

Technology Innovations in World War I Airplane Design

Scott Eberhardt
Independent Consultant

ABSTRACT

World War I began with the airplane as a frail, unarmed means of observing enemy troop movements and ended with the airplane as a powerful, much more evolved weapon of war. There were specialized roles for fighter, bomber and ground attack aircraft as well as newly developed aerial strategies and tactics for operational effectiveness.

Many aircraft design technologies greatly matured during the war. Four will be the subject of this paper: Drag reduction, aircraft handling qualities, stability and control, airfoil design technology, and structures design technology. Propulsion and armament also matured greatly but are not discussed in the paper.

The discussion of drag reduction will illustrate the innovations of the British on external wire bracing drag, the French on cowl design and the Germans on cantilevered wings and induced drag. Control surfaces and handling will show the invention of balanced controls, and the use of the equations of motion to design specific handling properties, as illustrated in several aircraft. Wind tunnel data of the Fokker Eindecker will be shown. Airfoil technology will discuss the innovations utilized by the Germans, which resulted in thick airfoils, allowing for internal, cantilevered structures. Finally, the welding techniques of Fokker's technicians to the all-metal aircraft of Hugo Junkers, will be used to illustrate the advancement of metal construction.

CITATION: Eberhardt, S., "Technology Innovations in World War I Airplane Design," *SAE Int. J. Aerosp.* 8(2):2015, doi:10.4271/2015-01-2581.

INTRODUCTION

One hundred years ago, in 1915 Anthony Fokker, using a 1913 patent of Franz Schneider, designed an interrupter gear for his Eindeckers (monoplanes), after the Germans captured Roland Garros and his bullet-deflector-equipped airplane. The otherwise inferior Eindecker E.III gained dominance in the skies for a period lasting from August 1915 to June 1916, a period known as the "Fokker Scourge." A lasting consequence of this period was the rapid technological innovations that one sees throughout the war as discussed in this paper.

There are many ways the First World War contributed to the advancement of aviation. Limiting to manageable topics is, in itself, a difficult task. In this paper, we use retrospective engineering analysis to take a new look into fighters of the Great War. First, we look at drag and drag reduction. In many ways, at the start of the war, drag reduction was an intuitive art. During the war, there was much research into reducing drag on well-known drag producers, such as wires and struts. A discussion of some of the methods of drag reduction and a drag buildup of an Eindecker E.III, to compare the drag of various components, is included.

As fighters gained recognition, their stability, control and handling characteristics become more important. Using two wind tunnel tests and computer simulations, linearized models of four WWI fighters will be presented. A discussion of the results will confirm some of the handling characteristics observed by the pilots of the time.

The next discussion will be on the evolution of airfoil technology. This played a key role in the superiority of the German fighters in late 1917 and early 1918, as well as laid the groundwork for the aircraft of the 1920's. Comparisons of several airfoils of the time will show the advantages achieved when more was understood about airfoils in the flight regime of the time.

Finally, a discussion will cover the innovative use of metals toward the end of the war. Early aircraft were built of wood and fabric. As welding methods and metal alloys improved, metal became a plausible airplane building material.

This list of innovations in the period of 1914 to 1918 is just four of many. The authors thought these four topics were among the top contributions toward aircraft design engineering innovation in the Great War.

DRAG REDUCTION

The effects of drag were well understood early on, but the way each designer went about reducing it was different. The British worked on major drag reduction campaigns, which perhaps were somewhat misguided because they involved streamlining the external wire bracing. It is interesting to note that, while Frederick William Lanchester is credited with inferring the beneficial effects of high aspect ratios, it was the Germans with the work of Ludwig Prandtl who really exploited higher aspect ratios to reduce induced drag in fighters. One of the biggest innovations was the discovery that thicker airfoils could be used without sacrificing form drag, which is discussed later in this paper. The consequence of this discovery was the development of cantilevered wings, seen early on the Fokker Dr.1 Triplane and the Fokker D.VII. External bracing and wiring, which the British were carefully studying became unnecessary.

The photo in [Figure 1](#) shows the streamlined wiring on a SE5a, and the cantilevered wing of the Fokker D.VIII is shown in [Figure 2](#).



