SAILPLANE AEROTOW TAKEOFF PERFORMANCE EVALUATION THROUGH MODEL VALIDATION

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ABSTRACT

USAF Test Pilot School (TPS) staff members conducted a flight test program to determine the takeoff and climb performance of the TG-15A Duo Discus at maximum gross weight, high density altitude, and calm wind with the USAF Academy CC18-180 Top Cub tow plane. In the paradigm of Predict-Test-Validate, a mathematical model was constructed to predict takeoff performance during the buildup in glider gross weight. After flight test, the model was adjusted to match the test results at the test conditions. Flight test data were standardized using the model to support conclusions about the feasibility of operations.

This paper discusses the simple instrumentation used, including a Wide Area Augmentation System (WAAS)-enabled GPS for Time-Space-Position Information. The approach to takeoff testing is detailed. The process for estimating performance models from published data is discussed, along with the methods used to model the takeoff and initial climb and factors for adjusting that model. The final results of the model matching are shown, and a t-distribution is fitted to the standardized data. Details for calculating the Student's t probability distribution function are also included.

BACKGROUND

The 94 Flight Training Squadron (FTS) conducts glider training at the USAF Academy to provide airmanship training to cadets. A small group of cadets who excel in this training form a team to compete in national competitions. For these competitions, the soaring team uses the TG-15A Duo Discus glider, which has a maximum gross weight with water ballast 37 percent greater than the TG-10B Super Blanik glider used for airmanship training. Since the tow plane support had been optimized for the lighter training glider, the 94 FTS was concerned about the ability to safely aerotow the heavier glider with the same tow plane fleet. Compounding the concern was the USAF Academy Airfield elevation (6505 feet) and temperatures in the summer months that could result in density altitudes of 10,000 feet (93 degrees Fahrenheit with standard atmospheric pressure) or greater. Thus the 94 FTS requested the USAF TPS to conduct flight tests to address this concern.

Glider operations were conducted from a 4,500-foot runway. The governing requirement for aerotow climb gradient came from AFI-11-2TG-10B/C/D Volume 3 paragraph 5.30.4, which read, “All tow operations will cease when a minimum altitude of 200 feet AGL (6,700 feet MSL) cannot be achieved by one nautical mile from the departure end of the runway.” (reference 1). The 94 FTS desired to meet or exceed this performance with the glider at maximum gross weight, 10,000 feet field density altitude, and zero wind.

In keeping with the current flight test philosophy taught at the USAF TPS, the test program was set up to follow the paradigm of Predict-Test-Validate.

TEST ITEM DESCRIPTION

The TG-15A Duo Discus glider was a two-seat sailplane for advanced training and cross-country flying, constructed from glass/carbon fiber reinforced plastic (G/CFRP) (figure 1). Maximum takeoff weight was 1,543 pounds.

Figure 1. Duo Discus Glider

The wing was a four-stage trapezoid in planform, consisting of two main panels with tip extensions having a swept leading edge. The wing span was 65.62 feet. The wing area was 176.53 square feet, for an aspect ratio of 24.4. The integral water ballast tanks had a total capacity of approximately 52.3 US gallons, for a maximum water ballast weight of 436 pounds (8.35 pounds/gallon).

The horizontal stabilizer was mounted on the vertical stabilizer in a T-tail arrangement. The vertical stabilizer contained a water ballast trim tank with a capacity of 2.9 US gallons (24 pounds).

The CC18-180 Top Cub tow plane was a two-place tandem, high-winged aircraft with conventional gear (figure 2). The steel tube fuselage frame and aluminum frame strut-braced wings were fabric covered. The engine was a 180 horsepower Lycoming O-360-C4P installed under a Supplemental Type Certificate and drove a fixed pitch propeller. Total fuel capacity was 35 US gallons. Aircraft empty weight was 1,000 pounds. The wingspan was 35 feet. The wing area was 178 square feet, with an aspect ratio of 6.88.

The tow ropes were 200±10 feet in length.

Figure 2. CC18-180 Top Cub Tow Plane

INSTRUMENTATION

Glider Time-Space-Position Information (TSPI) was recorded using a Garmin® GPSmap 296, GPS mounted in the rear cockpit (figure 3). The GPS recorded the time, elevation (altitude), distance traveled (leg length), ground speed, track, latitude, and longitude at a 1 hertz rate. The GPS could store up to 9,999 data points, which allowed for 2 hours, 46 minutes, 39 seconds of recording at the 1 hertz rate. These data were downloaded from the GPS after flight. The GPS unit used the WAAS to improve the accuracy of position and altitude values. Initial tests showed position uncertainties (error from absolute position) on the order of 10 feet. The uncertainty of the GPS distance and the GPS altitude from point to point were significantly less than the normal variations in the data. Figure 4 shows unfiltered data from Flight 28. The smoothness (lack of noise) of these data show that the GPS was a valid instrument for collecting position and altitude data. However, this quality of data was only available when WAAS was active. A good WAAS lock was confirmed before starting any test points.

