50	3	Evaluate	Assessment – Airplane Axis
				Cockpit Familiarization
11	60	10	Explore	Cockpit Familiarization Slides
12	72	12	Engage	Activity – Reading Flight Instruments (4)
13	74	2	Evaluate	**Summary**
14	80	6	Evaluate	**Discussion Questions**
15	82	2	Explore	**What's Next**
				End of Lesson

Parts of an Airplane

An airplane is comprised of several major parts that are common amongst several airplane types; general aviation, military or commercial. These airplane parts serve specific purposes and need to be designed to all work together. They are sized and located at specific locations to allow the airplane to be stable in flight. Review the diagram and table below to familiarize yourself on the parts of an airplane. Note: Smaller airplanes may not have all the parts as depicted in this military transport aircraft below.



Airplane Part	Function
Fuselage	The center section that holds the passengers
Wings	The long and slender sections that attach to the fuselage and produce the lift needed for flight.
Engines	These motors either in the forward fuselage or out on the wings produce the thrust needed to propel the airplane forward.
Cockpit/Flight deck	This is at the forward part of the fuselage and is where the pilots sit and control the airplane.
Vertical Stabilizer	Located at the rear of the fuselage, the vertical stabilizer is a wing-like structure pointed up.
Rudder	The rudder is the movable airfoil mounted behind the vertical stabilizer that yaws the airplane left and right about the vertical axis.
Horizontal Stabilizer	Located at the rear of the fuselage, the horizontal stabilizer is a wing-like structure aligned parallel with the wings.
Elevator	The elevator is the movable airfoil mounted behind the horizontal stabilizer that pitches the airplane up and down about the lateral axis.
Aileron	These movable surfaces are located near the rear outboard portion of the wing and work together to roll the airplane in a left or right bank about the longitudinal axis.
Landing Gear	These are the wheels that support the airplane on the ground. They may be retracted in flight to reduce drag or for smaller airplanes, are left down.
Flaps	Flaps are extensions of the wing along the rear of the wing that extend both rearward and down to produce more lift and also drag. They are extended for takeoff and landing and then retracted in cruise flight.
Slats	Slats can sometimes be seen at the leading edge of the wing on larger airplanes and when extended, together with the flaps, produce more lift for takeoffs and landings.
Spoiler	Located on the top of the wing, the spoilers are flat panels that rotate up to slow the airplane and to reduce lift. These are used on landings at touchdown.

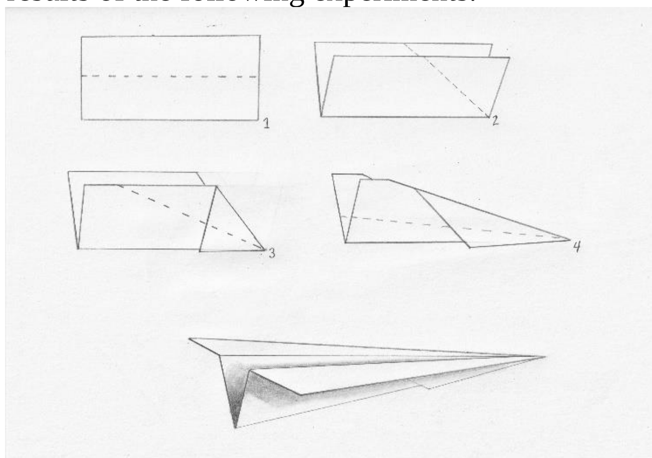
Balsa Airplane Activity

Put together your balsa airplane and then draw and label each piece. Can you identify the following list of parts: Cockpit, Wing, Vertical Stabilizer, Horizontal Stabilizer?

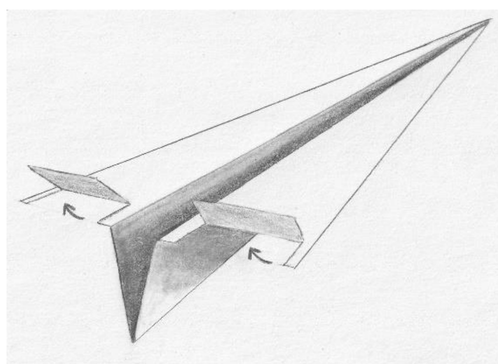
After you put your balsa airplane together so that it flies as level as possible, now take off the horizontal and vertical stabilizers, in turn, and try to fly the glider. What happens? Note the differences in your notebook. Can you infer what the purpose of these aircraft parts are used for and why?

Paper Plane Activity

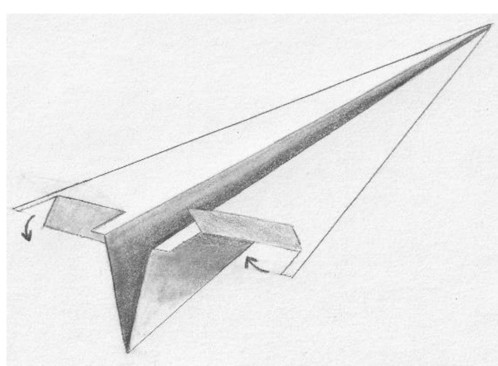
Make a paper airplane out of a sheet of paper as illustrated in the picture. Ensure that it flies straight and level. Take notes of the results of the following experiments.



Cut out the elevators as shown below and fold them up. Now fly it, what happens? Fold them down and fly it, what happens now? Record your findings.



Now fold them in an alternating configuration and fly it. What happens now? Reverse the surfaces and fly it, what happens now? Record your findings.



Can you now relate the orientation and location of these 'flight control surfaces' and their effect on aircraft flight?

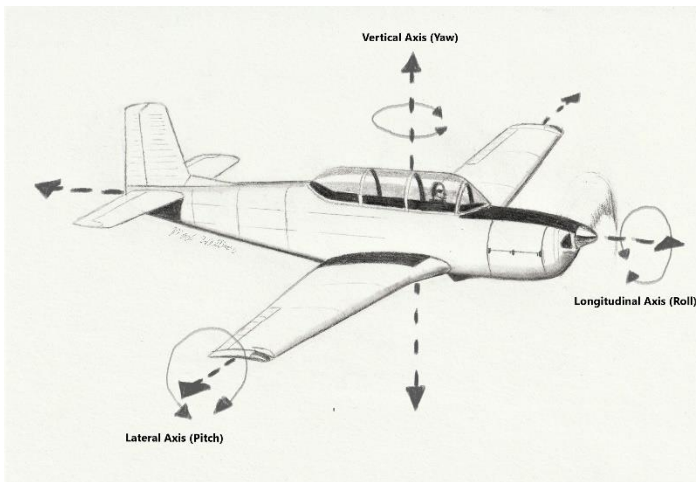
Airplane Axis

The Wright Brothers were engineers before they were test pilots

One of the many accomplishments of the Wright Brothers in the design of the airplane was the recognition that control and stability of flight were key components that would need to be incorporated in the design to successfully and safely obtain controlled flight.

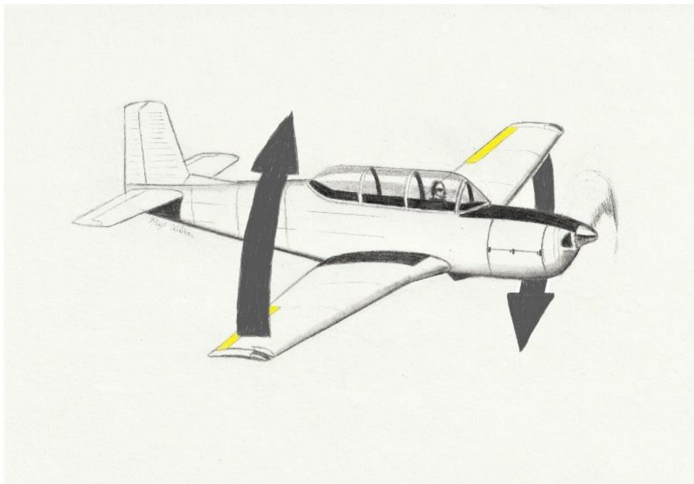
This recognition lead to the understanding of the three axis of rotation needed for flight called; pitch, roll and yaw. Each of these axis of rotation defines a separate 'degree of freedom' that needs to be controlled. This then led to the development of the three rotational axis of vertical, lateral and longitudinal.

Review the diagram below and identify the three rotational axis and the three axis of flight.

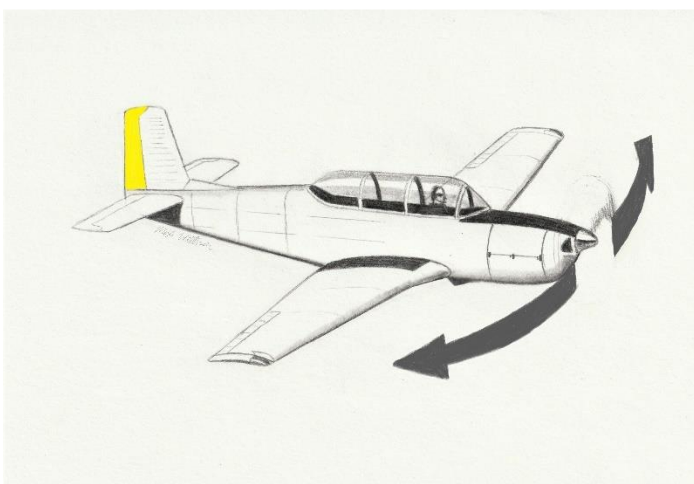


Pitch is described as the 'up and down' motion the airplane does as it rotates about the lateral axis. Adjusting pitch is useful when the pilot wants to have the airplane climb, dive or maintain level flight. The pilot moves the control column (or joystick) back or forward, that moves the elevator, to adjust the pitch to either climb or descend to maintain the desired flight angle as shown in the diagram below.

Roll is the banking of the airplane either left or right about the longitudinal axis and is used when the airplane turns. Rolling in an airplane is not the same as making a turn in a car. The roll the airplane makes in a turn can be compared to a bobsled race on an icy track where the sled banks to up to 45 degrees into a high speed turn allowing them to stay on the track and not slide off to the side (due to centrifugal force). To roll an airplane, the pilots moves the column (or joystick) to the left or right, that moves both ailerons in opposite directions, to make the airplane bank in the desired direction. Roll is used to initiate a turn and come into a bank, then again as the pilot 'rolls out' to stop the turn to maintain the bank angle and repeats the maneuver in the opposite directions to return to wings level flight. See the diagram below of the roll axis.



Yaw is the 'left and right' rotation about the vertical axis and is used in conjunction with roll when completing a turn. This allows a smooth and comfortable motion so that passengers don't feel like they are sliding in the seat in the turn, like you would experience in a car. The pilot uses rudder pedals with their feet to adjust yaw, that moves the rudder. Yaw is usually only needed when making a turn, on takeoff, on landing in crosswind conditions and when an engine fails (on multi-engine aircraft). See the diagram below for yaw.



Student Activity

Here are some exercises to do to reinforce the concept of airplane axis.

- Using your hand as an airplane, move your hand corresponding to each of the airplane axis of pitch, roll and yaw.
- Put your balsa glider together and move the airplane to correspond to each of the airplane axis of pitch, roll and yaw.
- Start up X-Plane and while your airplane is stationary on the runway, select the Chase view (a) and then click your mouse near the tail of the airplane to get a ‘control box’. Use your mouse inside the control box to move up/down and left/right. Describe what you are seeing. You should see the part of the tail called the elevator move up/down. When moving left and right, you should see the ailerons on the outer portions of the wing move (in opposite directions) along with the nose wheel, corresponding to your mouse inputs.

Cockpit Familiarization

Below is a screen shot of the cockpit of a Cessna 172, a very popular four seat general aviation aircraft that you will be using in X-Plane. As you can see the cockpit has many instruments. All of those ‘dials’ are instruments, and all have a unique purpose, but for our exercises, we’ll just focus on the six basic flight instruments listed below and located in the center of the instrument panel.

Cessna 172 Cockpit

Below are the six main basic flight instruments that we will discuss individually. Notice that they are situated in the center of the instrument panel and are generally in the same relative position from airplane model to airplane model. This standardization is to allow pilots to fly many different types of airplanes without a lot of re-training and re-learning.

Basic Flight Instruments

Airspeed Indicator

The airspeed indicator, shown below, measures how fast the airplane is traveling through the air. It works by measuring the impact air pressure from a horizontal tube outside the airplane called the ‘pitot tube’. Airspeed can be measured in units of either miles per hour or in the case below, knots, or nautical miles per hour. In the example below the range is from 40 to 200 knots. Notice colored markings on the outer circle of the instrument. These are indications to the pilot of areas of either going too slow or too fast. This important information is readily available to the pilot and is easier than having to look up those values in the pilots operating handbook (POH). What airspeed is the instrument below indicating?

Artificial Horizon

The artificial horizon provides the pilot an indication of the airplanes attitude referenced to the horizon. This is very useful for when the pilot cannot see the visual horizon outside the window because the pilot always needs to be able to see either the natural or artificial horizon to keep the airplane flying at the correct attitude, very useful for flying in the clouds. The instrument measures pitch and bank (roll) and is displayed in degrees either up/down or left/right. What is the airplane attitude in the picture below?

Altimeter

The altimeter measures the altitude the airplane is flying at in relation to sea level. The reason sea level is chosen is for two reasons. The first reason is that it is a universal value that has meaning no matter where or above what, you are flying. The second reason is in how the instrument works. It works by measuring the difference in pressure between sea level pressure and the static pressure where the airplane currently is. Keeping in mind that static air pressure decreases as you climb.

The units are feet above sea level and, in the example, below, the range is from zero to 10,000 ft, which is typical of a general aviation aircraft. Commercial and military airplanes have a much higher range.

