'Flight Test Academy'

A Video Based Instruction Series for Teachers and Students, Comprising of Aerospace STEM Projects that Explore Flight Test Engineering

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ABSTRACT

Science, Technology, Engineering and Math (STEM) is a curriculum concept that integrates these topics and provides students with not only the theory but the practice of science and math principles.

Flight Test Academy is a set of instructional videos along with a study guide that demonstrates to teachers, parents and students how to experience firsthand, successful aerospace STEM projects based on meaningful simulated airplane flight testing. This is being offered to junior high and high school teachers for incorporation into their classrooms at no cost. The basic project consists of using a desktop flight simulator to conduct a series of takeoff flight tests where students determine takeoff distance and correlate results with different variables of gross weight and flap setting. Students can then explore the effects of other independent variables such as temperature, altitude, winds and also then use kinematic equations to determine their own distances.

Advanced projects include both climb and cruise testing to determine best climb and maximum range. It concludes with a capstone project where detailed flight planning is required, using students flight test data, to determine the maximum payload that can be carried on a real-life cargo flight mission.

Flight Test Academy is completely self-contained and assumes no previous flying or airplane experience on the part of either teachers, parents or students.

This paper will describe Flight Test Academy and how it can be implemented into a classroom, remote learning or home school environment.

ABBREVIATIONS

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

INTRODUCTION

Flight Test Academy is a series of free instructional videos in the field of flight test engineering for students and teachers. It is a web-based source of authentic aerospace STEM projects, using a desktop simulator, and includes video instruction and other resources to guide teachers, parents and students through these projects. It can be used for in-person instruction as well as remote learning or home school classes. Starting off with a basic takeoff testing project and then progressing to more advanced topics, it is scalable to suit both Jr High and Sr High students and for a variety of time durations. No flying or airplane experience is assumed or required.

There is a companion printed study guide available as a free downloadable .pdf file from the Seattle SFTE Chapter web site, found in the Reference section. Videos and lesson plans are available for download free of charge as well.

DESCRIPTION

The foundational element of Flight Test Academy is where students perform real airplane takeoff testing by varying parameters and determining runway distance required to lift off. Students will then make inferences as to what variables effect takeoff distance and why, using physics-based reasoning.

The activities students will perform will be to plan and conduct takeoff flight tests, create time history data plots where they obtain speed and time data points, use kinematic equations to calculate runway distance needed for takeoff and then infer factors that either lengthen or shorten takeoff distance. Climb and cruise testing is done in subsequent units.

The curriculum is designed to accommodate students with little or no airplane knowledge and topics include; anatomy of an airplane, reading of flight instruments, forces in general and forces of flight in particular, test planning, a discussion of lift and introducing the lift equation, using data plotting tools for data analysis, units and unit conversions, and distance equations using either average velocity or acceleration. Other advanced topics such as drag force, climb, and cruise testing are also presented and culminates with a capstone project.

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

What is not included is supplemental material for homework, practice, review and assessments and any additional topics teachers may want to include such as Newtons Laws etc.

Additional advanced projects include climb testing to determine the best speed for the maximum rate of climb for an airplane and cruise testing to determine the best speed to obtain the maximum lift/drag, L/D, ratio for maximum range. Students will plot L/D ratio and range vs airspeed where they can see the effects of parasitic and induced drag.

Students can then accomplish a capstone project of a real-life cargo mission called the 'Apple Challenge' that requires detailed flight planning using students climb and cruise flight test data from an airplane of their choosing, in developing a flight plan for the transport of the maximum payload of apples between two cities. Their flight plan is then flight tested to confirm their predictions.

There are other skills that are concurrently developed by conducting these projects. Skills such as test planning to understand the goal and to develop test plans that support it. Test discipline skills that include; following a test plan, keeping track of test configuration, data recording and management, data recovery and plotting. Data analysis and reporting capabilities, developing conclusions and reporting on test results are also realized as well.

Many connections to mathematics are revealed in these projects as well. For example, relationships between velocity, time and distance; units and unit conversions; distance calculations using either average velocity or acceleration.

LEARNING STANDARDS

Flight Test Academy addresses the Next Generation Science Standards for Science and Engineering Practices (April 2013) in the following areas; planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking and constructing explanations and design solutions. These projects reinforce the scientific principle of making an observation and using mathematical tools to develop theories that can explain the observed behavior.

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 selected SLO's from each of the units. The study guide includes all SLO's the units.

- Define the role of the flight testing 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.
- Describe and differentiate between displacement, velocity and distance.
- Be able to compute velocity, distance or time, knowing any two of the three variables.
- 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 and 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 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.

CONNECTIONS TO MATHEMATICS

The connection to mathematical concepts is important in the process of validating test results against the theory and is useful in many other technical areas. Manipulating one variable in a three variable equation such as the distance equation using average velocity, is something junior high students can understand. Here are some other specific connections to mathematics.