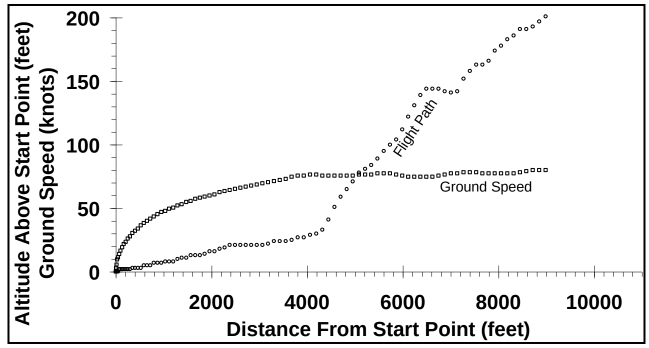

Figure 3. Garmin® GPSmap 296 in Rear Cockpit

Figure 4. Garmin® GPSmap 296 Data Quality Sample

Airspeed and altitude data were collected from the rear seat cockpit instruments. Additional data were collected by the launch crew during the takeoff roll. Pressure altitude was read from a MicroTim™ handheld altimeter (figure 5). Wind speed and temperature were read from a La Crosse® Technology handheld anemometer (figure 5). The wind speed measurement was limited to the headwind component by visually aligning the axis of the measurement turbine with the runway heading.

Figure 5. MicroTim™ Altimeter and La Crosse® Technology Anemometer

Water ballast was loaded in the wing tanks using a hose connected to a Great Plains Industries, Inc., Model 01A31GM Flow Totalizer (figure 6). This flow meter displayed the amount of water that had passed through it to the nearest tenth of a gallon. The required amount of water to reach the desired gross weight was calculated, and half of this amount was put in each wing tank.

Figure 6. Great Plains Industries Model 01A31GM Flow Totalizer

FLIGHT TESTING

In order to minimize the extrapolation required to predict the endpoint performance, testing was conducted in conditions very close to the endpoint conditions. This meant that the testing was conducted at the USAF Academy Airfield, Colorado, during the summer by a test team deployed from Edwards AFB, California. The benefits of this approach, besides credibility of the results, were that the glider and tow plane did not have to be moved cross-country, and the 94 FTS gained experience in heavyweight operations under the guidance of trained flight testers. The drawbacks of this approach were that all of the necessary equipment had to be transported to the test site, and with only a 1-week test window, test time was very compressed, even more so by weather and other factors. With a very compressed test window, it was also vital to prevent the inevitable "scope creep," limiting testing to only that required to answer the agreed-to objective.

In addition to following the paradigm of Predict-Test-Validate, it was critical to follow a build-up approach to keep the risks manageable while approaching what was expected to be a performance-limited situation. While the test team was highly experience in flying gliders, they had virtually no experience flying the TG-15A, flying at the USAF Academy airfield, or flying with the provided tow planes. Therefore, to build a rapid experience base and baseline data, each member of the test team flew four to five sorties in the TG-15A in the unballasted configuration.

Glider gross weight was adjusted by calculating the amount of water to be added to achieve the desired weight. Half of this amount was then added to each wing tank, measuring the volume with the flow totalizer. Except for one flight, no water was added to the tail tank. The purpose of the tail tank was to adjust the center of gravity rearward. On one early flight, the tail tank was filled, but the pilot could not detect any noticeable change in handling qualities. Because of a very small filler tube, the tail tank required over 20 minutes to fill, compared to less than five minutes for both wing tanks. In the interest of maximizing the number of flights in the allotted time, the tail tank was left empty for the remainder of the test.

Each sortie consisted of a takeoff and climb to a release point for an immediate approach and landing. Thus, each sortie was one trip around the traffic pattern, for a sortie duration of about 6 minutes. The takeoff was flown by a 94 FTS pilot from the front cockpit, while the test team test pilot/FTE managed the GPS and recorded hand-held data from the rear cockpit. Upon reaching 200 feet AGL, the quantitative portion of the data collection was complete, and the valves to dump the water ballast were opened. At this point the test team test pilot/FTE flew the glider for the remainder of the tow, release, approach and landing for a handling qualities evaluation. The water released at a slow enough rate that sufficient time was available to evaluate the handling qualities of the higher gross weights. The tow pilot recorded the engine rpm.