Although the newer digital variations, display a numeric altitude straight out, this older analog version shown below is read like a clock, with a *big hand* and a *little hand*. In the example below, the *little hand* indicates the number of 'thousands of feet', being somewhere between one and two thousand. The *big hand* indicates 'hundreds of feet' and looks to be between two and three hundred feet. When you add the two, after interpolating, you get an altitude of approximately 1000 + 220 = 1,220 ft.

Directional Gyro

This directional gyro instrument or DG, as it is sometimes called, measures the aircrafts heading with respect to magnetic North. It provides the pilot the direction the airplane is going and is critical for accurate navigation. Like a compass, the units are in degrees and range from 0 to 360. North is indicated as either 'N' or '0' or '36'; South is indicated as either 'S' or '18'; East is indicated as 'E' or '9' and West is indicated as 'W' or '27'. Note that in all cases, the last digit of zero in the heading is omitted for readability. In the example below, the airplane is flying a heading of 150 degrees, approximately southeast. If the pilot needed to fly a new heading of 180, she would make a right turn to acquire and hold that new heading.

Vertical Speed Indicator

The vertical speed indicator (VSI) measures the aircrafts climb or descent rate in units of ‘feet per minute’. It is usually displayed in hundreds of feet per minute, either up or down. The example below is indicating a 1000 ft/min climb. You will note that in actual flying, this instrument lags the airplane actual flight condition because of its construction making it difficult to maintain a constant altitude. To do that, the pilot uses the artificial horizon to level the aircraft and the reference the VSI after the correction. The VSI can be used as a reference to the magnitude to the either climb or descent and should only be read during a steady maneuver.

Tachometer

The tachometer measures the rotational speed of the engine, like an automobile’s engine. The units are in revolutions per minute (RPM) and have a typical range, for piston engines, of zero to 3000 or so. Included on the instrument are markings on the outer ring to indicate to the pilot the correct operating ranges.

For jet engines, indication of the actual RPM of the engine is not necessary as useful to the pilot in a piston engine. Since jet engines turn at thousands of RPMs and vary from engine type and manufacturer, another display method needed to be developed. To make it simpler for the pilot to know if the engine is at full speed, half speed or at idle, the indication is scaled and displayed in %RPM. For example, at 100%, the engine is at full speed or maximum RPM, whereas at 75% would indicate a somewhat reduced power level, three quarters, a more useful indication of engine speed. Another change for jet engines is that it is not called a tachometer per se, but rather N1, an identification of the fan section of the turbine engine. If there are more than one engine, that would be indicated by another digit added to the indication such as N11 for N1 for Engine 1 and N12 for N1 for Engine 2.

Reading the Instruments Activity

Look at the cockpit below and read and record the airplane state in terms of the flight instruments. Compare your results to the answers below.

Airspeed	94 kts
Attitude	Nose and wings level
Altitude	1050 ft
Heading	130 deg
Vertical Speed	100 fpm descent

Discussion Questions

- In terms of airplane axis, compare the experiences of riding in a car and flying in an airplane.
- Compare the instrument panel of an airplane to that of a car.

1-3 Airplane Forces

Lesson 1-3 Forces of Flight

In flight, there are always four forces of flight acting on the airplane. They are lift, weight, thrust and drag.   The reason an airplane gets and stays in the air is due to the forces it experiences and is the topic of this lesson.

Flight Test Academy Lesson Plans

Lesson 1-3   **Title**:   **Airplane Forces**

Objective: Understand the major components of the airplane and their purpose.

Supplies Needed: Slides**,** scissors, notebook

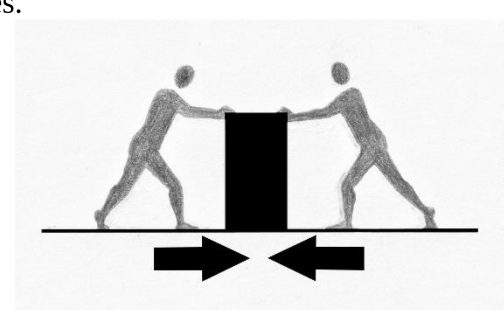
Item	**Running Time (min)**	**Est Time (min)**	**Explore Engage Evaluate**	**Lesson Activity**
1	2	2	Explore	Lesson Introduction
2	4	2	Explore	Project Roadmap slide
				Balanced and Unbalanced Forces
3	6	2	Explore	Balanced Forces slide
4	8	2	Explore	Unbalanced Forces slides
5	10	15	Engage	Build a Wind vane activity video
6	25	10	Engage	Experiment with Wind Vane
				Forces of Flight
7	35	10	Explore	Airplane Forces Slides
				Units
8	39	4	Explore	Unit slides
9	41	2	Evaluate	**Summary**
10	43	10	Evaluate	**Discussion Questions**

11	53	2	Explore	**What's Next**
	55			**End of Lesson**

Balanced and Unbalanced Forces

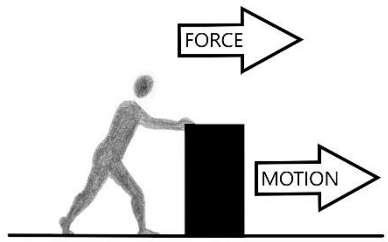
But before we discuss the forces of flight further, we'll need to investigate what a force is. A force is a 'push' or a 'pull' on an object that results in a motion of that object, if that motion is not opposed. Force has both size (magnitude) and direction (vector) associated with it to describe where the force is being applied and how much. For example, pulling a wagon. Since there is nothing holding back the wagon, it will move in the direction of the applied force (your arm) for as long as you pull it. The wagon moved because the pulling overcame any resistance from the wheels on the road. This is called an 'unbalanced' force. It is unbalanced because there is no (or little) opposing force stopping the wagon. The result of an unbalanced force is usually motion in the direction of the force.

Now let's talk about 'balanced' forces, for example a book sitting on a table. In this example, the weight of the book is creating a downward force due to gravity, and the table is 'holding up' the book because of its structure, resulting in no up/down motion of the book. The forces are in balance resulting in no movement in the book. Other examples of balanced forces are two children in balance on a 'teeter totter'. Another is in the game of 'tug of war' where two children are pulling on a rope equally and the rope between them is not moving. Another example is in the picture below of two people pushing on a box with equal and opposite forces.



Let's look at a box being pushed across the ground. In the beginning, there is an initial unbalanced force that causes the box to move from its stationary position. Friction is a force that opposes the motion of an object since there are no perfectly smooth surfaces and the rougher the surface is, the more friction there is between them. Also, heavier objects produce more friction than lighter ones. Friction also produces heat as the two surfaces are warmed by the interaction.

But now the box is traveling at a constant speed. This can be both seen and measured. If the force of the 'push' and the friction were measured, we would find that they were the same, but just in opposite directions. In this case the forces are 'in balance', but the box is still moving? It is true that for forces to be in balance, there can be either no movement, or as in this case, constant movement (speed). Forces are also in balance when there is no change in the speed (velocity) or direction of the object.

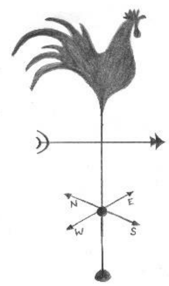


The concepts of balanced and unbalanced forces were developed by the famous English scientist Sir Isaac Newton and are better known as Newton's First Law of Motion. This law states that every object will remain at rest or in uniform motions in a straight line unless an external force causes it to change its speed or direction. Stated otherwise, objects at rest tend to stay at rest and objects in motion tend to stay in motion, unless they are acted upon by other forces. This is also taken as a common definition of the property of inertia.

Wind Vane Activity

To visualize balanced and unbalanced forces, let's build a wind vane. You will need a pencil with an eraser, a drinking straw, stick pin, an index card and some scissors. Put it together as shown in the picture below. Notice that it looks like an arrow. The arrow should be free to rotate smoothly so don't push the pin down through the straw too firmly. Cut slots in the straw to fit the arrow pieces and place the stick pin in the center. Ensure that the square piece is larger than the arrow.

Once you have built your wind vane, hold it up near your mouth and blow on it. Vary the direction of your breath. What happens? Did you see that the wind vane rotates to align with the direction pointing toward your breath? That is exactly what a wind vane indicates. You can see wind vanes all around, on top of houses, poles, weather stations etc. The arrows are pointing in the direction the wind is coming from and is important information in the understanding of changes in the weather. Here is another example you may have seen before. Windsocks at airports are examples of a wind direction indicators, because a pilot needs to know which way the wind is blowing for takeoff and landings.



Now can you explain why a wind vane works in terms of balanced and unbalanced forces? Try making another arrow, but this time, much larger that the tail. What happens when you blow on it now? What does it do and why?

The reasoning is that by blowing on both ends of the wind vane results in more force applied to the larger square piece then the smaller triangle piece, due to the larger area. This creates an unbalanced force on the wind vane, pushing the larger section out of the way and rotating to align with the wind, where the forces become balanced, allowing the wind vane to become stable. The larger 'tail' is why wind vanes point towards where the wind is coming from. There are direct parallels of this concept in airplane tail surfaces and the fins on rockets and hunting arrows.

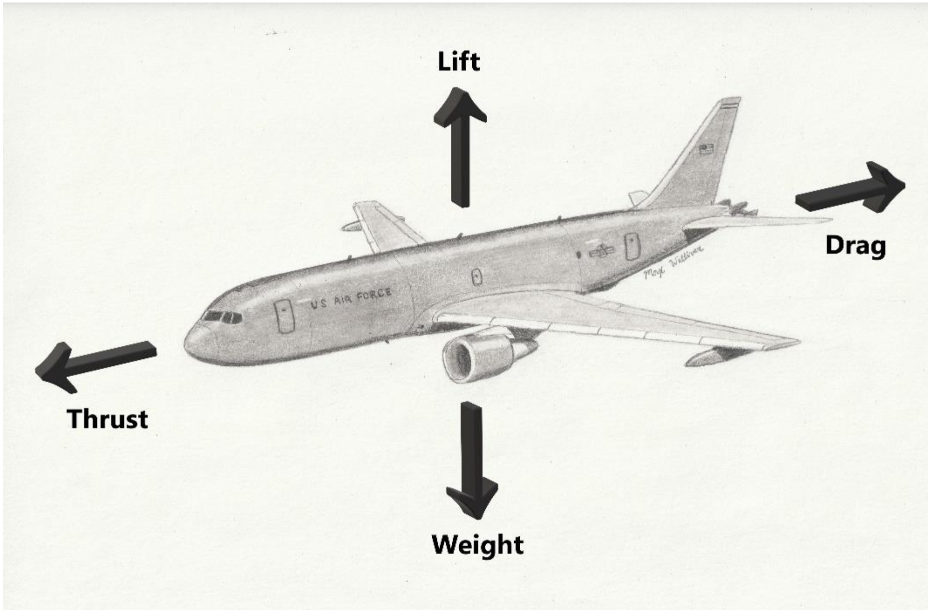
Forces of Flight

Now that we have discussed balanced and unbalanced forces, and participated in a demonstration, let's look at an airplane in level flight at a constant speed. As shown below is a diagram of the forces involved in keeping the airplane in the air. Notice that the four forces come in pairs that are in opposite directions.

Lift is the force generated by the wing that opposes the force of gravity, or sometimes referred to as weight. Both lift and weight must be equal and opposite, if not the airplane will climb or descend.

Thrust is the force developed from the engine/propeller combination that maintains the airplanes speed but is opposed to by the drag of the airplane in an attempt to slow it down. Drag can be thought of as the resistance of the airplane moving through the air. Thrust and drag must also be equal in magnitude to each other but in opposite directions or else the airplane will either go faster or slower.

In the case below, the airplane is in level flight at a constant speed, Lift = Gravity (weight of the airplane) and Thrust = Drag. Since the airplane is maintaining both speed and altitude, we can say that the forces are balanced. If they weren't then the airplane would be either changing speed or altitude. Note: All four forces are not all equal to each other, just the 'pairs' are equal to each other. We will be looking into both Lift and Drag in more detail in later lessons.



When thrust (forward force) of a plane is equal to drag (backward force), there is no change in forward or backward motion and forces are balanced, and its forward speed stays constant.

When lift (upward force) of a plane is equal to weight (downward force), there is no change in upward or downward motion and the airplane flies level at a constant altitude.

Note: With the airplane on the ground, where there is no lift, the weight of the airplane is supported by the landing gear.

Discussion Questions

1. On a takeoff when a plane speeds up. Which is bigger: thrust or drag?
2. In straight and level flight which is bigger? Lift or Weight? Thrust or Drag?
3. In straight and level flight, after flying for several hours, the weight is reduced due to the fuel being burned. What happens to Lift?
4. Are forces balanced or unbalanced for an airplane in straight and level flight at constant speed? Explain.
5. Are forces balanced or unbalanced for an airplane just starting a takeoff? Explain
6. Just at liftoff, where does the weight force move from and to? Explain
7. When you first blow on a wind vane, are the forces balanced or unbalanced? Explain
8. After the wind vane stabilizes, are the forces balanced or unbalanced? Explain

New Terms and Units

The following are some of the names and units of the new terms introduced in this lesson.

Forces (F):	Pounds (lbs.), Newtons (N)
Pressure (P):	Force per unit area; $P = F/A$; lbs./ft^2, N/m^2
Distance (d):	Miles (mile), nautical miles (nm), feet (ft), meters (m)
Speed or Velocity (v):	Miles per hour (mph), feet per second (fps), knots (nautical miles per hour (kts))
Acceleration (a):	Rate of change of velocity; ft/sec^2, m/sec^2 , 'g'

1-4 X-Plane Basics

Lesson 1-4 X-Plane Basics

In this lesson we'll be setting up and using a desktop aircraft simulator, X-Plane to conduct flight testing. This simulator is very capable in performing the flight tests within due to, in part, the data recording capability to be able to record hundreds of parameters at a sufficient sample rate in a file called 'data.txt' and then to be able to download that file and review it in a common spreadsheet program that will allow plots and graphs of the maneuvers to analyze and draw conclusions from.