Figure 1. RAF SE5a wire bracing, photo by Scott Eberhardt.



Figure 2. Fokker D.VIII, photo courtesy of Heath Moffet and the Museum of Flight.

Another notable difference was the treatment of the cowls. The SPAD, for example in [Figure 3](#), had a well streamlined cowl and radiator integration, which may have compensated for much

aerodynamic drag due to external bracing, reverse taper, and lower wing aspect ratio. This is in stark contrast to the cowls of other aircraft, most notably the RAF SE5a, shown in [Figure 4](#).

A drag buildup was performed on a Fokker Eindecker E.III to see the relative drag contributions of various parts of the airplane. The buildup was performed using methods outlined in (Hoerner 1993). The reason for this study was to understand the results from a wind tunnel test on the Eindecker E.III in 2005, reported in (Eberhardt 2006). [Figure 5](#) shows the Eindecker in the wind tunnel, [Figure 6](#) shows the drag polar from the tests and [Table 1](#) includes the breakdown of component drag.

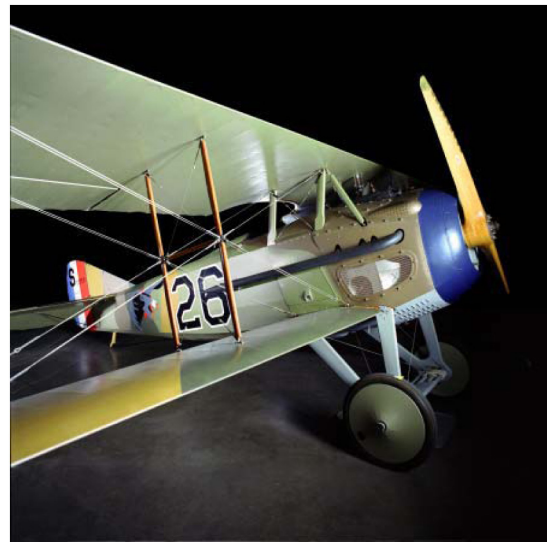


Figure 3. Spad XIII, photo by Heath Moffat and the Museum of Flight.



Figure 4. RAF SE5a, photo by Scott Eberhardt.

From the data in [Figure 6](#), C_{D0} was found to be 0.095. A NASA report (Loftin 1985) quotes a value of C_{D0} of 0.077 and was used in (S. Eberhardt 2005) to study fighter performance. Thus, a wide variation of C_{D0} is seen. The largest single drag contributor is the drag of the wires. It was observed visually in the wind tunnel that the wires bowed with the wind. That, plus Reynolds number effects on the wires, would likely be the greatest contributions to the mismatch of test data to flight data, or a drag buildup. Another possible contributor could be aeroelastic effects in the model that were not representative of the full scale aircraft.



Figure 5. Fokker E.III in Kirsten Wind Tunnel, photo by University of Washington Aeronautical Lab.

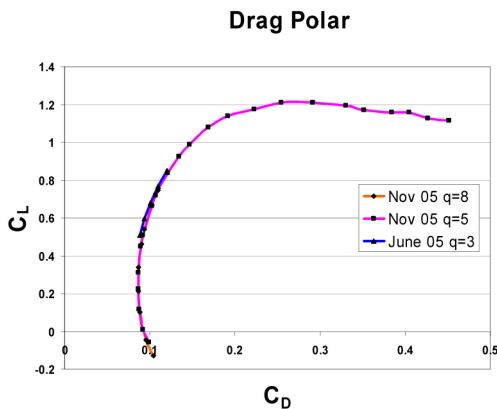


Figure 6. Drag polars from wind tunnel test (Eberhardt 2006).

Table 1. Drag buildup for Fokker Eindecker E.III.

Item	C_D
Wing	0.01120
Fuselage (Cowl, etc)	0.01607
Tail	0.00138
Wires	0.02316
Gear	0.01436
Cabane Struts/guns	0.01431
Escrescence	0.01431
Total	0.08586

Table 2 shows values of C_{D_0} from (Loftin 1985), which shows the high value of drag compared to even those of the DC-3 monoplane of the 1930s, with a C_{D_0} of 0.0249 (Anderson 2002, p. 200).

