Takeoff Chart Development for a Homebuilt Airplane by Numerical Simulation

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A Matlab simulation was created to model the takeoff performance of an Experimental Amateur Built Bearhawk, using aircraft, engine, and propeller models previously developed. This simulation calculated lift, drag, thrust, weight, and rolling friction forces throughout the takeoff roll. These forces were used to calculate acceleration, which was numerically integrated to find speed and distance. Input variables included pressure altitude, temperature, gross weight, and headwind. The general form of the simulation results was initially validated with flight test data from one takeoff, then a Takeoff Ground Roll Chart was created. The final chart was then validated with flight test data across a wide range of conditions.

I. Motivation

At some point, probably while living in Colorado as a USAF Academy cadet or more likely as a USAF Academy instructor, Russ heard people talk about flying a general aviation aircraft into and out of the Leadville Colorado airport, more correctly known as Lake County (KLXV) airport (Fig. 1). What was so significant about this airport? At an elevation of 9934 feet, Lake County airport is the highest public access airport in the lower 48 of these United States. This is so significant that the FBO actually hands out certificates to any aircraft that happens to land at the airport.

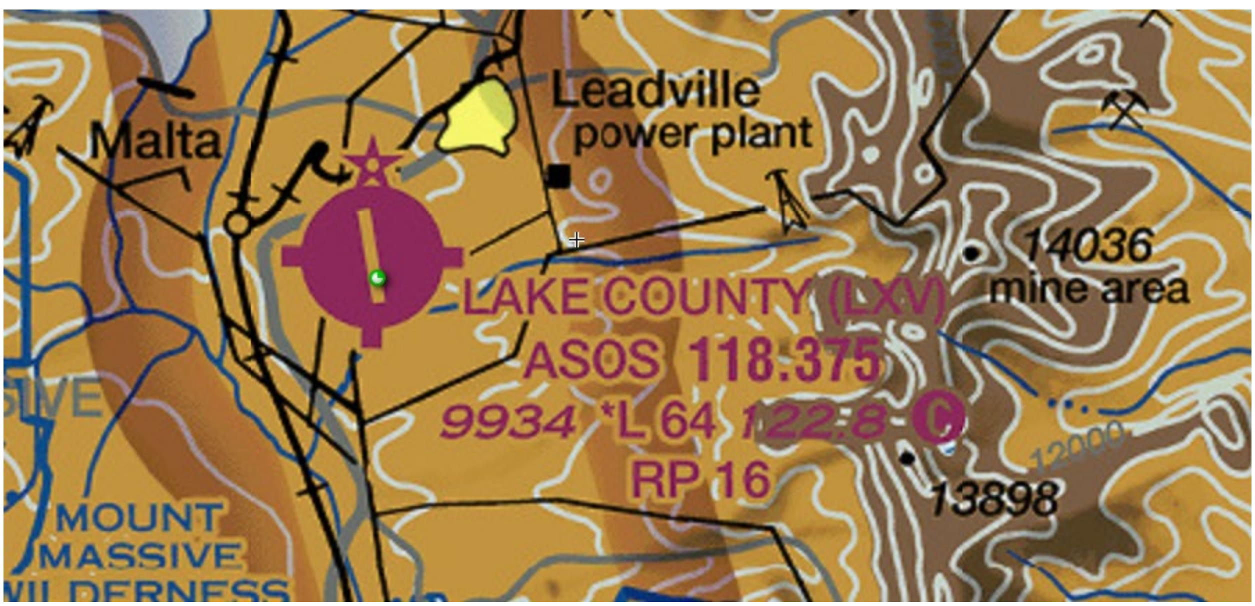

Fig. 1 Lake County Airport, Leadville, CO

Landing at the airport is less significant than taking off. Landing is a controlled process of losing altitude in such a way that you end up on the runway. If that runway is at a high elevation with threatening terrain nearby, the necessary

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initial altitude can be gained while far away from the runway. Even if the rate of climb available at the required altitude is low, climbing to the required altitude will just take more time.

Takeoff is another matter. Now the airplane must gain energy reasonably quickly while close to threatening terrain and evil wind gusts. YouTube contains many videos of aircraft taking off from Lake County airport and gaining altitude at painfully small rates of climb. Density altitude is always a factor. On May Day, as the first draft of this paper was written, the temperature at Lake County airport was 57°F, for a density altitude of 11,871 feet.

Russ's Bearhawk, N6786E, with its 260 horsepower Lycoming O-540 engine, certainly has a lot more performance for takeoff and climb than a typical Cessna 172, but is there some way that we can predict how limited the takeoff performance would be in these conditions?

The FAA ensures that every new Private Pilot knows how to predict his takeoff roll using manufacturer-supplied data, and emphasizes the importance of checking takeoff data before flight. However, with a lot of Experimental Amateur Built aircraft, predicting takeoff performance is much more a leap of faith, because such data are generally not published. Thus, takeoff performance is based on guesswork and prior experience. To some extent, if there is enough runway to land, then there is probably enough to take off, but this is not guaranteed. At most public use runways, this usually works, since they generally have runway lengths necessary to support larger aircraft.

The longest takeoff experienced in the Bearhawk was on 16 July 2011 at Albuquerque's Double Eagle (KAEG) airport. The Bearhawk was loaded to near maximum gross weight (2700 lbs for N6786E). Elevation was 5837 feet and the temperature was around 100°F, yielding a density altitude around 9600 feet. While the ground roll seemed three times as long as usual (it was probably much less than that), the Bearhawk still climbed away at 500 feet per minute.

According to the previously published performance report on this Bearhawk [1], at a more normal gross weight of 2400 lbs, on a standard day at 10,500 feet altitude, the expected climb rate is 900 feet per minute at 78 KCAS, or 500 feet per minute in a cruise climb at 100 KCAS. Therefore, climb rate should not be a problem departing Lake County airport, but how much ground roll would be required?

II. Previous Work

The Bearhawk limited performance evaluation [1] documented a performance model for cruise and climb performance. This included fairly sophisticated engine, propeller, and airframe models incorporated in Matlab. The validity of these models continues to be confirmed over many years of flying experience. The engine model is accurate enough to be used in-flight to set the mixture for lean of peak (LOP) operations. Further validation was published in "Bearhawk 20 Minute Flight Test" [2].

Previous work on takeoff testing included the HAVE DISCUS project [3, 4]. The HAVE DISCUS project used a numerical simulation of the takeoff incorporated in Matlab.

The present work combines these efforts to create a takeoff performance model for the Bearhawk. The engine, propeller, and aircraft models of the limited performance evaluation [1] were used to model the forces and thus calculate the accelerations. These accelerations were numerically integrated into velocities and distances using methods developed in HAVE DISCUS [3, 4].

