Analysis of F-104C World's Altitude Record Flight

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The goal of this project was to try and accurately model the performance of the F-104C Starfighter which achieved a new world altitude record on December 14th, 1959. In completing the project, the goal was to gain a better understanding of the performance modeling of today and flight test methods from the past while creating a drag polar and engine deck which could be used for future applications of performance modeling. Based on the results presented, it was found that the engine model used to predict the engine performance required adjustments to achieve the flight as it occurred, while the drag polar was much easier to accurately model due to extensive real drag data. While an engine deck was modeled it is unknown how reliable the model would be to model anything other than the world altitude record flight of the F-104. Further analysis of the aircraft performance characteristics is needed to determine the accuracy of the engine deck model; however, the modeled drag polar provides an accurate representation of the data throughout the flight envelope.

Nomenclature

F	= uninstalled thrust	lbs
M_0	= free stream Mach number	
P	= pressure	psi
S	= uninstalled fuel consumption	
T	= temperature	^oR
T	= installed thrust	lbs
TR	= throttle ratio	
TSFC	= thrust specific fuel consumption	1/hr
$\dot{w}_f$	= fuel flow	lb/hr
α	= thrust lapse	
δ_0	= dimensionless total pressure	
θ_0	= dimensionless total temperature	
γ	= specific heat ratio	

Subscripts:

SL = sea level

I. Introduction

The objective of this project was to model the performance of the F-104C Starfighter which performed the world's altitude record flight on December 14th, 1959, achieving an altitude of 103,395.5 feet[1]. The flight occurred during the height of the Cold War when demonstrating air superiority and technological superiority were of great importance. The flight was conducted to surpass the Russian altitude record of 94,661 feet. In completing analysis of this flight and attempting to model the performance, the goal was to gain an understanding of analysis methods as

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well as understanding the flight test methods used at the time. This report outlines the accomplishments and shortfalls of the analysis that was completed.

In order to accurately model the performance, drag data for the F-104 was used to create a drag polar model for the complete flight envelope. Along with creating a drag polar, the engine deck also had to be modeled, which proved to be difficult based on limited available data for the J79 engine. Data from the zoom climb on the morning of December 14th assisted in providing more accurate results and allowed for comparisons between predicted performance and the performance actually achieved in that flight.

The results of this project are intended to provide a useful drag polar model and engine deck, as well as an example of performance modeling for use in the aircraft performance class or otherwise.

II. Analysis

Drag Polar

Drag data was obtained for the F-104G variant of the Starfighter from the Lockheed California Company[2] which allowed for the creation of a drag polar to model the entire flight envelope. Using data from the 'G' variant was assumed to be accurate enough for the purposes of the analysis. The drag polar was created using a program created by Mike Vallone[3] which matched a function to the digitized drag data. The program uses an optimizer to fit 27 parameters creating a function which matches the given set of drag data. The resulting drag curve fit can be seen in Fig. 1. While this drag function matches the data and can be used to represent the entire flight envelope, it does not include limits for maximum lift coefficient, $C_{L,Max}$. Stall limits were provided for the F-104G in a chart demonstrating buffet onset, as well as stick shaker and stick pusher modes as seen in Fig. 2. The stick pusher mode was assumed to be limiting factor in achieving $C_{L,Max}$ and therefore was included in the drag function as the upper bounds of C_L.