- 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 desired units of feet.
- Unit conversion can also be used as an opportunity to introduce students to dimensional analysis whereby doing the units conversion 'longhand', but carrying all the units along with the numeric values in the equations and canceling 'like' units at the end as a method to independently verify correct units at the end.
- 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 acceleration is determined by: acceleration = $\Delta v/\Delta t$. Coupling this with another concept that the slope of the velocity plot equates to acceleration is another useful method to reinforce linear equation concepts.
- Introducing the lift equation, $L = \frac{1}{2}\rho SV^2C_L$, is important in understanding the parameters that affect wing lift. Knowing that the lift generated by the wing must equal the weight of the airplane, will illustrate to students the need to increase some other variable in the equation to produce the extra needed lift to accommodate additional weight. 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 at airports with various 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, $D = \frac{1}{2}\rho AV^2C_D$ that include 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.

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 and includes the topics covered. Lesson plans are available for each of the lessons and can be downloaded from the Seattle SFTE site as are the videos.

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	X-Plane Basics	X-Plane 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	Forces of Flight	Lift equation/ Angle of Attack
		2-3	Takeoff Test Planning	Test planning 777 Takeoff tests varying GW, Flaps or Thrust Data recovery
		2-4	Data Recover and Analysis	DatPlot demonstration Data Analysis – runway length determination Test reporting Extensions – Change airport and temp setting or make design changes to wing and repeat tests
3	Climb Testing	3-1	Drag Test Planning	Induced and Parasitic Drag Drag equation Climb testing of C172
		3-2	Data Recovery and Analysis	Develop speeds for best rate of climb Test reporting Extensions – Change flap setting or make design changes to wing and repeat tests
4	Cruise Testing	4-1	Cruise Test Planning	New terms; L/D, Range Test planning

		4-2	Data Recovery and Analysis	Cruise testing of C172 Develop speeds for maximum L/D and best range and duration Test reporting 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

CURRICULUM

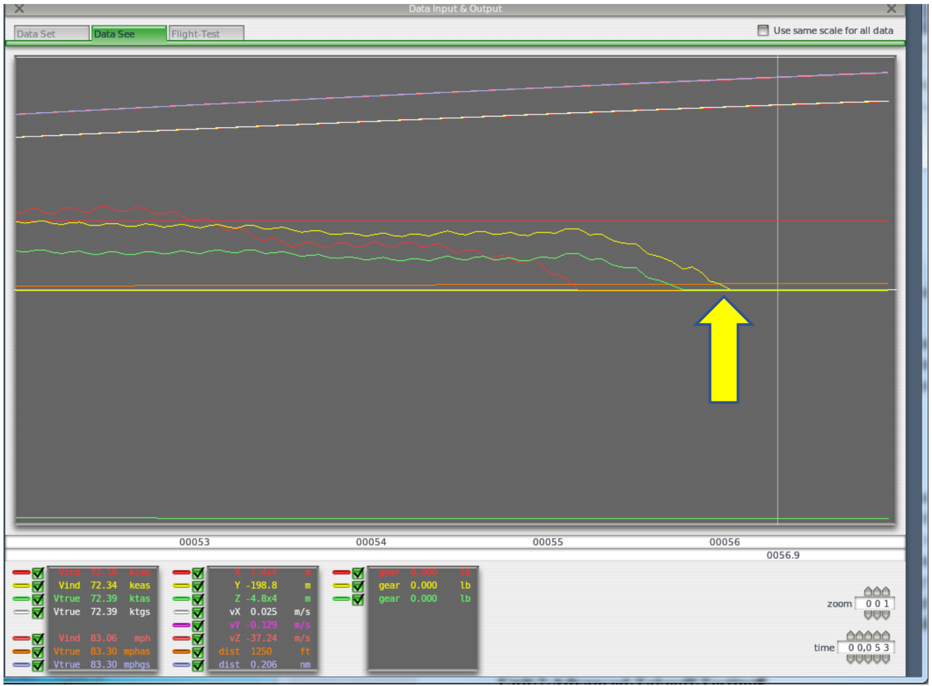
Flight Test Academy instruction is geared toward Jr High and Sr High school students and consists of six units, up to four lessons per unit, that cover airplane basics up through a capstone project. It can easily require a full semester to complete. The videos include the necessary background information, student activities and instructions, discussion questions and extensions. No aviation experience is required or expected for either students or teachers. The videos are between 12 and 30 minutes and should be paused, at the indicated places, to allow time for the discussion questions and/or activities and should be done in the given order.

Lesson plans are available for each lesson that provides the learning goal, an outline of the lesson topics, an estimate of the duration and needed supplies. Appropriate homework, worksheets to reinforce the concepts and assessments are not included. Extensions such as Newtons' Laws are also not included but could easily be incorporated. Below is a further description of the units.