III. Modeling Technique

For purposes of the takeoff performance model, the modeled takeoff technique was an approximation of the actual takeoff technique used for over 800 hours of flying. For ease of modeling, portions of the modeled takeoff technique were not exactly faithful to the actual takeoff technique. These differences will be evaluated later. The modeled takeoff technique was:

1. Takeoff began in the 3-point attitude (12 degrees nose up pitch) with the engine at takeoff manifold air pressure (MAP) and RPM. An input variable specified the mixture.
2. The first phase of the takeoff accelerated in the 3-point attitude.
3. Upon reaching a specified airspeed, the tail was raised, reducing the pitch angle by a specified amount. Acceleration continued at this pitch attitude.
4. Liftoff occurred at a specified calibrated airspeed, defining the ground distance traveled.

For modeling, manifold pressure was set to maximum available (wide open throttle). This was calculated according to this formula developed in Ref. [1].

$$MAP_{max} = (-6.087867x10^{-5}\ RPM + 1.102747)(29.92\ in\ Hg)(1 - 6.87559x10^{-6}\ H_c)^{5.2559} \quad (1)$$

RPM was set at redline RPM of 2700.

Desired mixture was input as a mass ratio of fuel to air. Any value could be specified, but two choices were Best Economy (0.0625 (1:16)), and Best Power (0.08 (1:12.5)) [5]. However, most takeoffs are done at Full Rich. For the original takeoff performance model, full rich mixture was set to a mass ratio of 0.102. It has been long enough that the rationale for choosing this ratio has been lost. In Ref. [6], the value for Full Rich mixture was calculated from flight test data to range from 0.0802 to 0.0966. Per Ref. [1], a mixture of 0.095 will reduce the power by a factor of 0.929. A mixture of 0.102 will reduce the power by a factor of 0.893. Using a richer mixture ratio will cause the calculated takeoff distance to be greater. If the takeoff performance model results match flight test results adequately, then this mixture value will be adequate. A lower actual mixture ratio would increase power and shorten the actual takeoff run.

Figure 2 shows the 3-point attitude for the first portion of the takeoff ground run.

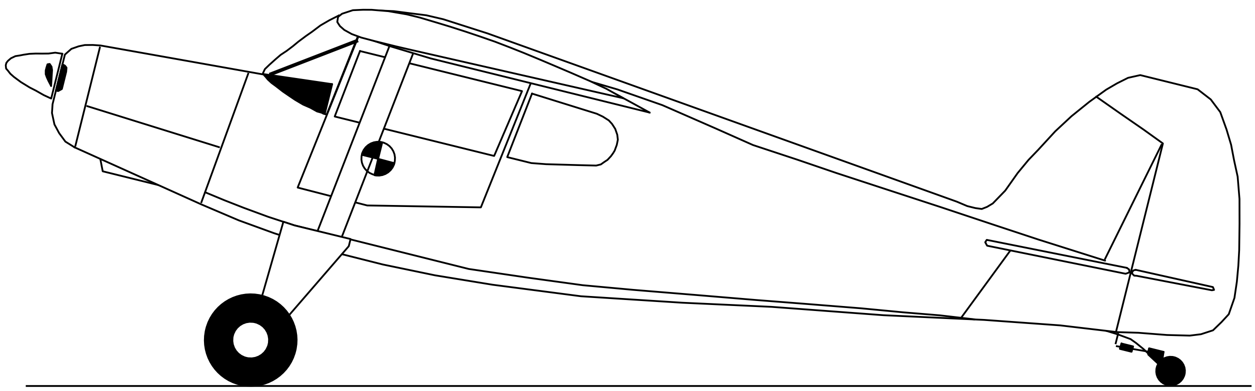

Fig. 2. 3-point Pitch Attitude

Tail Up Airspeed was specified as an input variable. For this analysis, the tail was raised as a step function at 45 KCAS. The pitch rotation when raising the tail was also specified as an input variable. For this analysis, the pitch angle was reduced by 5 degrees, as shown in Fig. 3. This equated to placing the top of the cowling on the horizon.

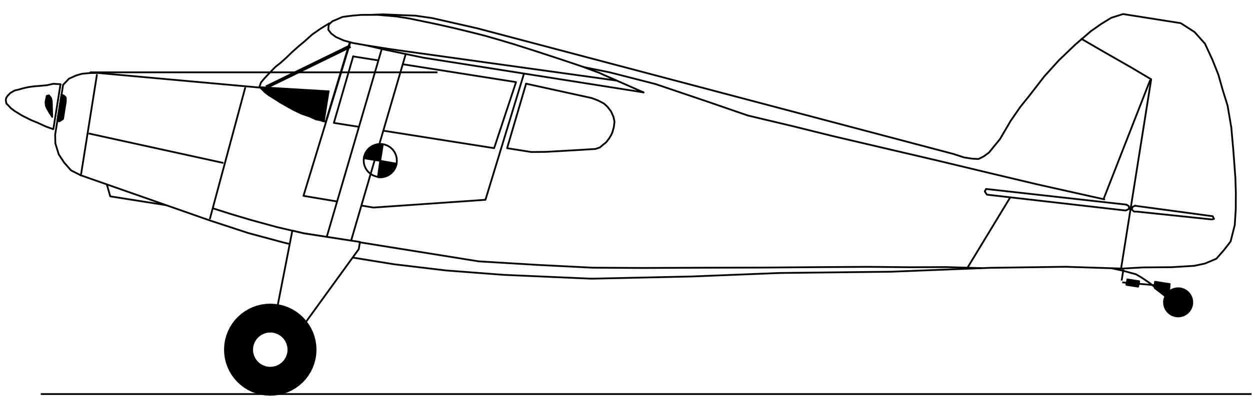

Fig. 3 Tail Up Pitch Attitude

Liftoff airspeed was defined as an input parameter. For this analysis, the liftoff airspeed was set at 61 KCAS. This was sufficiently fast to lift off at maximum gross weight. Using a single liftoff airspeed reduces pilot workload by removing the requirement to recalculate the liftoff speed for each gross weight. The tradeoff is that the takeoff ground run will be longer than when using the optimal takeoff speed. For expected operations from hard surface airports, this slight increase in takeoff roll was deemed acceptable.

A common technique in tailwheel aircraft for short field takeoffs is to not raise the tail, but to leave the aircraft in the 3-point attitude until it lifts off the ground. As written, the takeoff performance model can be used to calculate takeoff distance using this tail-low technique. To model liftoff in the 3-point attitude, set Tail Up Airspeed to a value higher than the rotation speed. The simulation will run until reaching the liftoff airspeed. Actual liftoff can be determined by examining the output for the distance where the lift exceeds the gross weight. This takeoff technique will not be covered further in this report.

To begin the simulation, the input file specified the pressure altitude, outside air temperature, gross weight, and headwind. In the initial time step, the true airspeed was set equal to the headwind. The headwind was assumed to remain constant throughout the takeoff roll.

Forces used in the calculations are shown in Fig. 4.