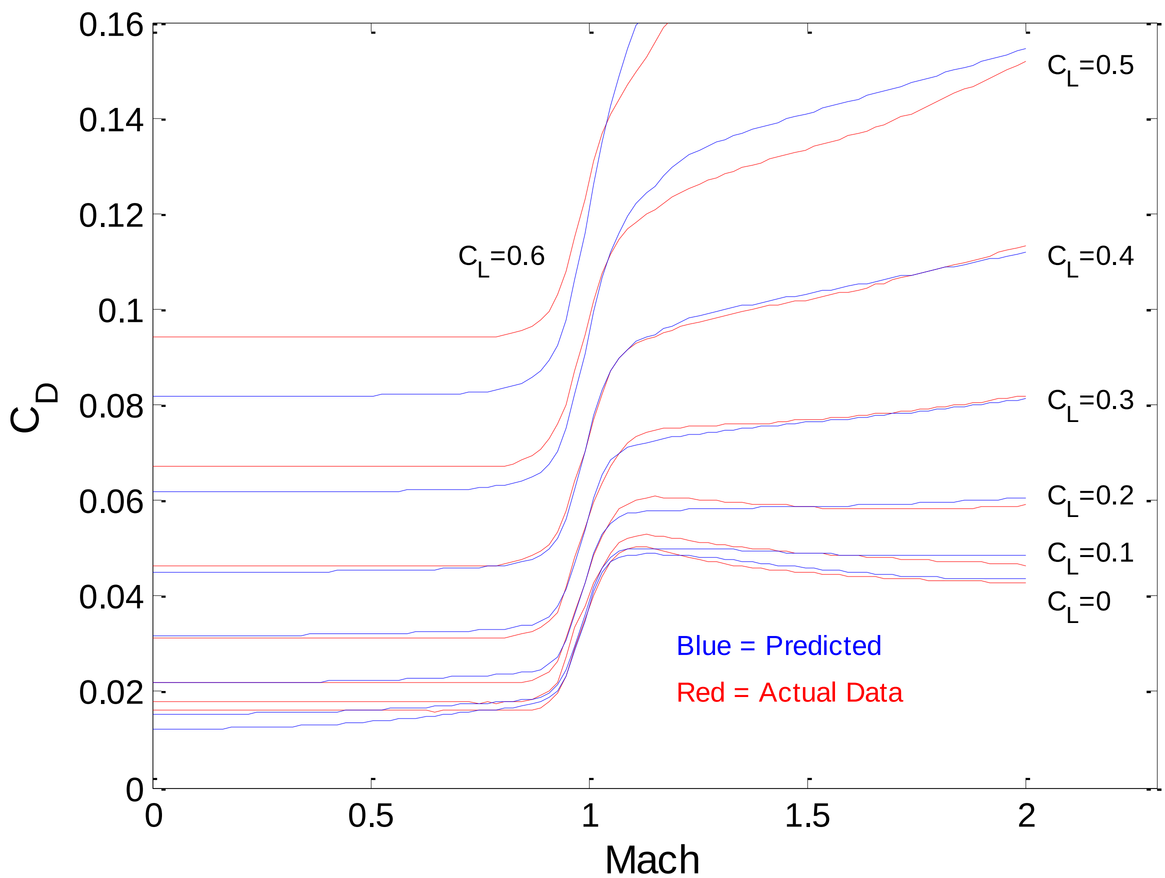

Figure 1. Drag Data Showing Match Between Predicted Drag Function and Real Drag Data

As seen in Fig. 1, the match is much more accurate for lower values of C_L, while higher values approaching stall do not match nearly as well outside of the sonic region.

