Measurement of Unknown Airfoils

The Bugatti 100P

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Abstract

Aircraft airfoils have been carefully and scientifically studied for more than 100 years, and as such, good working knowledge of airfoil is widely distributed. For general aviation in moderate airspeeds, many airfoils can produce good results, and as a consequence, many more airfoils have been applied to aircraft than have been cataloged and studied. Aircraft designers have many candidates from which to choose, and are free to modify, combine, and develop their own foils. In the U.S., the small aircraft designer may choose any foil that allows his aircraft to meet performance criteria, and is not required publish foil data or descriptions.

In the case of historical aircraft, such as the Bugatti 100P, the engineering record may be incomplete. Among the designer's drawings many foils are to be found, but since the designer officed in proximity with the aircraft prototype, there was no formal system of drawing revision control or submittal records to the shop floor. It was simply not known what foil was used.

In this paper, we present a method for measuring any existing airfoil on the aircraft.

Introduction and History of the Bugatti 100P

Louis de Monge was a successful French/Belgian aircraft designer and engineer. Family photographs show de Monge and his brothers with aircraft of their own designs as early as 1906. He is characterized in the British weekly Flight as the “famous French aircraft designer” in 1924. At least one of his designs from the 1920s used small, Bugatti-built engines.

In the late 1930s, Ettore Bugatti asked de Monge to design a race plane around Bugatti’s successful auto engines. The plane was to be built in Paris of mostly indigenous woods, in a converted furniture factory, as quickly as possible. De Monge took an office in the factory, nearby the plane, and construction began in 1937.

Louis de Monge had been an active designer throughout the 1920s and 1930s. He would have been knowledgeable about the work being in Göttingen and in Paris (and in parallel by the NACA) including new systems of describing and cataloging airfoils for study and application. By this time, a number of successfully high-speed race planes had been developed in Europe.

Among the surviving de Monge 100P drawings, many airfoils can be found. Unfortunately, title blocks, revision numbers, drawing catalogs, and work orders are incomplete, not legible, or not readily available for on-line research. Since the project was under a timeline and de Monge personally directed the construction, revision control may have been overlooked as a matter of expediency. There is much speculation as to what airfoil de Monge might have used on the Bugatti 100P.

The original 100P never flew, its development interrupted by the start of World War II. The plane – disassembled and hidden in a barn near Paris – survived the War but was not rediscovered until the late 1960s. Now restored, it is on display at the Experimental Aircraft Association in Oshkosh, Wisconsin, USA.

Our team, in an effort to build a replica faithful to the original Bugatti 100P (especially aerodynamically), faced a challenge: we needed to develop a method to accurately identify de Monge’s choice for the airfoil on the airplane. Our solution: we developed a novel device, software, and technique to trace and measure the existing airfoils directly from the plane itself.

(The Experimental Aircraft Association was gracious in allowing us unrestricted access to the plane, for which we owe them many thanks.)

Description of the Airfoil Tracing Device

The Airfoil Tracing device (Profiler) is a 2-dimensional digitizer that probes an existing wing surface and records a stream of data. The Tracer employs a swinging arm on a sliding carriage, with a plastic wheel probe for rolling against the surface of the wing to prevent damage. The sliding carriage employs a rack-and-pinion gear arrangement to convert its linear motion to rotary motion for measurement. The device is manually operated, with a PC and special software for recording a tracing session and reducing the raw data to a 2-dimensional plot.