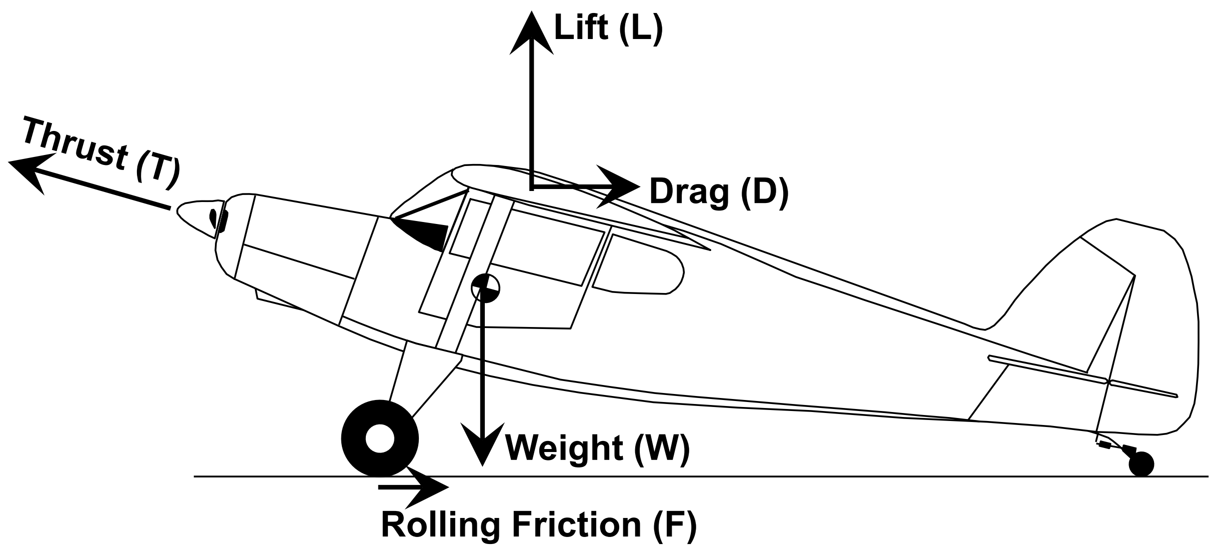

Fig. 4 Forces during takeoff roll

Thrust was calculated by the engine and propeller model. The lift curve slope for a 3-D wing was approximated by [7]

$$C_{L_\alpha} = \frac{a_0}{1+\frac{a_0}{\pi e AR}} \quad (2)$$

a_0 is the 2-D lift curve slope and is assumed to be 2π/radian, a theoretical approximation of lift curve slope for thin airfoils [8]. e is Oswald's efficiency factor and is assumed to be 0.7 [1]. AR is the aspect ratio, 6.05 for the Bearhawk.

The angle of attack (α) was given by

$$\alpha = \text{Pitch Angle} + \text{Wing Incidence} \quad (3)$$

since Pitch Angle was measured by the Fuselage Reference Line. Wing Incidence was 2 degrees (positive leading edge up). The lift coefficient was then calculated using the absolute angle of attack

$$C_L = C_{L_\alpha}(\alpha - \alpha_{0L}) \quad (4)$$

The zero lift angle of attack (α_{0L}), for the NACA 4412 airfoil was -4 degrees. Lift was then calculated

$$L = C_L \frac{\rho V_t^2}{2} S \quad (5)$$

The drag coefficient was calculated using the drag polar from Ref. [1]

$$C_D = 0.078972 - 0.17736\, C_L + \phi\, 0.2217 C_L^2 \quad (6)$$

The ϕ in the above equation is a correction for ground effect, given as [7]

$$\phi = \frac{\left(16\frac{h}{b}\right)^2}{1+\left(16\frac{h}{b}\right)^2} \tag{7}$$

where h is the height of the wing above the ground (assumed to be 5 feet) and b is the wingspan.

Drag was then calculated

$$D = C_D \frac{\rho V_t^2}{2} S \tag{8}$$

The rolling drag was calculated as

$$F = \mu\left(W - L - T\sin(Pitch)\right) \tag{9}$$

where μ is the coefficient of rolling friction, assumed to be 0.02 [7].

With all of the forces now available, the excess thrust was calculated by

$$T_{excess} = T\cos(Pitch) - (D + F) \tag{10}$$

The acceleration was then calculated as

$$a = \frac{T_{excess}}{m} = T_{excess}\frac{g}{W} \tag{11}$$

With the acceleration determined, it was integrated using Euler's method to find the velocity (true airspeed). This integration was done in the frame of reference of the air mass. The time step size can be defined. In this analysis, a time step of 0.5 seconds was used. This time step size was shown to give good results without excessive calculation in Ref. [3].

$$V_t = V_{t_0} + a\Delta t \tag{12}$$

This new true airspeed was used to find ground speed by subtracting the headwind. The ground speed was then integrated using Euler's method to find the ground distance traveled.

$$s = s_0 + (V_t - Headwind)\Delta t \tag{13}$$

IV. Takeoff Model Initial Validation

Before doing a lot of work to create charts, we wanted to convince ourselves that the model had at least some connection to reality. To do this validation, we needed some flight test data for a takeoff. Fortunately, such data had been recorded and analyzed in the Bearhawk 20 Minute Flight Test [2]. These data are shown in Fig. 5.

The Flight Test ground roll distance shown in Fig. 5 was calculated using the DAS recorded GPS latitude and longitude. The GPS coordinates were reported by the Garmin GNS480, with a Wide Area Augmentation System (WAAS) corrected solution certified for use under Instrument Flight Rules (IFR). The coordinates were recorded at 1 Hz. The distance between coordinates was calculated using the Law of Cosines as shown in Ref. [9]. Using the navigator's rule of thumb that one minute of latitude is equal to one nautical mile, the earth's circumference was 21,600 nautical miles for these calculations.

The latitude and longitude were recorded in decimal degrees to 14 digits. If all of these digits were significant, this would be sufficient resolution for a precision of 4×10^{-7} feet, or 4×10^{-6} inches. A micrometer typically measures to one thousandth or one ten thousandth of an inch. Fourteen significant figures of latitude or longitude would give a precision on the order of a millionth of an inch. Clearly there are enough digits in the reported latitude and longitude to have a precision much smaller than the foot we are interested in. However, the uncertainty in the latitude and longitude derived distances was expected to be much larger than the resolution available. Looking at Fig. 5, if we assume the actual flight test acceleration was perfectly smooth, the data shown would appear to be scattered around a smooth line by about ±20 feet, which is within the expected uncertainty of a WAAS corrected GPS position.