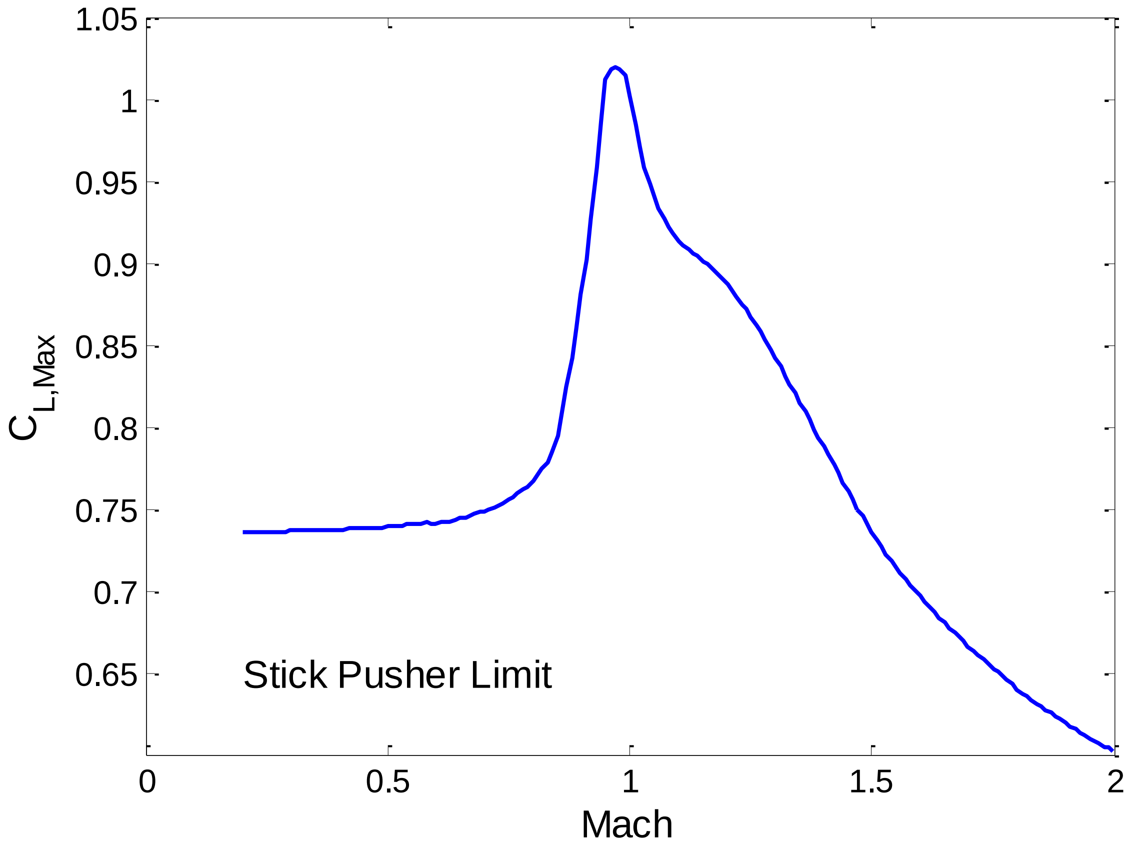

Figure 2. Maximum Lift Coefficient Limit Based on F-104 Stick Pusher Mode

Engine Deck

Unlike the drag data for the F-104, little information was readily available for the J79-GE-7 engine[4] which was used on the aircraft. The engine deck was constructed using a mathematical model presented by Jack Mattingly and William Heiser.[5] This method provided a way to model thrust lapse based on the type of engine, operating conditions, and some basic assumptions about the engine. The thrust lapse, α, for a turbojet engine can be modeled as given in Eq. 1 and Eq. 2 where M_0 is the free stream Mach number and *TR* is the throttle ratio for the engine.

Maximum Power:

$$\theta_0 \leq TR \quad \alpha = \delta_0\{1 - 0.3(\theta_0 - 1) - 0.1\sqrt{M_0}\} \tag{1}$$
$$\theta_0 > TR \quad \alpha = \delta_0\{1 - 0.3(\theta_0 - 1) - 0.1\sqrt{M_0} - 1.5(\theta_0 - TR)/\theta_0^2\}$$

Military Power:

$$\theta_0 \leq TR \quad \alpha = 0.8\,\delta_0\{1 - 0.16\sqrt{M_0}\} \tag{2}$$
$$\theta_0 \leq TR \quad \alpha = 0.8\,\delta_0\left\{1 - 0.16\sqrt{M_0} - \frac{24(\theta_0 - TR)}{(9 + M_0)\theta_0^2}\right\}$$

δ_0 and θ_0 are defined as

$$\delta_0 = \frac{P}{P_{SL}}\left(1 + \frac{\gamma - 1}{2}M_0^2\right)^{\frac{\gamma - 1}{\gamma}}$$

$$\theta_0 = \frac{T}{T_{SL}}\left(1 + \frac{\gamma - 1}{2}M_0^2\right)$$

The thrust specific fuel consumption, *TSFC,* of the engine can be modeled using Eq. 3 where $\dot{w}_f$ is the fuel flow of the engine, and *T* is the installed thrust of the engine.

$$TSFC = \dot{w}_f / T \quad (3)$$

S is the uninstalled fuel consumption and *F* is the uninstalled thrust with $\dot{w}_f$ defined as

$$\dot{w}_f = S * F$$

For the engine modeled in this analysis it was assumed that the throttle ratio is one as well as assuming that the 0.8 multiplier on the military power could be neglected as it appeared to be a scalar for removing afterburners. Also, due to lack of information about the engine, it was assumed that the installed thrust was equal to the given thrust in the engine data as no estimate could be made regarding installation losses. Further modifications made regarding the engine will be discussed in the results section of this report.

III. Results

The results will be presented as three subsections outlining changes which were made between each set of results.