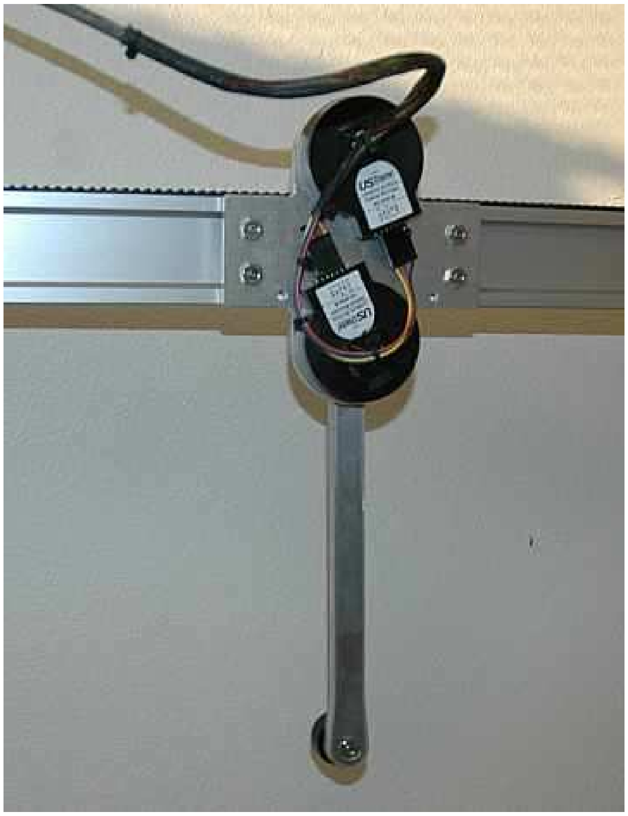
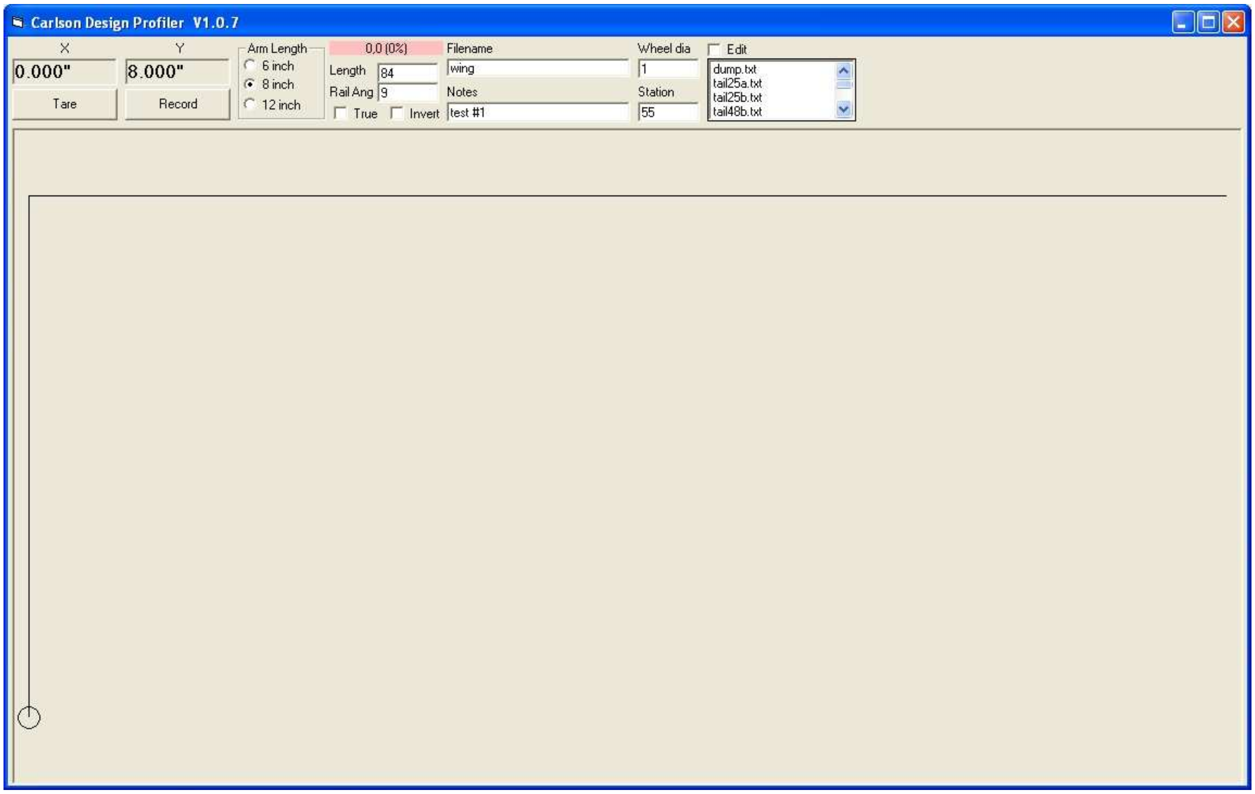