A Matlab® model was developed to simulate the aerotow takeoff and climb to 200 feet AGL prior to the start of flight testing. The original intent was to use this model to predict the degradation in takeoff performance for each increment of added weight, adjusting the model as required based on collected flight test data. While the initial model predictions were useful in showing the test team what should be expected, the model under predicted the ground roll distance and distance to 200 feet AGL by a significant amount. Because of the deployed nature of the testing, very limited time was available to adjust the model for these large discrepancies, and a suitable update was not determined in the time available. Therefore, the model was set aside for the duration of the flight testing and the test team reverted to estimating the degradation of performance for each gross weight increase based on qualitative evaluation of factors such as increase in ground roll distance and altitude at the runway end. Of course, this approach involved accepting a slightly greater risk, which required more caution and judgment on the part of the test team.

Once the baseline performance had been established, the objective was to build up to the maximum gross weight as quickly as was prudent. The takeoff performance at the intermediate weights was not really of interest, other than for risk reduction during the buildup. The test team decided on a minimum of three sorties at each gross weight as sufficient to establish the performance degradation. This number also worked well since there were three test pilots/FTEs on the team, and it gave each one a chance to see the results first hand. Upon reaching the glider maximum gross weight, as many sorties as possible were flown in the remaining time to build the largest possible statistical significance. Table 1 shows the buildup progression used.

Table 1. Buildup Sortie Progression

Glider Gross Weight (pounds)	Aerotow Airspeed (KIAS)	Number of Sorties
1306-1336 (no ballast)	60	13
1420	60	3
1480	60	4
1480	65	3
1543	65	12

AERODYNAMIC AND ENGINE MODEL ESTIMATION

Since the Matlab® model was created prior to the collection of any flight test data, the aircraft specific portions were estimated from aircraft measurements and published data.

For the tow plane, values for the wing span, wing area, empty weight, propeller diameter, and best glide speed were obtained from the 94 FTS. No performance data were available for the CC-180 Top Cub, but it was a clone of the Piper PA-18 Super Cub. From Jane's All the World's Aircraft 1976-77 (reference 2), the fuel capacity, cruising speed (75 percent power, sea level), and maximum speed (100 percent power, sea level) were found for a 150 horsepower Piper PA-18. Assuming that the airframes were essentially identical, the drag polar could be estimated using the speeds for power settings of the 150 horsepower airplane. The higher performance of the 180 horsepower airplane would be accounted for by using the 180 horsepower engine model.

Using the data from reference 2, the tow plane drag polar was estimated by the following process, which is shown in detail complete with equations and examples in reference 3.

1. The aspect ratio was calculated.
2. A value of Oswald's Efficiency Factor was estimated from previous tests and later refined by iteration.
3. The gross weight of the tow plane was calculated by adding the empty weight, assumed pilot weight, and fuel weight (assuming 6 pounds per gallon).
4. Since the quoted data were at sea level, the true airspeed was equal to the calibrated airspeed.
5. For both the cruise speed and maximum speed, the engine brake horsepower was calculated by multiplying 150 horsepower by the percent power specified.
6. A propeller efficiency was assumed based on available data from a similar propeller.
7. Multiplying the brake horsepower by the propeller efficiency yielded the thrust horsepower.
8. Dividing the thrust horsepower by the true airspeed yielded the thrust.
9. Assuming drag equaled thrust, the drag coefficient was calculated.
10. Assuming lift equaled weight, a lift coefficient was calculated.
11. The induced drag factor (K) was calculated as a function of Oswald's Efficiency Factor and the aspect ratio.
12. Subtracting the induced drag coefficient from the total drag coefficient yielded the parasite drag coefficient.
13. Knowing that at the best glide speed (L/D_{max}) the parasite drag coefficient and the induced drag coefficient were equal, the lift coefficient for best glide was calculated.
14. From this lift coefficient the level flight airspeed corresponding to this lift coefficient was calculated. This airspeed was compared to the stated airspeed for best glide, and the Oswald's Efficiency Factor was adjusted and the process repeated until the airspeeds matched.
15. For the tow plane brake horsepower model, an appropriate manufacturer published brake horsepower chart was used. To create the propeller efficiency curve, the planform of the propeller blade was measured. Using these data with a combination of blade element theory and momentum theory a propeller efficiency curve was estimated. The Matlab® code for this process is shown in reference 3.

