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Aerodynamic Analysis Methods
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David A. Lednicer and Ian J. Gilchrist

Analytical Methods, Inc.
Redmond WA

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A RETROSPECTIVE:
COMPUTATIONAL AERODYNAMIC ANALYSIS METHODS
APPLIED TO THE P-51 MUSTANG

David A. Lednicer*
Ian J. Gilchrist**
Analytical Methods, Inc.
Redmond, WA 98052

Abstract

Of the many aircraft developed during World War II, one of the most enduring has been the North American Aviation P-51 Mustang. The last examples of this aircraft were retired from military service only in the last decade. In the civil arena, development work on the Mustang continues in attempts to achieve higher speeds for air racing. Because the Mustang was developed before computational aerodynamics tools were available, it was considered appropriate to conduct a retrospective analysis on the aircraft on the occasion of its 50th birthday. The goals of this analysis were to learn the strengths and weaknesses inherent in the aerodynamics of the P-51.

To enable such an analysis, models of the P-51B and P-51D Mustang have been prepared for use with the VSAERO linearized potential flow aerodynamic analysis method. Comparisons among computer calculations, flight tests and wind tunnel tests will be presented. A discussion of general items of interest observed in the computational results follows. Because the greatest test of the Mustang these days is in air racing, results of work done on a P-51 modified for such activity are also discussed.

I. Introduction

In early 1940, North American Aviation (NAA) was approached by the British Direct Purchasing Commission about the possibility of NAA producing Curtiss P-40s under license for the Royal Air Force. North American instead proposed a new fighter aircraft that would be superior to the P-40. On the basis of this proposal, the purchasing commission gave the project the go-ahead shortly thereafter. Detail-designed and built in 102 days, the prototype NA-73X first flew on October 26, 1940. This aircraft represented a major step in fighter aircraft development. The NA-73X was not only one of the first applications of the then-new NACA laminar flow airfoils, but was also the first aircraft to be lofted using conic functions. Powered by an Allison V-1710 liquid-cooled V-12 engine, the aircraft was endowed with one of the lowest drag radiator installations of its time.

*Senior Research Scientist, AIAA member.

**Senior Research Engineer, AIAA member.

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These and other features combined to give the NA-73X prototype outstanding performance. The RAF found the aircraft to have twice the range of the Spitfire, in addition to being faster than the Spitfire VB up to 25,000 feet. This was despite the fact that the Mustang's Allison engine produced 290 hp less than the Spitfire's Merlin engine at 25,000 ft.¹ The British purchasing commission, suitably impressed, accepted production copies of the aircraft as the Mustang 1. The United States Army Air Corps requested two sample aircraft and received the fourth and tenth production examples, designated as XP-51. These two aircraft later passed on to NACA. The former of these aircraft survived and is now in the Experimental Aircraft Association museum in Oshkosh, Wisconsin. The USAAC later ordered Allison Mustangs designated P-51, P-51A and A-36.

The Mustang's performance above 13,000 feet suffered because the Allison engine's output fell off rapidly above this altitude. Much of the Spitfire's superior performance above 25,000 feet was due to its Rolls-Royce Merlin engine. In 1942, at the suggestion of Rolls-Royce, a V-1650 Merlin was installed in a Mustang. The resulting aircraft exhibited improved performance, especially at altitude. This elicited production orders for the Merlin-engined P-51B/C and Mustang III for the USAAF and RAF, respectively (Fig. 1). Two later changes, the cut-down rear fuselage and the bubble canopy, improved pilot visibility and resulted in the P-51D/K, the best-known Mustang variant (Fig. 2). The P-51 C and K models are identical to the P-51 B and D models, respectively. The different designation indicates that they were built at North American Aviation's plant in Dallas, Texas, rather than at the facility in Inglewood, California.

P-51s, whether received as a gift, bought or captured, have served in a large number of the world's air forces. Only in the previous decade were the last Mustangs retired from military service. Civil competition, such as the Reno National Air Races, has forced continuing development on the Mustang as higher speeds are sought. Racing developments include low-profile canopies, smaller radiator inlets, cropped wings, and, in two instances, re-engining with a Rolls-Royce Griffon engine. One of these Griffon-engined aircraft, *Red Baron*, held the world 3 km speed record of 499.018 mph from 1979

to 1989. Another Merlin-engined Mustang racer, *Dago Red*, was used to set a new 15/25 km speed record of 517.079 mph in 1983. This record still stands.

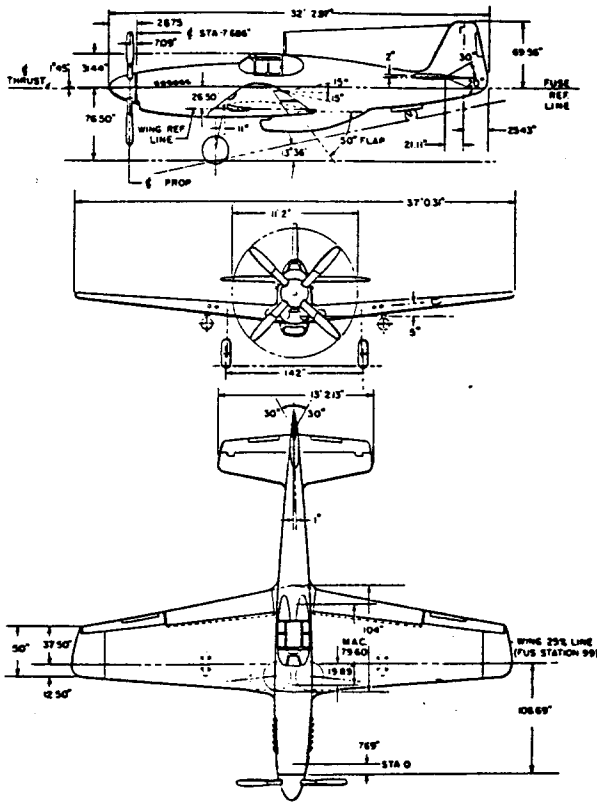


Fig. 1. P-51B Three-View

The original intent of the work described here was much like that of the first author's other recent papers^{2,3} - to model interesting aircraft and investigate their aerodynamics. The Mustang is particularly intriguing because much aerodynamic legend and lore surrounds the aircraft, but few hard facts are ever discussed. Stories of the extensive laminar flow on the wing and how the cooling system produces thrust are often told. The current work intends to investigate the Mustang's aerodynamics analytically and then to project what can be done to extend the Mustang's capabilities as a racing airplane.

II. Analysis Methods

The primary computational tool used in this work was the VSAERO (Vortex Separation AEROdynamics) computer code⁴. VSAERO, a product of Analytical Methods, Inc. (AMI), is widely used in the aircraft design and analysis environment. The VSAERO program is a full-configuration, subsonic aerodynamics analysis method that solves the linearized potential flow equations.