Flight Test Academy Lesson Plans

Lesson 1-4 **Title**:   **X-Plane Basics**

Objective: Learn to fly the X-Plane simulator and conduct the first takeoff tests.

Supplies Needed: Computer with X-Plane loaded, spreadsheet software, mouse or joystick

Item	Running Time (min)	Est Time (min)	Explore Engage Evaluate	Lesson Activity
1	2	2	Explore	Lesson Introduction
2	4	2	Explore	Project Roadmap slide
				Anatomy of a Takeoff
3	6	2	Explain	How to conduct a takeoff slides
4	8	4	Explore	747-8 Takeoff YouTube Video
				X-Plane Setup
5	12	5	Explain	Setting up X-Plane and Test Plan slides
6	17	5	Explain	Setup and Takeoff Test Video
				Data Recovery
7	22	5	Explain	Data recovery slides
8	27	5	Explain	Data recovery video
9	32	30	Explore	**Students conduct testing**

				Data Analysis
10	62	2	Explain	Takeoff test summary table
11	64	2	Explain	Data summary charts and conclusions
12	66	30	Explore	**Students Create Charts and Perform Data Analysis**
13	96	2	Evaluate	**Summary**
14	98	10	Evaluate	**Discussion Questions**
15	108	2	Explore	**What's Next**
	110			**End of Lesson**

Anatomy of an Aircraft Takeoff

Before we do takeoff flight testing, let's take a closer look on what happens during an airplane takeoff. The procedure is similar for both small and large airplanes, but larger airplanes make it is easier to see the different stages, exaggerated, because it doesn't happen quite so fast.

When the pilot is ready for takeoff and Air Traffic Control has 'cleared' her for takeoff, she accomplishes the following distinct steps:

- Aligns the airplane with the runway
- Sets flaps (if required)
- Sets engine to takeoff power
- Releases the wheel brakes
- Airplane accelerates to a specified 'rotation' speed
- At that speed, she gently pulls the control wheel back to raise the nose wheel off the runway and then holds that attitude.
- Airplane then lifts off, or actually 'flies' off the runway
- Airplane continues to climb

Note that there can be a noticeable time in between the 'rotation' and 'liftoff'. To see the difference between 'rotation' and 'liftoff' look at the referenced video. It is of a Boeing 747-8 conducting a Million Pound takeoff, the heaviest the 747-8 airplane has every flown at. Boeing 747-8's million pound takeoff - YouTube

Look closely at times of 1:50 vs 1:53 and you will see both the 'rotation' and the 'liftoff' as separate events. At 'rotation', the airplanes nose is lifted off while the main landing gear stays in contact with the runway. The airplane is actually 'rotating' about the main gear to arrive at the proper pitch attitude (angle) that will generate the amount of lift required for liftoff. Once that occurs, the weight of the airplane is transfered from the landing gear to the wings and the airplane 'flies' off, or liftoffs the runway.

X-Plane Setup

Prior to conducting testing, X-Plane needs to be set up for the correct airplane, weight, weather and data parameters. This ensures that we are in the proper configuration for the flight test.

Once Xplane starts, it will open up in the previous configuration. For our initial testing, we'll want to set it up from the beginning using the following steps.

Using the menu items across the top of the screen, select the following:

- Aircraft > Open Aircraft > General Aviation > Cessna 172 > Cessna 172SP
- Aircraft > Weight and Fuel > Payload weight: 300 lb. (per test plan)
- Location > Set Global Airport > LOWI > Rwy 8
- Environment > Weather > visibility > 25.0 sm: CAVOK; default temperature, winds and pressure
- Settings > Data Input & Output > Data Set tab
    - Select middle two check boxes for:
    - times [line 1]
    - speeds [line 3]
    - loc, vel, distance [line 21]
    - landing gear vert force [line 66]
- Settings > Joystick, Keys and Equipment
    - Calibrate Joystick (if used)

Takeoff Flight Test Plan

A flight test plan is a written record of what is to be flight tested and how it should be done. It documents the purpose of test, the airplane configuration for items like flap settings and weight and CG, the required data either recorded or pilot comments, and a description of the maneuver to be performed along with its risk and associated risk alleviation.

The test plan is prepared usually by flight test engineers and concurred to by the design engineers and approved by the pilot. It also serves as a documented record to the certifying agencies, such as the FAA, that the proposed testing is sufficient in both breadth and depth to allow for certification if testing is successful. In the cases for FAA certification testing, the FAA also approves the test plans.

Below is more information regarding each of the sections.

Test Title - A unique short identification of the test type and can be associated with a numbering system as well.

Purpose of Test - This section describes the reason for performing this test and the expected outcome.

Configuration - The test configuration identifies the required equipment and its software to be tested. It also identifies how the airplane is to be configured in areas such as flap settings, gross weight and center of gravity, to name a few. This then allows time for the ground crews to have the airplane properly configured prior to the test.

Data Required - The data to be obtained during the test needs to be identified and documented so that proper conclusions can be made during and after the test. Data can be in the form of instrumented flight parameters recorded on a computer system or video. In this case, the group installing that instrumentation needs to know that prior to the test. Data can also be in the form of manual notes from test participants that include pilot comments.

Test Procedure - This section documents the maneuver the pilot is to perform. It should be in enough detail to allow them to fly the airplane within the required parameters to allow the required data to be obtained. For example, a takeoff condition for a B777 might read like:

'Perform a normal flaps 15 takeoff by using full power to accelerate. At the specified rotation speed, start a 3 deg/sec rotation rate to obtain approximately 15 degrees of pitch. Hold that attitude until liftoff. After liftoff, continue climbing out at 15 degrees of pitch until reaching 200 feet above ground level.'

Using a 'checklist' can often reduce the tendency to forget steps. A table is often used to keep track of multiple conditions that are similar.

Risk - Test risk is assessed to identify both the consequences if things go wrong and the likelihood of that occurring. Once that is assessed, alleviations to either minimize the consequences or reduce the probability is incorporated in the test plan. For example, using build up conditions, that start in a safe zone and then, if successful, slowly progress to the riskier areas, would be considered an alleviation. Flutter testing is a good example of that where the testing starts off at a slow speed and then progresses to the faster ones until the riskiest condition is tested.

Below is an example of the test procedure section in a test plan to conduct a takeoff test for a Cessna 172 in X-Plane.

Takeoff Procedure

- Select airplane model (C172), and the data to record
- Set payload weight per the following condition table, LOWI airport runway, standard temperature/pressure, no wind, flaps up (Note: Maximum gross weight is 2550 lbs)
- Set Full takeoff power by selecting and holding the F2 key
- With mouse, click above instrument panel for a 'control box' to appear to move flight controls. (Or use joystick)
- Release Brakes by hitting the 'B' key
- Keep airplane centered on runway and apply gentle back pressure by slightly pulling back (down on the mouse) during the takeoff roll to allow the airplane 'fly' off the runway.
- Pause simulation by hitting the 'P' key, when reaching about 2000 ft altitude (100 ft above ground).

You will now recover the data and re-start X-Plane to repeat this test. You will conduct three trial for each of the three payload configurations.

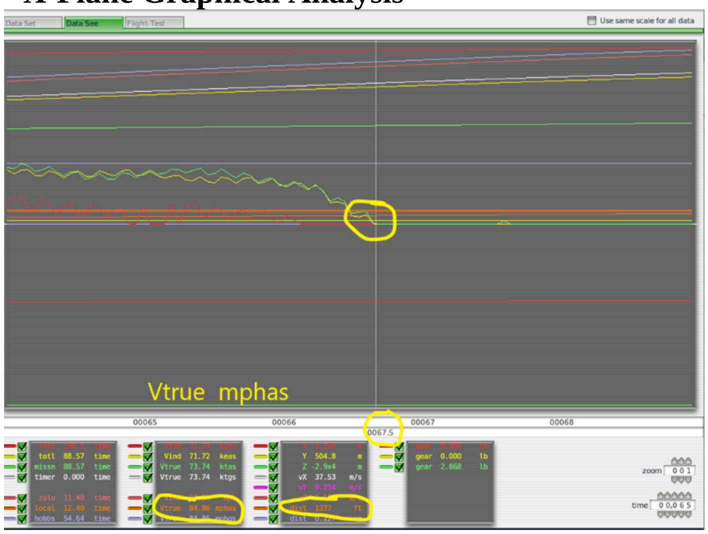
Set up your test condition table for the C172 testing as follows and record your data here.

Payload	Trial 1 distance	Trial 1 speed	Trial 2 distance	Trial 2 speed	Trial 3 distance	Trial 3 speed	Ave distance	Ave speed
300 lbs								
600 lbs								
750 lbs								

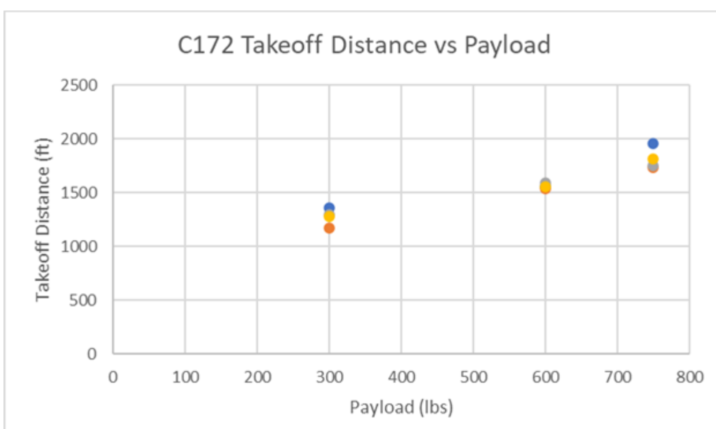
Data Recovery and Analysis

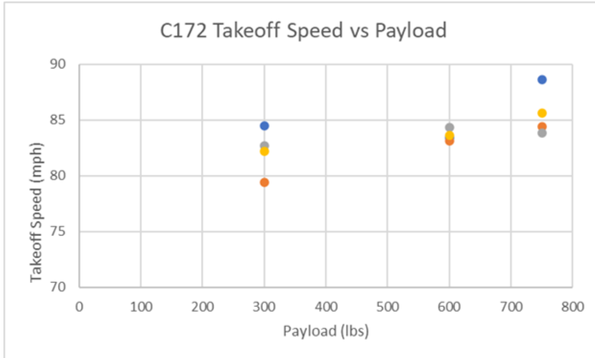
You will recover the data after each takeoff test and then re-start X-Plane for the next trial. To recover your data, after you pause the simulation go to Data View, slide the mouse to the right to the area where the liftoff occurs and write down takeoff speed and distance at liftoff (when all three landing gear are off the ground as indicated by all three gear loads being zero), in your data table (see highlighted areas in the screen shot below).

X-Plane Graphical Analysis



After filling out your test condition table from your test flights, it's time to analyze the data. But first, you will want to put it in a form that will be useful to draw conclusions from. Using a plotting program such as Excel, will display the data in a meaningful form. The plots below display both takeoff distance versus payload and takeoff speed respectively.





After plotting the data, review it for appropriateness. Is it reasonable? Are the data points in a tight area or spread out all over? Are there any outliers? If so, do any of the test conditions need to be re-flown? Can you see a trend to the data? After you are satisfied that the data seems reasonable, what insights can you read into it?

- What can be said about takeoff distance and payload weight for your tests?
- Is there a correlation? If so, what is that?
- What can be said about takeoff speed and payload weight?
- Is there a correlation? If so, what is that?

What conclusions can be drawn from this flight testing? How is takeoff distance and takeoff speed affected by payload (or weight)? Does that make intuitive sense? Does it make physical sense? Using this data, write your conclusion in the form of a statement. This will be part of the test report.

Follow on Questions

As an extension to this testing, the following questions can be addressed in terms of the previous work.

- What is the relationship between airplane payload weight and the length of the runway needed for takeoff?
- What is the relationship between airplane weight and takeoff speed?
- Using your own data can you estimate what the takeoff distance would be for a payload of 100 lbs. or 450 lbs? How would that be done?
- How does your takeoff distances compare with the pilots operating handbook for the Cessna 172 for the same weights? If different, explain why.

Unit 1 Basic Takeoff Testing - Assessments

- Define the role of the flight test engineer and pilot and identify their specific tasks and responsibilities in their role in testing and evaluating an airplane.
- Describe how math and science is used in flight test.
- List the major parts of the airplane and what they are used for.
- Identify the four major forces of flight and explain the relationships between them.
- Explain the aircrafts flight controls and the airplane axis they rotate about and how they affect flight.
- Describe the flight instruments of airspeed, altimeter, rate of climb, heading and engine tachometer in terms of use and their units.

- Demonstrate that you can set up X-Plane to: record the correct test data, configure the airplane with the proper payload and runway location, conduct consistent takeoff tests and determine the runway distance required for takeoff using the graphical feature of X-Plane.

Unit 2 - Advanced Takeoff Testing

Unit 2 expands on the initial takeoff testing by introducing kinematic equations and advanced forces of flight to include the lift equation, $L = \frac{1}{2}\rho S V^2 C_L$.

After baseline testing, airplane or environmental variables in the lift equation are modified in X-Plane and takeoff testing is repeated to see these effects. For example, adding flaps or testing on a hot day at a high-altitude airport.