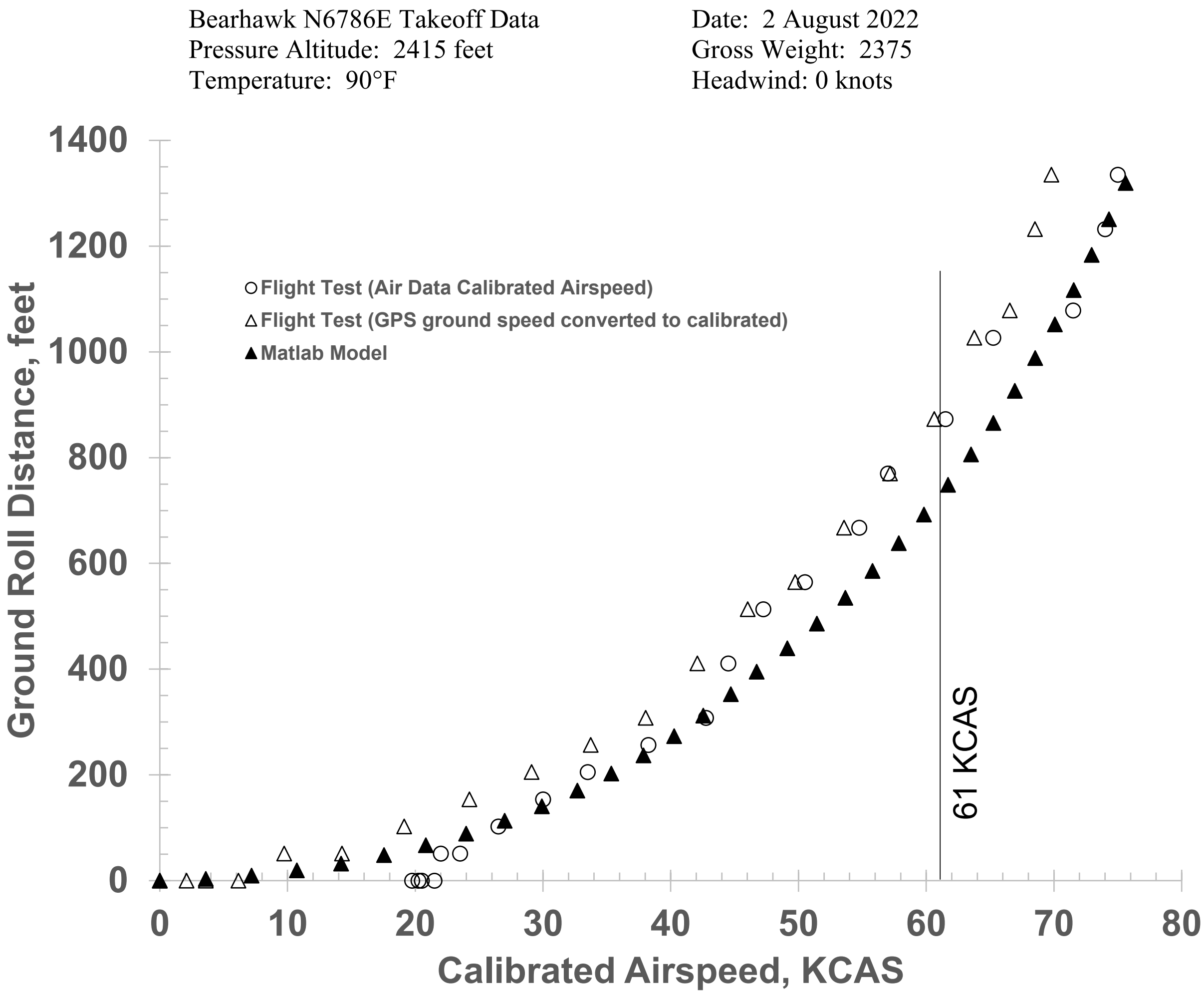

Fig. 5 Bearhawk Takeoff Model Initial Validation

The Matlab model was run at the same conditions (shown above Fig. 5) present during the actual takeoff. Because our interest is the ground roll distance when reaching 61 KCAS, the ground roll distance is plotted against the calibrated airspeed. The shapes of the curves are very similar, which leads to the conclusion that the simulation method is reasonable. Small differences in acceleration lead to a difference of ground roll distance of 124 feet at the liftoff airspeed of 61 KCAS. While 124 feet may sound like a lot, consider that the aircraft travels this distance in 1.5 seconds. Remember that the simulation parameters were not tweaked to create this match, but rather the engine, propeller, and airframe model used in the simulation were unchanged from those developed in the limited performance evaluation [1].

In the actual takeoff shown in Fig. 5, liftoff did not occur at 61 KCAS as modeled. On this takeoff, the pilot was slow to rotate, finally lifting off at 75 KCAS, four seconds after reaching the desired rotation speed of 61 KCAS. Even so, the model continues to follow the flight test data during this delayed liftoff. Of note, because of the higher speeds involved, this late rotation added 463 feet to the ground roll, showing that liftoff technique is important to actual takeoff distance. Late rotations will generally be mitigated on shorter runways, because a pilot will see that he is rapidly running out of runway and will be motivated to lift off quicker.

The impact of throttle technique is worthy of discussion. The Matlab model assumes that the brakes are released with the engine already at full throttle and turning 2700 RPM. Operationally, for multiple reasons it is better to release brakes and then smoothly advance the throttle to full, which can take up to 8 seconds as shown in Fig. 6. (Engine data were only recorded at 0.5 Hz.) The aircraft does not start to accelerate significantly until 3 seconds after the initiation of the throttle advance. Analysis of the ground speed data showed that because of the low speeds, the difference in throttle technique added only around 20 feet to the takeoff roll. In Fig. 5, the data show the airplane jumping forward

50 feet in the first second (and then zero feet in the second second), which seems to have more to do with the uncertainty in the distance measurement than actual movement. Thus, the error introduced by a different throttle technique is lost within the uncertainty of the distance measurement and can thus safely be ignored.

Another question to consider is when does the propeller reach 2700 RPM? A fixed pitch propeller will typically achieve a static RPM (RPM at zero airspeed) 200 to 300 RPM lower than it will reach at the end of the takeoff run. The constant speed propeller installed on the Bearhawk initially acts as a fixed pitch propeller with the blades on the low pitch stop until sufficient power is input to reach the set RPM, at which point the propeller blades start pitching to control the RPM. Since this behaviour is not modeled, it is important to determine if this is an issue. Fig. 6 shows the actual RPM of the propeller as the throttle is advanced. The propeller reached full RPM within 2 seconds of the throttle reaching wide open throttle (WOT) as shown by the manifold pressure trace. In keeping with the small distance traveled while advancing the throttle, these two seconds are insignificant within the present uncertainties, and thus it is reasonable to model the propeller RPM as 2700 throughout the takeoff run.

