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History of Key Technologies

Birth of Sweepback: Related Research at Luftfahrtforschungsanstalt—Germany

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"Be more attentive to new ideas from the research world."
George S. Schairer, former Vice President Research, Boeing (1989)

An extended historical review is given about German World War II scientific and industrial research on the beneficial effects of wing sweep on aircraft design by reducing transonic drag rise. The specific role of the former Luftfahrtforschungsanstalt (LFA), which was located in Braunschweig-Voelkenrode, is emphasized. Reference is given to LFA's partner research organization Aerodynamische Versuchsanstalt in Goettingen, the scientific birthplace of modern aerodynamics. Wind-tunnel facilities at LFA, which were taken out of existence after World War II, are illustrated. Advanced missile research and aircraft support projects at LFA are illuminated. Further, the postwar technical know-how transfer and its implementation to U.S. and other international aircraft projects is highlighted together with contributions of some former German researchers to the advances of aeronautics.

Introduction and Beginnings

LOOKING back over the 110 years that have passed since the Otto Lilienthal brothers' aerodynamic model experiments yielded the world's first manned glider flights at Berlin-Lichterfelde (1891), and reflecting the first centenary since the Wright brothers' wind-tunnel model tests resulted in the historic manned powered flights at Kitty Hawk (1903), we also recall that there was another important event in year 2000, that is, the 125th anniversary of Ludwig Prandtl's birth. It seems appropriate to present some short reflections about Ludwig Prandtl. As Theodore von Kármán, a former student of Prandtl, stated, Prandtl was a "great master in combining simple mathematical formulation and clear physical understanding in solving problems important for technical applications,"[1] and "he was the leading genius in the early development of modern aerodynamics."[2] Prandtl is generally accepted to be the father of modern fluid dynamics.[3–5]

The history of swept-wing design and its benefits for reducing compressibility effects and transonic in drag is well documented and referenced.[6–10]

Early studies describing the benefits of wing sweep delaying Mach drag divergence while concurrently weakening oblique shock waves for high-speed flight gained significant attention in the late 1930s and early 1940s when it became apparent that power plants and aircraft design requirements were approaching rapidly the transonic Mach numbers. The unloading characteristics of a swept wing, which tends to minimize gust loads, is a further dividend.

During the 1935 Volta congress on High Speeds in Aviation, Adolf Busemann, also a Prandtl student, presented in his paper on aerodynamic lift at supersonic speeds for the first time an arrow-wing configuration[11] (Fig. 1). Since 1939, Prandtl's closest associate A. Betz and the young H. Ludwieg were the leading aerodynamicists at the Aerodynamische Versuchsanstalt (AVA) in Goettingen, who established systematic wind-tunnel tests to generate a world-first database for future transonic aircraft configurations with wing sweep[7,12] (Figs. 2a and 2b).

Complementary swept-wing model wind-tunnel tests were successively accomplished at Luftfahrtforschungsanstalt (LFA) in Braunschweig-Voelkenrode (Fig. 3) and Deutsche Versuchsanstalt für Luftfahrt (DVL) in Berlin. Further, systematic research on the effect of wing sweep on wing-body interference was undertaken by Hermann Schlichting at the Braunschweig Institute of Technology. A Schlichting report, which was originally published in February 1945, was seven years later translated and published as a NACA Technical Memorandum.[13] Figure 3 has been drawn from this report, and it can be realized that wind-tunnel sweepback and sweep-forward configuration measurements were already accomplished by the Braunschweig University in the early 1940s.

Luftfahrtforschungsanstalt

In the following, the most spectacular Second World War (WWII) research activities at the German research establishment LFA will be illuminated (Blenk, H., "Geschichte des Instituts für Aerodynamik der LFA," unpublished monograph, 1945).[14,15]

LFA occupied an area of about four square miles, including an airfield, and the majority of the buildings were hidden in woods or intelligently camouflaged (Fig. 4). The precise location of the establishment in Voelkenrode near the city of Braunschweig was not discovered by the Allies during the war. By 1945 LFA was one of the most magnificent aeronautical research establishments of the world.

The construction of the research institutes and laboratories commenced in 1935. LFA was declared operational in 1936, and Prandtl's former student Hermann Blenk was assigned on scientific grounds to become the first and only director of the LFA (1936–1945; Fig. 5). Blenk was also the refounder of the German Aerospace Society DGLR after WWII. Since 1936, Busemann continued his scientific work at LFA on high-speed aerodynamics and gasdynamics and the beneficial effects of wing sweep on stability and control, and since 1937 he was in close contact about this subject with A. Betz of the AVA in Goettingen yielding a common patent on the idea of sweepback for reducing drag and improving flight control issues at high subsonic speeds. In 1938 he again advocated the potential of wing sweep in order to maintain at least partially the favorable aerodynamic and flight mechanic properties of wings at lower speeds.[16] Since 1940, Busemann was visited by leading industrial

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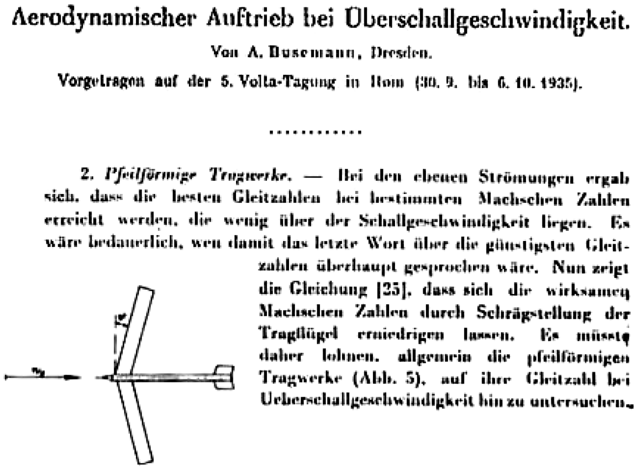


Aerodynamischer Auftrieb bei Überschallgeschwindigkeit.