2-1 Kinematic Equations

Lesson 2-1 Kinematic Equations

In lesson 2-1 students will be introduced to the concepts of displacement, velocity and time and then to the kinematic equations to be able to compute distance from the two variables of time and speed. The kinematic equations are introduced to enable students to calculate their own takeoff distances. To accomplish this, the plotting program 'DatPlot' is demonstrated to allow students to quickly produce 'industry standard' strip chart time history data. This 'easy to use' program creates multi-variable time history plots that allow many variables to be displayed on the same time axis. A very useful tool to see the interaction of the many variables at a time and to easily identify the numeric values for those variables at a specified point in time.

Flight Test Academy Lesson Plans

Lesson 2-1   Title: Kinematic Equations

Objective: Learn to compute takeoff distance using flight test data and compare it to Xplane.

Supplies Needed: Computer with Xplane loaded, spreadsheet software, calculator, mouse or joystick

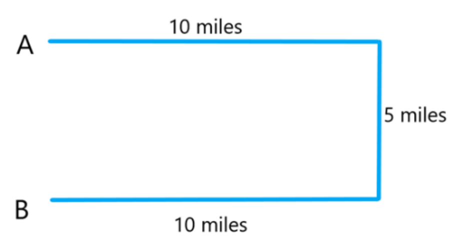
Item	Running Time (min)	Est Time (min)	Explore Engage Evaluate	Lesson Activity
1	0	2	Explore	Lesson Introduction
2	2	2	Explore	Project Roadmap slide
3	4	6		**Displacement**
			Explain	Displacement and Distance Traveled slides
			Engage	Exercise
4	10	10		**Position vs Time**
			Explain	Introducing time to positions
			Engage	Exercise
5	20	10		**Velocity**
			Explore	Determining velocity from distance and time slides
			Engage	Exercise
6	30	5		**Unit Conversions**
			Explain	Converting mph to fps slides

7	35	10		**Distance**
			Explain	Computing distance using average velocity slides
			Engage	Exercise
8	45	30	Engage	**Distance Student Activity**
9	75	2	Evaluate	**Summary**
10	85	10	Evaluate	**Discussion Questions**
11	95	10	Explore	**Extension – Refused Takeoff**
			Engage	Exercise
12	97	2	Explore	**What's Next**
	99			**End of Lesson**

Displacement

In order to determine runway takeoff distance, some new terms need to be introduced and defined. In the diagram below two points, A and B are separated by several miles, depending on the 'route' chosen. Distance Traveled is defined as the 'total distance between an initial position and a final position along the traveled route'. Where Displacement is defined as 'a measure of the shortest distance between an initial position and a final position regardless of the route taken'. A 'direction' is implied with reference to Displacement.

In the example below for the points A and B, the displacement would be 5 miles, in the down direction, where the distance traveled would be 25 miles.

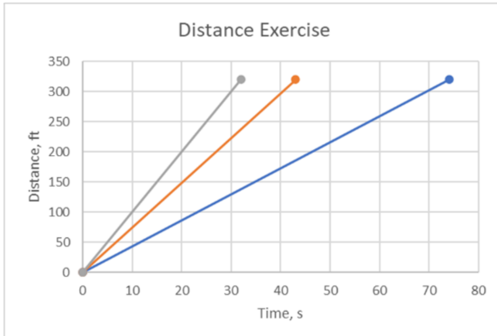


Position vs Time

Now let's include the element of time to the concept of distance traveled. But first we need some data to work with. In the table below is data from traveling a defined distance using different modes; walking, jogging and running and the time associated with each. You can develop your own data as well. Note that for each mode, the time it took was different, which makes sense. Running would take a shorter time than walking the same distance.

Mode	Distance (ft)	Time (s)
Walk	320	74
Jog	320	43
Run	320	32

Instead of a table, use a plot to show the data. Plot the distance, which is constant versus the time it took, as shown below. Which mode corresponds to which line? Why? What mode would be associated to the 'steeper' line? The 'shallower' line?



Velocity

Velocity is the rate of change in the distance traveled, or in other words, is the distance an object travels (in a particular direction) in a given amount of time. It is not quite the same as speed (which has no directional component). Velocity or speed is given in units of distance per time (distance/time), for example:

- Miles/hour, mph, read as 'miles per hour'
- Feet/sec, fps
- Meters/sec, mps
- Nautical miles/hour, knots
- Kilometers/hour, kph

The following are some examples of riding in a car where distances are related to times:

- If we travel 60 miles in one hour, our speed is 60 miles per hour.
- If we travel 60 miles in 2 hours, our speed is 30 miles per hour.
- If we travel 60 miles in ¼ hour, our speed is 240 miles per hour.

As you can see there are three variables; distance, time and speed. By using some basic algebra and knowing any two of those variables, the third one can be determined.

Finding Velocity

To find velocity, divide the distance traveled by the time it took.

$$velocity\left(\frac{ft}{s}\right) = \frac{distance\ traveled\ (ft)}{time\,(s)}$$

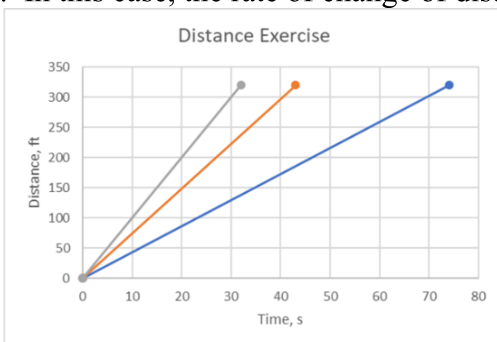
Or in shorthand form:

$$v = \frac{d}{t}$$

The table below has calculated the speed (velocity) for the different modes of traveling the 320 feet. Notice the higher speed is associated with running while the slower speed is with walking. The units of speed will be, the units of distance per units of time, in this case, feet per second. To find the speed in the example for running mode, you would take the 320 feet divided by the 74 seconds to get 4.3 feet/second. Do that for the remaining jogging and walking modes in the table above.

Mode	Distance (ft)	Time (s)	Speed (ft/s)
Walk	320	74	4.3
Jog	320	43	7.4
Run	320	32	10.0

Now look again at the plot below. Let's use another way to find speed by determining the slope of each of these lines. Remember to find the slope of a line we take the 'rise over the run'. In the case of the steeper line, the 'rise' would be 320 feet. The 'run' would be approximately 32 seconds. Taking 320 and dividing it by 32 results in 4.3 feet/second, the speed. Note these are the same values as was obtained before. It is an important concept to understand that the slope of a linear line is 'rate of change' between the two variables. In this case, the rate of change of distance and time is speed.



Average Velocity

Another useful concept if that of *average velocity*. Average velocity is used to find distance traveled for when the velocity can be assumed to be linear, i.e. a straight line. When you know an object's initial velocity and its final velocity, you can calculate its average velocity. The average velocity is the sum of the initial and final velocity divided by two, represented by the formula below:

$$Vave = \frac{v_i + v_f}{2}$$

Example: A Boeing 777 starts the takeoff at 0 mph and liftoffs at 136 mph. What is *Vave*?
Answer: (0 + 136)/2 = 68 mph

Finding Time

We can find how long it will take to travel a certain distance if we know our velocity and the distance we wish to travel. The formula below states to find time, take distance and divide it by the speed or velocity. Notice that the units of '*ft* 'cancel out and you are left with units of '*s*', seconds, which is the correct unit for time.

$$time\ (s) = \frac{distance\ (ft)}{velocity\ (\frac{ft}{s})}$$

Acceleration

So far, the discussion has been with a constant velocity. But what if the velocity is changing? For example, on a takeoff, the airplane starts off at zero velocity and at takeoff it is at a much higher speed. This was seen in the example for average velocity.

There is another term that describes this change in velocity or speed. It is called 'acceleration'. Acceleration is what we feel when in a car as it quickly speeds up or slows down to stop. That sensation is what is called acceleration (or deceleration). It is defined as the change in speed divided by the change in time and has units of, for example, ft/sec^2. The empirical formula for acceleration is:

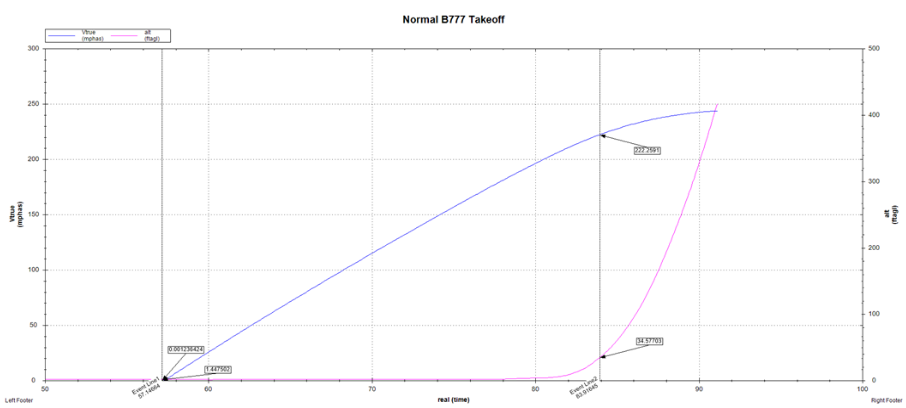
$$a = \Delta\ v/\Delta t.$$

Just like it was with displacement and time, you can determine acceleration graphically in the same way. Using a plot of speed vs time, for example on a takeoff, find the slope of that velocity line and it will be acceleration.

Distance Calculations

The example below describes the steps in reducing the flight test data from the takeoff testing into runway distance. The example is a plot of just two variables, speed and altitude, against time (in seconds). From these two parameters, runway distance can be determined by selecting the times associated with the start and end of the takeoff, in this case the end was determined to be when the airplane reached an altitude of 35 feet. The example below used DatPlot as the charting software.

There are two ways to compute distance, the average velocity method or the acceleration method. We'll look at both ways.



Example Steps:

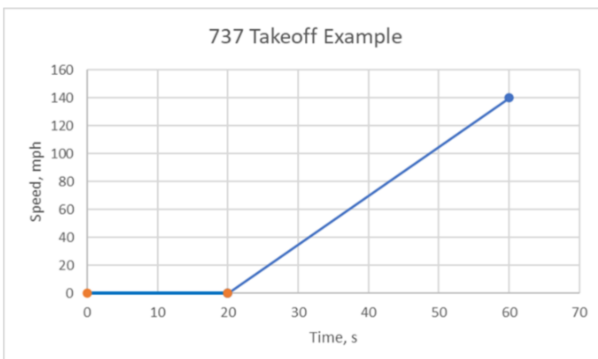
1. Plot True Airspeed and Altitude above ground vs time in seconds
2. Obtain appropriate times for both start and end. Add Event Markers for the takeoff start and at 35 feet to obtain numeric values at these times.
3. Convert speed from MPH to ft/s for the two speeds
   a. 0 MPH = 0 ft/s

b. 222 MPH = 325 ft/s

4. Determine time => (83.9 - 57.1) = 26.8 sec
5. Determine distance using the Average Velocity Method
   a. Determine average velocity => 1/2*(0 + 325) = 162.5 ft/s
   b. Calculate distance => $d = v_{ave} * time$
   c. distance = (162.5 ft/s * 26.8 s) = 4355 ft.
6. Determine distance using the Acceleration Method
   a. Determine acceleration => $\Delta v/\Delta t$: (325 - 0)/ (83.9 - 57.1) = 12.1 ft/sec^2
   b. Calculate distance: D = ½at2 => ½* 12.1 * (83.9 - 57.1)2 = 4355 ft.

Example

A Boeing 737 jet starts a takeoff at 20s and lifts off at 60s at a speed of 140 mph. Find the distance required for the takeoff.



Answer:

Determine: average velocity = ½ (140+0) = 70 mph
Covert 70 mph to ft/s = 102 ft/s
Determine time: 60-20 = 40s
Calculate distance: *d* = (average velocity) * (t) = 102 ft/s * 40s = 4080 ft

Note: Distance can also be found by determining the area underneath the triangle, because the formula for area is the same as for distance $a = 1/2bh$. Try it!

Important Kinematic Equations

$$velocity\left(\frac{ft}{s}\right) = \frac{distance\ traveled\ (ft)}{time(s)}$$

$$v = \frac{d}{t}$$

$$Vave = \frac{v_i + v_f}{2}$$

$$time\ (s) = \frac{distance\ \ (ft)}{velocity\ (\frac{ft}{s})}$$

$$d = v_{ave} * time$$

$$a = \frac{v_f - v_i}{t_f - t_i}$$

$$d = {}^{1}\!/_{2}\, at^2$$

Student Activity

Repeat some takeoff testing and compute your own values of takeoff distance and compare your results with X-Plane.

2-2 Forces of Flight - Lift

Lesson 2-2 Forces of Flight 'Lift'

In an earlier lesson the four forces of flight of lift, weight, thrust and drag were introduced. It was said that lift must equal weight for the airplane to fly, or takeoff. In this lesson we'll explore how that lift is developed and what factors affect the amount of that lift is produced.

Flight Test Academy Lesson Plans

Lesson 2-2 **Title**: **Forces of Flight - Lift**

Objective: To understand about lift and how the lift force can be affected.