Figure 1 Airfoil Tracing Head

Two high-resolution, precision, ball-bearing, large-diameter quadrature optical encoders record the linear motion of the rack-and-pinion, and the rotary motion of the arm. The raw count is streamed and recorded at high speed by a PC with special hardware and custom software to read encoders. A recording session is begun by an operator keystroke. The raw data is resolved onto an X-Y plane in real time by scaling the counts and resolving the swinging arm by trigonometry. These X-Y points are displayed on the screen for the operator. The program also records these data in a second stream each time the movement exceeds a predefined increment so as to avoid excess data points. Since access to the airplane may be limited, it was important to save both raw and reduced data.



X 0.000"
Y 8.000"
Arm Length ○ 6 inch ● 8 inch ○ 12 inch
Length 84
Rail Ang 9
☐ True ☐ Invert
Filename wing
Notes test #1
Wheel dia 1
Station 55
☐ Edit
dump.txt
tail25a.txt
tail25b.txt
tail48b.txt

Figure 2 Tracing Device Software. The horizontal line represents the rail and the hanging arm with circle represents the rolling probe.

Swinging arms were machined in 6, 8 and 12 inch nominal lengths, and are easily interchanged and supported by the software. The machine traces only the airfoil upper or lower surface at a time, allowing tracing of wings of a thickness up to about twice the length of an arm. Since the encoder count is fixed, the smallest arm should be used when possible to maximize resolution.

The Head assembly slides along a stiff and light rail, which is suspended on both ends, either above or below the wing, by tripods. Both the supporting tubular rail and head are lightweight aluminum of considerable rigidity, so while sag could be accounted in software, it was not accounted for since its magnitude was much less than the resolution of the device.

The geometry of the device is simply:

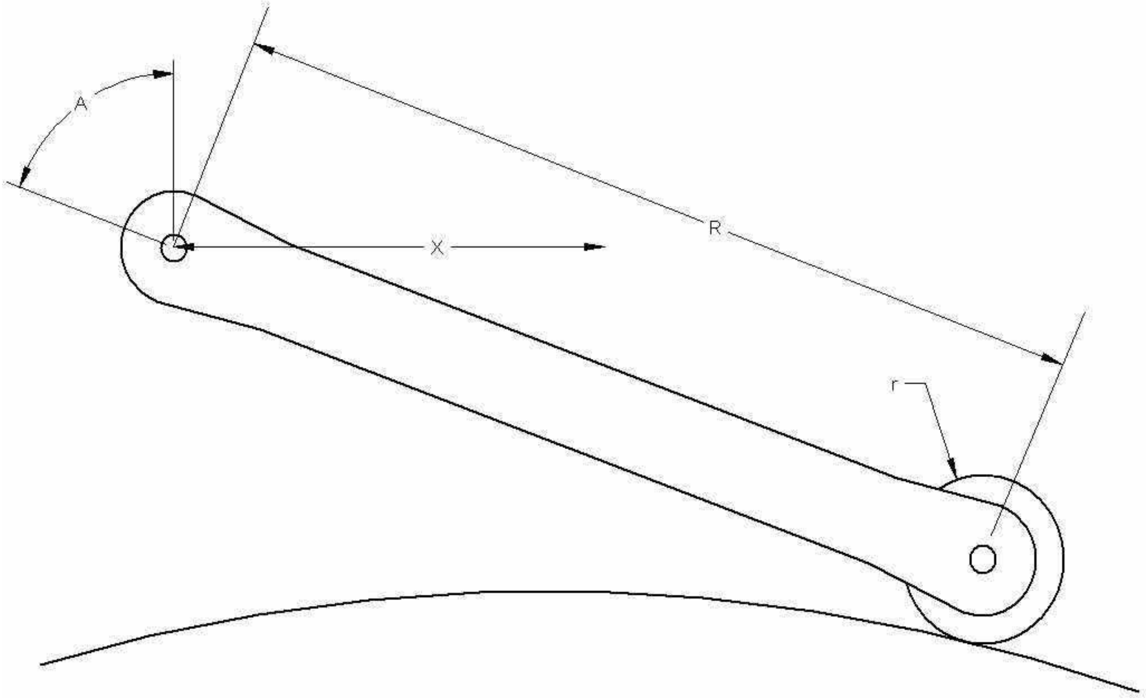


Figure 3 Probe Geometry.