Unit 1 - Basic Takeoff Testing

Unit 1 comprises the project introduction along with anatomy of an airplane, airplane axis and cockpit familiarization to provide teachers and students without an aviation background the information to understand how an airplane works. It also covers basic airplane forces and their corresponding units. The simulation software, X-Plane, is introduced and steps are provided on how to set up for a takeoff test including recording the 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.

The screen shot below is from X-Plane's *Data Input and Output* option where time history data can be displayed after the flight. The top lines are of increasing airspeed, and the lines sloping down are the forces on the landing gear, gear loads. When the gear loads go to zero, the airplane has lifted off (see yellow arrow). The distance traveled in both feet and nautical miles is listed in the data table. Time in seconds, is displayed on the X axis.

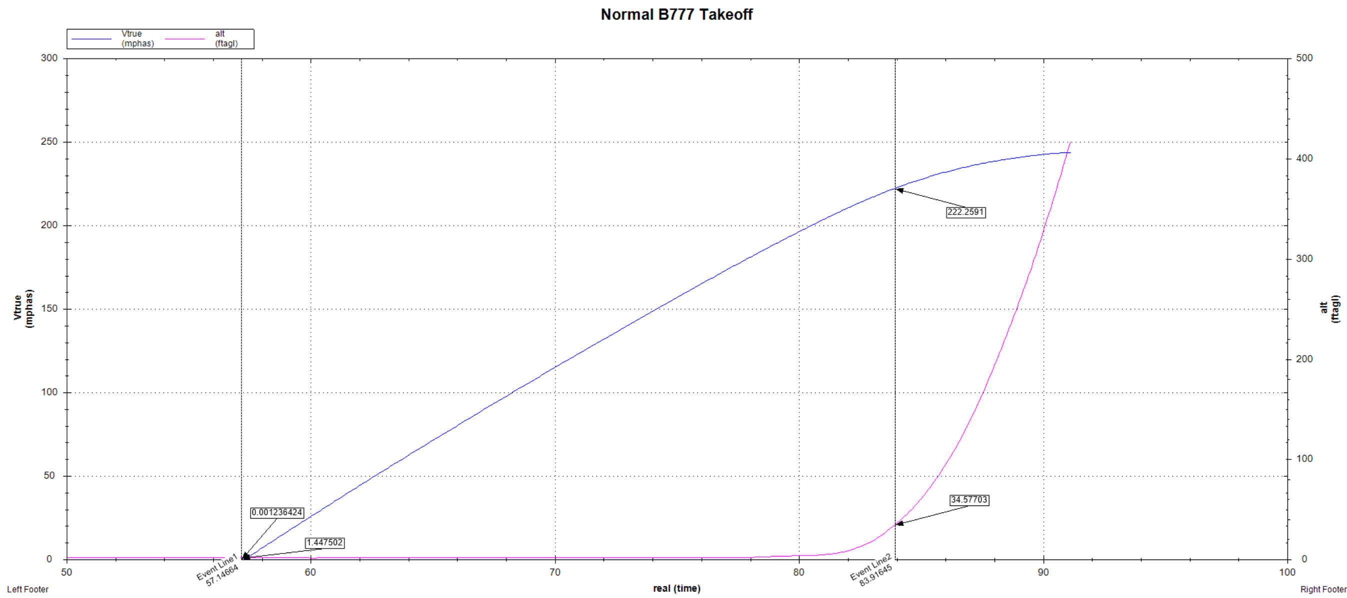


Unit 2 - Advanced Takeoff Testing

Unit 2 expands on the initial takeoff testing by introducing 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 the effects. For example, adding flaps or testing on a hot day at a high-altitude airport.

The kinematic equations are introduced in Unit 2 to enable students to calculate their own takeoff distances. To accomplish this, the plotting program 'DatPlot' is introduced to allow students to quickly produce 'industry standard' strip chart time history data. This 'easy to use' program creates multivariable 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.

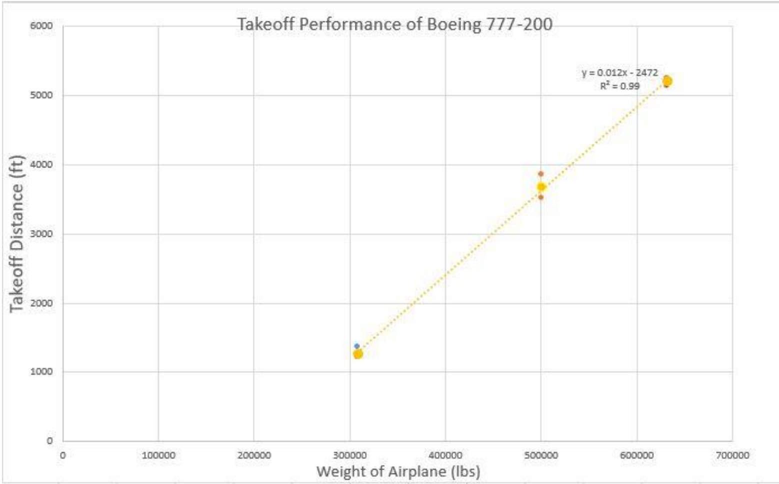
The example below demonstrates the steps in reducing the flight test data from the takeoff testing into runway distance using the time history strip chart data. The example is a plot of just two variables, speed and altitude, against time (in seconds). From these two parameters, runway distance can be 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 above ground level. The example below used DatPlot as the charting software.