The glider drag polar was estimated by the following process, which is shown in detail complete with equations and examples in reference 3.

1. Data were pulled from the manufacturer published chart of sink rate vs. airspeed.
2. For multiple points on this chart, values for airspeed and sink rate were extracted.
3. At each airspeed, the lift to drag ratio (L/D) was equal to the airspeed divided by the sink rate.
4. Assuming lift equal to weight, the drag was calculated from the L/D.
5. The lift and drag values were converted to coefficients.
6. The coefficients were plotted C_D vs C_L^2 and a straight line was fit to the data. From this line the drag polar was derived.

TAKEOFF MODELING TECHNIQUE

The takeoff procedure was broken into three phases; tow plane and glider on the ground, tow plane on the ground and glider flying, and tow plane and glider flying. The description below does not exactly describe the actual technique flown (for instance the tail of the tow plane was typically raised earlier than modeled), but was close enough to the actual procedure to get the required accuracy.

The takeoff was modeled by calculating the forces on the tow plane and glider, and then using the mass of the tow plane and glider to convert these forces into accelerations and rates. These accelerations and rates were then integrated over a small time step using Euler's method, which was just the first two terms of a Taylor series

$$\text{Value}(t + \Delta t) = \text{Value}(t) + \text{Slope}(t) * \Delta t$$

Because the values calculated (distance, speed) were well behaved and did not have sudden changes in slope, this simple integration method was suitable. A time step of 0.5 seconds was sufficiently small. Changing the time step to 0.0333 seconds changed the calculated total distance for the entire takeoff by only 0.1 percent. Thus, a more complicated numerical integration, such as a fourth-order Runge-Kutta was not required.

For the initial conditions, the true airspeed was set equal to the headwind. Altitude was set by the pressure altitude, and the density was calculated from the pressure altitude and temperature.

Takeoff Phase 1

Phase 1 of the takeoff roll was from the start of the takeoff until an indicated airspeed of 40 KIAS. In this phase, the tow plane was modeled in the three-point attitude (tail on ground). For ground effect calculations the tow plane wing was assumed to be 5 feet above the ground. The glider was assumed to produce no lift and thus no induced drag.

1. The tow plane thrust was calculated using the engine model and propeller model. The engine model assumed all operations were at wide open throttle. Engine rpm was adjusted until the power output of the engine equaled the power required to turn the propeller at the same rpm.
2. The tow plane lift coefficient was calculated using an estimated lift curve slope based on the aspect ratio of the wing. The angle of attack was assumed to be equal to the deck angle (angle of the fuselage reference line), and assuming the wing zero lift line was parallel to the fuselage reference line. From reference 2, "Wing section USA 35B…No incidence at mean aerodynamic chord. Total washout of 3° 18'."
3. The tow plane lift was calculated from the lift coefficient, dynamic pressure, and wing area.

4. The tow plane drag coefficient was calculated from the drag polar. Ground effect was estimated by multiplying the induced drag coefficient by the factor (reference 4):

$$\varphi = \frac{\left(16\, h/b\right)^2}{1 + \left(16\, h/b\right)^2}$$

where h is the height of the wing above the ground and b is the wingspan.

5. The tow plane drag was calculated from the drag coefficient, dynamic pressure, and wing area.
6. The tow plane rolling friction was calculated by multiplying the rolling friction coefficient (assumed at 0.02 per reference 4) by the normal force, which was the weight minus the lift and the vertical component of the thrust.
7. The glider lift and lift coefficient were set to zero.
8. The glider drag coefficient was calculated from the drag polar, which was solely parasite drag in this phase. Ground effect was not an issue since the lift was assumed zero.
9. The glider drag was calculated from the drag coefficient, dynamic pressure, and wing area.
10. The glider rolling friction was calculated by multiplying the rolling friction coefficient (assumed at 0.02 per reference 4) by the normal force, which was simply the weight.
11. The excess thrust was the difference between the horizontal component of thrust and the sum of the tow plane drag, tow plane rolling friction, glider drag, and glider rolling friction.
12. The acceleration was the excess thrust divided by the total mass of the tow plane and glider.
13. The acceleration was multiplied by the time step to find the increase in true airspeed.
14. The difference in true airspeed and headwind (i.e. ground speed) was multiplied by the time step to find the increase in distance.

Takeoff Phase 2

Phase 2 of the takeoff roll was from an indicated airspeed of 40 KIAS to the specified climb speed. In this phase, the tow plane was modeled in the two-point attitude (tail off ground) with zero lift and thus zero induced drag. The glider was modeled flying 2 feet above the ground.