The position of the probe at the center of the wheel is given by:

$$X = (Xcount / Xscale) + R * Cos(Acount * Ascale) - Xtare \quad (1)$$

$$Y = R * Sin((Acount - ATare) / Ascale) \quad (2)$$

The probe position is represented by the centerline of the plastic wheel, which is 1.00" in diameter, so the taken taken is actually a line .50" parallel to the true surface, which can be removed in software or in CAD. The real-time display provides feedback for the operator:

Resolution and Precision

The encoders used provide counts of 2048 per revolution. The counting circuitry is able to count both the rising and training edge of each of the pair of quadrature counts, which provide

4X counts, or 8192 counts per revolution. This provides a resolution of +/- .0004 inch along the rail and +/- .006 inch on the arm, using the 8” long probe. The scale factors are given by:

$$\text{Xscale} = 8192 / (\text{Number\_Pinion\_Teeth} * \text{Rack\_Pitch}), \text{ counts / inch} \tag{3}$$

$$\text{Ascale} = 360 / 8192, \text{ degrees / count} \tag{4}$$

Tare

The optical encoders are at unknown positions when the system starts. They are two methods for starting the system in a known position. One method is to level the rail and waiting the arm to stop swinging. The repeatability with this technique was within a single raw count, although the precision in leveling the bar was limited by the technique used, including spririt level and digital level. The second method is to bring the arm up an in contact with the rail, where the exact geometry is known. The software supports both methods.

Operation of the Device and Data Reduction

The operator plan a wing measuring session by first measuring the wing and marking the positions along the wing they would like to take data. In the case of the 100P, we decided to take five airfoils evenly spaced out the length of the wing from root to tip. Those stations should be measured from the centerline of the aircraft and noted.

The tracing machine is suspended over the wing such that the probe rolls on the marks, and within the limits of motion of the arm. If the rail must be set at an angle, that angle is noted. The recording session is begun, and the operator carefully rolls the probe along the wing. He may move the probe back and forth as many times as he wants to get a large amount of data and to increase the precision. Since the wing limits the probe in one direction only, resolution is improved by taking as much data as practical.

The operator should also roll around both the leading and trailing edges to image those curves as far as possible for later reconstruction. There is no problem in moving the probe away from the wing also to get it in the proper position – those data are easily discarded since the only important data are all the points closest to the wing.

Figure 4 Long chord lengths may require a helper hands.

A typical trace of the upper surface of the wing shows movements to re-orient the probe for reaching under the wing, but do not confuse the data.

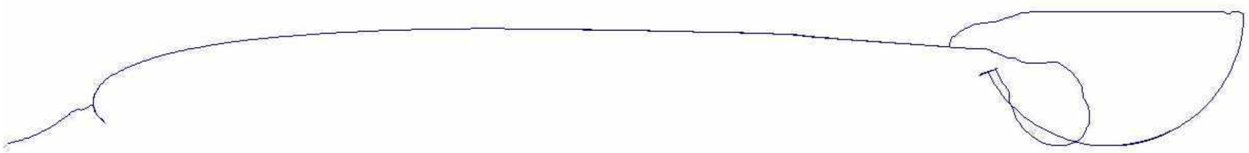


Figure 5 A raw trace of an upper wing surface. The loops represents the operator swinging the arm around to reach the opposing surface.

The tracing machine is next moved to a new station along the wing, or repositioned below the wing in one the desired stations. If the rail must be tilted, that angle may be noted. A new trace of the bottom of the wing is made.