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. 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 => $\Delta\, v$: (325 – 0) = 325 ft/sec
    b. Determine delta time => Δt : (83.9 - 57.1) = 26.8 sec
    c. Determine acceleration => $\Delta\, v/\Delta t$: (325-0)/(26.8) = 12.1 ft/sec^2
4. Calculate distance $d = \frac{1}{2}at^2$ => ½* 12.1 * $(26.8)^2$ = 4345 ft.

These steps are repeated for the remaining tests and then summarized in charts. Such an example is the one below plotted 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 that results with no significant outliers. Note: The same results can be achieved using the average velocity formula, $d = V_{ave}$*t, where $V_{ave} = (V_f + V_i)/2$.



Student Plot of B777 Takeoff Distance vs Gross Weight

Unit 3 - Climb Testing

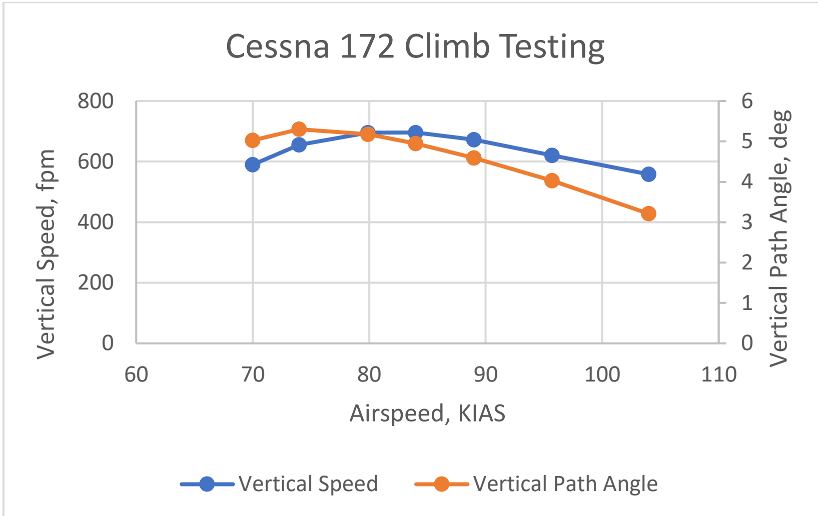
Climb testing is used to determine the airspeeds for the best angle and best rate of climb. This is important for pilots to know for example, when trying to climb over the trees at the end of the runway. These speeds are a function of the Lift Coefficient, Angle of Attack and the total drag of the wing 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.

In Unit 3, the drag equation is introduced, $D = \frac{1}{2}\rho A V^2 C_D$ where the concepts of both parasitic and induced drag are explained. Parasitic drag is directly related to the frontal area of the airplane and wing, and the force it applies to the vehicle, wanting to slow it down. This drag is a function of airspeed and increases fourfold when airspeed is doubled due to velocity being a squared term. Streamlining the aircraft and wing structure reduces this drag.

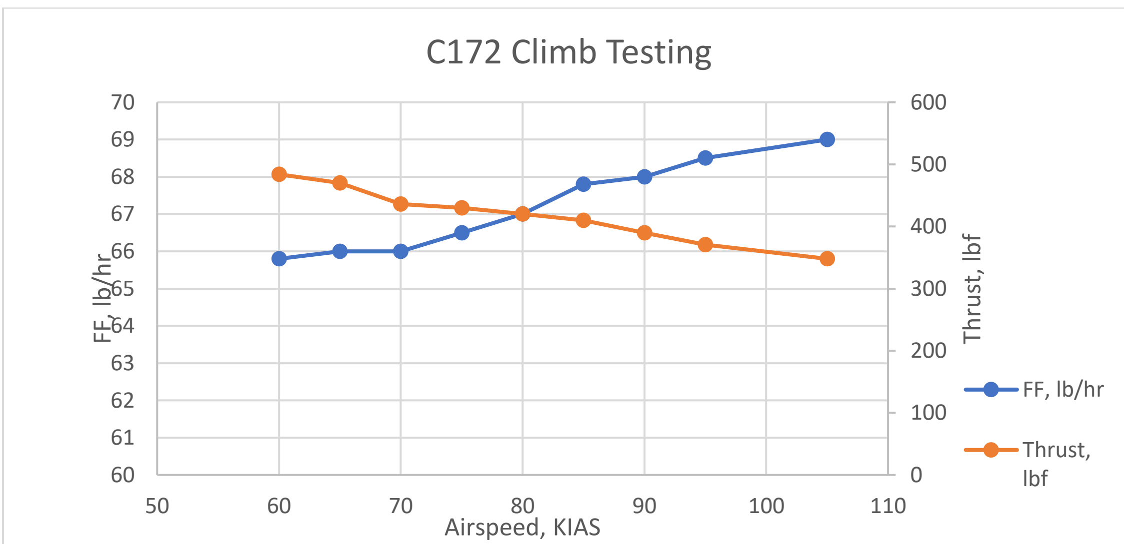
Induced drag is inherent to the direction of the lift vector and is more dominant at low speed, high angle of attack situations. In these cases where the wing is at high angle of attack, (AOA), the lift vector, which is always perpendicular to the wing, has a component pointing somewhat backward and therefore results in a horizontal component of lift that is retarding the aircrafts forward motion. Induced drag is directly related to angle of attack, and is prevalent at low speeds.