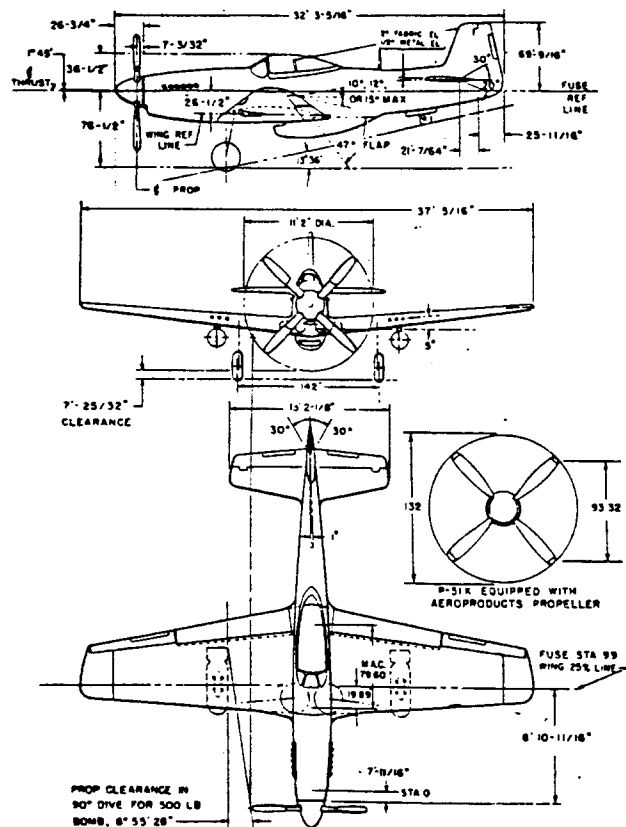


Fig. 2. P-51D Three-View

VSAERO uses piecewise constant singularity strengths on surface panels to represent arbitrary three-dimensional configurations. The use of piecewise constant surface singularity strengths results in VSAERO being classified as a low-order method. The VSAERO program includes features such as wake shape and boundary-layer iteration and streamline and off-body calculations.

VSAERO is capable of being run on a wide variety of computers and operating systems. Most of the work reported here was done using VSAERO version E.0 on a Silicon Graphics 4D/240 Power Series IRIS mini-supercomputer under the UNIX operating system. All visualization of VSAERO results was done with the OMNI3D and OMNILOT postprocessing programs, also AMI products.

III. Geometry Definition

An accurate model of a configuration is important if one is to obtain meaningful results. In this case, though the Mustang has been the subject of a vast number of books and magazine articles, not even the wing airfoils have been documented. This project started after two books by R.A. Liming, the engineer who lofted the aircraft^{5,6}, were found to contain the conic coefficients for the fuselage and loft stack diagrams for other parts of the

aircraft. Unfortunately, when the coefficients were translated into coordinates, it was found that they were for the NA-73X prototype.

Finally, through a set of family relations of the this paper's second author, a set of original NAA P-51B drawings were located in the possession of Arthur Bentley, an engineer with the British Aerospace division in Hatfield, England. Data blocks on these drawings contained actual surface coordinates for the fuselage, the carburetor inlet duct and the radiator/intercooler/oil cooler duct (Fig. 3).

The table in Figure 3 is a data block from a technical drawing. It is organized into two main sections: 'WING' and 'RADIATOR'. Each section has a header row for 'STATIONS' and a sub-header for 'COORDINATES (DUCT CONTOURS)'. The 'WING' section contains data for stations 17.5 through 22.5, and the 'RADIATOR' section contains data for stations 17.5 through 22.5. The data consists of numerical values representing coordinates for various points on the wing and radiator surfaces.

Fig. 3. Sample Data Block

Once entered into the computer, the points were visualized from different viewpoints and errors (there were many!) were corrected. Copies of pages supplied by Mr. Bentley from the P-51 maintenance manual provided the vertical and horizontal tail airfoils and the wing layout. Other geometry details were supplied by aviation writer Jeff Ethell. Only the wing airfoils were missing. It was known that a later Mustang variant, the P-51H, was designed with a NACA 66,2-(1.8)15.5 $a=.6$ at the root and a NACA 66,2-(1.8)12 $a=.6$ at the tip, so an initial assumption was made that all Mustangs had these wing airfoils. On request, Jeff Viken at NASA Langley Research Center reconstructed these airfoils using a computer program available from NASA.

However, information came to light that the Horten IVb flying wing sailplane, built in Germany during World War II, had an airfoil copied from a captured P-51. Coincidentally, Mr. Bentley had also supplied information on this aircraft to the first author regarding a different project. An overlay of the Horten wing sections

and the P-51H wing sections showed that they were different airfoils, but it was impossible to ascertain where on the span of the Mustang the Horten's sections came from. Information obtained shortly thereafter from Bruce Holmes of NASA Langley Research Center⁷ suggested that the wing was made up of NACA 64 and 65 series sections. Jeff Viken once again constructed airfoils, this time to the camber and thickness descriptions contained in ref. 7.

Initially, models of the P-51B and P-51D were prepared for input to the VSAERO program with a wing composed of these airfoils. However, the airfoils failed to produce a perfect match with a tracing of the wing section at Buttline 189.75 supplied by Jim Larsen, an engineer responsible for the design of modifications made to several of the racing Mustangs. Fortunately, R. Wagner's *Mustang Designer - Edgar Schmued and the Development of the P-51*⁸ was discovered at this stage. It quoted Edward Horkey, the chief aerodynamicist on the P-51, as saying that the wing airfoils were NACA 45-100 sections. This information was later confirmed by Millikan's wind-tunnel test report on the NA-73X⁹. Mr. Horkey was able to provide NAA data blocks describing the wing airfoils. Using this information, it was possible to construct accurate wings for the P-51B and D and to add them to the fuselage models.

Analysis reveals that the root airfoil at Buttline 17.5 (the fuselage side) is 16.55% thick and has 1.20% camber without the leading edge root extension (Fig. 4).

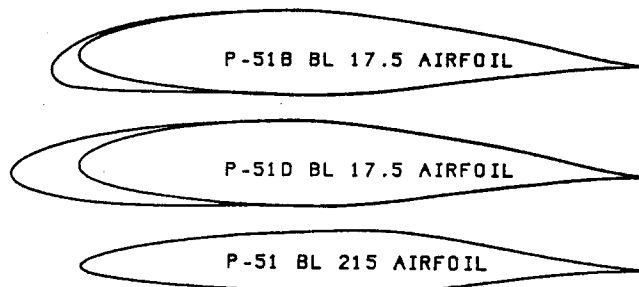


Fig. 4. Wing Airfoils

Similarly, the tip airfoil at Buttline 215 is 11.44% thick and has 1.30% camber. The search for information about the NACA 45-100 sections is continuing. Contrary to statements in Abbott and von Doenhoff's classic reference source on NACA airfoils¹⁰, the 30, 40 and 50 series of NACA airfoils are not documented in Jacob's preliminary report on laminar flow airfoils¹¹.

The geometries of the P-51B and D models differ in several respects. The most obvious (see Figs. 1 and 2), is the change from a framed canopy on the B model to a

bubble canopy on the D model. Also, the D model, found to be lacking slightly in directional stability due to the lowered rear fuselage dorsal spine, gained a dorsal fin after an initial production run. Less obvious is a change in the wing - the leading-edge root extension on the P-51B was enlarged in span and chord and also recambered to produce the D model wing. All of these changes were taken into account when constructing the computational models. Mr. Bentley lacked information about the P-51D aft fuselage, but an examination of side views showed that the D model rear fuselage was lofted by cutting the B model rear fuselage at a given waterline and refairing the spine to a new crest line. Station cuts of the D model canopy supplied by Mr. Bentley provided points at the bottom of the canopy, which defined the new contour.

The resulting VSAERO models of the P-51B (Fig. 5) and D (Fig. 6) are composed of 2,582 and 2,737 panels, respectively.