Supplies Needed: Computer with Xplane loaded, spreadsheet software, calculator, mouse or joystick

Item	Running Time (min)	Est Time (min)	Explore Engage Evaluate	Lesson Activity
1	0	2	Explore	Lesson Introduction
2	2	2	Explore	Project Roadmap slide
3	4	15	Explore	**Lift**
				Lift Equation
				Air Density
				Coefficient of Lift
4	24	60	Engage	**Student Activity**
				Develop Test Plan Advanced Takeoff Testing
				Conduct Advanced Takeoff Testing
5	84	2	Evaluate	**Summary**
6	86	5	Evaluate	**Discussion Questions**
7	91	2	Explore	**What's Next**

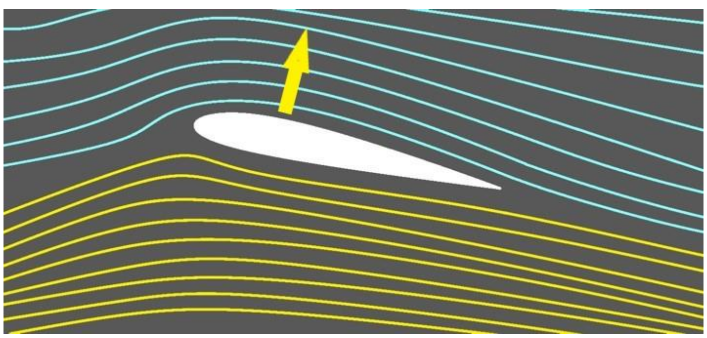
	93			**End of Lesson**

Lift

Lift is a force that is developed by the wing as it interacts with the surrounding moving air. If there is no moving air, there is no lift. The wing has a unique shape and size that effects the amount of lift generated. The wing's orientation to the moving air is also a factor. These are just some of the factors that affect the wings ability to generate lift.

The interaction of the wing shape to the moving air creates pressure differences surrounding the wing, some higher, some lower. When there is a higher pressure below the wing and a lower pressure above the wing, lift is created, and the wing is pushed upward towards the lower pressure due to the higher pressure below.

The diagram below depicts a cross section of a wing, called an airfoil, as seen in a 'wind tunnel' where a stream of air is blown against the static wing model. A series of smoke jets are interjected in the airstream to allow visualization of the air flow. The airfoil is seen to be tilted up a few degrees (to the horizon) and the surrounding airstreams seem to 'bend' around the wing. The airstreams on top of the wing are spaced further apart than the ones below the wing which are squeezed together. This 'compression' of the airstreams below the wing, produces various pressure differences around the wing, lower on top, higher below, which produces the lift in the upward direction. The arrow indicates the direction of the lift and note that lift is always perpendicular to the wing/airfoil.

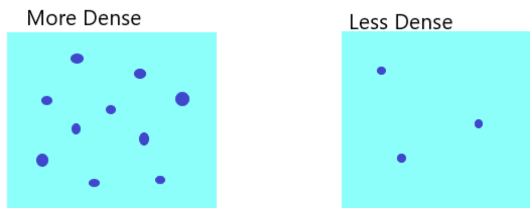


There are many popular and competing theories as to why lift is produced, for example, Bernoulli's equation or Newton's Third Law. This area of study is called fluid dynamics and is beyond the scope of this study guide. (See further explanations in the books in the reference section). Fundamentally, we can quantify the amount of lift that can be produced by a wing by looking at the lift equation. But first let's explore some of the properties of the air that we breathe every day.

Air Density

We'll start the air properties discussion by learning about a property that all substances possess, even air, and that is called density. Density is a characteristic of a substance that relates the mass of the item to the volume it occupies. For example, a specific volume of concrete is heavier than the same volume of wood. The reason being that concrete is denser than wood, (on average 100 lbs./ft^3 for concrete versus 40 lbs./ft^3 for fir). Density has units of mass divided by units of volume, for example pounds per cubic foot or Kg/m^3 read as kilograms per cubic meter. Another way to think of density is that it is just a mass to volume ratio.

The air that surrounds us and that we breathe is primarily comprised of Nitrogen and Oxygen molecules, has a density as well. The mass of 'air' or weight of the molecules within a certain volume is the density. Look at the following picture below. Both volumes are the same, but the one on the left has more particles, or mass of the molecules, than the one on the right, for the same volume. The left one is said to be 'denser'. The difference in the densities of air can be attributed to two primary variables, temperature and pressure. The symbol for air density is 'ρ' and is pronounced Rho.



As the temperature increases, the molecules spread farther apart due to their increased kinetic energy, resulting in less dense air. Conversely as temperature decreases, air density increases. It is similar for atmospheric air pressure. As you climb in altitude, either flying or even driving a car in the mountains, the atmospheric pressure of the surrounding air decreases and allows the molecules to spread apart, resulting in a lower density. Descending to a lower altitude will cause the atmospheric pressure to increase. This phenomenon can be felt in your ears when driving through the mountains (or flying). As the outside pressure changes, your ears can feel 'stuffy' and when you swallow, it clears up. When you swallow, you've just equalized the pressure between your inner ear and the outside atmospheric pressure.

For airplanes, both the outside air temperature as well as the atmospheric pressure have profound effects on the performance of airplanes. For example, runways in Denver, CO are typically longer due to the airport being at 5433 feet above sea level and in the summer, it gets hot there as well.

Look at the comparisons of air density for two major airports. There is a 20% reduction in the density of air between Seattle and Denver with those temperatures, which in terms of airplane performance, is significant. Additionally, aircraft engines are adversely affected by lower air density as well.

Airport	Location	Elevation	Temperature	Air Density
KBFI	Seattle, WA	20 ft	60 deg F	0.07627 lb./ft^3
KDEN	Denver, CO	5433 ft	80 deg F	0.06017 lb./ft^3

Lift Equation

After learning about air density and how that can be changed by temperature and altitude, we're ready to look at the lift equation in detail. The lift equation is listed below.

$$L = \frac{1}{2}v^2 S\rho C_L$$

Where: L = Lift in lbs.

v = velocity in ft/s

S = wing area in ft^2

ρ = air density in $lbs./ft^3$

C_L= Coefficient of Lift, dim

For an airplane to takeoff and stay in the air, the lift generated by the wing must be at least equal to the weight of the airplane. All the variables in the lift equation are directly related to lift, increasing any one of them, will increase total lift.

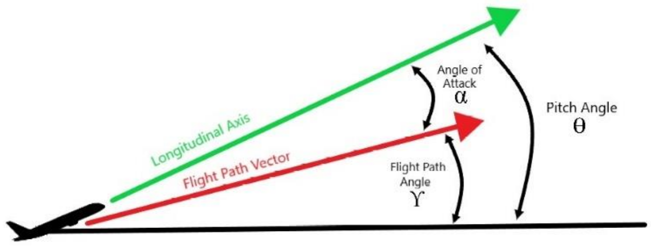
The new term of C_L is dimensionless and is determined experimentally in a laboratory wind tunnel and is usually in the range from 0 to 2. It is specific to a particular wing and it depends on, among other things, the specific airfoil shape and its orientation to the incoming wind. The more curved the wing is (the more camber) the higher the lift coefficient. Increasing the width and thickness of the wing will also increase the lift coefficient as well. Increasing the angle at which the wing meets the air stream will also increase C_L. It is useful to use the lift coefficient in the comparison of similar wings.

Airplane wings have extensions to them in the trailing edge, and sometimes in the leading edge, called flaps. Flaps are temporary extensions from behind the wing, as seen in the picture below of a jet transport, to both increase the wing area and to increase lift coefficient, two factors in the lift equation. It does this by increasing the wing camber. This is very useful for both takeoff and landing phases of flight to enable the airplane to fly at slower speeds. After using flaps for takeoff, the flaps are then 'retracted' back into the wing to allow a more streamlined wing for cruise, which has less drag (and also less lift, but the airplane is going fast enough for the wing to produce the required amount of lift to stay in the air). The flaps are then deployed for landing to allow the pilot to fly the approach at a slower speed.

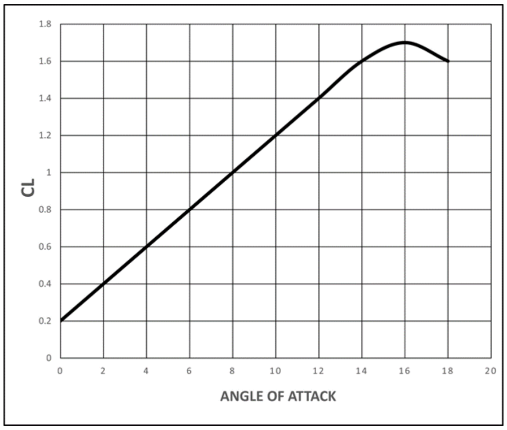
Photo credits: Wikimedia Commons

The lift coefficient is also greatly influenced by the 'angle of attack' of the wing to the incoming airstream. A good way to remember 'angle of attack (AoA)' or 'alpha (α)' is that AoA is the angle difference between where the airplane is *pointing* and where it is *going*.

In the diagram below you will see three angles the airplane is making with respect to the horizon, the bottom line. The top line is where the airplane is pointing and the angle it makes with the horizon is called pitch, or ‘theta (θ)’. Pitch is what the pilot sees on the flight instruments in the flight deck. The middle line is where the airplane is going, relative to the horizon and that is called flight path angle or ‘gamma (γ)’. This is the actual path that the airplane is going. The difference between pitch and flight path angle is called angle of attack. As you increase pitch, you increase angle of attack, but up to a point called the critical AoA. Beyond this critical AoA, the wing will stop producing lift which results in a wing ‘stall’.



The relationship between AoA and C_L is shown in the graph below. As AoA is increased, C_L increases, up to a point where it peaks and then decreases. This peak is called the stall point, beyond which, no lift is produced by the wing.



Student Activity

Develop a test plan for the following takeoff test for a Boeing 777 that includes title, purpose, required data, airplane configuration and test maneuver. Use the following outline of a Boeing 777 takeoff test that investigates how changes in the factors of the lift equation affect takeoff distance.

- Use and vary one of the factors that affect the lift equation; C_L or ρ. Choose and fly three different values (low, medium, high) from one of the following categories. For example:
  - Flaps: 0, 15, 30 Or
  - Temp: 0 deg, 60 deg, 120 deg Or
  - Altitude: KBFI, Seattle; KDEN, Denver; SLLP, La Paz Bolivia

- Keep a constant gross weight
- Obtain values for speeds and times using the graphical feature of X-Plane.
- Use delta time and average velocity to determine distance.

- Compile results in a table or spreadsheet
- Conduct three takeoffs for each value (for a total of nine) and compute an average distance for the three.
- Plot your takeoff results on a graph

Follow on Questions

- Explain your results in terms of the chosen factor from the lift equation.
- Do your results support your theory about changes in lift?
- What factor or factors of the lift equation has the largest impact to lift? Justify your answer.

2-3 Takeoff Data Recovery and Analysis

Lesson 2-3 Takeoff Data Recovery and Analysis

In this lesson you will learn important skills and tools in recovering and analyzing flight test data. You will learn how to create industry standard 'strip chart' that display multiple parameters of different scales on the same time scale. You will also learn about reporting the test results in a flight test report.

Flight Test Academy Lesson Plans

Lesson 2-3 **Title**: **Data Recovery and Analysis**

Objective: To learn about how to share the results of the flight tests.

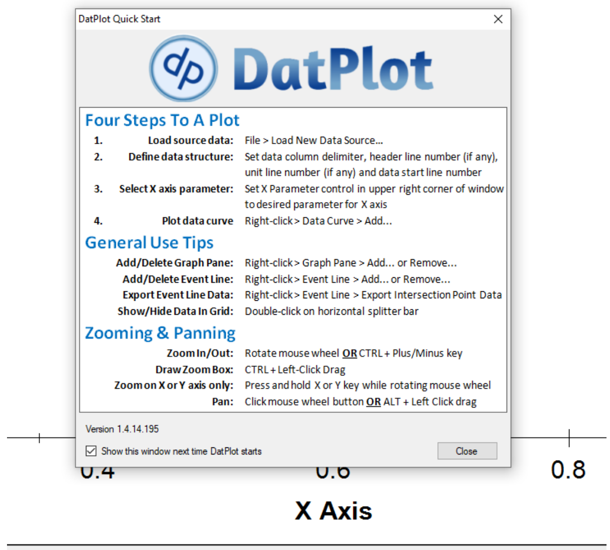
Supplies Needed: Computer with Xplane loaded, spreadsheet software, calculator, mouse or joystick, DatPlot program loaded

Item	Running Time (min)	Est Time (min)	Explore Engage Evaluate	Lesson Activity
1	0	2	Explore	Lesson Introduction
2	2	2	Explore	Project Roadmap slide
3	4	5	Explore	**Data Recording Setup**
4	9	10	Explore	**DatPlot Video**
				Creating strip chart data
5	19	60	Engage	**Student Activity**
				Create a Test Report from Advanced Takeoff Testing
6	79	2	Evaluate	**Summary**
7	81	2	Explore	**What's Next**
	83			**End of Lesson**

DatPlot Introduction

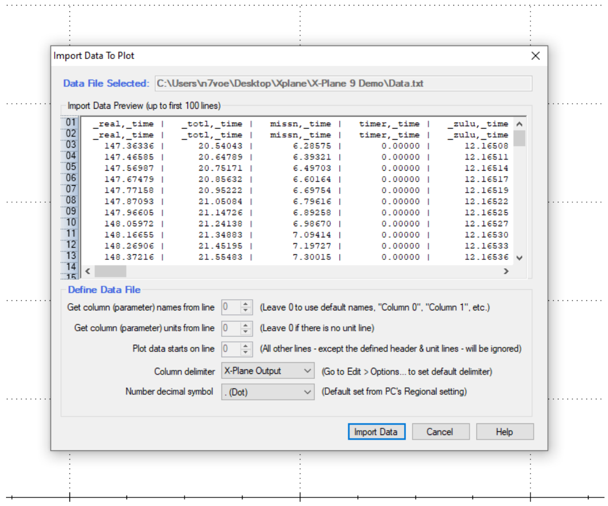
So far, we have used X-Plane to display our takeoff testing parameters. Now we will learn how to create ‘industry standard’ strip charts of our own using the program DatPlot. DatPlot is a program that takes the time history data file from X-Plane (data.txt) or other .csv formats and allows the data to be displayed in the ‘strip chart’ format. (Note: DatPlot will only work on PCs, not Macs).