1. The tow plane thrust was calculated using the engine model and propeller model. The engine model assumed all operations were at wide open throttle. Engine rpm was adjusted until the power output of the engine equaled the power required to turn the propeller at the same rpm.
2. The tow plane lift coefficient and lift were set to zero.
3. The tow plane drag coefficient was calculated from the drag polar, which was solely parasite drag in this phase. Ground effect was not an issue since the lift was assumed zero.
4. The tow plane drag was calculated from the drag coefficient, dynamic pressure, and wing area.
5. The tow plane rolling friction was calculated by multiplying the rolling friction coefficient by the normal force, which was just the weight for this phase.

6. The glider lift was assumed equal to the glider weight and lift coefficient for level flight was calculated.
7. The glider drag coefficient was calculated from the drag polar accounting for ground effect.
8. The glider drag was calculated from the drag coefficient, dynamic pressure, and wing area.
9. The excess thrust was the difference between the thrust (now fully horizontal) and the sum of the tow plane drag, tow plane rolling friction, and glider drag.
10. The acceleration was the excess thrust divided by the total mass of the tow plane and glider.
11. The acceleration was multiplied by the time step to find the increase in true airspeed.
12. The difference in true airspeed and headwind (i.e., ground speed) was multiplied by the time step to find the increase in distance.

Takeoff Phase 3

Phase 3 of the takeoff started when the tow plane and glider reached the specified climb speed and ended upon reaching 200 feet altitude above the starting point. Airspeed was held constant at the climb speed and excess thrust was used to climb. Ground effect was calculated, but rapidly washed out as altitude increases.

1. The tow plane thrust was calculated using the engine model and propeller model. The engine model assumed all operations were at wide open throttle. Engine rpm was adjusted until the power output of the engine equaled the power required to turn the propeller at the same rpm.
2. The tow plane lift was assumed equal to the tow plane weight and the lift coefficient for level flight was calculated. Effects of climb angle or non-horizontal thrust were considered negligible since the climb angle was very small.
3. The tow plane drag coefficient was calculated from the drag polar accounting for ground effect.
4. The tow plane drag was calculated from the drag coefficient, dynamic pressure, and wing area.
5. The glider lift was assumed equal to the glider weight and lift coefficient for level flight was calculated.
6. The glider drag coefficient was calculated from the drag polar accounting for ground effect.
7. The glider drag was calculated from the drag coefficient, dynamic pressure, and wing area.
8. Downwash drag was calculated by tilting the glider lift vector back at an angle equal to the assumed tow plane downwash and calculating the horizontal component.
9. The rate of climb was calculated from the specific excess power, given by

$$ROC = \frac{(T - D)V}{W}$$

10. The rate of climb was multiplied by the time step to find the increase in altitude.

11. The difference in true airspeed and headwind (i.e. ground speed) was multiplied by the time step to find the increase in distance.

MODEL ADJUSTMENT FACTORS

Numerous factors could be adjusted to match the model to the flight test results, as shown in Table 2. Depending on the magnitude of the forces, some parameters had more effect than others. Some parameters only affected part of the simulation, such as rolling friction. Factors that started with high confidence were typically not modified, while factors that started with low confidence were the best candidates for adjustment.

FINAL RESULTS

Since flights were not allowed at conditions beyond the endpoint conditions (10,000 feet density altitude, glider maximum gross weight, calm winds), the intent of the test was to validate a model and use it to predict the performance at the endpoint conditions. One takeoff was flown at glider maximum gross weight, calm winds, and 9,962 feet density altitude. At only 38 feet below the target density altitude (0.38 percent), this flight was considered an effective demonstration of the required performance.

The model was adjusted to achieve the best match with all takeoffs for the distance and the climb angle to 200 feet above the start point. The same drag polars and other parameters were used for all cases. The model was varied for changing conditions only by entering the actual glider weight, headwind, temperature, and pressure altitude present at the time of the flight. Figure 7 shows the model results for the endpoint conditions with data from five takeoffs at close to the endpoint conditions. The beginning of the data traces shows the 0.8 percent grade of the runway.