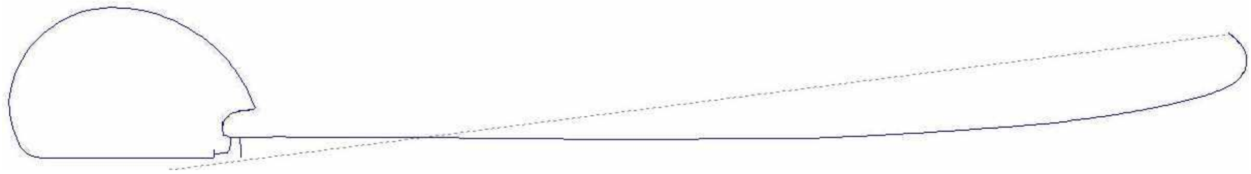


Figure 6 A raw trace of a lower wing surface.

The raw data now consist of a series of X-Y data in free space, without reference to a datum, and in the case of the 100p, spaced at about a .050” interval. The raw data is also saved, spaced as close as the encoder count.

The data pairs, top and bottom, are imported into a CAD program for reduction into final airfoils. The first step is to selected the inner-most data and ignore any data where the operator may have pulled the probe off the surface.

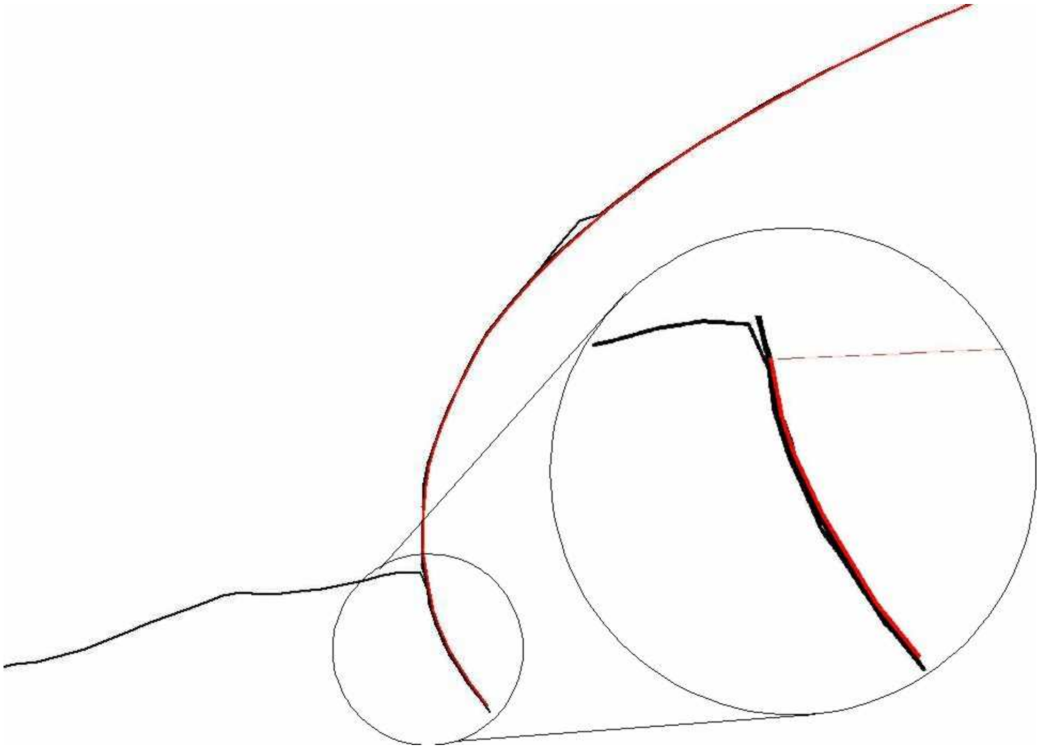


Figure 7 Reduction of the data into an airfoil surface.

The next step is to remove the probe wheel offset by creating a line parallel, inset towards the centerline of the wing by .500 inch.