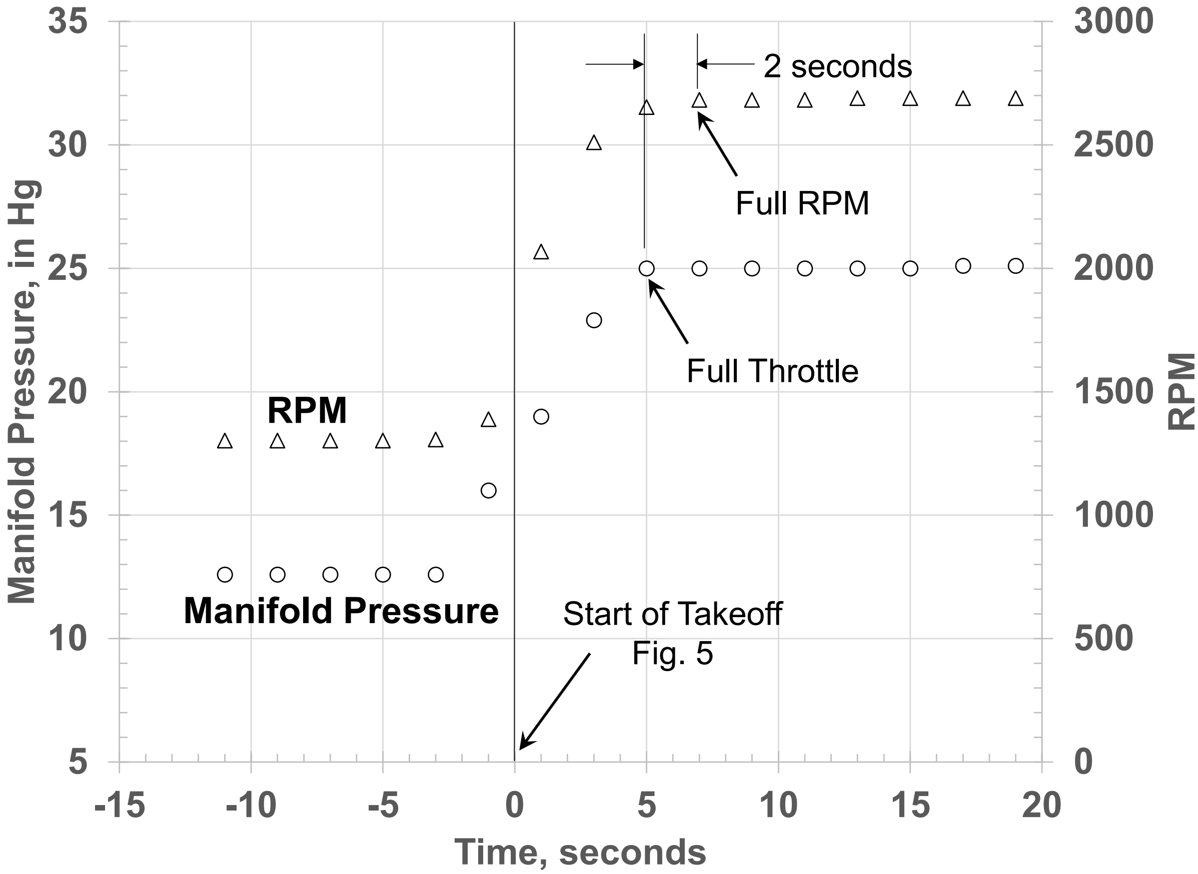

Fig. 6 Relationship of RPM and Manifold Pressure during throttle opening

V. Final Chart Construction

The takeoff distance was modeled as a function of three inputs: air density (represented by pressure altitude and outside air temperature), gross weight, and headwind/tailwind.

To model the air density effect, the model was run at 11 pressure altitudes (1000 feet intervals from Sea Level to 10,000 feet) and 11 temperatures (10°F intervals from 0 to 100°F). Gross weight was set at 2400 pounds, a typical takeoff weight with full tanks and two crew. Headwind was set to 0 knots. These results were plotted as the left set of curves in Fig. 7.

To model the gross weight effect, values of pressure altitude and temperature were selected that produced takeoff distances of each 100 feet from 500 to 1600 feet at 2400 pounds and zero headwind. For each input pressure altitude/temperature, the model was run at 8 gross weights (100 pound intervals from 2000 to 2700 pounds). Headwind was set to 0 knots. These results were plotted as the middle set of curves in Fig. 7.

To model the wind effect, pressure altitude and temperature were set as for modeling the gross weight effect. Gross weight was set at 2400 pounds. For each pressure altitude/temperature combination, the model was run at five wind conditions: 0, 10, and 20 knots of headwind and 5 and 10 knots of tailwind (represented as a negative headwind). These results were plotted as the right set of curves in Fig. 7.

The data in Fig. 7 are plotted as they were calculated, with no smoothing applied to the curves. The slight wiggles in the curves are indicative of the level of uncertainty in the calculations.

Bearhawk N6786E Takeoff Data	Wide Open Throttle
Tail Up 5° at 45 KCAS	2700 RPM
Liftoff Airspeed: 61 KCAS	Mixture Full Rich