Once the program starts, an instruction screen comes up like the one below.



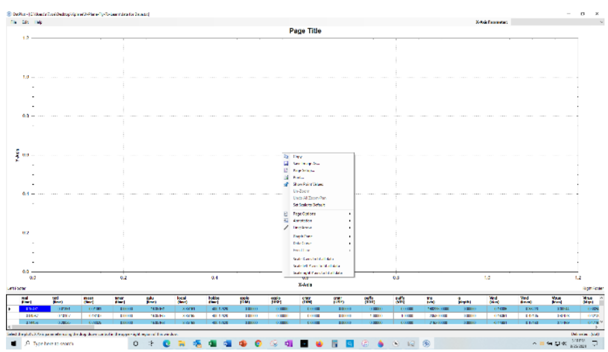
Next you will want to Load a New Data file. This is where you will navigate to the X-Plane directory and select the file data.txt. (Actually, good test discipline would suggest that prior to this you rename the data.txt file to a name that resembles your test, such as *777 Takeoff test1.txt*. In that way you can refer to the data from this flight at a later time. If not, the data.txt file will be overwritten the next time X-Plane starts and the previous test data will be lost.)

Once you select the file, it pre-loads the data and gives you a screen to select the format. Select the column delimiter of ‘X-Plane’ which will correctly format the data with the proper titles.

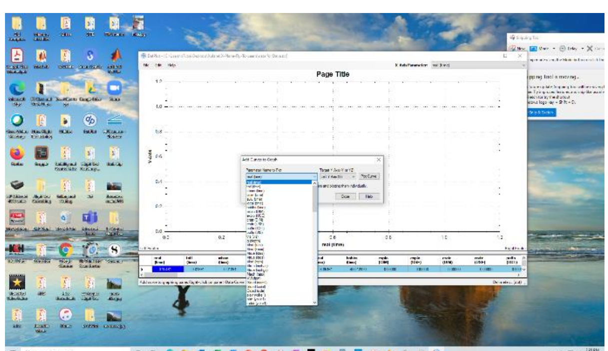


Next, you want to select the time parameter from the recorded list of data for the X axis. Go to the top right of the screen and select ‘real time’. It should populate at the bottom.

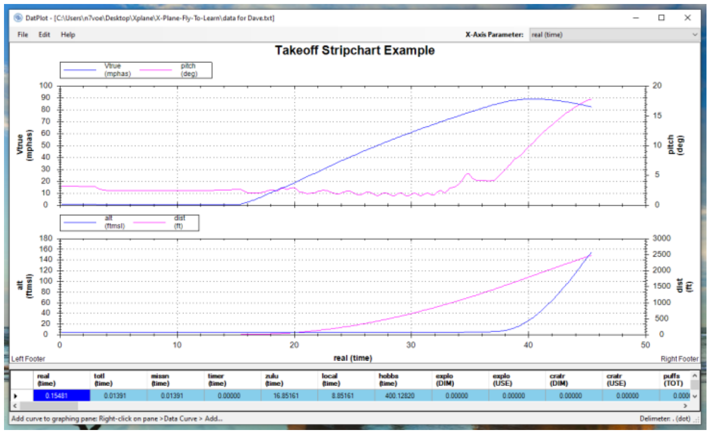
You are now ready to plot some data. Right click on the screen and a set of menus appear. Select ‘Data Curve/Add’.



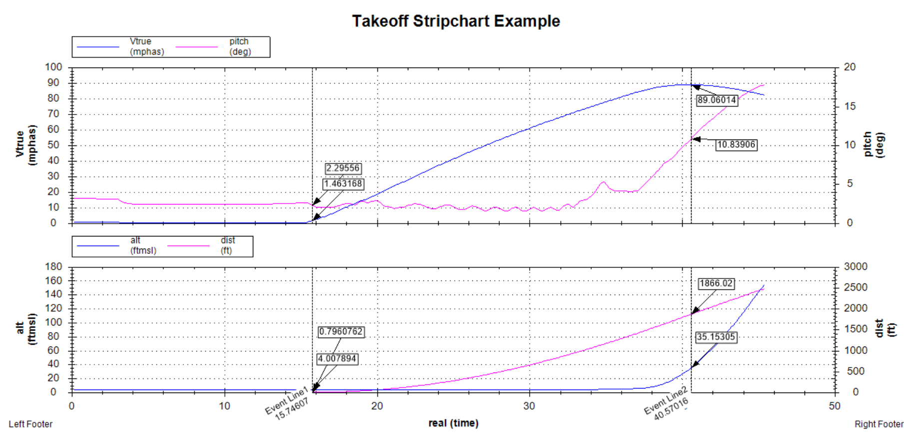
Another drop down menu will appear that lists all the parameters that were recorded. Just select which one you want and then select ‘Plot Curve’ (for example; Vtrue mphas, Pitch, alt ftmsl, dist nm). Your parameter will appear on the plot, correctly scaled. You can add another parameter to the same plot, only on the right axis, by selecting another one and the selecting ‘Right Axis’ and then ‘Plot Curve’. You will now have two parameters with different scaling’s plotted on the same strip chart.



You can also add another 'strip chart' by selecting 'Graph Pane/Add'. This will give you another chart which to add parameters. Include a meaningful title to the plot as well. See example below.



Now add Event Lines to the plot and slide them to the point of interest. There you can see the actual values of the plot where those lines intersect with the data plots, very useful for recording takeoff times and speeds for subsequent calculations.



After you are finished with the formatting, the plot can be saved for future edits. The chart can also be 'Copied' into your clipboard and then 'Pasted' into your test report or presentations.

Note: Avoid pausing and un-pausing the flight simulation as this adds large jumps in time. Also, DatPlot requires a unique title to each parameter, for example X-Plane uses the same name for each of the three gear loads, which DatPlot cannot handle, so avoid recording this data to the data.txt file.

Test Reporting

Flight test reports are an important part of flight testing because they are the way tests results are documented and communicated to others. The flight test report documents the test, what actually was flown and what the results were (both good and bad). The major sections of a test report include sections from the flight test plan such as; Title, Test Purpose, Data Required, Airplane Configuration and Test Maneuver but include additional sections of Test Results Summary, Summary Data Plots and Conclusion, as explained below.

Test Title The title of the test should be a short, unique and meaningful identification of the test.

Test Purpose This section should describe the purpose of the test and what the data will be eventually used for. An example could be to determine stall speeds of the airplane at a certain flap setting. Or it could be to conduct drag testing to determine fuel mileage information. Another example would be a demonstration flight to the FAA (Federal Aviation Administration) to allow certification of that equipment or airplane.

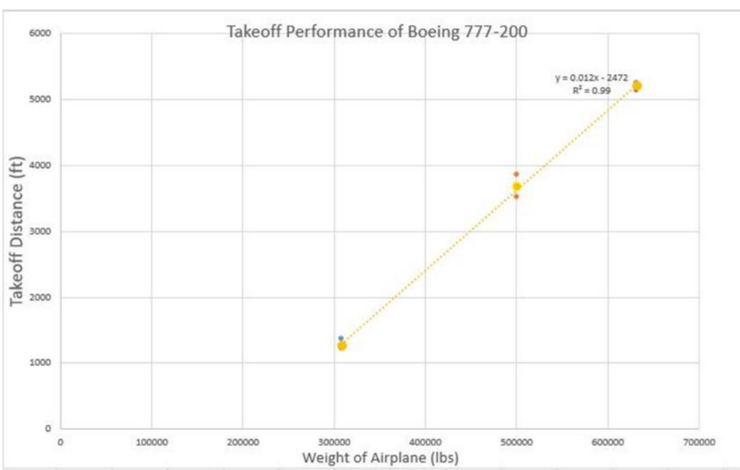
Required Data The data that is to be obtained from the flight is documented is this section. Data can be in the form of recorded data from the installed instrumentation, or it could be in the form of videos from the flight deck or even the manual notes recorded from test participants during the flight. These would include pilot comments as well. All of this is considered test data. For X-Plane, the parameters to be recorded in the data file would be listed here.

Configuration The as-flown configuration of the airplane must be documented in the test report which may have been slightly different than what was planned. This would include airplane weight, flap settings, software configurations etc.

Maneuver The test maneuver described as to what the pilot actually performed during the flight, which may be slightly different than the description in the test plan.

Test Results This is a summary of the test results, whether it be good or bad, they are still the results. Strip chart data as well as an explanation of this data is included in this section of the report.

Data Plots Summary data plots are included to better describe the maneuver and results. An example of a data plot summary is below. It depicts takeoff testing on a Boeing 777 with varying gross weights.



Conclusion This is an overall conclusion of the testing performed and whether or not it met the intended requirements set forth in the test plan.

Unit 2 Advanced Takeoff Testing - Assessments

- Describe and differentiate between displacement, velocity and distance.
- Compute velocity, distance or time, knowing any two of the three variables.
- Differentiate between speed in knots and miles per hour and be able to convert both to feet per second.
- Utilize the kinematic equations to calculate distance needed for takeoff using either the average velocity or acceleration method.
- Describe the Lift equation in general, and specially describe each parameter along with its corresponding units.
- Describe and differentiate between airplane pitch, flight path angle and angle of attack.
- Describe the lift coefficient, $C_{L,}$ and the factors that influence it.
- Set up X-Plane and conduct advanced takeoff testing varying parameters associated with the lift equation.
- Predict the required runway length, in general terms, based on changes to takeoff parameters.
- Utilize the software DatPlot to create properly formatted time history strip charts of their takeoff tests. Identify the takeoff start/stop times as well as initial and final velocities.
- Analyze time history data of the tests for reasonableness and consistency.
- Prepare summary charts that plot runway distance vs. manipulated variable.
- Compare the predicted distance with the actual takeoff distance and make inferences to the accuracy of the prediction.
- Identify any possible issues with the test data and determine if it can be used or needs to be re-flown.
- Prepare a Flight Test Report that includes: Title, Test Purpose, Data Required, Airplane Configuration, Test Procedure, Test Results summary, Summary data plots and Conclusion.

Takeoff Testing Extensions

The following are extensions for the advanced takeoff testing previously conducted to allow further exploration into real world airline operations. Repeat some of your previous takeoff testing but using these additional variables.

Takeoffs in Winds

Pilots are taught to always takeoff and land into the wind. But why is that? Wouldn't it be better for the wind to be 'behind' the airplane to help 'push' the airplane down the runway? Let's find out.

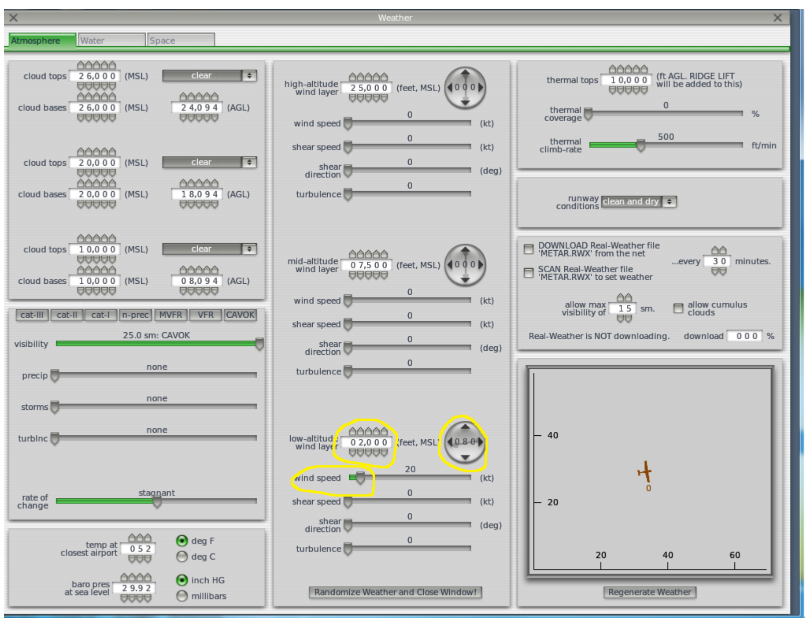
Background

Awareness of the wind is very important for pilots for all phases of flight, but especially for takeoffs and landings as we shall see. Wind information comes in two pieces, the direction and speed. The direction it is reported, is where the wind is coming from, not going toward. So, a north wind is wind from the north blowing toward the south. The direction is reported in degrees with respect to compass headings (referenced to magnetic North, not True North). For example, wind coming from the south would be reported as '180'. Speed is given in 'knots' or nautical miles per hour. So, a reported wind of '180 at 7' would be a wind from the south at 7 knots.

One reason that wind direction is reported in 'degrees from' is that allows the pilot to compare the wind direction to where the airplane is pointing, i.e. heading, and determine if it is a cross wind, head wind or tail wind or something in between. Look at the cockpit display below. The airplane is at the LOWI airport positioned on Runway 08 for takeoff. (Note: Runway 'headings' are also referenced to magnetic North as well). This can be verified by inspection of the directional gyro, DG, that provides heading. It reads '8' as well. If the tower winds were reported as '08 at 15' that would mean a direct headwind at 15 knots. Whereas if it was reported as '160 at 10', that would indicate a right cross wind at 10 knots. By comparing the reported wind direction with the aircrafts heading, the pilot can immediately determine if the wind will be assisting on the takeoff or not.