Both induced and parasitic drag coexist in a flight profile, but to more or less of an extent, based on the aircrafts speed and thus angle of attack. This can be visualized in the data results for climb flight testing in X-Plane, where students perform a constant speed climb with full power and then determine the total drag (both induced and parasitic) for a series of airspeeds. When total drag is plotted against airspeed, a predominant parabola is depicted with the total drag being greater at the slow and fast speeds and is minimized at mid-speeds. The difference between the engine thrust needed to overcome total drag and the total amount of thrust the engine can deliver, manifests itself in climb performance, i.e. rate of climb. This 'excess horsepower' as it sometimes referred to, is what the airplane needs to climb, the more of it, the faster the airplane will climb. Climb rate is measured in feet per minute.

Below is a plot from testing done by the author of a climb test of a Cessna 172 that depicts the differences in both vertical path angle and vertical speed as a function of airspeed. As depicted by the parabola, the different drag influences being apparent. The data also points out the airspeed differences between the best angle of climb and the best rate of climb.



Also plotted below is fuel flow as a function of airspeed. Note there are only three lbs./hour fuel flow difference (~4%) between the airspeed range, which is reasonable since the engine RPM is at maximum for this testing.

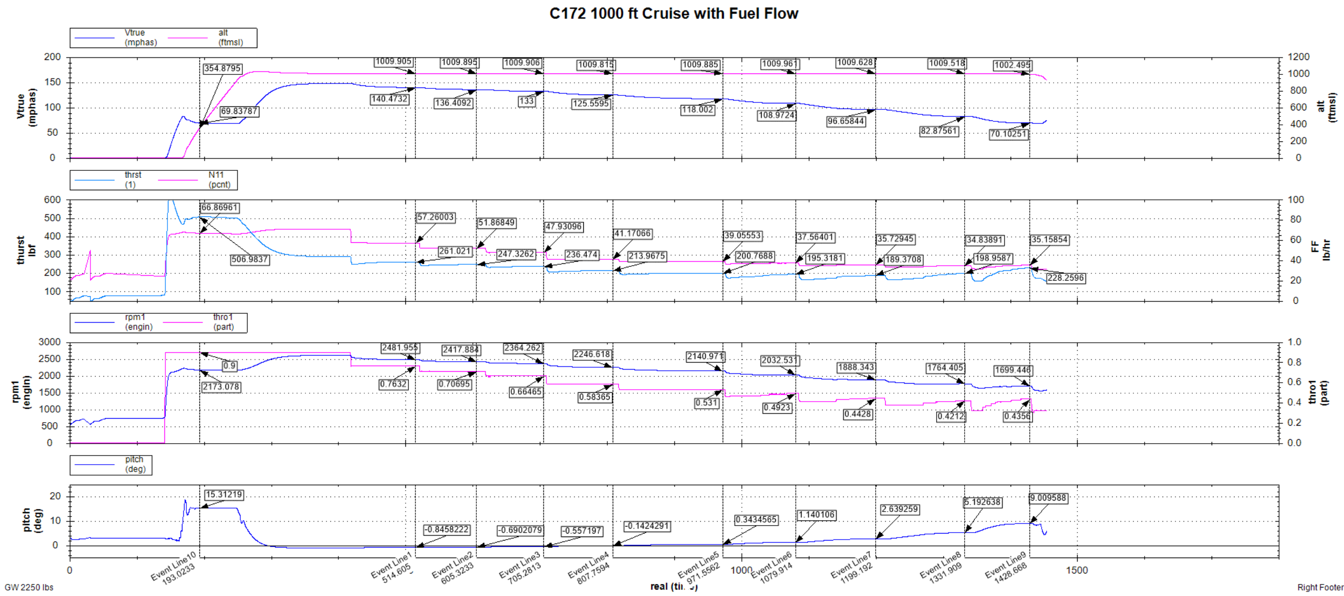


Unit 4 - Cruise Testing

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 new Boeing airplanes, 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.