Match Attempt One

Initially, attempts to match the actual flight data from the record flight using the modeled drag polar and engine deck proved very inaccurate. It was known that the engine deck provided a very poor representation of the actual engine used for the record flight. One source of error when attempting to match the given data was the discrepancy between indicated airspeed and true airspeed as the airspeed was among the most important variables in achieving decent results. In order to correct this error, information from a 1959 flight test handbook from Edwards AFB[6] was used to make the adjustments from given indicated airspeeds to true airspeeds.

An example of this is the indicated airspeed of 757.5 knots at the start of the record zoom climb[1]. This speed when corrected to true airspeed at 39,575 feet corresponds to a true airspeed of 1,349.7 knots and a Mach number of 2.35. This airspeed was used to calibrate the thrust on the engine deck to achieve the maximum speed at that altitude. Calibrations to the engine deck were only made in terms of maximum thrust; the actual given equations for thrust lapse were not altered except as previously mentioned. The maximum thrust of the J79-GE-7 engine is given to be 15,800 pounds sea level static. While the modifications made to the engine for the record flight were not accounted for in this value, it was assumed that the maximum thrust would not be significantly increased beyond this limit. Before any calibrations were made to the engine deck, the 15,800 pound maximum thrust value was plugged into the given equations and used along with the drag polar to determine the maximum speed at 39,575 feet. The resulting maximum speed was 554.8 knots, well below the actual maximum speed.

To calibrate the engine, the thrust was increased until the maximum speed of 1,349.7 knots was achieved at 39,575 feet. The input thrust required was 187,000 pounds, an increase of 11.84 times the original thrust. This new calibration was also assumed to take into account the modifications which would have been made to the record setting engine. The thrust increase factor of 11.84 was also applied to the military thrust value of 10,000 pounds, resulting in a maximum military thrust of 118,400 pounds input to the engine deck. With the engine calibrated to provide enough thrust, an attempt was made to match the trajectory of the record flight. The results are demonstrated in Fig. 3. It was found that for the flight modeled, the required lift coefficient exceeded the maximum after the plane passed through 57,880 feet at 30 seconds into the climb. An attempt was made to use the TSFC to predict the change in weight of the aircraft; however, it was found that there was an error which created a decrease in weight and then an increase in weight. Therefore the change in weight was not modeled which may affect the aircraft going beyond the maximum lift coefficient limits.