Setup

As part of the set-up of X-Plane, you will need to go to the ‘Environmental/Weather’ page as seen below. At the indicated areas below, is where you input your wind information starting with the altitude. In this case, the airport elevation is used as the altitude level. Next information on the wind direction and speed is inputted as shown. Now you are ready to perform some takeoffs.



Activity

Conduct a series of takeoffs in a B777 airplane at an airport of your choosing. You’ll do takeoffs in headwinds, tailwinds, and cross winds. You will conduct the takeoff as before with flaps 15 and at a constant gross weight and determine the takeoff distance required as before. Use the following table for the test conditions. Do three takeoffs for each and average the distances per condition. Develop a flight test plan that details this testing. The table below is for the airport LOWI, runway 08.

Condition	Wind Direction	Wind Speed	Average Distance
No wind	0	0	
Headwind	080	15	
Tailwind	260	15	
Right Cross wind	170	10	

What can you say about your results?
What is more beneficial in a takeoff, a headwind or a tailwind?
Document your results in a flight test report.

Refused Takeoffs RTOs

For commercial, multi-engine jets, just knowing the distance for takeoff is not enough. If one engine fails somewhere on the takeoff roll, depending on when, the pilot could decide either to stop, or continue the takeoff (engines are powerful enough to continue the takeoff on one engine). The Go/NoGo decision point is defined as a V_1 speed. If an engine failure occurs before reaching V_1, you stop, if it occurs after that, you continue the takeoff. Therefore, the total runway requirements must include 'stopping' distance as well as the takeoff distance to ensure that the airplane aborting the takeoff will still have runway remaining to stop.

You can try this RTO out in X-Plane by conducting the following testing.

Setup

In X-Plane, RTOs can be done by setting up the engine failure with this function:

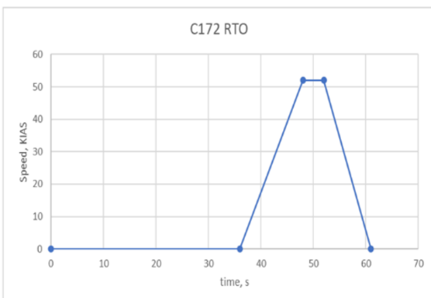
- Aircraft/Eqpt Failures/Engines/Fail at Exact Speed (Fail all engines)

Procedure

- Select engine fail speed of 50 KIAS for small airplanes and 120 KIAS for large transport
- For transport airplanes, fail all engines, not just one, so it's easier to stay on the runway.
- Conduct a normal takeoff (engine will automatically fail)
- When the engine fails, keep lined up with the runway and immediately apply brakes by selecting 'B' once
- Continue to a full stop and then collect data as usual, recording the start, engine fail and stop times as well as the maximum speed that was achieved.

Data Recovery and Reduction

Create strip charts as before that include event times and record the times for each of the events; takeoff start, engine failure, braking start, stop time and plot them with speed versus time as shown below. You will note that the takeoff started, the engine failed and then brakes were applied. Your data will look something like this.



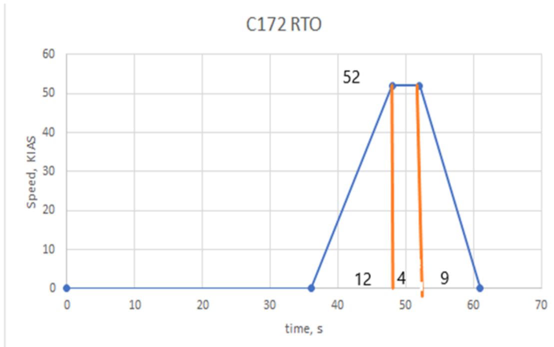
Data Analysis - Area Method

You will notice three unique sections (2 triangles, 1 rectangle)

- Takeoff roll for 12s (1/2 * 87.7 ft/s * 12 sec = 526 ft)
- Engine failure 4s at 52 knots (4 sec * 87.7 ft/s = 351 ft)
- Braking for 9s (1/2 * 87.7 ft/s * 9 sec = 395 ft)

Calculate the distance for all three using distance formulas as before or use the area formulas

Now add all the distances up for the total distance for the entire maneuver. (526 + 351 + 395 = 1272 ft)



Further Discussion Questions

What do you think happens if the pilot decides to stop after reaching V1 instead of continuing the takeoff as they should? To see an example, review this link:

[Kalitta revises RTO training after 747's post-V1 abort | News | Flight Global]

Unit 3 - Climb Testing (TBD)

Climb testing is used to determine the airspeeds for the best angle and best rate of climb. This is important for pilots to know for example, when trying to climb over the trees at the end of the runway. These speeds are a function of the Lift Coefficient, Angle of Attack and the total drag of the wing at that speed. Testing requires stable airspeed control throughout the climb and is done over a wide range of speeds. Pitch is used to control the airspeed for the test; pitching down, increases speed; pitching up, decreases speed.

For the activity, do 2 tests to control airspeed in cruise and climb/descent.

Unit 3 Climb Testing - Assessments

At the conclusion of Unit 3, students will be able to:

- Understand and describe the Drag equation in general, and specially describe each parameter along with its corresponding units.
- Describe and differentiate between the two types of drag, induced and parasitic and as it relates to angle of attack.
- Develop a climb test flight test plan.
- Conduct a series of climb tests to determine the airspeeds to fly for optimum rate of climb and best flight path angle.
- Recover flight test data and create time history strip charts.
- Identify issues with the test data and determine if it can be used or needs to be re-flown.
- Plot summary results of climb performance and airspeed.
- Analyze results and draw conclusions from the data.
- Prepare a climb test flight test report that identifies the airspeeds to fly for optimum rate of climb and best flight path angle.

Unit 4 - Cruise Testing (TBD)

Cruise testing is covered in Unit 4 and is very important in the flight testing of a new model airplane or major modification. Cruise test data determines the fuel mileage i.e. miles/gal that the airplane can perform. This along with the airplanes fuel capacity goes directly into computing the maximum range of the aircraft. Both values are important to the marketing of the airplane and in some cases, like Boeing, are contractual binding. Drag testing can be contentious and is always high stakes. Since thrust is equal to drag, when fuel mileage estimates are not met, airframe manufactures tend to 'point the finger' to engine manufacturers for not having a more fuel-efficient engine, while engine manufacturers blame airframe manufacturers for designing an airplane with too much drag.

Unit 4 Cruise Testing - Assessments

At the conclusion of Unit 4, students will be able to:

- Develop a cruise test flight test plan.
- Conduct a cruise flight test to determine airspeeds to fly for maximum duration and range.
- Recover flight test data and create time history strip charts.
- Identify issues with the test data and determine if it can be used or needs to be re-flown.
- Plot the summary results of cruise performance and airspeed.
- Plot a Lift/Drag curve vs. airspeed curve.
- Analyze results and draw conclusions from the data.
- Prepare a cruise test flight test report and include L/D curve and identify airspeeds to fly for maximum duration and range.

Unit 5 'Apple Challenge' Capstone Project (TBD)

Introduction

This project will combine most of what you have learned in these flight test classes into a real-life airline example. The project takes place in apple country of eastern Washington State. The towns in eastern Washington near the Columbia river are home to the country's best apple orchards and are shipped all over the world. The mission is to transport as many apples you can, by weight, into a C172 and load up just enough fuel (with reserves) to make the flight from Ellensburg to Seattle. You will also predict your arrival time.

You will use data from your recent cruise testing to determine the best speed at which to climb and to cruise to minimize the fuel needed and therefore maximize the amount of apples you can carry.

Test Procedure:

- Using test data from your cruise test, determine your optimum climb and cruise speed.
- Assuming 77 miles for the flight and using your chosen cruise speed determine how much time your flight will take including the climb and descent from 6000 ft.
- Using that time, now determine how much fuel you will need. Include the required 45-minute reserve as well (use 25 lbs. for C172). Load fuel in Xplane.
- Determine Total payload by adding 200 lb for pilot and gear to the amount of apples you intend to carry. This along with the fuel should be very close to but not exceed the gross weight of the airplane (2250 lbs.).
- Record the following data to file: Time (1), Speed (3), VVI (4), Alt (20), Dist (21), Throttle (26), Engine rpm (37), Fuel flow (45), Fuel weight (62), Payload (63)
- When you are lined up and ready for takeoff on Runway 25 at KELN, predict your estimated time of arrival (make a note of it by adding your estimated flight time to the current time)
- Takeoff and climb to 6000 ft. Maintain a heading of 270 deg (W). Use Heading Hold of autopilot.
- Climb at your predicted speed by adjusting pitch, by hand flying, to control speed.
- Level off at approximately 6000 ft, use Alt Hold mode of autopilot.
- Adjust throttle to acquire and maintain your selected cruise speed. (Use ';' to make cockpit transparent and 'Ctl+T' to speed up simulation)

- Bring up Local Map and select Low Enroute chart and make sure you are near V2-V298 route. Adjust heading to fly that route toward KSEA.
- Determine your distance to KSEA by adjusting the Local Map, X Axis to determine your distance. When your destination comes in view on the left, align it at the vertical Y axis and then read your distance from there on the horizontal X axis.
- At about 30 miles from KSEA Start your descent, at -1000 ft/min.
- Descend until 1000 msl and fly directly over the airport to intersect the runways.
- When you are directly over the airport, select Pause on the simulator, make a note of arrival time.
- Go to Airplane/Weight and Fuel and record the current amount of fuel, in lbs., that is in the tanks.
- Quit Xplane and rename the Data.txt file.
- Plot up the following data in DatPlot
- Airspeed/Altitude
- Distance/ FF
- Engine RPM/ Fuel weight
- Record data in a table; final distance, final altitude, final fuel remaining and apple payload weight and arrival time.
- Apply scaling factors

Unit 5 Apple Challenge - Assessments

At the conclusion of Unit 5, students will be able to:

- Measure distance between two cities by referring to either paper or digital map.
- Develop a flight plan that uses flight test data for the optimum climb and cruise speeds.
- Determine the amount of fuel to be used for the desired route.
- Determine the correct aircraft loading to include fuel and reserves, pilot and apple payload.
- Fly the flight plan and evaluate how close their estimate of fuel usage matched.
- Recover flight test data and create time history strip charts.
- Identify issues with the test data and determine if it can be used or needs to be re-flown.
- Plot the summary results of the Apple Challenge.
- Prepare a Flight Test Report of the Apple Challenge testing.

Flight Test Academy
Part 2

Flight Test Stories

Flight Test Stories Introduction

To an aviation enthusiast, there is nothing better than learning the 'behind the scenes' story of aircraft development and flying. Great stories of flight abound from aviation museums to small airport offices are so prevalent, pilots coined the term 'hangar flying' to describe it. These tales range from bush flying in Alaska to everyday commercial airline flying. Some of the best stories include accounts of flight testing. Flight test stories add technical elements to the aviation parts that fascinate both engineers and pilots alike. Unlike the more easily understandable commercial aviation or private plane flying, the world of flight test is unique in its structure and organization. Getting a feel for this unique world, will help provide the appropriate backdrop to allow a better understanding of the flight test stories and is described in the background information in the following section.

Background Information on Flight Test

Below is a generalization of how flight testing works, from my experience at Boeing Flight Test, that is somewhat common throughout the industry. This will provide the reader with a foundation to understand and follow the subsequent flight test stories.

The flight test organization is distinct from any other engineering organizations in an airplane company. Since flight testing is technically oriented, most personnel are engineers or technicians. Many are private pilots and almost all share a common love for the job and an overwhelming common interest in airplanes and flying. Flight test engineering positions are highly sought after, and the organization experiences a low attrition rate. Many 'flight test lifers' prefer to stay their entire career with the organization, often passing up promotions and other transfers that would likely improve their salary. Flight test pilots are experienced military and/or commercial pilots that typically have graduated from a test pilot school or some equivalent of that specialized training. They are all engineers and many carry advanced degrees. For test pilots, you must be the best of the best to be a flight test pilot.

The makeup of the flight test organization consists of two major groups: test pilots and flight test engineers (FTEs). The primary job of the test pilot is to fly the plane in the tested configuration per the flight test plan. Conversely, the flight test engineer has many roles. These jobs include preparing the test plans, installing and maintaining instrumentation, developing test schedules, determining the test points for the day, configuring the airplane, directing the test, reviewing the data and preparing a test report. Depending on the size of the company and the amount of testing done, there can be a single flight test engineer or there can be teams of flight test engineers performing all these jobs. During a test program, the hardships of long hours, harsh conditions, and sometimes hazardous tests, create a special bond between the FTEs and the test pilots. This bond is considered a good attribute of a well-functioning flight test organization for no other reason than the role of the FTE and the pilot are so complimentary, that for some tests, they actually put their lives in each other's hands. Conducting testing off-site at remote locations for weeks at a time only re-enforces this bond of the flight test crews.

Flight test has a distinct, unwritten 'dress code'. Throughout the organization, flight test pilots and engineers wear unique jackets. Originally starting off as brown leather coats as seen in World War II aviation movies. Some still exist, but over time, they have become more 'practical'. Now most are in a high visibility color so the wearer can be seen walking on the flight line at night and low visibility conditions. These jackets are often adorned with small colorful patches that can be considered 'badges of honor' from past test programs or test pilot schools. The variety seems endless and each one carries its own significance. Most people limit the number of patches to one on each sleeve and a general one in front along with the person's name/rank/position. But some have resorted to filling up the jacket with a patch from every program they were associated with! Others keep the extra patches as souvenirs that decorate their office walls.