Von A. Busemann, Dresden.

Vorgetragen auf der 5. Volta-Tagung in Rom (30. 9. bis 6. 10. 1935).

....

2. *Pfeilförmige Tragwerke.* — Bei den ebenen Strömungen ergab sich, dass die besten Gleitzahlen bei bestimmten Machschen Zahlen erreicht werden, die wenig über der Schallgeschwindigkeit liegen. Es wäre bedauerlich, wen damit das letzte Wort über die günstigsten Gleitzahlen überhaupt gesprochen wäre. Nun zeigt die Gleichung [25], dass sich die wirksamen Machschen Zahlen durch Schrägstellung der Tragflügel erniedrigen lassen. Es müsste daher lohnen, allgemein die pfeilförmigen Tragwerke (Abb. 5), auf ihre Gleitzahl bei Ueberschallgeschwindigkeit hin zu untersuchen.

Fig. 1 First publication on the effects of wing sweep.[11]

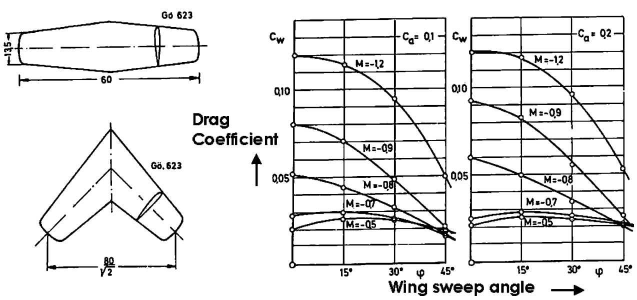


Fig. 2a Early wind-tunnel test results on the effects of wing sweep (AVA 1940).[9]

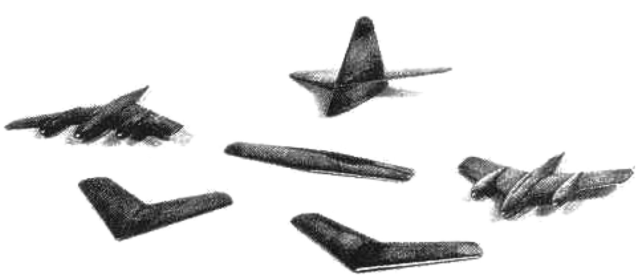


Fig. 2b Early swept-wing wind-tunnel models (AVA 1940).[12]

aerodynamicists at LFA who picked up the idea of sweepback and initialized more wind-tunnel data bases at AVA, LFA, and DVL.

By 1945 the entire German aircraft industry had a multitude of experimental swept-wing aircraft and missile designs in a final realization phase. Also, a Me 262 had been retrofitted with a 35-deg arrow wing and was ready for first flight. A further version (Me 262 HG II) with 45-deg sweepback was under final construction at the end of WWII. The first true industry project utilizing an aft-swept-wing concept was the P 1101 designed by Messerschmitt in 1944/45 (Ref. 6).

Aeronautical research in Germany was directed by the German Air Ministry Reichsluftfahrt-ministerium (RLM), which set up an advisory board headed by A. Baeumker and three leading scientists, that is, L. Prandtl, A. Seewald, and W. Georgii. Direct liaison and cooperation between the aeronautical research establishments such as LFA and AVA and the German Air Ministry RLM and the German Luftwaffe was practically nonexistent.[15]

Although LFA was later entitled by the Nazi government "Hermann Goering Aeronautical Research Establishment" Hitler's paladine Goering never visited "his" research organization, he only went to the Braunschweig forests for hunting in his national responsibility as Reichsjaegermeister.

From the rare Fig. 6 it can be anticipated how leading scientists such as Blenk and Busemann had to welcome so-called Nazi subordinates dubbed fruit salad holders ("Lametta-Träger"), which refers

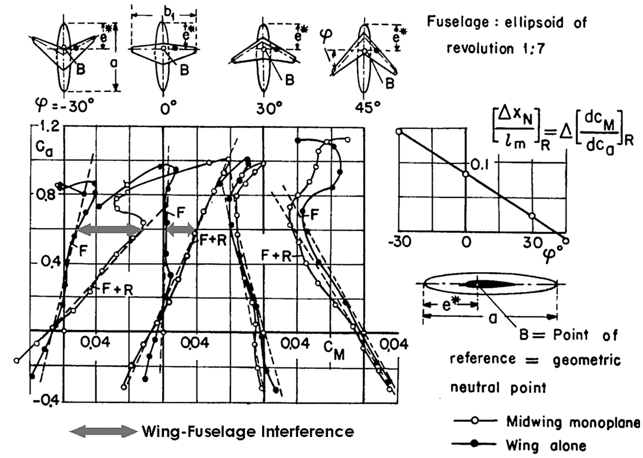


Fig. 3 Wing sweep and interference effects.[13]

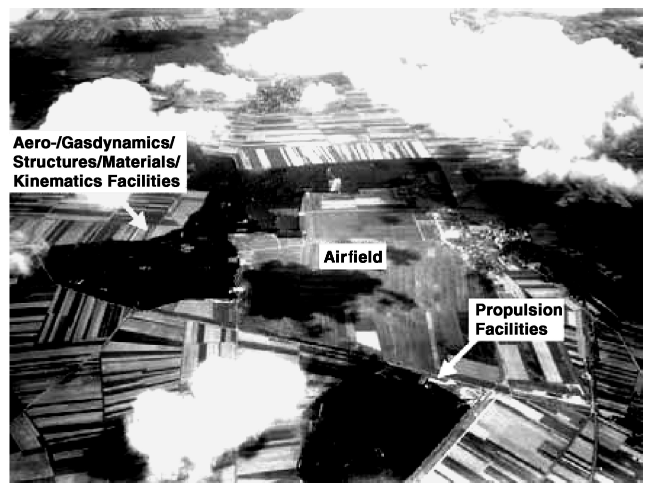


Fig. 4 LFA Braunschweig (1936–1945).