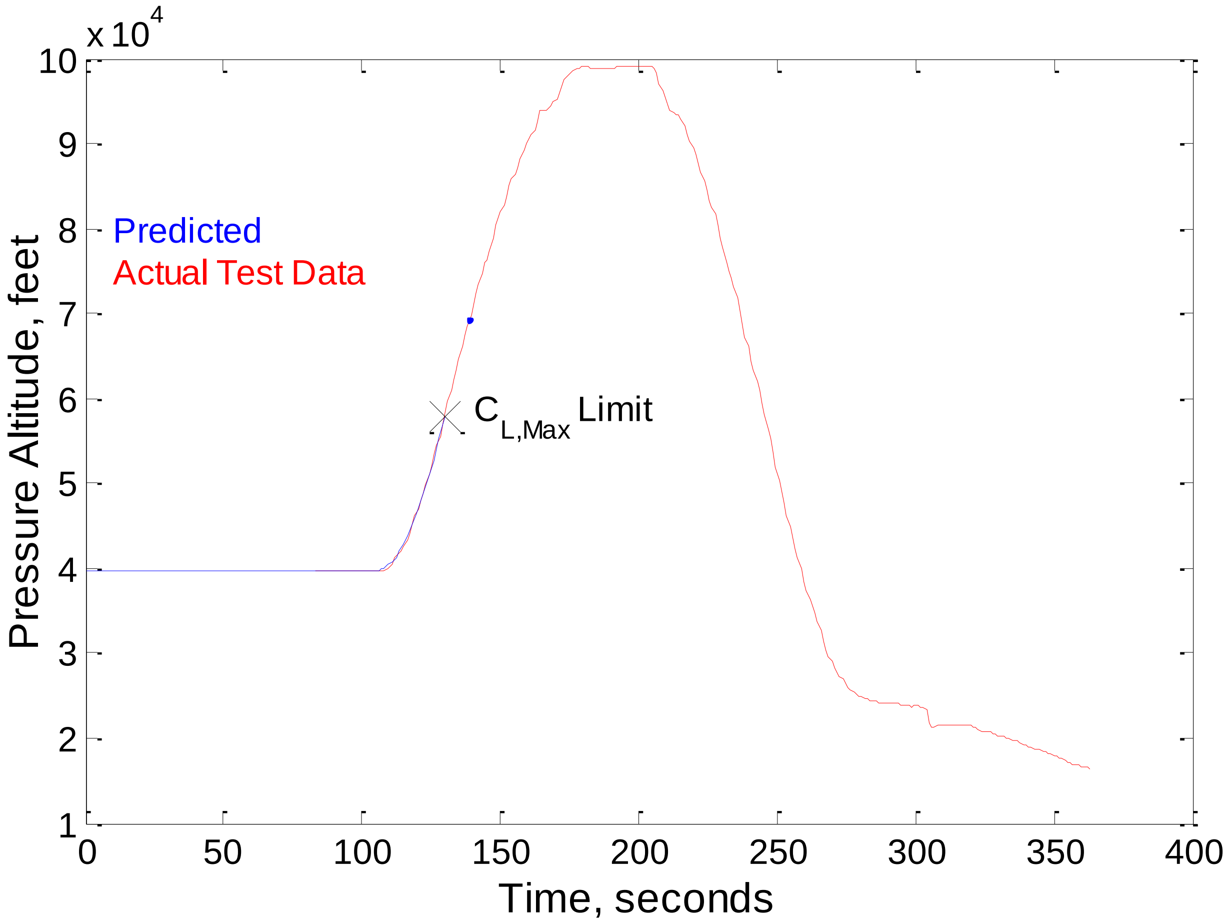

Figure 3. First Attempt to Match Performance, $C_{L,Max}$ Limit Achieved at 57,880 feet

Match Attempt Two

With the first attempt showing the aircraft stalled out at 57,880 feet, it was decided to see what would occur if the $C_{L,Max}$ limits were removed from the drag polar. The resulting plot, Fig. 4, shows the aircraft achieving the entire climb; however, it falls short of the 103,395.5 foot mark. The maximum altitude achieved is 98,860 feet. This attempt modeled the flight as it was documented[1]. The afterburners were blown out at 70,000 feet, reducing throttle to military power. The resulting Mach number at afterburner blowout was 1.61 compared with the documented Mach number of 1.78. The aircraft then climbed to 81,700 feet at which time the engine was shut down by the pilot to avoid engine overspeed. The rest of the flight was completed engine out following the given normal acceleration demonstrated by the test data which is shown in Fig. 5.