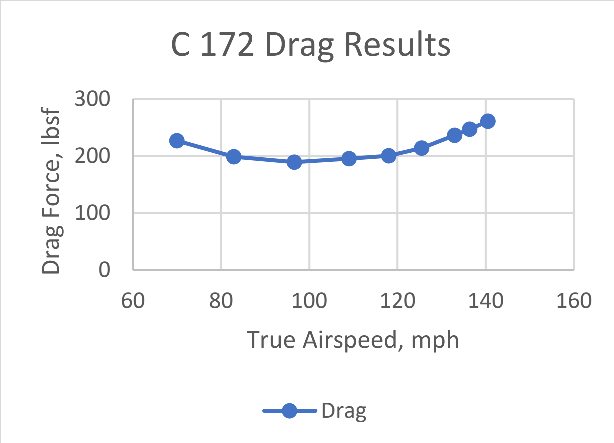
Drag testing of the Cessna 172 was done in X-Plane to compare the simulation model with the Pilots Operating Handbook, POH. Testing consisted of one flight that included a takeoff to 1000 ft and then a series of throttle reductions, allowing speed to vary and stabilize. After each thrust reductions, speed is slowly bled-off and when stabilized the next throttle reduction is made. Once eight conditions of RPM and speed combinations were flown, data was recovered and analyzed. It was critical that altitude was maintained exactly so the autopilot was utilized.

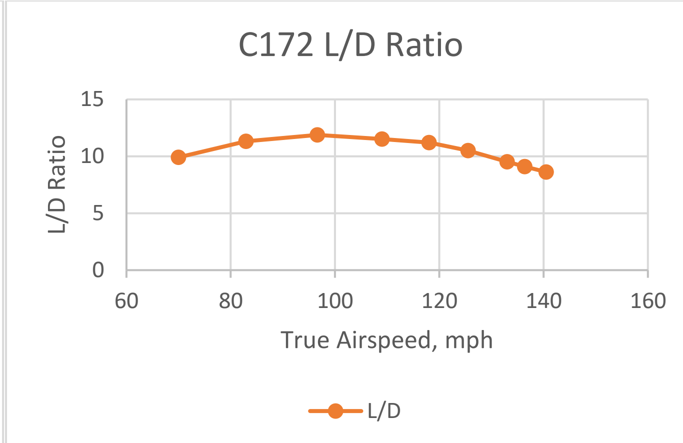
The plot below shows the entire cruise test flight of the C172. From the data you can see a constant altitude with a series of throttle reductions and subsequent speed reductions. Thrust is computed by X-Plane and that is plotted as well as fuel flow.



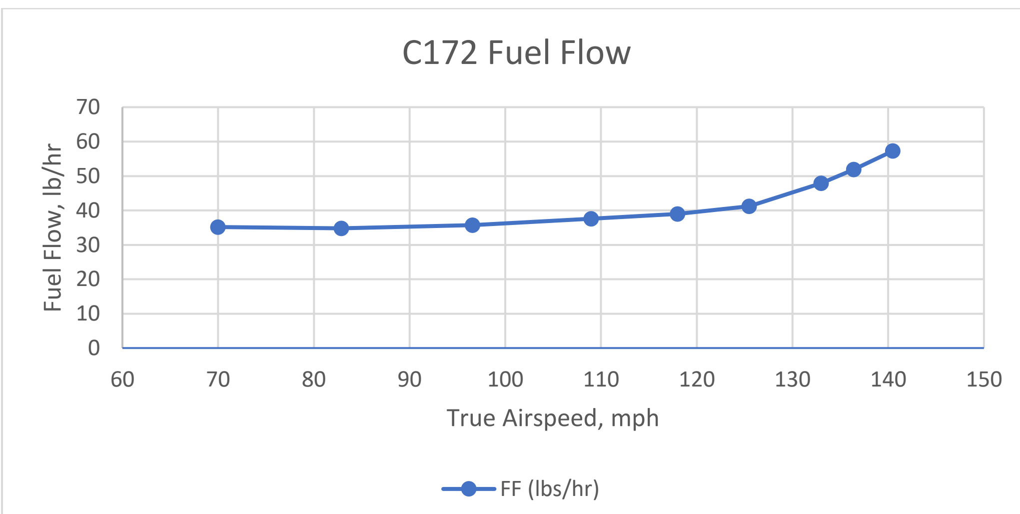
Remembering that thrust is equal to drag, the analysis used the thrust output by X-Plane for drag. In the left figure below, drag is plotted against true airspeed. You will see a noticeable shallow section of the curve, being typical of the total drag curve. At low speeds, *induced* drag is predominant while at high speed, *parasitic* drag is dominant. The overall minimum drag is in-between.