Fig. 5 Prandtl (left) and Blenk aboard Hapag ship "New York" returning from United States (1938).

to highly decorated officers who had seen little or no combat, on one of their rare visits to the scientific community of LFA.

LFA was divided into four leading research institutes (aerodynamics, structures and materials, engine research, and weapon research), and several workshops and service buildings—in total about 60 buildings. About 1500 persons were employed; of this 150 were university graduates, and only an admiringly low number of 70 employees were associated with administration.

In the following only selected aerodynamic and flight control problems and related wind-tunnel test activities at low and high subsonic speeds will be reviewed and discussed. In 1945 there were

Fig. 6 Blenk (right) and Busemann awaiting official "medal service" holders.

Fig. 7 Hidden locations of two important LFA wind tunnels.

at least eight subsonic, transonic, and supersonic wind tunnels in operation or in calibration phases for basic and applied research as well as for industrial research and project support. Three of these facilities (A-1, A-2, A-3) played a major role for these purposes (Blenk, H., "Geschichte des Instituts für Aerodynamik der LFA," unpublished monograph, 1945):

1) A-1—speed: 55 m/s; test section: 2.5 m$^{\varnothing}$.
2) A-2—speed: 300 m/s; test section: 2.8 m$^{\varnothing}$.
3) A-3—speed: 95 m/s; test section: 8.0 m$^{\varnothing}$.

The A-1 low-speed wind tunnel facility was mainly operated for LFA's basic and applied vehicle research requirements. Important long-term basic research included measurements of lift, drag, pitching moment, and control hinge moments at very small angle of attack and control angle increments. Also, laminar-flow airfoils were investigated.

Applied vehicle research included the Hecht air-to-ground research missile and the Feuerlilie ground-to-air defense missile. The Hecht program was originally developed at LFA, not for military purposes but for flight research at transonic Mach numbers ($M \sim 1.3$). For more pictorial details about these missiles programs, see the next section. Industrial measurements included tests of the BV 141 asymmetric aircraft and miscellaneous wings with sweepback and sweep forward.

Mach numbers of 0.82 with model were obtainable in the high-subsonic-speed wind tunnel A-2 (Fig. 7). The Argus-pulse-jet engine of the Fi-103 (V-1) flying bomb was developed in this test facility (Blenk, H., "Geschichte des Instituts für Aerodynamik der LFA," unpublished monograph, 1945).[15]

Remarkable early high-subsonic wind-tunnel test results were achieved by Th. Zobel in A-2 (Fig. 7). Impressive drag rise delays were measured at a body of revolution by extreme aft shifting of the maximum thickness,[17] which was becoming important for the design of jet and pulse-jet engine nacelles of high-speed aircraft (Fig. 8). This was in a general sense also a first step into the direction, which was 20 years later taken for the design of so-called supercritical configurations.

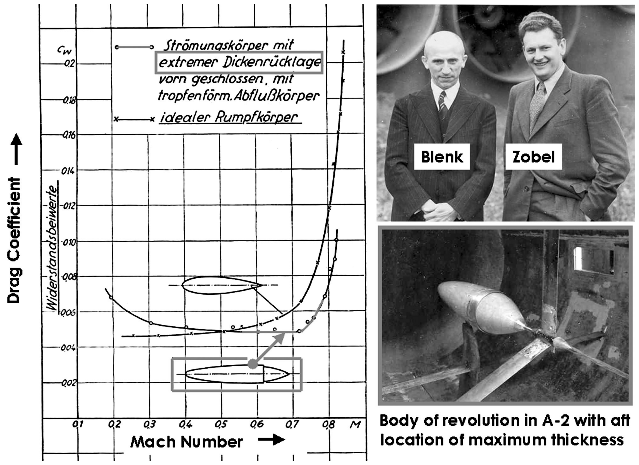


Fig. 8 Drag rise delay as a result of rearward location of maximum thickness.

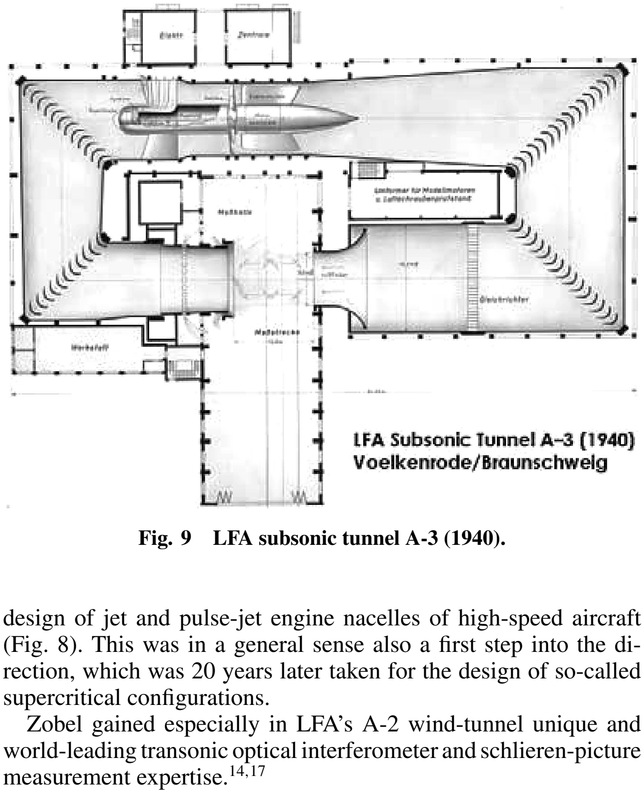


Fig. 9 LFA subsonic tunnel A-3 (1940).