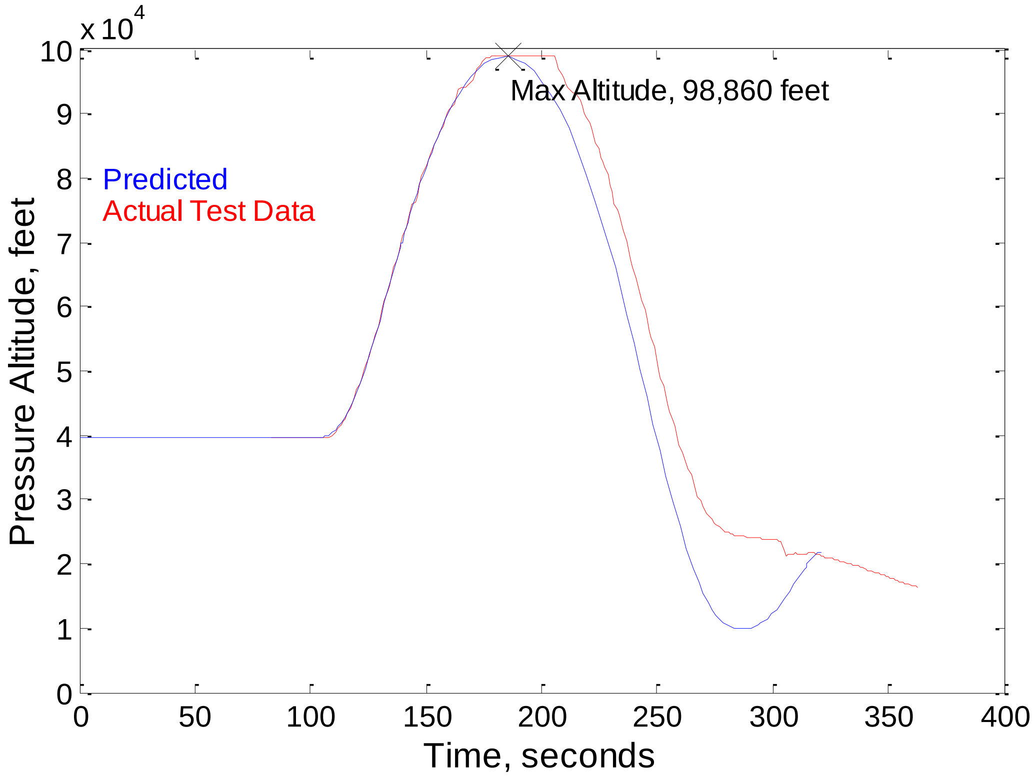

Figure 4. Second Attempt to Match Performance, Maximum Altitude Achieved at 98,860 feet

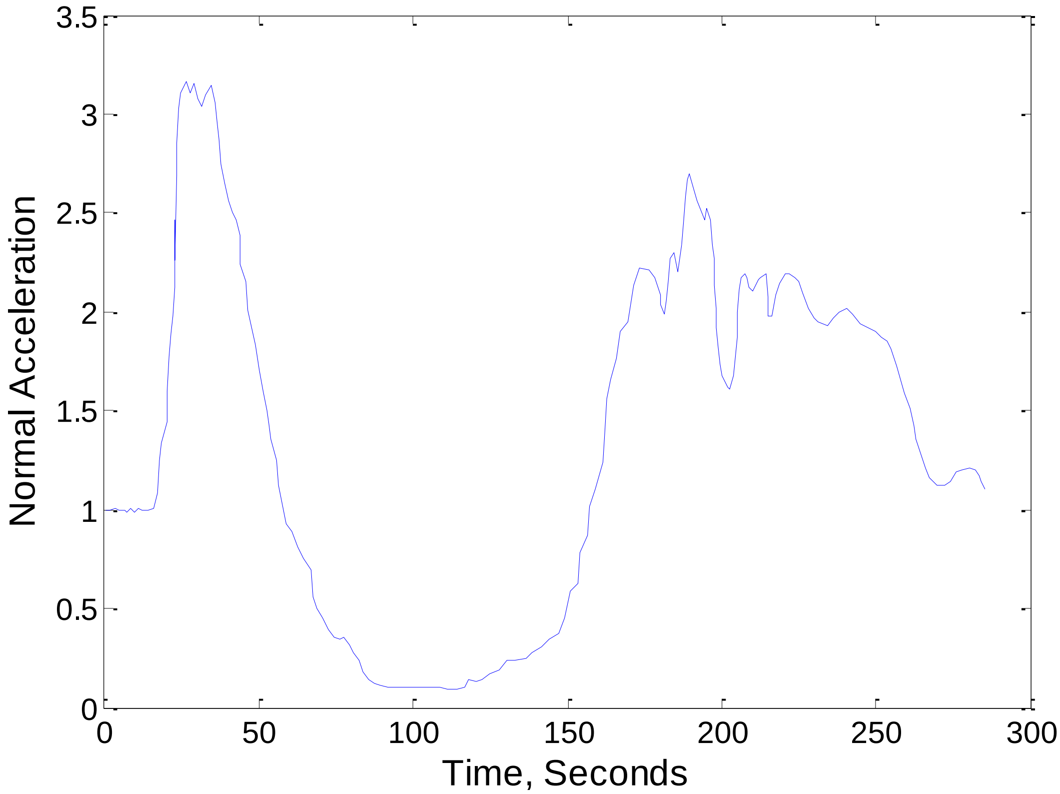

Figure 5. Normal Acceleration vs. Time for World's Altitude Record Flight (Actual Data)

Final Match Attempt

With decent results achieved it was decided to see what kind of military thrust increase would be necessary to achieve the record altitude. The maximum military thrust input to the modeled engine deck ended up being 450,000 pounds. This not only suggests, but absolutely means that this engine model cannot accurately predict the performance of the J79-GE-7 engine which was used by the F-104 and specifically the engine used for this flight. While this necessary calibration suggests that the engine model is not very accurate, the final match proved to be very good. The final matched plot is shown in Fig. 6, and demonstrates achieving the record altitude as well as matching the altitude versus time trajectory almost perfectly, aside from the high point where the altimeter was pegged. The airspeed at the top of the climb was predicted to be 258.3 knots, which is significantly slower than the approximately 457 knots as determined to be the true airspeed from the actual flight.