Table 2. C_{D_0} from (Loftin 1985).

Fighter	C_{D_0}
Fokker Eindecker E.III	0.0771
Fokker D.VII	0.0404
SPAD XIII C.1	0.0367
Sopwith F.1 Camel	0.0378

CONTROL SURFACES AND HANDLING

Lanchester experimented with free-flight gliders to develop ideas which are now considered the foundation of stability and control of airplanes. He published his works in 1907 and 1908. As early as 1911, George Hartley Bryan published the equations for six degree-of-freedom rigid model dynamics of an aircraft. Bryan's equations are the same equations engineers are familiar with today. However, in the early days of flight there was not an understanding of the components that were needed to fill the linearized equations. Nevertheless, WWI fighters such as the Sopwith Camel were designed using these equations and the best approximations and guesses of the day. The Camel was designed to be unstable to promote high maneuverability. As a consequence, the Camel was credited with the most victories of any WWI fighter and yet lost many of its pilots to landing and takeoff accidents, typically due to poor low speed handling characteristics (Robertson 1970).

A retrospective look at the stability, control and handling of sample WWI fighters was undertaken for this paper. Two German fighters, the Fokker Eindecker E.III and the Fokker D.VII were tested in the University of Washington Aeronautical Lab's Kirsten wind tunnel (UWAL) in 2005. These 1/4-scale models used moving control surfaces to pull out both lateral and longitudinal stability derivatives. The initial report on the tests was presented in (Eberhardt 2006). More detailed reports were presented at an AIAA student conference in 2006, but are not available for reference. A sample pitch plot of C_M - C_L is shown in Figure 7. These data were used to calibrate a stability and control, vortex-lattice code, Analytical Method's VLAERO+, which was then used to study four Fighters, the two Fokkers, the SPAD XIII and the Sopwith Camel.

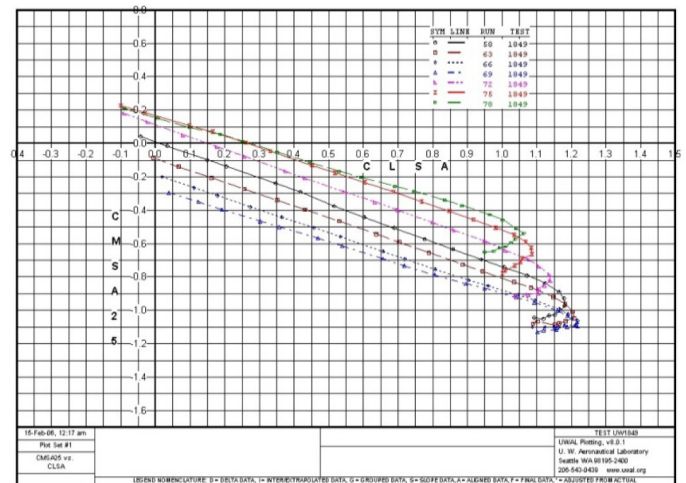


Figure 7. Pitch stability from Eindecker E.III wind tunnel test.

Two models were created for each aircraft, a longitudinal and a lateral model. Since vortex lattice is a linear model, only the linear range of the wind tunnel data was used, and this discussion will limit itself to only the linear stability and control regime.

Table 3 shows close longitudinal stability calibration results for C_L - α , C_M - α and C_M - C_L (per degree).



In each longitudinal model and a lateral case, the surfaces important to those axes are built into the model. Figure 8 and 9 show a longitudinal model for the Fokker D.VII and a lateral model for the Sopwith Camel, respectively. (Note that the longitudinal model is only a half-model, but is reflected about the centerline for visualization).

Table 3. UWAL linear slopes verses calibrated VLAERO+.