Zobel gained especially in LFA's A-2 wind-tunnel unique and world-leading transonic optical interferometer and schlieren-picture measurement expertise.[14,17]

Considerable work has been done on winged missiles including a complete Fi-103 (V-1) flying bomb with the Argus-ramjet engine operating (see later section). Also, stability and control tests of submarine models and full-size torpedos with and without power were tested in A-3.

In the large 8-m-diam open-jet wind tunnel A-3 90% of the work was accomplished for industry including running piston and jet engines from firms like BMW and Junkers. Various Junkers flutter models made from innovative Vinidur plastic material were investigated. Systematic series of tests on the effect of wing aft and forward sweep were undertaken. Special Ju-287-type model tests in this respect will be discussed in a later section of this paper.

Layout and dimensions of the impressive large A-3 wind-tunnel facility can be drawn from Fig. 9. Construction of the tunnel was entirely in reinforced concrete with the reinforcing steel intersecting to form a web. The tunnel was very elaborately camouflaged. Trees, bushes, and long grass were located around A-3 and on top (Fig. 7).

In fall 1948 all LFA wind tunnels including A-2 and A-3 were cannibalized and destroyed by order of the British military government in Germany (Fig. 10).

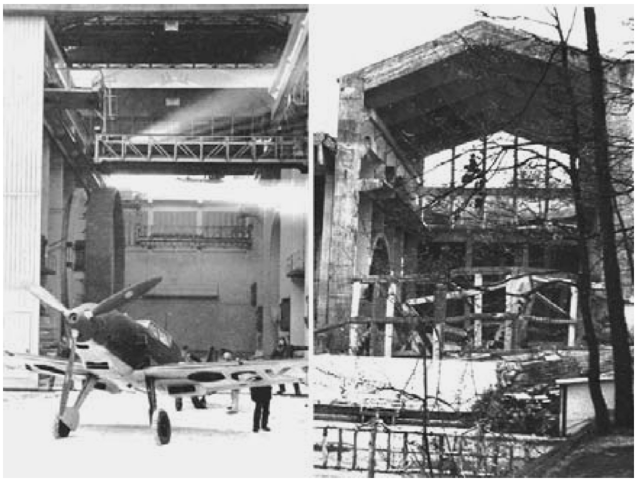


Fig. 10 Wind-tunnel facility A-3 before and after demolition by British authorities (1948).

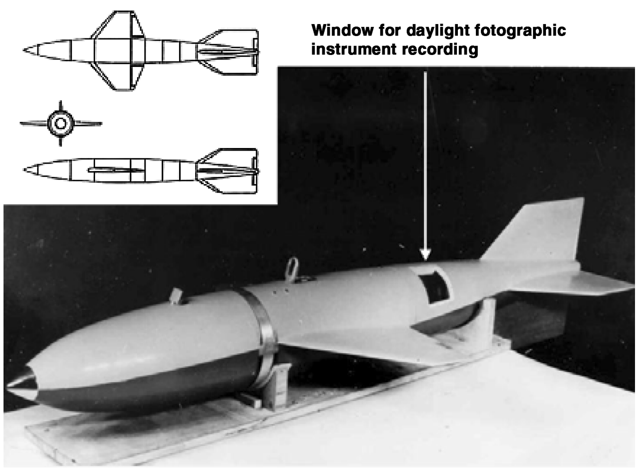


Fig. 11 Drop model of Hecht AGM (1940).

Many parts of the LFA wind tunnels including Busemann's transonic A-9a/b wind-tunnel facility were dismantled, removed, and reerected at the Bedford Wind Tunnel Site in the United Kingdom (Operation "Surgeon").[18] The demolition of these research facilities that were originally dedicated to basic aeronautical research and that could have been utilized in the future for civil purposes was rated by H. Blenk in 1948 as barbarism.

Applied Vehicle Research at LFA

Applied flight vehicle research was performed at LFA mainly in the fields of remotely controlled air-to-ground (AGM) and surface-to-air missiles (SAM). Three main independent research projects—partially supported by Rheinmetall-Borsig, Messerschmitt, and the Walter-Company–were undertaken.[19]

The AGM-Hecht-research project (Figs. 11 and 12) had extreme short-span wings for internal store carriage. The main objective was to test and evaluate flight guidance and stability and control problems associated with gliding bombs to be used as antiship missiles. Subsonic speeds up to 280 m/s and maximum ranges of 8 km were envisaged. The challenge for LFA was to generate and correlate wind-tunnel and flight-test databases. Because of high wing loading of the short-span wings, it was evident that roll stability of the missile must be artificially accomplished by an autostabilizer that also would minimize lateral roll-yaw coupling. Mechanically tuned roll attitude and rate gyros mounted in the forward fuselage provided adequate signals for an electromagnetic bang-bang controller switched to the ailerons.

The control system was tested in A-3. Flight-path tracking during drop tests was arranged by cine-theodolites, whereas onboard measurements included 8-mm-cine-camera filming of airspeed, sideslip, pitch attitude, acceleration instruments, and elevator and aileron deflection readings. The required filming light intensity was provided by a small window hatch in the upper-aft fuselage (Fig. 11). The data were used to reconstruct via paper and pencil the flight path and to estimate the lift-and-drag time histories of the Hecht missile (G. Braun).