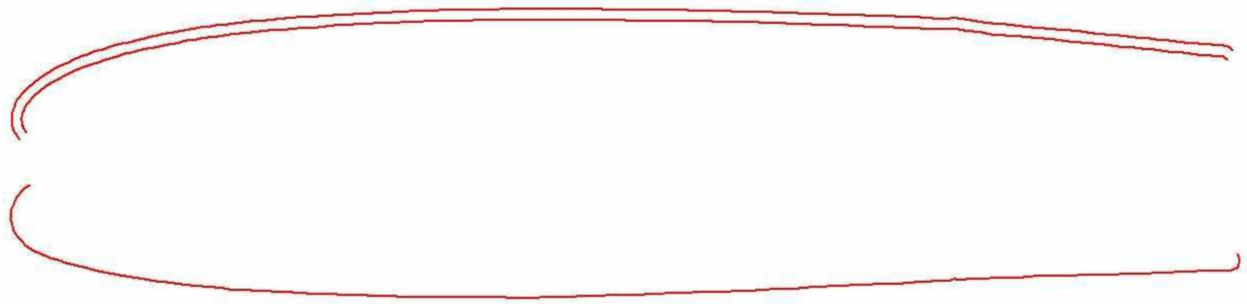


Figure 8 Remove the probe wheel offset.

Finally, the wing upper and lower surfaces must be joined. If the angle of the rail was recorded for top and bottom passes of the wing, the two foils may be rotated to reflect those two angles and slid together. The hook shapes around the leading and trailing edges are used to complete the proper registration and create the finished airfoil.

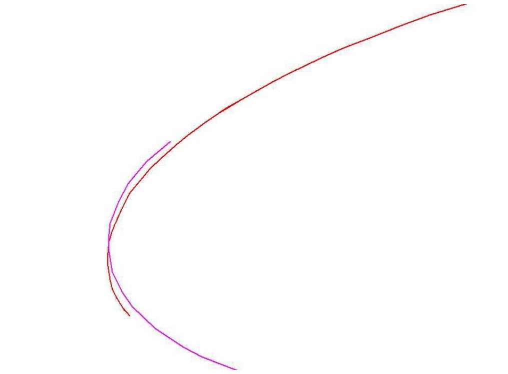


Figure 9 Carefully joining the top and bottom profiles by eye.

Note that it would be possible to automate this process with curve-fitting software, or simplify and remove uncertainty be employing a pair of rails in a fixed-distance frame around the wing.