In the figure on the right, lift is divided by drag and the ratio L/D, is computed and plotted. This ratio is important in comparing wings from one airplane to another or for comparing changes to a wing. Finding the L/D maximum determines what airspeed will be used for most efficient range. To obtain Lift, the gross weight of the airplane is used, and is in this case 2250 lbs.

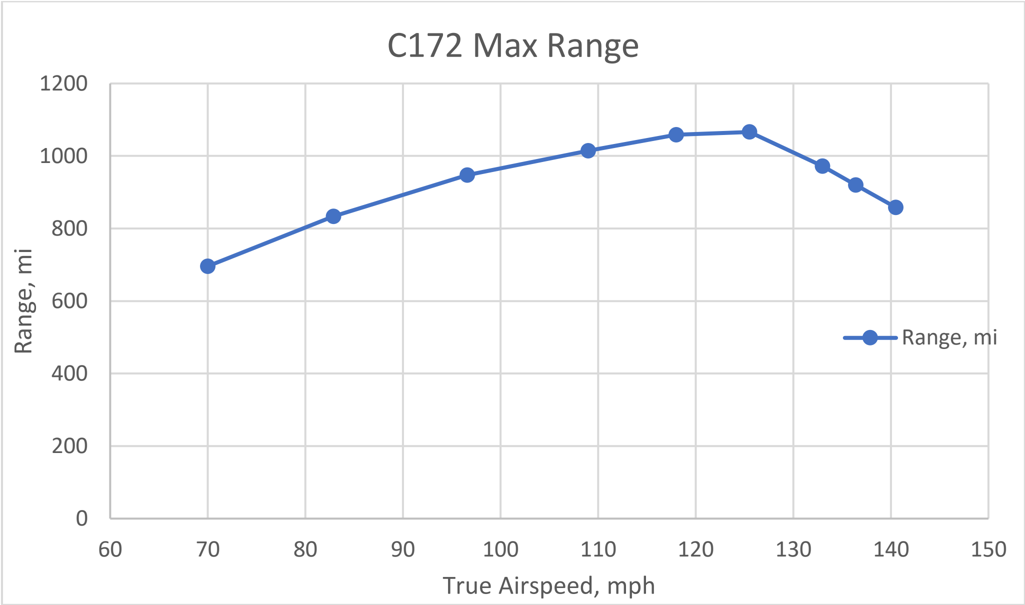




Fuel flow was then plotted versus true airspeed in the graph below and appropriately reflects the increased fuel needed to maintain the faster speeds, because of the higher drag. The minimum fuel flow is a range of airspeeds, from 70 to almost 90 as depicted by the flat portion of the curve. This value is useful if a pilot wanted to know how long the airplane can ‘stay in the air’, useful for aerial surveillance purposes. For example, for a fuel flow of 35 lbs./hr. and 350 lbs. of total fuel on board, the maximum duration is almost 10 hours at a speed of 85 mph.



Additionally, the maximum range can be calculated using speed and total fuel capacity and then plotting against airspeed as in the graph below. The highest range is over 1000 miles (not including reserves) providing the airplane is flown at approximately 125 mph. Any different speed will reduce that range. This speed is useful to know if a pilot is concerned about running out of gas in flight! Note the speeds differences between maximum range and maximum duration.