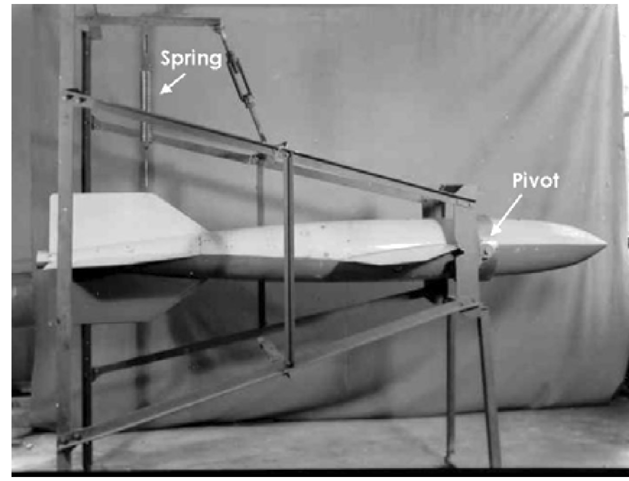


Fig. 12 Dynamic test rig for Hecht AGM.

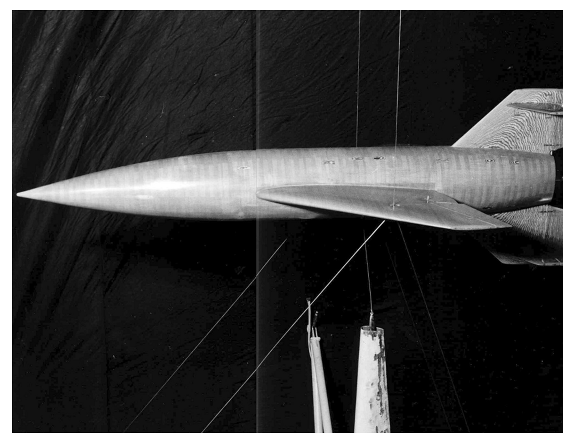


Fig. 13 Research SAM Feuerlilie F-25 in A-1.

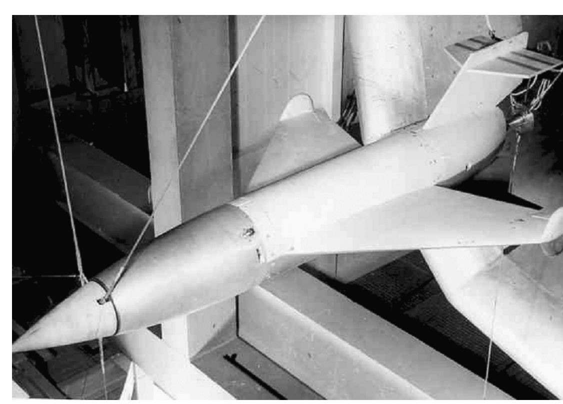


Fig. 14 Research SAM Feuerlilie F-25 with RI 502 rocket in A-1.

Similar approaches of LFA's methods of roll-autostabilizer design and flight-path reconstruction were applied during the Henschel Hs 293 glide bomb development and test evaluation phase. A full-scale Hecht drop test was conducted at Peenemuende-West on 9 April 1943 with partial success. Further tests were cancelled in favor of the SAM research program Feuerlilie.

The Feuerlilie F-25 (subsonic, Figs. 13 and 14) and F-55 (supersonic, Figs. 15 and 16) incorporated newest swept-wing design

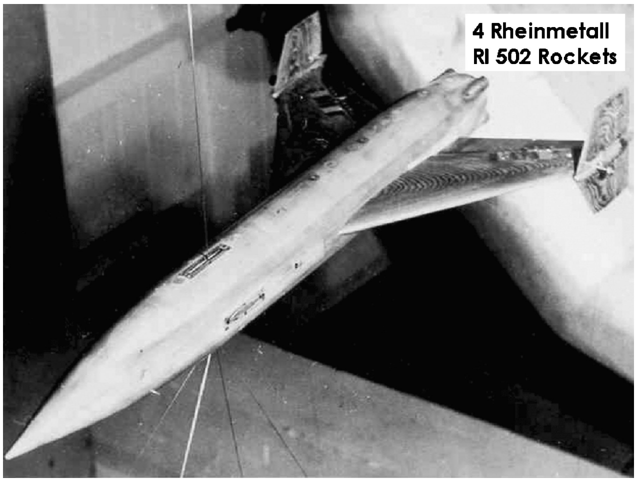


Fig. 15 Research SAM Feuerlilie F-55 in A-1.

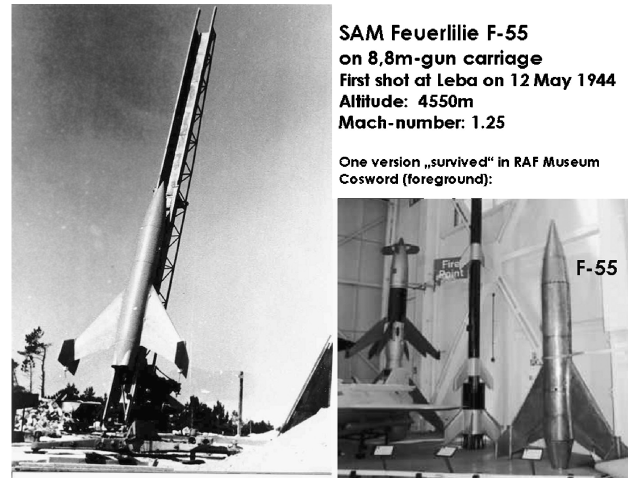


Fig. 17 Research SAM Feuerlilie F-55.