Another uniform you will see a certain group wear, especially the flight crew, is called a flight suit. These ‘coveralls’ are a solid color that are zipped up from the front that require you to step ‘into’ to put on. These too may be adorned with patches. Originally these ‘uniforms’ were to protect the person while climbing in and around various places of the airplane, not usually accessible to passengers, such as cargo compartments etc. Besides dirt and grease, hydraulic fluid and jet fuel are always nearby and can present a mess. Additionally, some flight suits are made of fire resistant ‘Nomex’ to reduce injury in case of an on-board fire or crash, because unlike normal commercial jet flying, flight testing, by nature, can be dangerous.

‘Day in the Life’

Viewed from afar, a test flight looks like any other flight. Personnel get the airplane ready for flight, the ‘passengers’ (test crew) boards, the airplane takes off, flies and then returns. But unlike commercial flying, there is certain structure to the preparing for and conducting a test.

Prior to the day of the test, the test plans have all been previously prepared along with the planning needed to get to this flight. This often requires weeks of work. These test plans specify what maneuver is to be flown, e.g., a takeoff with various flap settings, and what data is to be recorded and retrieved. Data can be in the form of computer-recorded parameters, video, photos and/or hand-written comments or observations made during the test by crew members.

The following is from my flight test experience at Boeing Commercial Airplanes but is representative of other companies. Boeing carries a test crew of FTEs on board, in addition to the pilots. These planes are large enough to accommodate other crew members that can make valuable real time test decisions as to the conduct of the test in real time. Other companies, including the military and Airbus fly a smaller crew and use telemetry to transmit much of the data to a control room (similar to NASA’s mission control). In those situations, the FTEs, test conductor, and systems experts sit and communicate with the flight crew via a radio link. One limitation of a telemetry flight is that the airplane must be in a “line of sight” range of the control room in order to receive the data. For the most part, the roles and responsibilities of the FTEs remain the same for whether they are on the plane with the pilots or conducting the test from the control room on the ground.

On the day of the test, the plans are in place, the airplane has been fueled and modified as specified in the test plan, and all aspects of the tests are ‘readied’ early in the morning for any last-minute maintenance items. During this time, the flight test crew attends a meeting to brief the flight to all of the test participants. This meeting is known as the ‘preflight briefing’.

A few things to note about ‘preflights’. These meetings are run by an FTE called a test director or test conductor. Everyone associated with the test is required to be there. For the safety of everyone involved, the meetings do not start until every person who is flying has arrived. (As the saying goes, “If you are not five minutes early to the brief, you’re late!”). No matter who will end up flying on the flight, whether it’s two or twenty, all supporting groups attend and, as such the room can get crowded. There is unwritten etiquette regarding seating in the preflight. The table is reserved for those flying: pilots, test directors, weights and instrumentation engineers and test engineers, etc. The test director chairs the meeting and so is seated at the head of the table alongside the pilots. Others fill the chairs at the back of the conference room wall or just stand. The test director conducts the meeting and reviews items such as test plan maneuvers in the order to be flown, safety assessments and alleviations, route of flight, weather, etc. Others in the room contribute to the meeting with status of the airplane configuration and data system. A final safety brief is giving to the crew by the pilot in command or their representative ending with a discussion of where to meet in the event of an airplane evacuation (typically, 100 yards off the nose or upwind). When all questions are addressed, and the airplane is ready or 'released for flight', the test crew departs the meeting to "step" to the airplane for the day's testing.

As one approaches the test airplane, it only resembles a commercial airplane from the outside. On the inside airline seats are replaced with racks of computer equipment bolted to the floor on either side of a center aisle. Very few seats exist and the ones that are there are positioned behind the instrumentation racks to allow engineers to monitor the data during the test flight in real time. This allows real time decisions to be made on both the quality of the test condition being flown and also for safety monitoring, exceeding speed or "g-loads'. (The pictures below are from the first Boeing 747 flight test airplane, who's first-flight was flown on February 9, 1969, with some of the original remaining flight test equipment, seats and stations and is a typical flight test installation for a large airplane. This airplane on display at the Museum of Flight in Seattle, WA).


During the flight test, the test director (TD) is responsible for the successful conduct of the test and is seated in the 'jump seat' up front in the flight deck. They 'queues up' the 'test card' of the test maneuver or test condition to be done next, observing the proper setup and then taking notes from the pilot comments as to the success or failure of the maneuver. This is repeated until the 'deck' of test cards are completed or determined cannot be done and the crew returns to base (home). The TD leads the test crew and together with the pilot is responsible for any adjustments to the test plan or sequence when things don't go as planned the first time.

Throughout the test, communications about the test maneuver and/or results from the crew in the back go through the test director (TD) to be forwarded to the pilots through the airplanes 'inter-phone' system (pilots must listen for Air Traffic Control (ATC) commands on the radio on a second audio as well). For all on-board, good 'inter-phone' etiquette must be followed to ensure a clear channel to the TD. This protocol usually advocates crew member identification by 'position' or 'role' in favor of personnel names, for examples; TD, Instrumentation, Weights, Analysis. Unless the communication is deemed important, those in the back just listen and speak when addressed and must never talk over, "step on", the pilot's communication with ATC or another pilot.

Analysis FTEs as well as the invited design engineers are responsible to review the data from the test conditions as they are performed. They look at data in real time to determine if the test condition was flown correctly or needs to be repeated. They also make careful notes if something strange occurs in the data that might need a further look later.

Another role of the Analysis FTE during flight is in the flight deck (if there is room), either standing in the doorway (during cruise) or in the second jump seat. There they can interface directly with the TD and/or pilots on alterations to the test plan due to Air Traffic Control constraints, answer questions from the pilots and/or obtain pilot comments and help clarify the intent of the test condition. This is especially important when the pilots are providing a qualitative evaluation of the system.

During the flight, the Instrumentation and Weights FTEs support the test by ensuring the data recording and monitoring system is functioning correctly and that the gross weight and center of gravity (GW and CG) are at the proper values for each test point.

At the end of the test, the test crew once again gathers for a ‘post flight briefing’ to summarize the days testing. The test director again chairs this meeting. They summarize the results of the test and solicit inputs from pilots and FTEs and then assign follow-on actions for future testing and aircraft maintenance issues (squawks). Other engineers (lead by Analysis FTE) afterward write test summaries, review data, and compile a formal test report.

This cycle of preparation, testing, summarizing and reporting then repeats for the next tests throughout the test program.

757 Dual-Servo Autothrottle Takeoff Test

By Dan Hrehov

After a few years in the Systems FTE group, I was asked to join the Autoflight FTE group which tested avionics systems like the autopilot, autothrottle and flight management computer. One of the early flight tests in that group was testing of the autothrottle on takeoff. Here is one of my memorable experiences early in my career doing that testing from the mid 1980's.

The autothrottle on an airplane has two functions. One function is similar to the cruise control on your car where the throttle is adjusted to maintain a selected speed (airspeed or Mach) while in cruise or on the approach. The other function is to maintain proper engine power setting for takeoffs and climbs while not 'over boosting' the engines by exceeding certain limits such as temperature and/or RPMs. Takeoffs can be made at 'full power' or at a reduced power setting to reduce the wear and tear on the engine. These "de-rate" takeoffs are available depending on the airplane's gross weight and runway length. Full power takeoffs are used on short runways, when planes are heavily loaded, or both; otherwise, runways are typically long enough for reduced thrust takeoff tests. On this particular test, I was conducting full rated autothrottle takeoffs on the Boeing Model 757 with Rolls Royce engines.

In addition to the increased bypass ratio for the 757 engines, the mechanical means to control the engine core power consisting of cables and pulleys were being slowly replaced by computers, called Electronic Engine Controls, or EECs. EECs reduced complexity, maintenance and costs to the airline by replacing many of the cables, pulleys, brackets etc. that take the pilots input from the throttles in the flight deck to the engines on the wing. The autothrottle's function was to use a computer to power a servo (actuator) that would move the throttles much like a pilot would to control the engine. This was driven through clutches so the pilot could override the autothrottle movement if needed. For this particular test configuration, there were two independent servos, one for each engine installed. (Later variations only had a single servo and a single clutch.)

For a normal takeoff, the autothrottle (or pilot) would advance the throttles to the required thrust limit and then maintain that limit throughout the takeoff and climb, making minor adjustments to account for temperature, speed and altitude. The limits were constantly changing during the climb so it was important for the autothrottle not to exceed the target limit as that would result in an 'over boost' of the engine that could cause damage. That was one of the pass/fail criteria of autothrottle operation.

For this test, we were sitting at the end of Runway 13R at Boeing Field ready for takeoff. Captain Bob was the test pilot; the other pilot, test director and I filled out the flight deck. My role for this takeoff test was to monitor the test condition and ensure proper setup, and to take manual notes of the operation and record pilot comments. My colleague back in the cabin was monitoring data on a computer screen and using plotted strip charts for more detailed analysis.

We were cleared for takeoff for our first autothrottle takeoff condition with the new software load with the engines starting in the 'idle' position. While doing a full rated takeoff with the throttles from the idle position is considered an 'abuse' condition, and so because it could happen, it needed to be tested (Crew procedures for using the autothrottle on takeoff call for them to bring the throttles off of idle to about 35% N1, referred to as 'stand them up' before engaging the autothrottle).

With the test configuration, flaps and trim set for takeoff, and the engines at idle, the pilot selected the Thrust button on the glare shield panel to engage the autothrottle for takeoff. As the throttles independently came up, we noticed they were not coming up together, first starting with a minor difference (throttle split) and then to an ever increasing one. In fact, the farther along we went, the further apart the throttles got. When we were at about 60 knots, one engine was at 90% N1 while the other one was lagging behind at 60% N1. Based on the nature of jet turbine engines we were in a situation where one engine was at almost full power and the other one just getting off idle, all happening at the early portion of the takeoff roll. Since we were moving too slowly for the rudder to be effective with the large amount of asymmetrical thrust, the airplane yawed (turned) unabated toward the slower engine. We were literally ‘heading for the bushes’ at a 30 degree angle from the runway, with the rudder not helping, we would have run off the side of the runway if it weren’t for the quick reaction of Captain Bob who quickly brought both throttles back to idle to stop the yaw and then used the brakes to realign and to stop. We would have crashed if the takeoff were not aborted. After the airplane came to a stop back on the center of the runway and notifying ATC of the aborted takeoff, we collected ourselves and taxied back for another takeoff with the pilot calmly but firmly stating, “We’re not doing that again!”. This time a manual takeoff was done and no more autothrottle tests were done that day. I left the flight deck to review the strip chart data in the back of the airplane to figure out what happened while the other scheduled flight tests of other disciplines were conducted that flight. Just another day in flight test.

After the design engineers looked at the data, they discovered an omission in the software. Missing from the autothrottle programming logic was an instruction that would hold back the ‘lead’ throttle to provide time for the lagging engine to ‘catch up’ before continuing advancing to a higher power setting. It was a scenario that was difficult to predict and that didn’t appear in the lab testing, but came out in flight test, which is often the case and why flight testing is an important method of evaluating. When the software was revised, it was tested again, this time successfully, although not as exciting as the first.

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Airplane Glossary

Aerodynamics The study of how air flows around the airplane.

Airfoils The wings of a plane

Ailerons They are hinged on the wings and move downward to push the air down and make the wing tilt up

Drag Resistance that slows an object down in the air. Items that are streamlined have less drag in air

Elevators are found at the rear of the plane. They can be raised or lowered to change the direction of the plane's nose. The plane will go up or down depending on the direction of that the elevators are moved

Fin is the vertical part of the tail

Flaps The flaps slide back and down to increase the surface of the wing area.

Fuselage The body of the plane

Gravity a force that pushes objects down to the earth.

Laws of Motion - Sir Isaac Newton proposed three laws of motion.

1. If an object is not moving, it will not start moving by itself. If an object is moving, it will not stop or change direction unless something pushes it.
2. Objects will move farther and faster when they are pushed harder.
3. When an object is pushed in one direction, there is always a resistance of the same size in the opposite direction.

Lift A force that pushes objects upward

Pitch	Pitch is to make a plane descend or climb. The pilot adjusts the elevators on the tail to make a plane descend or climb. Lowering the elevators caused the airplane's nose to drop, sending the plane into a down. Raising the elevators causes the airplane to climb.
Roll	To roll the plane to the right or left, the ailerons are raised on one wing and lowered on the other. The wing with the lowered aileron rises while the wing with the raised aileron drops.
Rudder	The rudder is found on the tail of the plane. Moving it right and left controls the left and right movements of the plane.
Slats	The slats move out from the front of the wings to make the wing space larger. This helps to increase the lifting force of the wing at slower speeds like takeoff and landing.
Spoilers	The spoilers are used like air brakes to reduce any remaining lift and slow down the airplane
Tail	The part of the plane that provides stability for the plane
Thrust	The force of flight that pushes a plane forward. The engine provides the thrust for flight.
Turbine	A part of the jet engine
Weight	A force that acts on the plane to pull it back to earth.
Wings	Also called airfoils. The wings provide the lift for the plane.
Yaw	Yaw is the turning of a plane. When the rudder is turned to one side, the airplane moves left or right. The airplane's nose is pointed in the same direction as the direction of the rudder. The rudder and the ailerons are used together to make a turn

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Biography

Dan Hrehov has over thirty-five years flight test experience in the Seattle area and has worked on most avionics systems on many Boeing Commercial Model types from the 727 to the 787. His primary work has been flight testing avionics and automatic flight controls systems as well as navigational and communication radios, and flight management computers.

Dan is a professional engineer and a Fellow in the Society of Flight Test Engineers and has published several papers and conducted many symposium workshops on the subjects of Flight Management Computer testing, Lightning, Electromagnetic Compatibility, Data Systems Certification, and Safety of Instrumentation Installations.

He also has a master's in teaching degree and holds a Washington State Teachers certificate for secondary education with a physics endorsement.
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