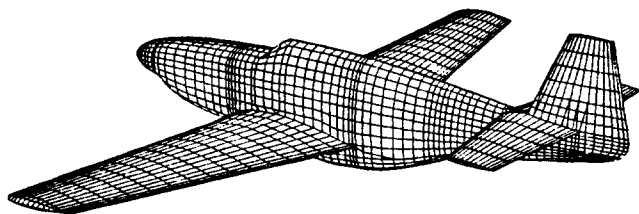


Fig. 5. P-51 B VSAERO Model

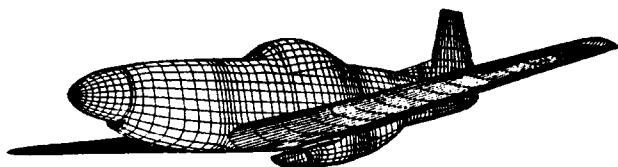


Fig. 6. VSAERO Model of P-51D

The only major details missing are the engine exhaust stacks. The out-of-contour aileron and elevator of the actual aircraft are not modeled. A short length of the carburetor inlet below the spinner is included in the model, as is the complete radiator/intercooler/oil cooler duct in the fuselage. All three coolers are fed by one inlet (Fig. 7). The oil cooler is positioned in front of and below the radiator and intercooler. The models discussed here do not have the oil cooler exhaust modeled. The main cooler block on the actual aircraft is composed of three zones. One is used to cool the water/glycol mixture coming from the intercooler downstream of the engine's supercharger, while the other two zones cool the primary engine coolant.

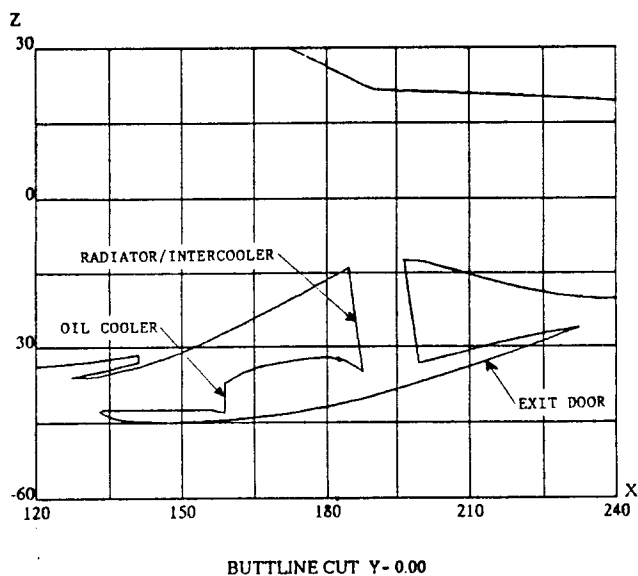


Fig. 7. P-51B/C and D/K Cooling Duct Centerline Section

In the VSAERO model, the front and rear faces of the main cooler block and the oil radiator are modeled as solid surfaces with specified normal velocities. It should be noted that the door at the duct exit is modeled in its nominal cruise position, which is flush with the external duct contours.

The boundary layer was calculated along approximately 170 streamlines distributed over the entire surface of the airplane, including internal ducts. The calculated boundary-layer thickness was represented by transpiration on the surface panels. Three viscous/potential iterations and one wake relaxation iteration were run for each case. All results to be presented are for the model trimmed about a given center-of-gravity location. Trimming was accomplished by rotating the normals of the surface panels representing the elevator to simulate the elevator deflection and produce the required pitching moment. Table 1 lists the reference lengths and areas of the aircraft.

Table 1. Reference Areas and Lengths

Wing Area: 235 sq. ft.
 Wing Span: 444.3124 inches
 Wing MAC: 79.6 inches

IV. Comparison of P-51B Wind Tunnel Data with VSAERO Calculations

Results of a test of the P-51B in the 10-foot-diameter Guggenheim Aeronautics Laboratory (GALCIT) wind tunnel were reported to the USAAF in 1943¹³. A quarter-scale model, equipped with an electrically driven propeller, was tested. The majority of the tests were run

at a tunnel dynamic pressure of 30 pounds per sq. ft., yielding a speed of 105 miles per hour and a Reynolds number of 1.68 million based on the MAC of the model. Moments were taken about 24.6% MAC. While the documentation of this test does not cover the simulation of radiator, it is known that during tests of the NA-73X in the same tunnel¹³, a baffle plate was used in the radiator duct to produce the correct pressure drop.

The trimmed lift curve is well predicted by VSAERO in the linear range (Fig. 8). Both the lift curve slope and the zero lift angle of attack are accurately calculated. In the linear range, the same level of agreement is apparent in the comparison of measured and calculated pitching moment about the CG (Fig. 9).

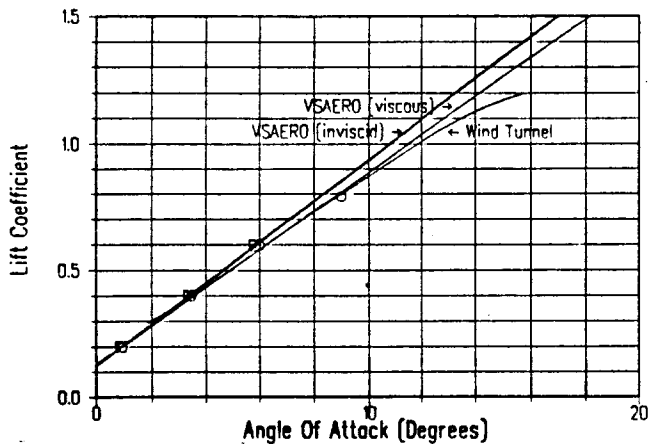


Fig. 8. Trimmed Lift Coefficient vs. Angle of Attack

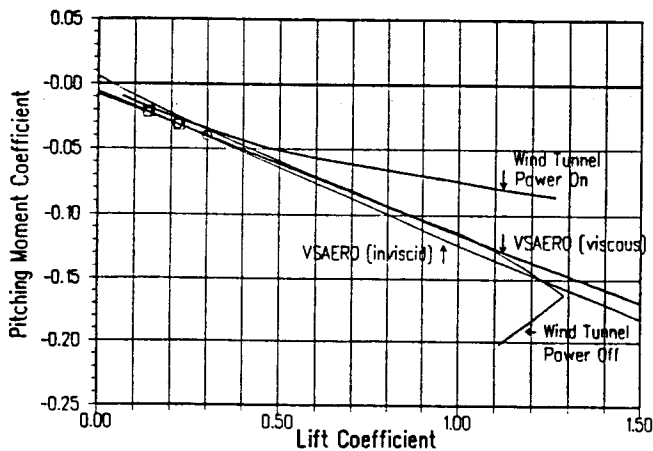


Fig. 9. Pitching Moment Coefficient vs. Angle of Attack

It has often been stated that the P-51's longitudinal stability is adversely effected by power effects. This is evident in the change in slope of the power on pitching moment curve measured in the wind tunnel (Fig. 9).

VSAERO does not do quite as well predicting the aircraft's trimmed drag, giving a zero lift drag coefficient of .0141 compared to the value of .0163 measured in the wind tunnel (Fig. 10).