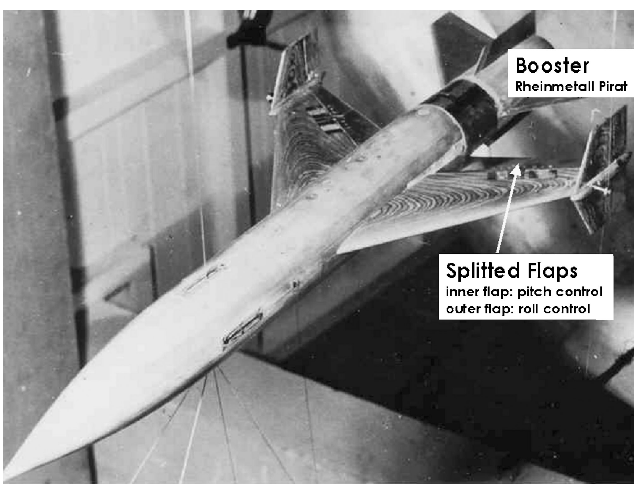


Fig. 16 Boostered SAM Feuerlilie F-55 in A-1.

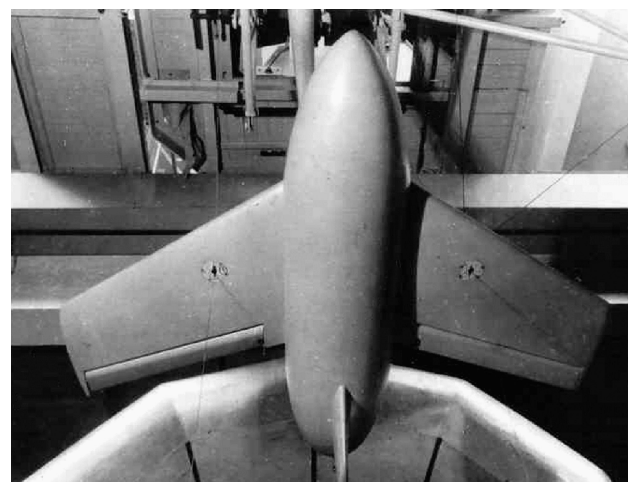


Fig. 18 Model of Enzian SAM in LFA A-3 (control surface effectiveness experiments, 1944).

features. All aerodynamic data were gathered in the A-1 subsonic ($2{,}5^{\varnothing}$m, 55 m/s) and partially in the A-2 high subsonic ($2{,}8^{\varnothing}$m, 300 m/s) wind tunnel. The objective of LFA's Feuerlilie research program was to generate and correlate wind-tunnel and flight-test databases of aerodynamic and stability and control parameter at high subsonic and transonic speeds for future high-speed aircraft and guided missiles with swept-back wings. A. Busemann and G. Braun were the main designers of a swept wing research missile with wing-mounted pitch-and-roll control surfaces. An automatic pilot was developed by A. Kerris for vertical plane flight path control.

Feuerlilie F-25 had a cylindrical body of 25 cm diam and a pointed nose and two vertical fin surfaces (dorsal and ventral) without rudders. Two horizontal stabilizers were mounted on the vertical fins, the upper surface fitted with an adjustable elevator, which was preset before launching (Fig. 13). Gyroscopic control of the wing-mounted ailerons was sufficient to minimize roll disturbances. Rheinmetall–Borsig valve-controlled rocket units (RI-502) provided constant takeoff thrust for 6 s (Fig. 14).

Feuerlilie F-55 had a tapered swept wing attached to the rear section of the fuselage, which had a 55 cm diam. The configuration was tailless. Small vertical surfaces were added to the wing tips for improved directional stability. Electromagnetic actuators for the outer-flap operation (aileron mode) were housed in wing-mounted streamlined fairings (Figs. 15 and 16).

The F-25 and F-55 flights were performed at various test sites and recorded with cine-theodolites. The analysis of the aerodynamic forces was carried out by G. Braun and correlated with A-1/A-2 wind-tunnel test data at LFA. The control commands were transmitted via high-frequency transmitters.

The first F-55 flight test at Leba was successful with a Mach-number range between 0.85 and 1.25 (Fig. 17). At Peenemuende-West a second F-55 test missile went out of control.

A historical analysis and critical appraisal of LFA's advanced missile research during WWII has been recently conducted by Krag.[20]

Industry Support at LFA

Industrial flight vehicle research at LFA was mainly supported by the three wind tunnels A-1, A-2, and A-3 ($8^{\varnothing}$m, 95 m/s). Specific A-3 project support was concerned with the guided missile SAM Enzian and aircraft projects such as He 162, Fi 103, BV 246, Ar 234, and Ju 287.

The SAM project Enzian incorporated a Me-163-type shape (Figs. 18 and 19) and could be considered as a cheap and scaled-down subsonic pilotless version of the Me-163 interceptor. The 30-deg swept-back wings had only two flight control surfaces, which were operated in symmetric and asymmetric (differential) modes by fuselage-mounted electric motors through simple rod transmissions. Four auxiliary takeoff rockets were mounted in pairs outside the fuselage and held in place by explosive bolts. Two symmetric vertical fins (ventral and dorsal) were attached to the fuselage.

The vehicle wings and fuselage were made of moulded plywood, which consisted of several layers of beach veneer pressed into the required shape. Also other wooden construction techniques were tried. The rocket nozzles were displaced by 30 deg so that the thrust axes passed through the center of gravity of the missile. Development began in June 1943, and various models were designed. LFA's wind-tunnel data confirmed the general layout and provided the

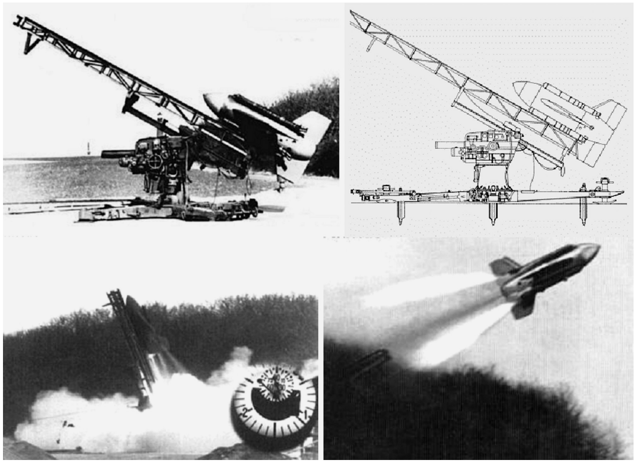


Fig. 19 Enzian SAM full-scale flight-test setup.