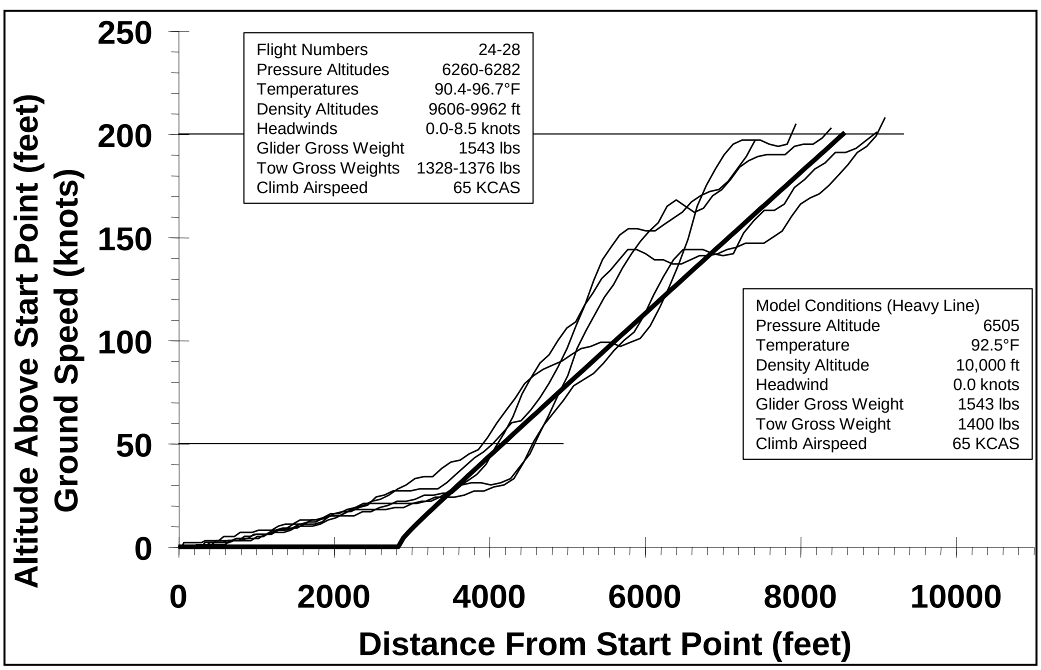

Figure 7. Endpoint Climb Performance and Model Prediction

To lend more statistical credence to the data, all takeoffs were standardized to the endpoint conditions using the increment method and the aforementioned model. These results were plotted as histograms shown in figure 8.

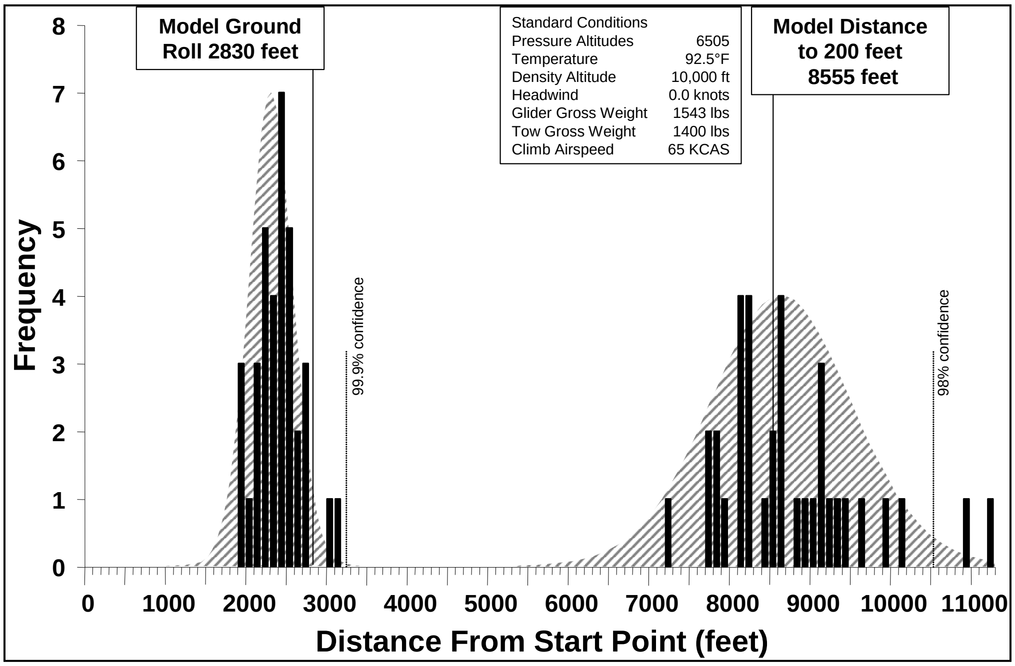

Figure 8. Test Results Standardized to Endpoint Conditions

When the actual data were compared to the model, it was seen that the actual ground roll distances were less than that predicted by the model. This difference was because in the actual takeoff the tow plane would lift off before reaching climb speed, whereas the model assumed the tow plane remained on the ground until reaching climb speed.