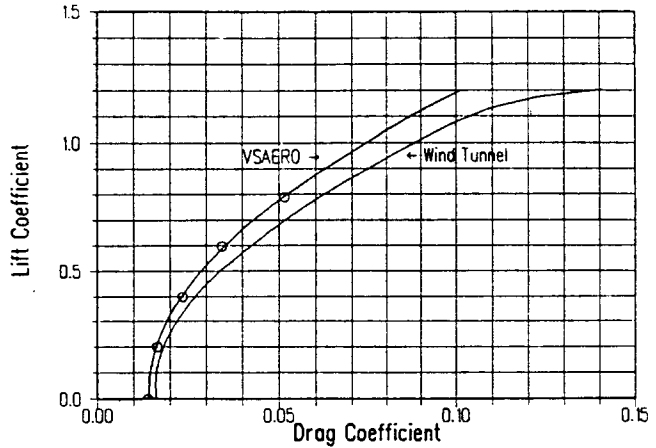


Fig. 10. Drag Polar

The drag calculated by VSAERO is the sum of the induced drag, pressure drag and skin-friction drag. Induced drag and pressure drag are calculated by summing the components of pressure in the streamwise direction on all panels. The pressure drag is present in this summation as a result of the boundary-layer displacement effects, which were modeled by surface transpiration. The values of skin friction calculated along streamlines are distributed over the patches traversed by the streamlines. Skin friction is then calculated by summation of the streamwise component of this force found to be acting on each panel.

It is not known if transition was fixed on the model, or what mounting system tares were applied to the data. The drag due to lift measured in the wind tunnel is considerably greater than that calculated by VSAERO. This is surprising in the low lift coefficient range and again raises questions about corrections applied to the wind tunnel data.

Figure 11 compares the elevator deflection required to trim and shows that elevator effectiveness is overpredicted by VSAERO. One possible explanation for this is that VSAERO, as a potential flow method, assumes that the flow field has a constant total pressure⁸. The elevator is actually operating in the viscous wake of the wing and fuselage, which are regions of reduced total pressure. VSAERO predicts power-off longitudinal stability reasonably well, and control effectiveness could be empirically adjusted based on wind tunnel or flight experience.

In summary, VSAERO appears to do a good job of producing results that compare favorably to wind-tunnel

results. The relatively close match in zero lift drag implies that the extent of laminar flow on the wind-tunnel model and that calculated by VSAERO agree quite well.

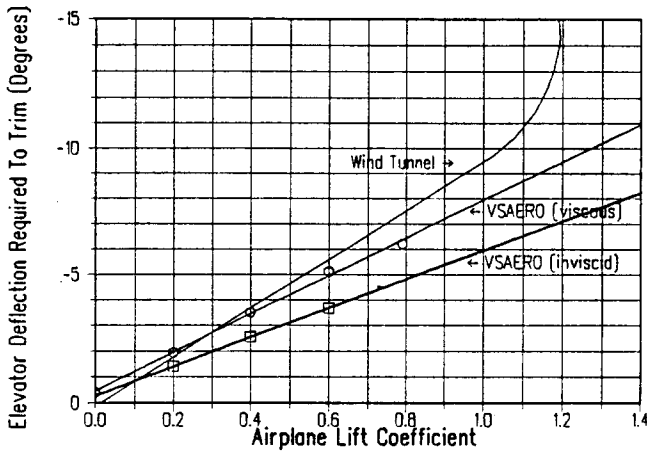


Fig. 11. Elevator Deflection Required to Trim

Reduction of the wind-tunnel data results in a Neutral Point at Fuselage Station 110.2 (39.11% MAC), while VSAERO results give a Neutral Point at Fuselage Station 109.1 (37.73% MAC) and 110.1 (38.97% MAC) with and without boundary-layer effects, respectively.

V. Comparison of P-51 Flight Test Drag Data With VSAERO Calculations

A second comparison, of a different nature, was suggested by the results of a flight test conducted by NACA in 1942¹⁴. In this test, one of the two XP-51s was flown with a wake rake affixed behind the wing. Positioned 16 inches outboard of the inboard end of the aileron (approximately Buttline 148.313), the rake was used to measure the profile drag of the wing at this location. Measurements were made with the wing in an "as received" finish, a factory-fresh finish, with the painted insignia on the wing sanded and with the wing smoothed and faired. All of the tests were made at an altitude of 10,000 feet and at airspeeds of between 190 and 340 miles per hour. The corresponding range of Reynolds numbers (on the 66.25-inch local chord) were from approximately 9 million to 16 million. The Mach number range was from 0.3 to 0.5.

An attempt to duplicate these tests with VSAERO required the use of a compressibility correction. Attempts to use the Prandtl-Glauert corrections in VSAERO led to problems in achieving the correct flow conditions in the cooling duct. While not of consequence here, work to be presented later required that this flow be correctly modeled. After trial and error, it was found that the Lieblein-Stockman correction¹⁵ produced very good results on both the external and internal surfaces wetted by the flow.

Initially, it was thought that it might be necessary to produce an XP-51 VSAERO model for a comparison with these results. The XP-51 has a different engine cowl and a completely different cooling duct arrangement, and the wing is three inches higher on the fuselage than on the P-51B. However, upon examination, it was decided that because the XP-51 and P-51B wings were the same, the P-51B VSAERO model would suffice.

No CG location was given for the experimental results, so a nominal value of 26.25% MAC (Fuselage Station 100) was assumed. VSAERO runs were made at several lift coefficients, with the aircraft trimmed to this location. The two boundary layers on each surface of the wing closest to Buttline 148.313 were then found and their Shape Factor (H), Momentum Thickness Reynolds number and edge velocities at the trailing edge were recorded. Squire-Young¹⁶ analyses were done to determine the profile drag of the boundary layers, and the results were interpolated to Buttline 148.313. The resulting values compare favorably with the experimental results (Fig. 12).

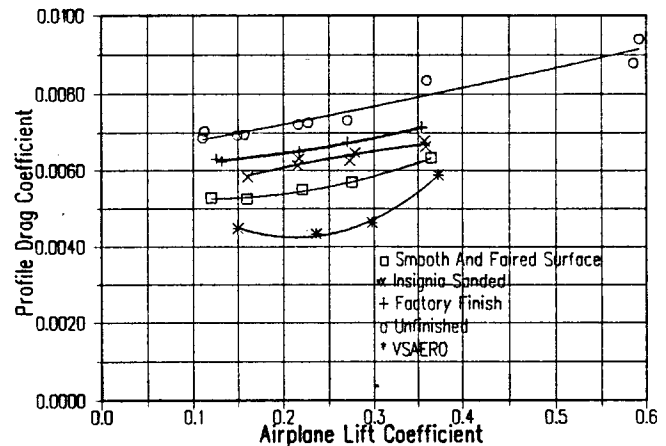


Fig. 12. Measured and Calculated Wing Section Drag Coefficient

Because the VSAERO model does not include the spanwise gaps ahead of the aileron and trimtab that were ahead of the wake rake, the VSAERO profile drag should be the lowest value, which it is. (This aircraft might have also had an out-of-contour aileron profile at this time.) It is of particular interest that the profile drag calculated by VSAERO is parabolic with lift coefficient, while the measured values are linear, convex the wrong way, or, at best, only slightly parabolic. These experimental results also show that the extensive laminar flow and resulting low drag of the wing designed into the airplane and measured in the wind tunnel was not fully realized on production Mustangs.

VI. Comparison of P-51 Pressure Data (Measured In Flight) and VSAERO Calculations

During World War II, the Royal Aircraft Establishment conducted extensive investigations into high-speed aerodynamics, both in flight and in wind tunnels¹⁷. Three aircraft, including a Mustang I, were flown with pressure-tapped wings to gather in-flight pressure measurements. This Mustang had 33 taps distributed about the Buttline 114 section on the wing. Data was collected at Mach numbers up to 0.78. For comparison purposes, the data taken at a Mach number of 0.6 have been used here. As in the previous example, the P-51B model was used in lieu of a Mustang I (P-51A) model to generate the VSAERO results. The angle of attack of the VSAERO model was adjusted until the resulting lift coefficient at Buttline 114 matched the lift coefficient found by integrating the RAE data. To help account for differences that might be due to geometry discrepancies or possible shortcomings of the Lieblein-Stockman compressibility correction used with VSAERO, the results from a two-dimensional Euler code, ISES¹⁸, are also presented for the section at Buttline 114. The ISES, VSAERO and flight test results are all for the same lift coefficient. The resulting comparison (Fig. 13) shows reasonable agreement among the three sets of data.