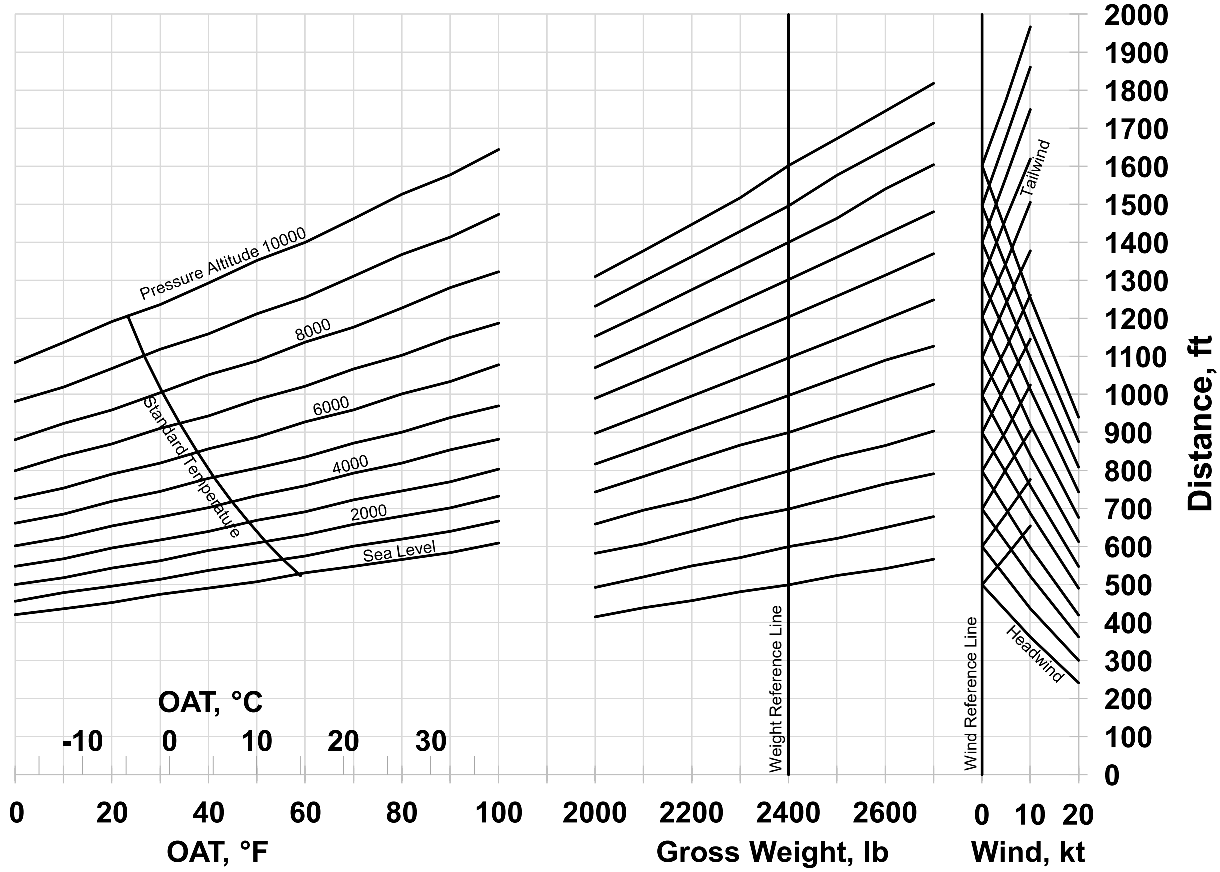

Fig. 7 Bearhawk N6786E Takeoff Ground Roll Chart

To use Fig. 7, enter at the Outside Air Temperature and go up to the appropriate Pressure Altitude. This is the takeoff roll at 2400 pounds and zero wind. Go right at this ground roll distance to the Weight Reference Line at 2400 pounds. Follow parallel to the curves either left or right to the appropriate gross weight. This is the zero wind takeoff roll. Go right at this ground roll distance to the Wind Reference Line at 0 knots wind speed. Follow parallel to the curves either down for headwind or up for tail wind to the wind speed. This is the final predicted takeoff roll.

The construction of Fig. 7 assumes that the effects of pressure altitude, temperature, gross weight, and wind are independent, such that each effect can be calculated separately and multiplied together. This is a time-honoured method for creating takeoff charts for easily determining takeoff distance.

The combination of pressure altitude and outside air temperature will result in a particular air density. This air density will affect the aerodynamic forces of lift and drag on the airplane and thrust and torque on the propeller. The air density will also change the true airspeed that corresponds to the designated liftoff airspeed of 61 KCAS. The differing pressure altitude and outside air temperature will also affect the engine power, but each has an independent effect and the results do not map exactly to air density but are very close.

The gross weight represents the mass of the aircraft and how it will accelerate but does not affect the aerodynamic forces. The gross weight will affect the rolling friction, which could affect the forces causing acceleration. However, the rolling friction is at least one order of magnitude less than the thrust, so this coupling effect is very small and can be ignored.

The headwind changes the relationship of airspeed and ground speed linearly, but has no other effect on forces or acceleration. Changes in the liftoff true airspeed will make small changes of how long the wind affects the takeoff roll.

The effects of pressure altitude, outside air temperature, gross weight, and headwind were only considered separately for creating Fig. 7. All of these factors were considered simultaneously in the Matlab simulation, so any cross-product effects would be present in the Matlab model output.

To confirm the assumption that any cross product effects were small enough to be ignored, the Matlab model was run at several random combinations of pressure altitude, temperature, gross weight, and headwind. In each case, the value calculated by the model was the same as the value predicted by the chart within the uncertainty of reading the chart.

VI. Model Validation by Flight Test

Having a model can make for nice brochures, but the model has no real value unless it is validated. While we looked at one takeoff in section IV, for further validation a flight test campaign was launched to validate the model at a much wider range of conditions. Testing was accomplished at four different density altitude ranges with varying amounts of wind. The test procedure was identical to that described in section IV. Fig. 8 compares the measured ground roll to 61 KCAS to the Matlab model predicted ground roll for 13 separate takeoffs.

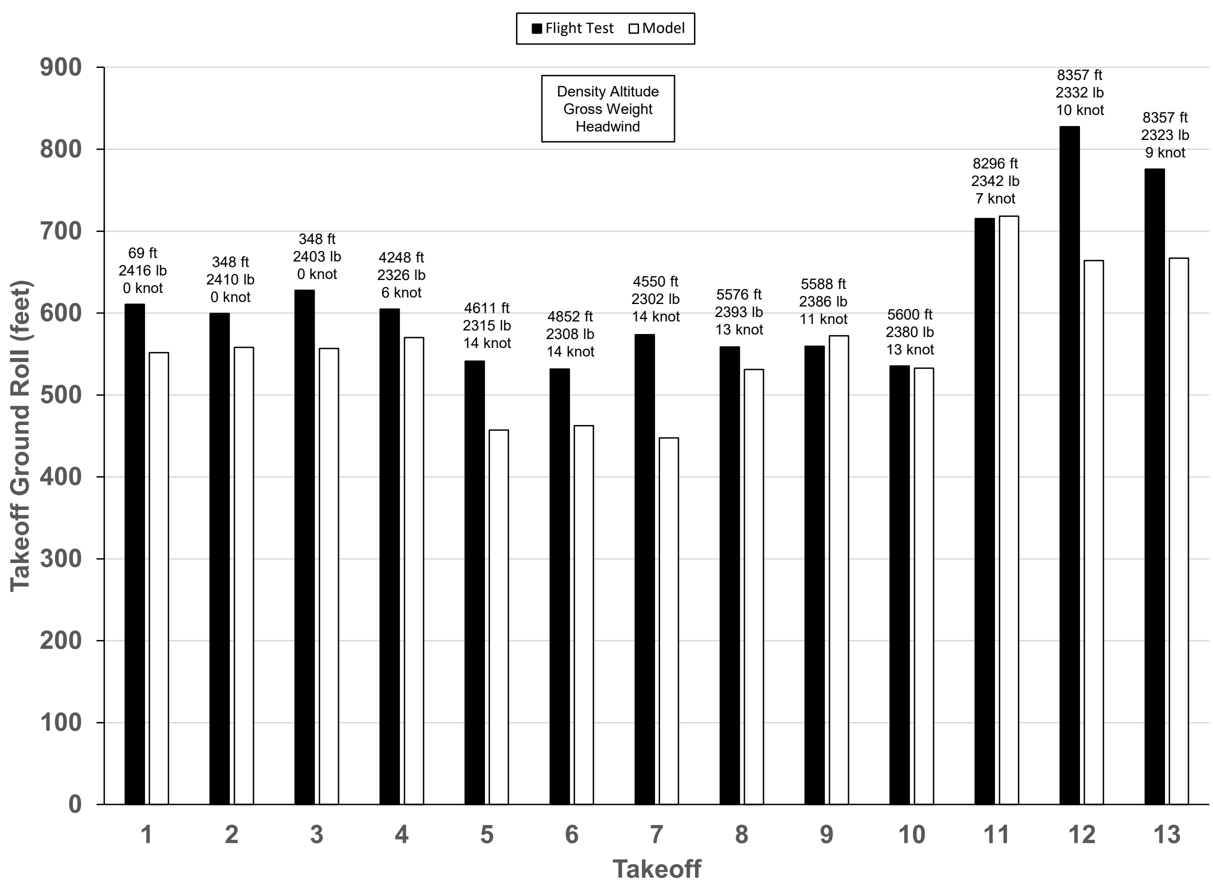

Fig. 8 Comparison of Flight Test Ground Roll Distance to Matlab model predicted Ground Roll Distance