The model distance to 200 feet above the start point matched very closely with the experimental mean value for distance to 200 feet. Of course, this was to be expected since the model was adjusted specifically to make these two values match.

A Student's t distribution with matching mean, standard deviation, and degrees of freedom was overlaid on both the ground roll distances and the distances to 200 feet above the start point. These distributions follow the data very well, and allowed conclusions that sufficient runway was available to a 99.9 percent confidence level and that the tow plane/glider combination would meet the climb gradient requirements to a 98 percent confidence level.

MATCHING STUDENT T DISTRIBUTIONS

A plethora of references were available to calculate the probability of a statistic (cumulative distribution) given a particular Student's t distribution, but information on how to plot the probability density function was difficult to find. Therefore, a technique for plotting the t-distribution for graphical reference is provided here.

The probability density function is

$$f(t) = \frac{\Gamma\left(\frac{v+1}{2}\right)}{\sqrt{v\pi}\,\Gamma\left(\frac{v}{2}\right)}\left(1+\frac{t^2}{v}\right)^{\frac{-(v+1)}{2}}$$

where t is the statistic (the value along the horizontal axis) and ν is the degrees of freedom (ν = n - 1 where n is the number of samples). The Gamma function (Γ) is the continuous equivalent to the factorial function for integers.

The Gamma function was not one that could be easily calculated by hand or simple spreadsheet formula. However, Microsoft® Excel provided a function GAMMALN() which returned the natural logarithm of the Gamma function. Used in conjunction with the exponentiation function, as in EXP(GAMMALN(x)), the value of the Gamma function at x could be calculated.

To plot the probability distribution function for a known sample mean ($\bar{x}$) and standard deviation (s), the horizontal coordinate is given by

$$x = t * s + \bar{x}$$

The vertical coordinate is given by

$$y = f(t) * k$$

where k is a constant that gives the distribution the desired height. The height of the unmodified t distribution varies with the degrees of freedom. The desire here is to use a value of k that gives a nice match with the histogram.

CONCLUSIONS

Heavyweight takeoffs for the Duo Discus glider towed by the Top Cub tow plane were successfully modeled.

The resulting model, results, conclusions, and recommendations were delivered to the customer. With this information, the customer was able to build a soaring program for these gliders using known performance rather than guesses and intuition.

Table 2. Model Adjustment Factors

Parameter	Effect on Ground Phase I (Tow Plane tail down, glider on ground)	Effect on Ground Phase II (Tow Plane tail up, glider flying in ground effect)	Effect on Air Phase (Initial Climb)	Confidence in Initial Value
Tow Plane Parasite Drag Coefficient (C_{D_0})	Increasing C_{D_0} lengthens Ground Phase I, effect increases with increasing airspeed	Increasing C_{D_0} lengthens Ground Phase II, effect increases with increasing airspeed	Increasing C_{D_0} lengthens Air Phase and shallows climb angle; tow plane parasite drag is roughly equal to tow plane induced drag	Moderately high. Based on published data with some assumptions. Moderately high confidence in relative values of parasite and induced drag from knowing best glide speed ($[L/D]_{max}$)
Tow Plane Induced Drag Coefficient (K)	Increasing K lengthens Ground Phase I, effect increases with increasing airspeed	No effect. Tow Plane is assumed to be at the zero lift angle of attack	Increasing K lengthens Air Phase and shallows climb angle; tow plane induced drag is roughly equal to tow plane parasite drag	Moderately high. Based on published data with some assumptions. Moderately high confidence in relative values of parasite and induced drag from knowing best glide speed ($[L/D]_{max}$)
Tow Plane Rolling Friction Coefficient (μ)	Increasing μ lengthens Ground Phase I, effect reduces with increasing airspeed as tow plane lift increases	Increasing μ lengthens Ground Phase II, rolling friction is constant throughout Ground Phase II because tow plane lift is assumed to be zero	No effect	Moderate. Value selected based on published "typical" values (reference 5). No experimental verification.
Tow Plane Gross Weight	Increasing weight lengthens Ground Phase I; Ground Phase I is dominated by the thrust required to accelerate the mass (increase kinetic energy)	Increasing weight lengthens Ground Phase I; Ground Phase I is dominated by the thrust required to accelerate the mass (increase kinetic energy)	Increasing weight lengthens Air Phase and shallows climb angle; excess power is used to raise the mass (increase potential energy)	High. Gross weight was experimentally determined.