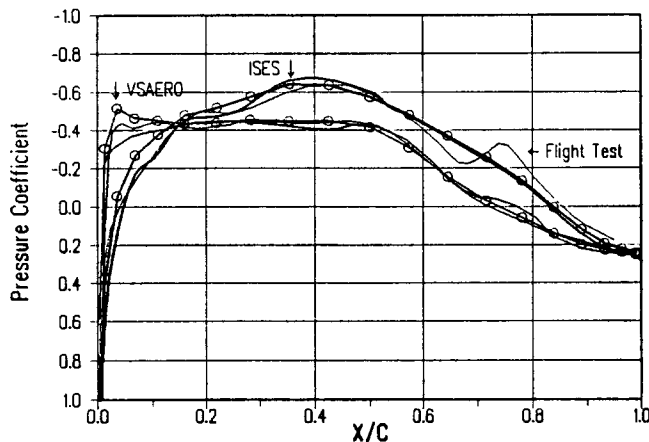


Fig. 13. Measured and Calculated Wing Section Pressure Coefficients

The hump in the upper surface pressure distribution at 40% chord appears in all three sets of data, though to varying degrees. The RAE report theorizes that part of this hump might be due to the deformation of the ammunition bay doors because of aerodynamic loading. The "S" curve in the flight data on the upper surface in the trailing-edge area is due to the surface discontinuity where the flap cut-out occurs. The only major discrepancy among the three sets of data is in the leading-edge area. Here, VSAERO predicts too high a suction on both the lower and upper surfaces. This is typical of linear compressibility

corrections. It should be noted that ISES also overpredicts the upper surface leading edge suction.

VII. Mustang Airframe Drag

Quite often the parameter of $C_{D_{wet}}$ (drag coefficient based upon wetted area) is used as a measure of a design's aerodynamic cleanliness. Charts of equivalent parasitic drag versus wetted area with lines of constant $C_{D_{wet}}$ abound (Fig. 14).

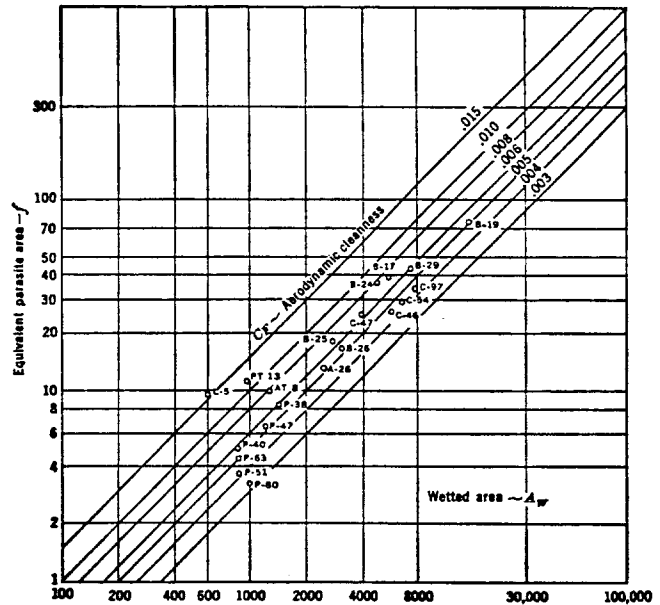


Fig. 14. Equivalent Parasitic Drag Area As a Function of Wetted Area²³

One popular piece of aerodynamic folklore is the low $C_{D_{wet}}$ value achieved with the Mustang. Various sources quote this value as ranging from .0038 to .0043¹⁹⁻²³. Before commenting on these values, the Mustang's wetted area must be defined. There are two possible values, depending whether or not the duct surfaces are included. With the duct surfaces, VSAERO calculates the wetted area of the P-51B and D models at 925.2 and 933.4 sq. ft., respectively. Without the duct surfaces, these areas are 869.8 and 878.0 sq. ft., respectively. These differences are important because it is likely that drag measurements were made of the complete aircraft, but that only the external wetted area was taken into consideration in determining $C_{D_{wet}}$. All the results presented here will use the wetted area excluding the duct area.

At a representative cruise lift coefficient of .18 and a Reynolds number of 1.68 million, the results of the GALCIT wind-tunnel test of the P-51B¹² reduce to a $C_{D_{wet}}$ of .0046 (Table 2). The equivalent value calculated with VSAERO is .0040. Results from a test of a 1/3 scale

P-51B in the NACA Ames Aeronautical Laboratory 16-foot Wind Tunnel²⁴ reduce to a $C_{D_{wet}}$ of .0047 (without boundary-layer trips). Comparable data from a 1/6 scale test of a Mustang I (P-51A) in the RAE High-Speed Wind Tunnel²⁵ reduce to a $C_{D_{wet}}$ value of .0047, using the wetted area of the P-51B. In contrast, the wind-tunnel test of a full-scale P-51B, conducted at the NACA Langley Memorial Aeronautical Laboratory, found the aircraft to have a $C_{D_{wet}}$ of .0055. This test is unique because the aircraft was in a "service condition," lacking only a propeller.

Table 2. Drag Coefficient Based On Wetted Area
($C = 79.6$ inches, S_{wet} does not include duct surfaces)

Source	Model	Re	Mach	$C_{D_{wet}}$
Roskam ¹⁹	P-51B			.0043
Lan and Roskam ²⁰	P-51D			.0043
Hoerner ²¹	P-51			.0040
Stinton ²²	P-51			.0038
Perkins and Hage ²³	P-51			.0041
VSAERO	P-51B	1.68M	0	.0040
VSAERO	P-51B	15.37M	0.5	.0033
VSAERO	P-51D	15.37M	0.5	.0031
GALCIT ¹²	P-51B	1.68M	0.14	.0046
NACA-tunnel ²⁴	P-51B	6.5M	0.5	.0047
RAE-tunnel ²⁵	P-51A	1.0M	0.5	.0047
NACA-tunnel ²⁶	P-51B	6.2M	0.13	.0055
NACA-flight ²⁴	P-51B	15.37M	0.5	.0053
RAE-flight ²⁵	P-51A	15.37M	0.5	.0053

At the flight conditions, VSAERO calculates the value of $C_{D_{wet}}$ to be .0033. This run was made with all of the boundary layers that start on the spinner tripped at the propeller plane and all those starting on exterior duct surfaces tripped shortly behind the highlight. The equivalent value calculated by VSAERO for the P-51D is .0031. Results from a NACA dive test of a P-51B without a propeller²⁴ reduce to a $C_{D_{wet}}$ of .0053 at approximately the same conditions. RAE flight test data taken with a Mustang I (P-51A)^{17,25} are in agreement with these results. It should be noted that neither most of the wind-tunnel tests nor the VSAERO calculations include the drag of the exhaust stacks, other excrescence drag, or power effects. In addition, as discussed above, it has been shown that the induced drag calculated by VSAERO for the Mustang is too low and that the extent of laminar flow calculated by VSAERO and seen in the wind tunnel was not realized in flight. It can be concluded that the drag values reported in the literature are all too low.