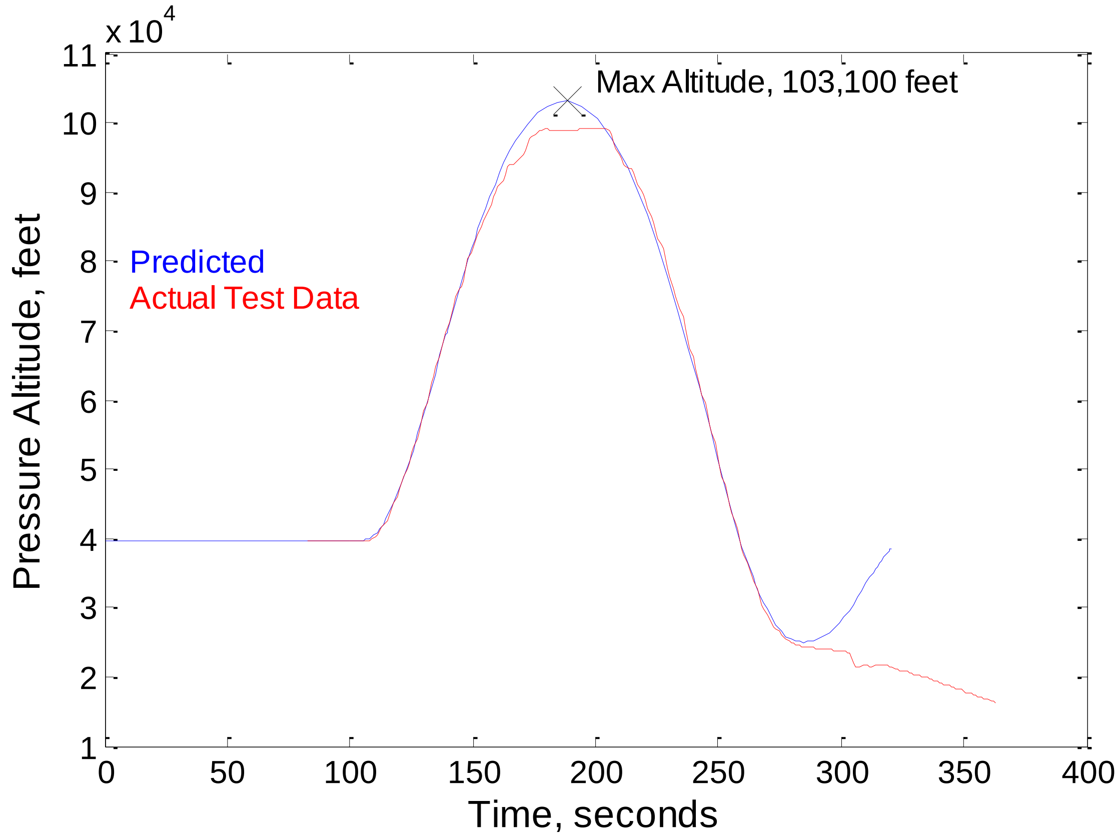

Figure 6. Final Attempt to Model Record Altitude Performance

III. Conclusion

The goal of this project was to try and accurately model the performance of the F-104C Starfighter which achieved a new world altitude record on December 14th, 1959. In completing the project, the goal was to gain a better understanding of the performance modeling of today and flight test methods from the past while creating a drag polar and engine deck which could be used for future applications of performance modeling.

In creating the performance models, it was found that the engine deck modeling equations used did not provide an accurate representation of the engine without significant increases in the maximum thrust. The drag model created using Mike Vallone's program seemed to be much more accurate and with the calibrated engine deck seemed to work as expected when modeling the flight. In order to create a more accurate representation of the whole flight, it may be necessary to build up an engine cycle analysis to try and model some of the modifications made to the engine. A more complete set of data for the J79 would be desirable in completing a full analysis of this historic flight; however, with the results seen in the final attempt to match the performance, the engine deck that was created as a result of this analysis may indeed provide an accurate representation of the thrust lapse as long as a correction factor is taken into account.

Overall, the results of the drag polar and the project itself seem reasonable; however, it is felt that more could have been done to more accurately model the engine.

References

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