	Fokker D.VII		Fokker E.III	
	Tail Off		Tail On	
	UWAL	VLAERO+	UWAL	VLAERO+
$C_L-\alpha$	0.0724	0.0723	0.106	0.109
$C_M-\alpha$	0.0142	0.0140	-0.0151	-0.0118
C_M-C_L	0.196	0.197	-0.142	-0.108

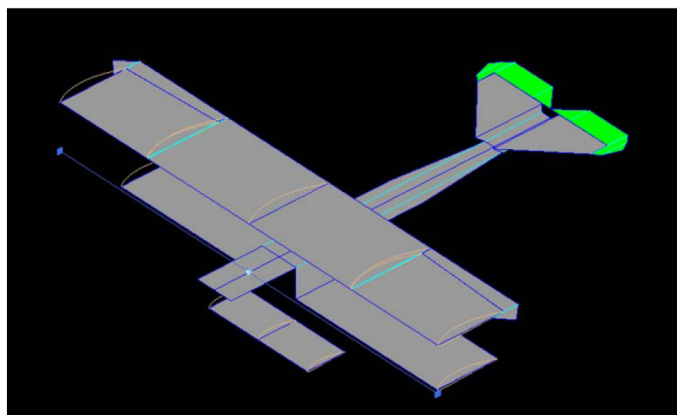


Figure 8. Longitudinal stability VLAERO+ model for Fokker D.VII.

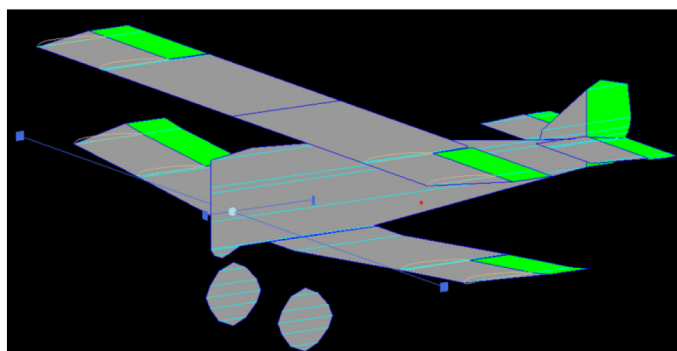


Figure 9. Lateral stability VLAERO+ model for Sopwith Camel.

Table 4 lists the some of the stability derivatives obtained from the VLAERO+ simulations. The next table, table 5, shows the damping in pitch, yaw and roll due to pitch rate, yaw rate and roll rate.

Table 4. Stability derivatives for VLAERO+.

	$\frac{dC_M}{d\delta_e}$	$\frac{dC_N}{d\beta}$ ($\times 10^{-2}$)	$\frac{dC_N}{d\delta_r}$ ($\times 10^{-2}$)	$\frac{dC_R}{d\delta_a}$ ($\times 10^{-2}$)
E.III	-0.026	0.060	0.847	-0.037*
D.VII	-0.019	0.025	0.078	-0.252
SPAD	-0.020	0.278	0.211	-0.537
CAMEL	-0.021	-0.347	0.558	-0.918
Cessna 172	-0.024	0.093	0.202	-0.561

*uses wing warping

Table 5. Rate damping derivatives for VLAERO+.

	$\frac{dC_M}{d\left(\frac{qc}{2V}\right)}$	$\frac{dC_N}{d\left(\frac{Rb}{2V}\right)}$	$\frac{dC_R}{d\left(\frac{Pb}{2V}\right)}$
E.III	-9.8	-0.058	-0.607
D.VII	-11.4	-0.063	-0.350
SPAD	-12.0	-0.183	-0.668
CAMEL	-12.6	-0.126	-0.766
Cessna 172	-12.7	-0.141	-0.517

Ideally, these stability derivatives could be used in a linear model simulation to study the dynamics of these airplanes, with some additional data. However, that is beyond the scope of this paper. This paper will discuss the relative effectiveness of the various controls. Note that the Fokker Eindecker E.III uses wing warping, instead of

aileron. The stability derivative, $\frac{dC_R}{d\delta_a}$, was obtained by building a lateral-model with $\pm 1^\circ$ of wing twist and taking the slope between that model and the baseline model.

The first thing to note is that elevator effectiveness is pretty even across all the aircraft. Bear in mind that this is only a linear analysis, and therefore does not include stall effects, which can dramatically change behavior at unusual attitudes. It is also noted that the pitch

rate damping, $\frac{dC_M}{d\left(\frac{qc}{2V}\right)}$, is also fairly even, with the exception of the Eindecker, which implies a high or workload in pitch for the pilot. A