VIII. Mustang Engine Cooling System Performance

A particularly difficult aspect of the development of the Mustang was its cooling system. The geometry of this part of the aircraft was changed several times during the Mustang's production run (Fig. 15) and elicited sever-

al wind-tunnel tests. A "duct rumble" heard in flight on the prototype P-51B resulted in a full-scale wind-tunnel test at Ames Aeronautical Laboratory²⁷. This was carried out by inserting the airplane, with the outer wing panels removed, into the 16-foot tunnel. It was eventually found that the rumble could be eliminated by increasing the gap between the lower surface of the wing and the lip of the cooling system duct from 1 inch to 2 inches (Fig. 16).

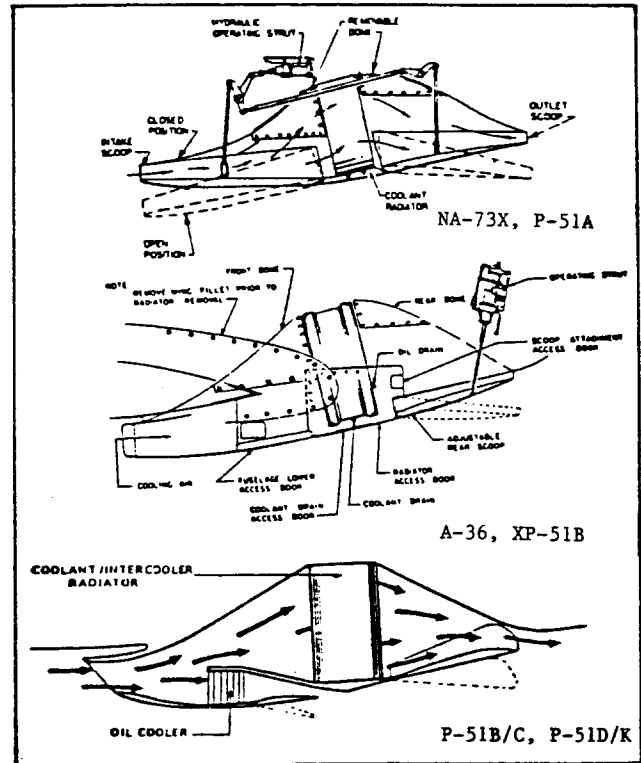


Fig. 15. P-51 Production Cooling System Ducts

Duct	FLAP OPENING - INCHES		RUMBLE	
	IN	OUT	10-15 MPH	15-20 MPH
Standard Duct	0.6	1.8	SEVERE	---
	0.6	3.6	SEVERE	---
Standard Duct with 1/2" Gap	0.6	1.8	SEVERE	---
	0.6	3.6	SEVERE	---
Standard Duct with 1" Gap	0.6	1.8	SEVERE	SEVERE
	0.6	1.8	SEVERE	---
Standard Duct with 1.5" Gap	0.6	1.8	SEVERE	SEVERE
	0.6	3.6	SEVERE	SEVERE
Standard Duct with 2" Gap	0.6	1.8	SEVERE	SEVERE
	0.6	3.6	SEVERE	SEVERE
Standard Duct with 2.5" Gap	0.6	1.8	SEVERE	SEVERE
	0.6	3.6	SEVERE	SEVERE

Fig. 16. Cooling System Ducts Tested To Alleviate "Duct Rumble"

The conclusion was that part of the boundary layer on the lower surface of the wing was being ingested into the inlet and separating, causing the radiator to vibrate and producing the rumble. The average boundary-layer displacement thickness calculated by VSAERO in this area of the lower surface of the wing is 1.62 inches. This computational result confirms the conclusions reached in the wind tunnel. It should be noted that the inlet that went into production on the P-51B was lowered even further to give a separation of 2.63 inches from the bottom of the wing. In addition, the shelf that extended above the oil cooler face was removed.

In the test at Ames, measurements were taken of the mass flow through the oil cooler and the radiator/intercooler. These results were used to calculate the normal velocities used on the inlet faces of these heat exchangers in the VSAERO models. An examination of the resulting calculated flow pattern at the inlet shows a little spillage on the lower sides of the highlight face, but otherwise a well-positioned stagnation point. The value on the exhaust side of the radiator/intercooler was iterated on to achieve a good Kutta condition (Fig. 17).

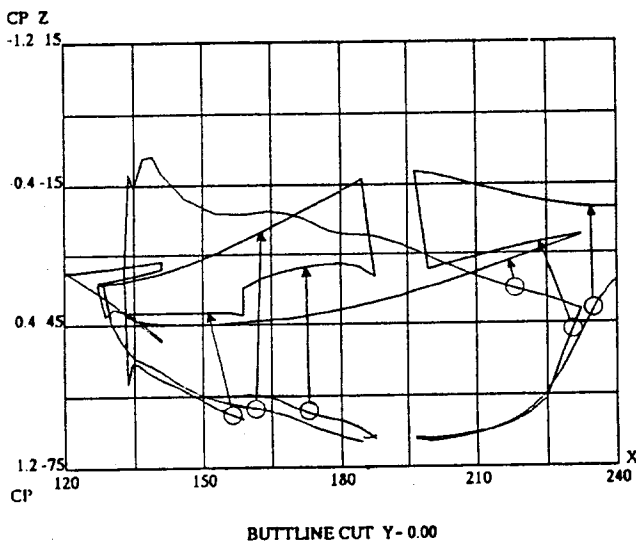


Fig. 17. Cooling System Duct Calculated Pressure Coefficients

Another piece of Mustang aerodynamic folklore is that the cooling system produced a net thrust. As noted elsewhere²⁸, available literature on this subject is entirely theoretical and is divided between a favorable British position and adverse American and German positions. This issue was explored using the experience gained with automotive radiator duct work at AMI. The three forces that must be accounted for in this case are the duct surface drag, the pressure drop drag of the radiator, and the thrust created by the transfer of heat from the radiator to the air in the duct. The duct surface drag was found in the VSAERO results and actually amounted to a slight thrust,

probably caused by the boundary-layer thickness tilting the pressure force vectors in the diffuser forward. The propulsive force from the heat transfer was found by calculating thermal efficiency and jet efficiency, the two components of propulsive efficiency, as outlined in ref. 29.

Information found in ref. 8 indicated that the Harrison Radiator Division of General Motors had produced the radiator/intercooler for the Mustang. Hank Deemer of Harrison was kind enough to dig through the archives, where he found the experimental pressure drop curves for this heat exchanger. Unfortunately, these curves were measured on a test stand meant for automotive radiators and needed to be extrapolated for flight conditions. At what might be typical cruise operating conditions, a pressure drop of 13.3 in H₂O on the water/glycol radiator and 32.8 in H₂O on the oil radiator is found. Coupled with an assumed 170° F outlet air temperature, a drag of 29 lb. is incurred (Fig. 18). At this high-speed cruise condition ($M = .5$) at 15,000 feet, the cooling system drag is approximately 2-3% of total airframe drag. What particularly hinders the cooling system as a thrust-producing device is its low propulsive efficiency. Figure 18 shows that by increasing the outlet air temperature, there is the potential for an increase in the thrust by the system.