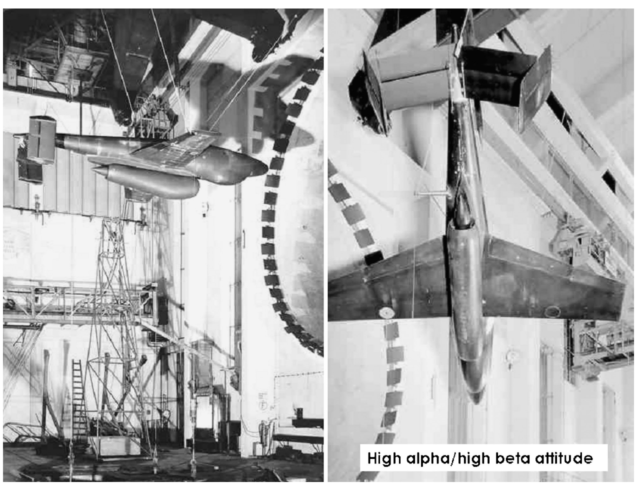


Fig. 20 $\frac{1}{3}$-scale He 162 model inverted in A-3.

design parameter for the very simple flight control system. Between April 1944 and January 1945, 38 Enzian configurations were flight tested at Peenemuende-West, some of them under radio control.[19]

Early in September 1944 a request was issued by the German Air Ministry for the design of a cheap and expandable jet fighter capable of 750 km/h and ready for production in January 1945! The Heinkel company responded with the He 162 Salamander project also dubbed "Volksjaeger." A twin vertical-fin configuration was constructed largely of wood with the jet engine mounted on top of the fuselage. First flight of the 7.2-m span aircraft took place only three months later (6 December 1944). Series production commenced in January 1945. By the time WWII ended, some 300 had been built. Mainly because of fuel shortage, only a very few operational sorties could be flown until the German Nazi regime collapse.

Complementary $\frac{1}{3}$-scale wind-tunnel model testing at LFA Braunschweig–Voelkenrode was arranged and monitored by company aerodynamicist X. Hafer from late 1944 until March 1945 (Fig. 20) (Hafer, X., Letter to P. Hamel, 3 Oct. 2002). A full-scale He 162 model was completed in March 1945, but it came too late for the development program. Flight identified low lateral stability characteristics of the high-wing configuration were compensated by downclipping the wing tips of the He 162 production version by 40 deg, for example, by reducing the static lateral stability derivative (dihedral effect, Fig. 21).

Because of urgent inquiries from Peenemuende, LFA was ordered on 19 June 1942 to test a full-size Argus pulse-jet engine of the Fi 103 flying bomb in the A-2 high-speed wind tunnel. The tests indicated that the effective thrust went down to almost zero at velocities higher than 600 km/h. The whole Fi 103 project could have been a complete failure if Th. Zobel had not succeeded in aerodynamically improving the air intake by adding an entrance diffusor with a well-rounded

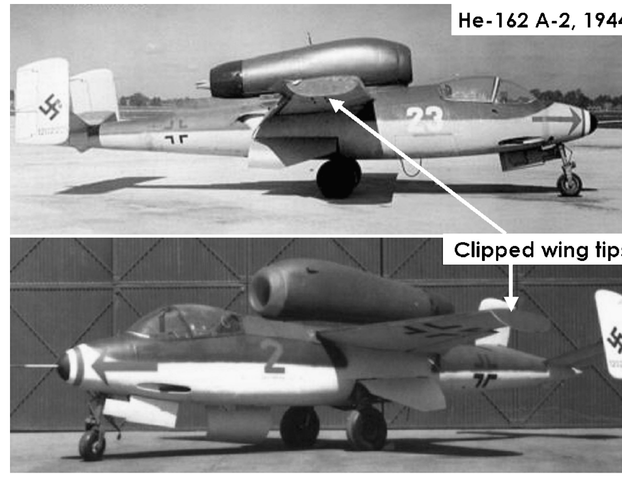


Fig. 21 He 162 A-2 production version.

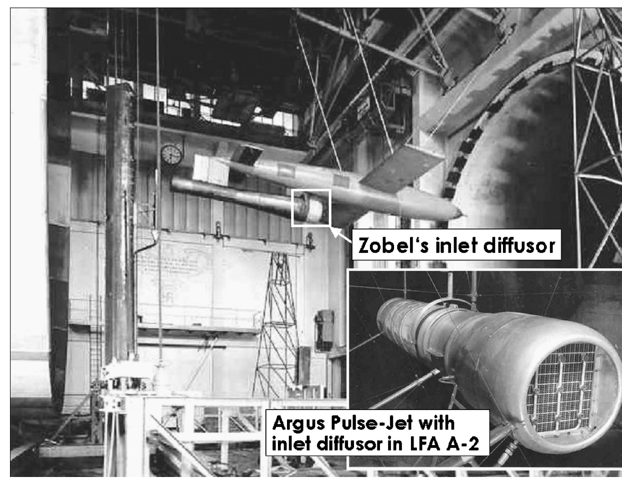


Fig. 22 Full-scale Fi 103 (V-1) in A-3.