Analysis of Fig. 8 indicates that in general the Matlab model predicts a slightly shorter ground roll distance, but not always shorter. Fig. 9 shows a histogram of the percentage difference between the measured distance and the predicted difference. Negative values show when the model predicted a shorter ground roll than actually measured. While in many engineering endeavors we strive for model errors to be limited to very small percentages, in the case of the takeoff maneuver, there are so many factors that can affect the result, including many factors that have not been modeled but just assumed small. As discussed in section VII, in this case, results within 20 percent are still operationally useful because of the additional padding that is added for risk mitigation.

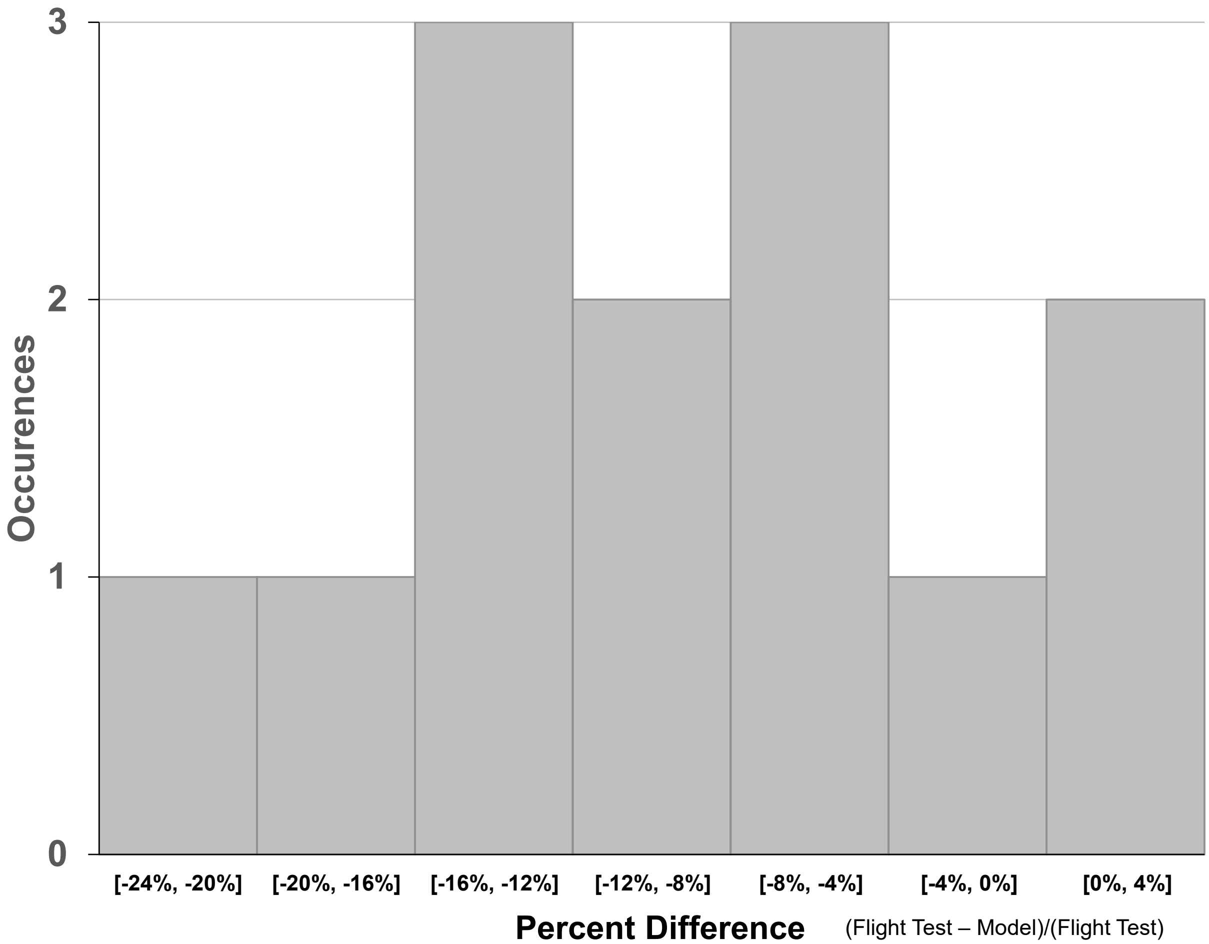

Fig. 9 Matlab model prediction error histogram

Remember that the Matlab model was built on the validated model from Ref. [1], not tweaked to specifically meet these flight test results, so some variation is expected. It is encouraging that aircraft and engine models which have been shown to reasonably predict airborne performance also create a reasonably "in the ballpark" model for takeoff performance as well.

Fig. 10 is a reproduction of Fig. 7, showing the locations of the flight test takeoffs. Red circles in the density altitude section (left side) show the pressure altitude and temperature range covered by the flight test takeoffs. There appear to be less than 13 circles because some of the takeoffs were at almost identical conditions, so those circles overlap.

Red lines in the gross weight section (center) show how far the actual gross weight varied from the nominal 2400 pounds. Red lines in the winds section (right side) show how strong the headwinds were during testing.

While the flight test does not cover all of the extremes of the chart, it does cover a sufficient area to show that the model was not just optimized for one set of conditions, but rather is reasonably representative for the whole range of possible conditions.