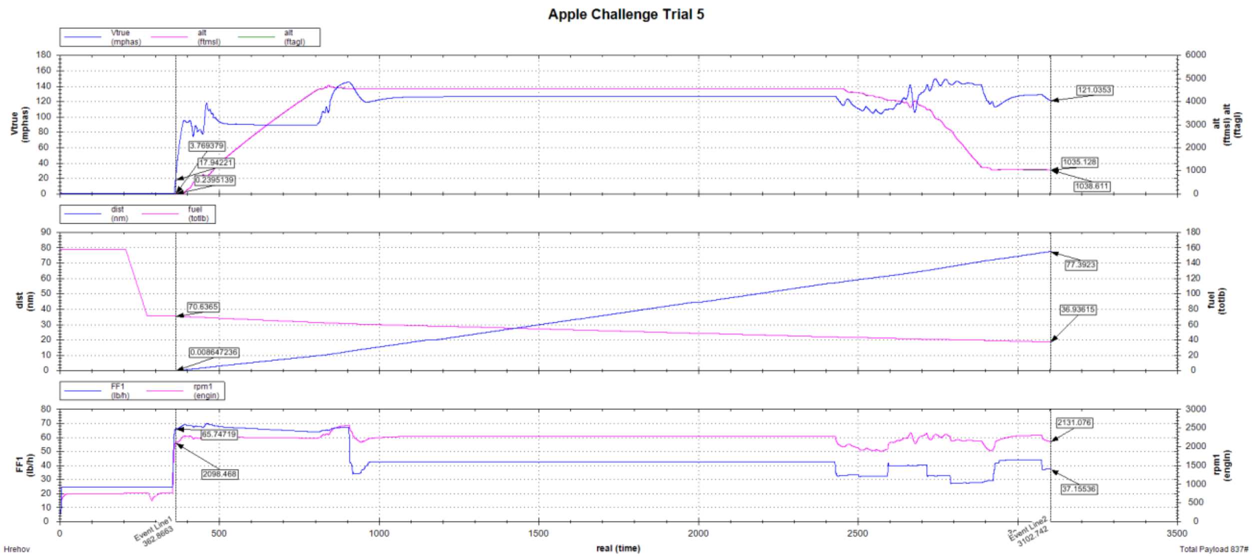


Unit 5 - 'Apple Challenge' Capstone Project

The Apple Challenge project combines much of what students have learned in the previous units and their flight testing, into a real-life airline industry example. The project takes place in apple country of eastern Washington State. The towns in eastern Washington, along the Columbia River, are home to some of the country's best apples that are then shipped all over the world. The mission is to transport as many apples you can, by weight, in a C172 and load up just enough fuel (with reserves) to make the flight between the two Washington cities of Ellensburg and Seattle.

Students will use data from their recent climb and cruise testing (or provided test data) to determine the best speed at which to climb and to cruise that minimizes the fuel needed and therefore maximizes the amount of apples that can be transported. They will then flight test their flight plan and see how well it did. Included are some simplifying assumptions such as course and altitude as to not make it overly complicated.

The test is then flown in real time and post flight data is plotted and results are tabulated and reviewed. The plot below is an example test flight by the author.



Unit 6 - Extensions

There can be a design element to this project as well. X-Plane contains PlaneMaker software that allows students to modify the airplane, such as for example, changing the wing shape and dimensions or adding winglets or changing the wing aspect ratio. The takeoff, climb and cruise testing would them be repeated and students would then compare these results to the baseline configuration results and determine if the change was beneficial. All of this is 'real world' aerospace engineering activities that professional engineers in the industry will recognize.

Disclaimer: All testing involved with these projects was done with X-Plane v9, Fly to Learn version, using a mouse and was either hand flown by the author, or for the cruise testing and the Apple Challenge, the autopilot was used. Not all the test results matched the pilots operating handbook exactly but were reasonably close to confirm that the fidelity in the X-Plane simulation model adequately demonstrated the intended aerodynamics concepts that were meant to be conveyed. The results obtained here are not meant to replace the information contained in the POH for actual flying, but only serve to illustrate aerodynamic principles.

FLIGHT TEST ACADEMY WEB SITE

The primary location for Flight Test Academy is on the STEM Outreach page of the Seattle Chapter SFTE web site; STEM Outreach – Seattle SFTE where all of the related material can be found, viewed and downloaded.

Under STEM Outreach page, the primary *Flight Test Academy* page will provide links to the curriculum, the syllabus, links to the videos, downloadable lesson plans and the study guide.

Other related pages will include *Examples of Student Work*, *Student Comments*, *Teacher Resources*, *Past Events* and *Contact* pages.

HOW TO GET STARTED

For SFTE members and chapters who want to get involved, experience it yourself firsthand. Look at some of the videos, review the study guide and try out the software. Then connect with a local school, a teacher, a PTA, or a home school parent. Let them know about Flight Test Academy and that support for incorporating this material in their classroom is available. Assistance in the form of either guest speakers or project helpers can also be arranged. Use the following references and links to discussion boards for reference material and to post questions.

SFTE Facebook page: https://www.facebook.com/groups/SFTE1/

Other web-based resources are listed below in the Reference section.

CONCLUSION

For almost 10 years this flight testing project has been successfully used by hundreds of students in ninth-grade science classes. Teachers, parents and participating SFTE members all agree that this is a meaningful demonstration of flight test engineering that provides students with an authentic aerospace industry experience.

REFERENCES

Hrehov, D. W. '*STEM, Education Reform, SFTE and You*', 2013, 44th Annual SFTE Symposium, FT Worth, TX.

Hrehov, D. W. '*Flight Test STEM Project*', 2018, 49th Annual SFTE Symposium, Savannah, GA.

Seattle SFTE Chapter website: http://www.seattlesfte.org/stem-outreach

X-Plane Web site: http://www.x-plane.com/desktop/try-it/older/

DatPlot web site: http://www.datplot.com /

Fly To Learn website http://flytolearn.com/

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

BIOGRAPHY

Dan Hrehov has over thirty-five years of flight test experience in the Seattle area and has worked on most avionics systems on 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, flight management computers and for electromagnetic compatibility.

Dan is a Professional Engineer and a Fellow in SFTE and has published several papers and conducted many symposium workshops on the subjects of FMC testing, Lightning, EMC, 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. https://www.linkedin.com/in/danhrehov/