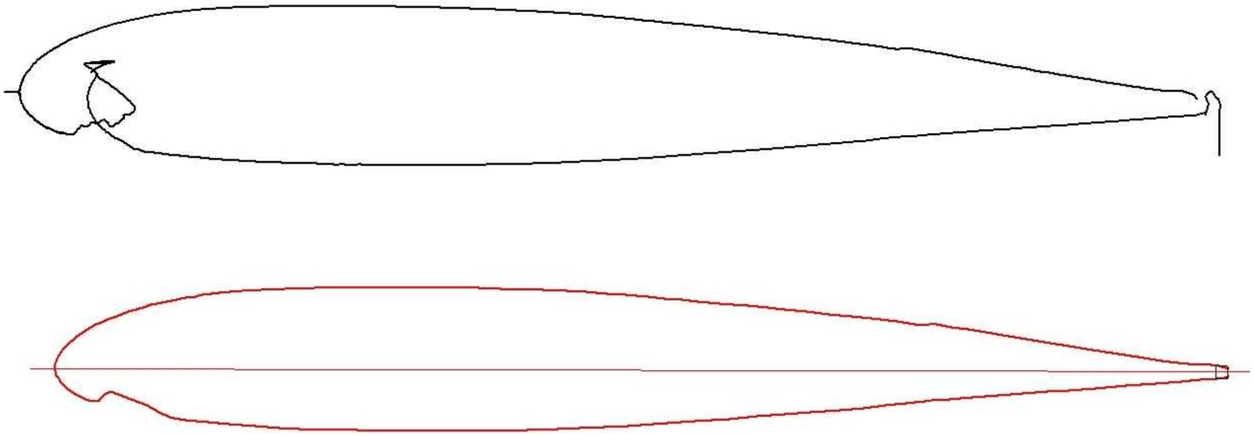
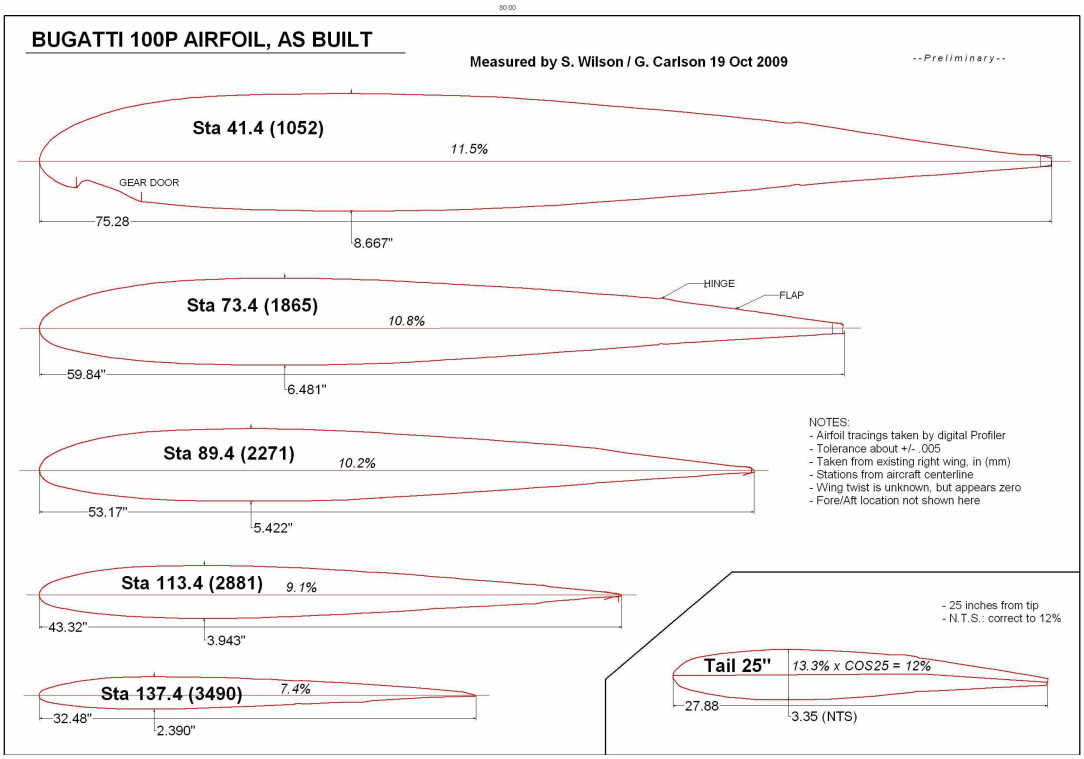


Figure 10 Complete Airfoil profiles showing open gear door, hinges, flaps and flaws.

The Bugatti 100P Airfoils

The Bugatti 100P wing employs a somewhat ordinary, if somewhat thin, airfoil, probably similar to a NACA 5 series. The airfoil appears similar out the length of the wing, but varies in thickness from root to tip from about 11.5% to 7.5%.



NOTES:
- Airfoil tracings taken by digital Profiler
- Tolerance about +/- .005
- Taken from existing right wing, in (mm)
- Stations from aircraft centerline
- Wing twist is unknown, but appears zero
- Fore/Aft location not shown here