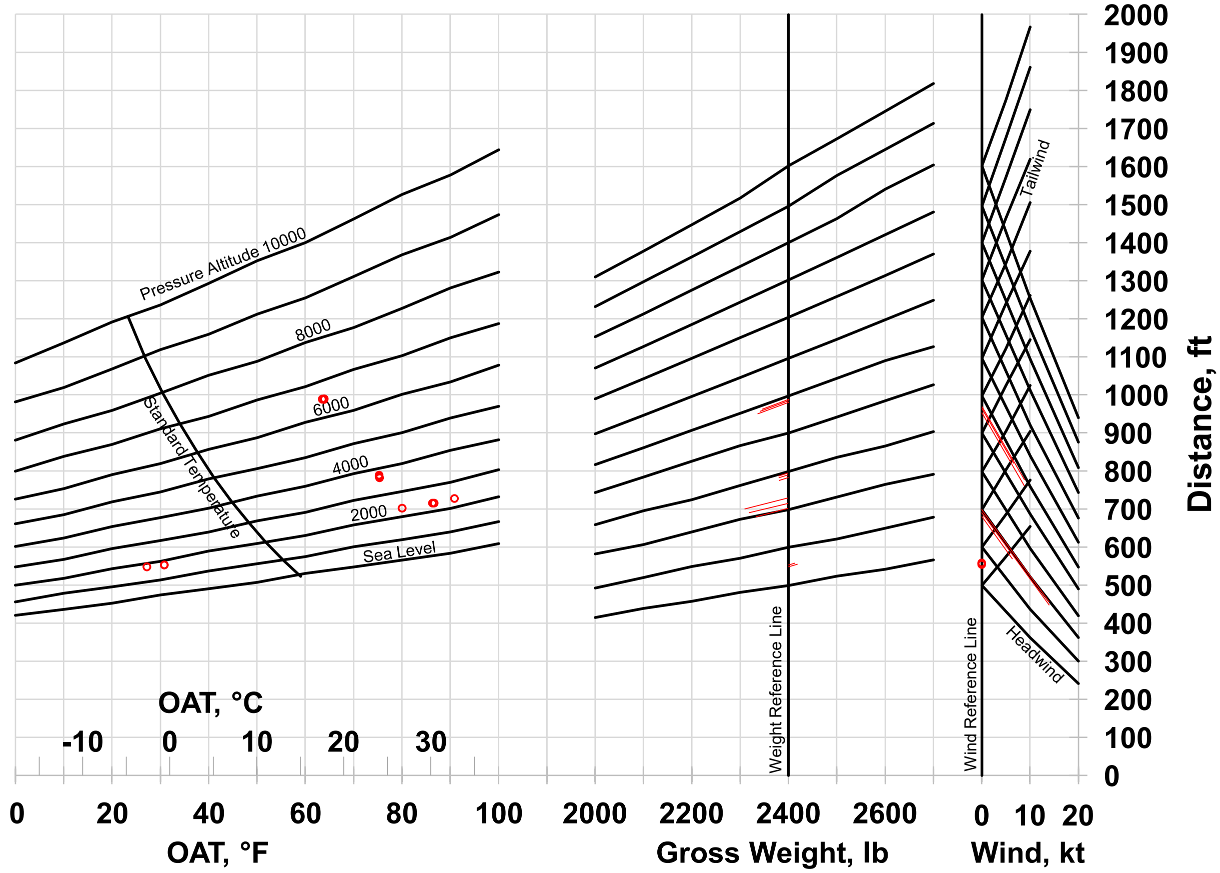

Fig. 10 Flight Test variation from nominal conditions

VII. Acceptable Uncertainty

When evaluating a takeoff model, it is helpful to get a feeling for the size of uncertainty possible in takeoff testing. There is no need to sweat about a micrometer prediction when cutting with an ax. There is a large uncertainty in takeoff ground roll caused by multiple factors, the largest factor being pilot technique. Because this model is built for one single aircraft, variations caused by differing aircraft conditions were not considered. The Aircraft Owners and Pilots Association (AOPA) Air Safety Institute (ASI) recommends adding 50 percent to the Pilot's Operating Handbook takeoff distance over a 50-foot obstacle [10]. Even though this model focuses on ground roll distance, ASI's recommendation implies that the uncertainty in takeoff calculations when compared to actual takeoff performance is not within a few percent but can be on the order of 50 percent. This very generous pad accounts for less than stellar pilot technique. This also implies that small variations in the model can be safely ignored, as the actual required runway length will be significantly longer than the calculated length.

If there is so much uncertainty, why bother doing the calculations? As mentioned earlier, for many experimental amateur built aircraft, takeoff performance is based on guesswork and prior experience. Building a model cuts down on the amount of guesswork and experience needed for making good decisions.

VIII. So, Can the Bearhawk Fly Out of Leadville?

For the conditions at Lake County airport stated earlier, 9934 feet pressure altitude, 57°F, and assuming 2400 pounds gross weight and zero headwind, the Matlab model predicts a takeoff ground roll of 1,378 feet. The runway is 6,400 feet long, so clearly there is plenty of runway.

The ground roll above was calculated for a Full Rich mixture. Many sources recommend leaning to best power for high altitude takeoffs. Running the Matlab simulation at Best Power mixture results in a predicted takeoff ground roll of 1,221 feet, or 157 feet shorter.

Earlier we predicted a climb rate of 500 feet per minute or more at Leadville, so the answer to "Can we safely takeoff?" appears to be "yes". Now we just need to find ourselves in Colorado. Then we could get a certificate, which might look something like Fig. 11.

Fig. 11 Sample Leadville Certificate

References

[1] Erb, R. E., "Bearhawk N6786E #164 Limited Performance Evaluation," http://erbman.org/bearhawkbits/bearhawk%20report.pdf, August 2017.

[2] Erb, R. E., "Bearhawk 20 Minute Flight Test," http://www.erbman.org/bearhawkbits/2303%2020%20min%20flight%20test.pdf

[3] Erb, R. E., "USAF Academy TG-15A (Duo Discus)/CC18-180 (Top Cub) Takeoff Performance Limited Evaluation (Project HAVE DISCUS)", AFFTC-TIM-06-11, Air Force Flight Test Center, Edwards Air Force Base California, December 2006.

[4] Erb, R. E., Aldrich, G. L., Vanhoy, D. L., "Sailplane Aerotow Takeoff Performance Evaluation Through Model Validation," http://www.erbman.org/sfte/sfte%20have%20discus.pdf, Society of Flight Test Engineers Annual Symposium, 2006.

[5] Roberts, Seán C., *Light Aircraft Performance for Test Pilots and Flight Test Engineers*, Flight Research, Inc., Mojave, California, 1980.

[6] Erb, R. E., "Readjusting Mixture After Altitude Changes," EAA Chapter 1000 Newsletter "The Leading Edge", http://eaa1000.org/1903nltr.pdf#page=4 , March 2019

[7] Anderson, J. D. Jr., *Introduction to Flight* Third Edition, McGraw-Hill Book Company, New York, 1989.

[8] *Theory of Wing Sections*, https://aeroknowledge77.wordpress.com/wp-content/uploads/2011/09/58986488-theory-of-wing-sections-including-a-summary-of-airfoil-data.pdf, Abbott, I. A. and von Doenhoff, 1959.

[9] Erb, R. E., *Pitot-Statics and the Standard Atmosphere*, Fifth Edition, http://erbman.org/Pitot%20Statics%20and%20the%20Standard%20Atmosphere%205th%20ed%20signed.pdf , Air Force Test Center, Edwards AFB, 2021.

[10] "Safety Advisor Mastering Takeoffs & Landings," https://download.aopa.org/asi/flightreview/PositiveAircraftControl.pdf, Aircraft Owner's and Pilot's Association Air Safety Institute, 2008.

Bearhawk N6786E Takeoff Data
Tail Up 5° at 45 KCAS
Liftoff Airspeed: 61 KCAS

Wide Open Throttle
2700 RPM
Mixture Full Rich