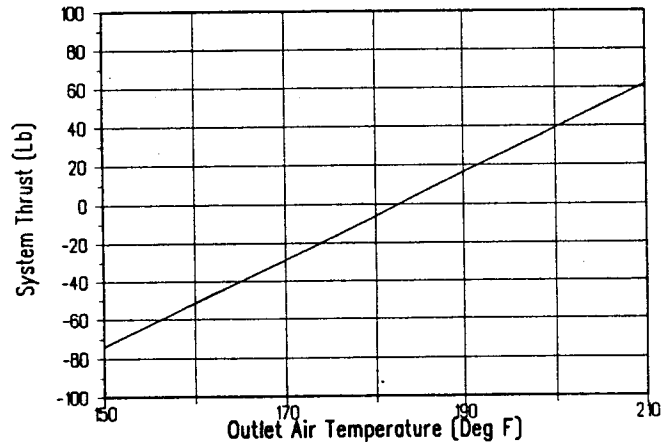


Fig. 18. Cooling System Thrust As a Function of Outlet Air Temperature

When examining the VSAERO analysis of the flow in the cooling system, it was observed that the boundary layer separates from the ceiling of the duct well before the radiator, which probably reduces the radiator's effectiveness in flight (Fig. 19).

The duct floor has the geometry of a "streamline diffuser", as advocated by Kuchemann and Weber³⁰, and exhibits a separation point immediately in front of the radiator. The ceiling is more of a conventional diffuser, which has been shown in ref. 30 to be less effective. A modified ceiling with a rapid area expansion started much

later, making it a "streamline diffuser," would have a separation point much closer to the radiator. This would cover less of the radiator with separated flow and would increase its cooling effectiveness.

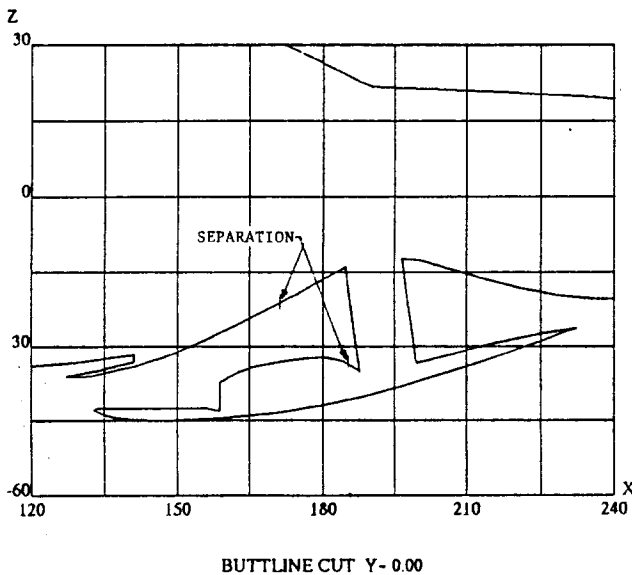


Fig. 19. Separation Points in the Cooling System

IX. Mustang Carburetor Inlet Performance

Because the VSAERO models used here include a short length of the carburetor inlet duct, it was necessary to specify a normal velocity through the face at the end of this duct. The mass flow required by the engine for a high-speed cruise at 15,000 feet was calculated using the analysis presented in Appendix IV of ref. 31. Using this value with the VSAERO model resulted in excessive spillage at the duct highlight. It was later determined that this duct was originally sized for the high power conditions experienced at take-off. Even so, the duct seems oversized. Hindsight suggests that it could have been made much smaller, thereby reducing spillage drag. A review of the literature revealed that one racing Mustang, N13Y, raced by Anson Johnson in the 1949 National Air Races, was quite successfully modified to have a substantially smaller than standard carburetor inlet³².

X. *Strega* - A Modern Racing Mustang

To round out the P-51 configurations considered here, a P-51 modified for racing, the *Strega* ("Witch" in Italian) was modeled. This aircraft won the Reno National Air Races Unlimited Championship in 1987 with a record speed of 452.559 mph. Originally modified by Bill "Tiger" Destenfani, *Strega* improves on experience gained with the modified racing Mustangs, *Dago Red* and *Jeanie* (formerly *Miss Candace* and now *Leeward Air Ranch Special*). With the assistance of Jim Larsen, who engineered many of the modifications made to this airplane,

the VSAERO model of the P-51D was modified to represent *Strega* (Fig. 20).

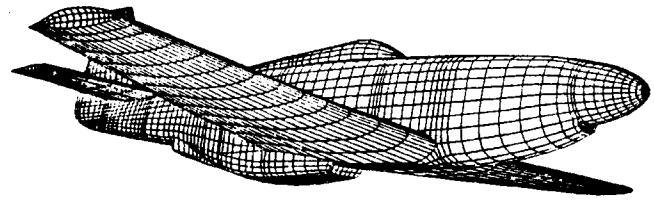


Fig. 20. *Strega*

The wings were clipped at the production break at Buttline 189.75, and Hoerner tips were added. This represents a reduction in span of approximately 15% and a reduction of aspect ratio of 20%. The wing sections were modified by reflexing the flaps and ailerons 1.5°. The original canopy was removed and the fuselage top smoothed before adding a smaller bubble canopy and associated fairing. Also, 6½ inches were removed from the span of the horizontal tail on each side and the cooling system was extensively modified. The exit door was extended aft about 18 inches and then rotated to give the proper exit area. Side walls were added to the door to seal it to the sides of the fuselage. The oil cooler was removed, and the radiator was rotated to a vertical position from its normal 8° degree inclination. On the actual aircraft, oil cooling is now accomplished in the one-third of the radiator formerly used by the intercooler, and engine charge air is cooled by water injection rather than by the intercooler. A completely new experimental cooling system inlet duct was added flush up against the underside of the wing with a reduced highlight area (Fig. 21).

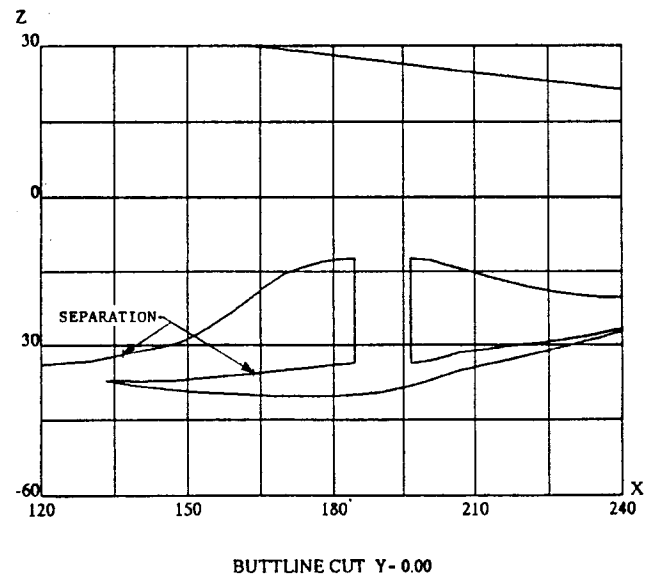


Fig. 21. *Strega's* Cooling System Duct

These modifications represent the configuration most likely seen at the Reno Air Races this fall. A total of

2,761 panels were used to model this configuration. The modifications made to create *Strega* (with the original duct) have reduced the airframe's wetted area to 894.9 sq. ft., of which approximately 58 sq. ft. consists of the cooling system ducting. This represents a 4.5% reduction in wetted area. For comparison, the wetted area of two other air race competitors is known from VSAERO modeling done during their development. One of *Strega's* major competitors is the highly modified Grumman F8F-2 Bearcat *Rare Bear* (Fig. 22).