- 25 inches from tip
- N.T.S.: correct to 12%

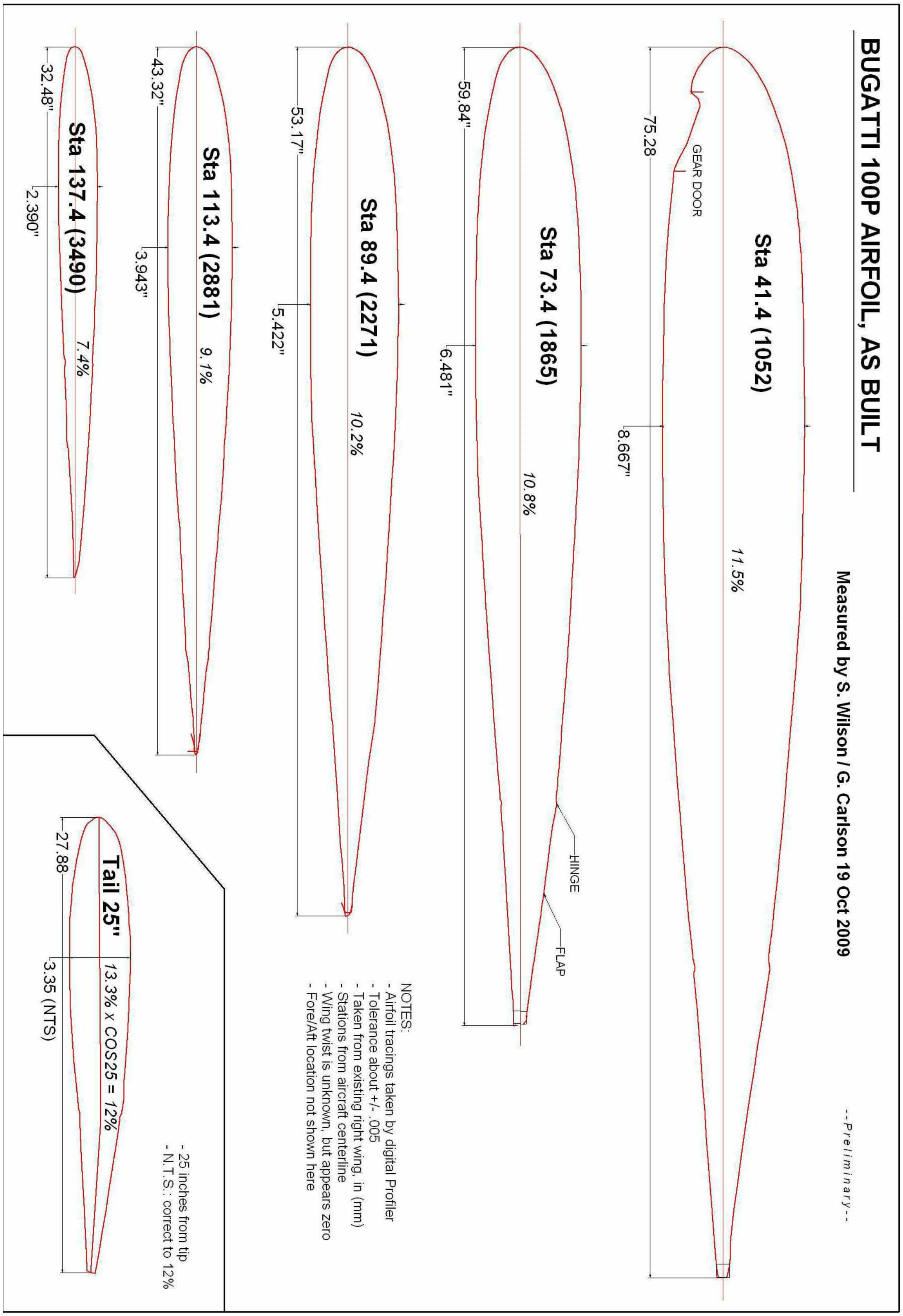
Figure 11 The Bugatti 100P Airfoil.

The tail foil measurements are less reliable than those for the wing due to errors and difficulties in arranging the apparatus at the correct angles and measuring around the cooling openings and joining the top and bottom data sets. It is likely the tail section is actually 11%.

Bugatti 100P Airfoil Conclusion

The Bugatti 100P airfoil resembles those in the NACA 5-digit class, appearing similar to the NACA 23012 series airfoils. These airfoils were being developed independently on both sides of the Atlantic in the 1930s and would have been available to de Monge (as would Göttingen or other European naming conventions of the era). The 230xx airfoil series has a lower pitching moment and reduced trim drag when compared to earlier airfoils. And, while they do have higher lift coefficients than do the earlier airfoils, their stall characteristics are more abrupt.

Appendix A The Bugatti 100P Airfoils



Note: Due to measurement difficulties in data collection, the tail foil is more likely to be 11%.