Table 2. Model Adjustment Factors (Concluded)

Parameter	Effect on Ground Phase I (Tow Plane tail down, glider on ground)	Effect on Ground Phase II (Tow Plane tail up, glider flying in ground effect)	Effect on Air Phase (Initial Climb)	Confidence in Initial Value
Glider Parasite Drag Coefficient (C_{D_0})	Increasing C_{D_0} lengthens Ground Phase I, effect increases with increasing airspeed	Increasing C_{D_0} lengthens Ground Phase II, effect increases with increasing airspeed	Increasing C_{D_0} lengthens Air Phase and shallows climb angle; glider parasite drag is slightly greater than glider induced drag	High. Based on published data with no major assumptions.
Glider Induced Drag Coefficient (K)	No effect. Glider Induced Drag is assumed zero.	Negligible effect. Glider induced drag is very small because of ground effect	Increasing K lengthens Air Phase and shallows climb angle; glider parasite drag is slightly greater than glider induced drag	High. Based on published data with no major assumptions.
Glider Rolling Friction Coefficient (μ)	Increasing μ lengthens Ground Phase I; rolling friction is constant throughout Ground Phase I because glider lift is assumed to be zero	No effect	No effect	Moderate. Value selected based on published "typical" values (reference 5). No experimental verification.
Glider Gross Weight	Increasing weight lengthens Ground Phase I; Ground Phase I is dominated by the thrust required to accelerate the mass (increase kinetic energy)	Increasing weight lengthens Ground Phase I; Ground Phase I is dominated by the thrust required to accelerate the mass (increase kinetic energy)	Increasing weight lengthens Air Phase and shallows climb angle; excess power is used to raise the mass (increase potential energy)	High. Gross weight was experimentally determined.
Engine Power	Increasing power shortens Ground Phase I	Increasing power shortens Ground Phase II	Increasing power shortens Air Phase and steepens climb angle	Low. Though starting with manufacturer's charts, condition of engines and installation losses not known
Downwash Angle	No effect. Ground cancels out downwash	No effect. Towplane lift is assumed zero, hence no downwash	Increasing downwash increases glider drag, shallows climb angle	Low. Guess based on previous testing of different tow plane and glider
Prop Pitch	Adjusted with engine power to match model rpm to flight test rpm			

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AUTHORS

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Mr. Erb is a long time member of SFTE, having joined in 1983 as a charter member of the Texas A&M University student chapter, the very first student chapter ever. He has held positions in the Antelope Valley Chapter and is currently a Senior Member. He has previously presented two Symposium papers and two Symposium training classes.

Gary L. Aldrich

Mr. Aldrich is the Test Management Master Instructor for the USAF Test Pilot School. A Flight Test Engineer graduate of USAF TPS Class 82A, he is responsible for the overarching phase of instruction which teaches Test Pilots and Flight Test Engineers the methods for setting up and running a military flight test program, from the initial customer request to the publishing of the final report. In addition to classroom instruction, he flies to teach and evaluate airborne test conduct, and is the Chief Flight Instructor for the curriculum events accomplished in gliders. His flight test experience includes the A-10, T-46, and F-16 programs.

Mr. Aldrich was the 2006 SFTE Kelly Johnson award recipient, in recognition for his long career of educating flight test professionals.

David L. Vanhoy

Mr. Vanhoy serves in the 773 Test Squadron where he is the Performance and Flying Qualities Flight Chief. At the time of this program, he was the Flying Qualities Master Instructor for the USAF Test Pilot School. A Flight Test Engineer graduate of USAF TPS Class 94A, he was responsible for the second phase of instruction which teaches Test Pilots and Flight Test Engineers to measure and evaluate open-loop and closed-loop aircraft flying qualities and aircraft flight control systems and introduces the test discipline necessary for execution of elevated risk flight test. In addition to classroom instruction, he flies to teach and evaluate airborne test conduct and is a Certified Flight Instructor for the curriculum events accomplished in gliders. His flight test experience includes the X-29 research program, numerous F-16 high angle-of-attack programs including the Multi-Axis Thrust vectoring program, and the JSF X-32 / X-35 competition.

Mr. Vanhoy is currently a Senior Member and has served many roles in SFTE, including the President of the Antelope Valley Chapter and organizer of the 2006 SFTE Symposium. He has presented several papers, taught multiple symposium training classes, and judged the technical paper presentations.