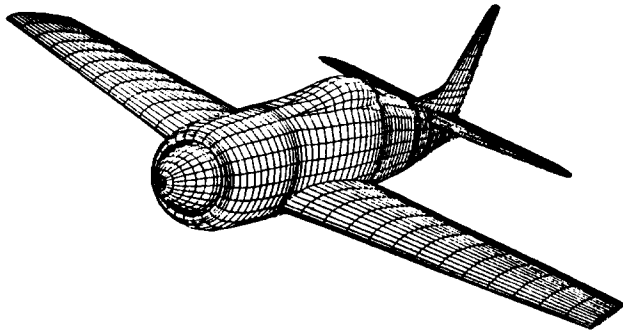


Fig. 22. The Grumman F8F-2 *Rare Bear*

This aircraft now holds the world 3 km. speed record of 528.329 mph. The wetted area of the *Rare Bear* is 893 sq. ft. This fall should see the Reno debut of a new unlimited racer, the Rutan-designed and -built *Pond Racer*.

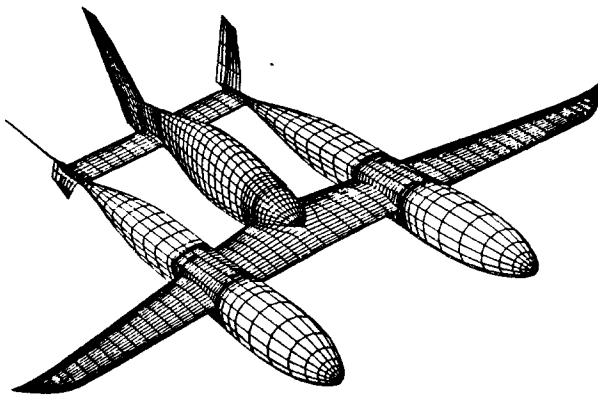


Fig. 23. Rutan *Pond Racer*

This aircraft has a substantially smaller wetted area of 478 sq. ft. However, while *Strega* and *Rare Bear* have approximately 3,000 to 4,000 installed horsepower, *Pond Racer* has only 2,000 installed horsepower.

When the production standard Mustang models were first analyzed with VSAERO, it was noted that there appeared to be a vortex along the sides of the cooling system exhaust chute aft of the trailing edge of the door (Fig. 24).

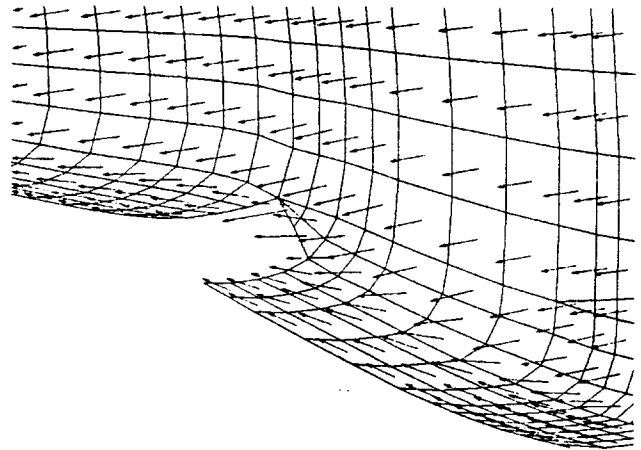


Fig. 24. Vortex on P-51D Cooling System Exhaust

This can be seen in the large downward and inward velocities in this area (panels in the duct are not shown in this figure). The extended exit door on *Strega*, designed as a result of tuft tests on the aircraft in flight, was found to eliminate this adverse phenomenon. This extended door has been credited with improving the aircraft's performance.

Based upon the previous discussion of the Mustang's cooling system inlet, the new inlet on *Strega* would seem to be a high-risk item. The results calculated by VSAERO confirm this (Fig. 21).

It can be seen that the wing boundary layer separates as soon as it enters the duct. In addition, the boundary layer on the floor of the duct also separates well before the radiator face. Based on the experience gained analyzing these cooling system ducts, an improved duct was designed for racing applications (Fig. 25).

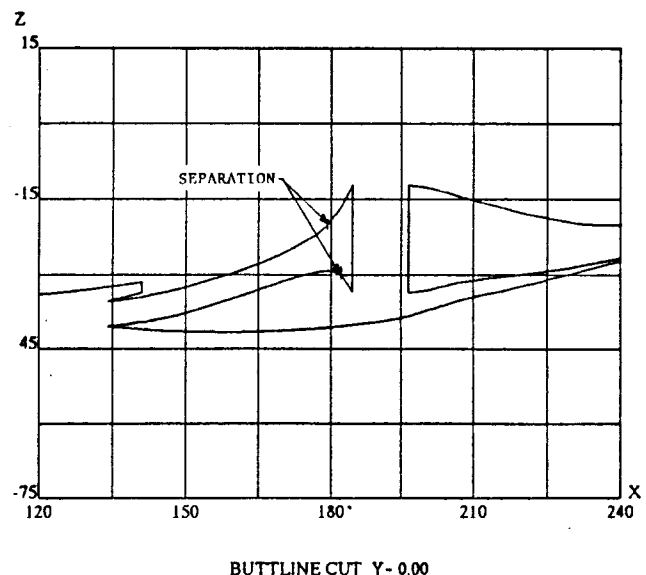


Fig. 25. Improved Cooling System Duct

The highlight area is unchanged, but a 2-inch-high wing lower surface boundary-layer diverter was incorporated. The duct area distribution is based upon that of a streamline diffuser as given by Kuchemann and Weber³⁰. This distribution was modified over the course of several iterations to improve the duct's separation point locations. The resulting duct exhibits separation points quite close to the radiator face, which will improve the performance of this heat exchanger.

XI. Conclusion

The results of a retrospective analysis of the P-51 Mustang have been presented. These results confirm the soundness of the P-51's overall design. However, certain details could have been improved had VSAERO or other analytical tools been available. A major example is the cooling system inlet and duct. Much trial-and-error testing could have been avoided by using a viscous/potential flow analysis method. In addition, the carburetor inlet duct could have been sized better, and the wing airfoils could have been designed for greater laminar flow stability. It has been shown that improvements to racing Mustangs can be made using computational fluid dynamics tools.

Acknowledgements

At the risk of forgetting someone, we would like to thank the many people who aided and abetted this project. Most importantly, Ed Horkey, chief aerodynamicist on the Mustang, Arthur Bentley of British Aerospace, and Jim Larsen of AeroAcoustics together supplied the necessary geometry. Other conspirators included Bruce Holmes of NASA/Langley, Ed Wagner of the San Diego Aerospace Museum, and Paul Robertson, Jeff Ethell and Paul Ludwig, who made their P-51 files available to us. Jeff Viken, of PRC Kentron and NASA/Langley, was helpful in generating airfoils - we apologize that they were all the wrong ones! Hank Deemer of Harrison Radiator dug through the archives, uncovering invaluable radiator data. We thank Mike Nixon and the staff of Vintage V-12s for answering all of our Merlin questions. We are grateful to Bud Shoemaker, who responded to a unknown voice on the telephone asking the width of the P-51 radiator by saying, "Wait a minute, let me go measure one," and also to Steve Hinton of Fighter Rebuilders and Bruce Boland of Lockheed, who supplied carburetor duct information and general impressions. Steve Ericson of Scaled Composites and Paul Finn of Rockwell gave us a lot of encouragement. The management and staff of Analytical Methods, Inc. must be thanked for their support. Lastly, the first author would like to thank the second author for planting the seed of this project and nurturing it.

VSAERO input files for the models of the P-51B and D shown in this paper are available from the authors in return for the magnetic media necessary to ship them.

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