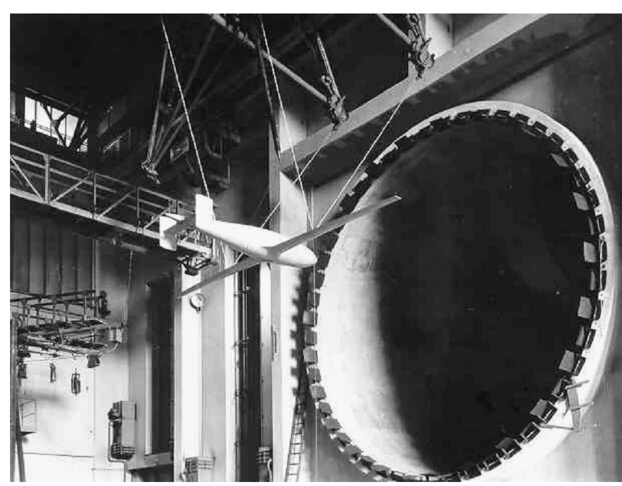


Fig. 23 BV 246 air-to-ground glide bomb in A-3.

mouth.[17] In cooperation with the Argus company, the engine inlet was finally altered, and a complete full-scale Fi 103 was tested in the A-3 with an operating engine (Fig. 22).

A special long-range gliding bomb with radio control to be coupled to the frequency of the Loran stations to be destroyed was projected by R. Vogt. The BV 246 Hagelkorn stand-off missile to be dropped from a high-altitude carrier aircraft had an exceptional good aerodynamic shape allowing gliding distances of 200 km. Aerodynamic testing in the A-3 wind tunnel revealed lift-to-drag ratios in the range of more than 20 and confirmed the aerodynamic quality of this configuration with about 6-m wing span (Fig. 23). Initial flight

Fig. 24 Ar 234 V-6 aircraft.

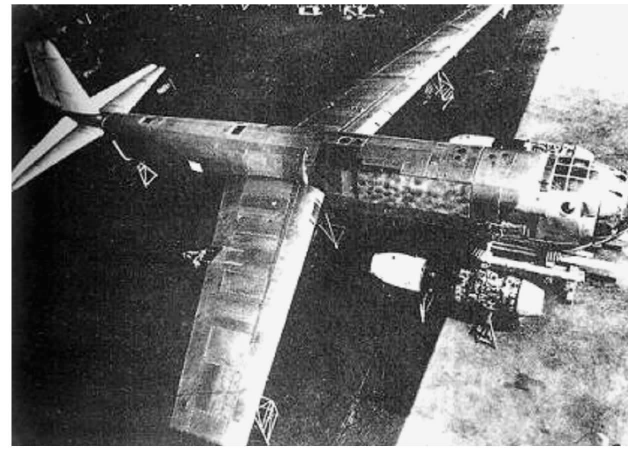


Fig. 26 Ju 287 V-1 during final assembly (1944).

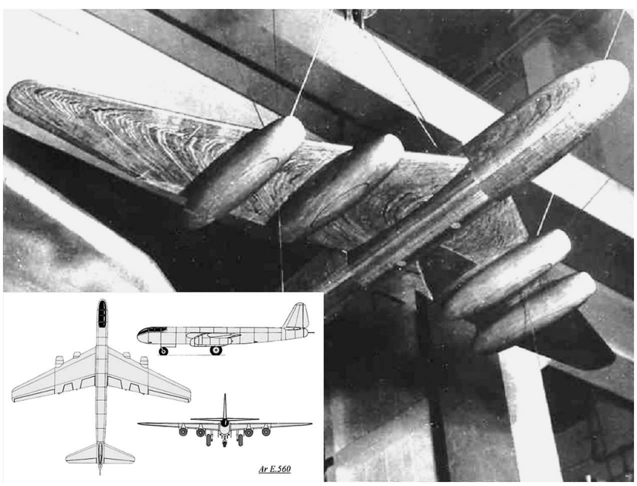


Fig. 25 Ar 234-V-6-type swept-wing model in A-3.

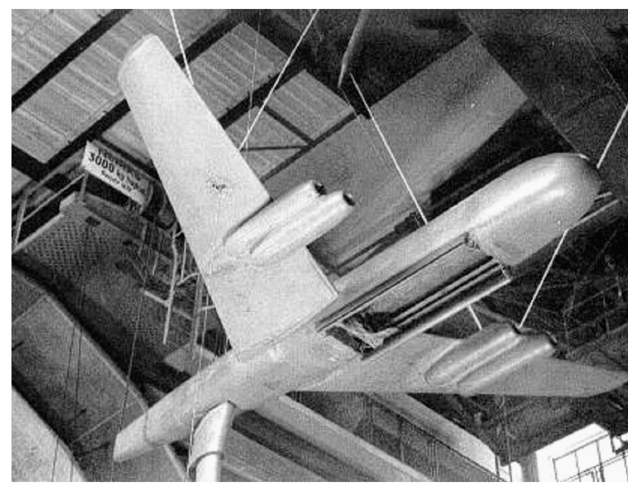


Fig. 27 Ju 287 FSW wind-tunnel model for pressure measurements in A-3.

tests in late 1944 indicated stability and control and autostabilizing problems resulting in unacceptable flight-path scattering. The project was finally cancelled.

A further A-3 wind-tunnel program was undertaken with a derivative of an Ar 234-type four-engine configuration as depicted in Fig. 24. By the time of 1943, the entire German aircraft industry had picked up the idea and benefits of swept-wing configuration, and it can be assumed that LFA had also investigated in their A-2 and A-3 wind tunnels drag rise delay and stability and control phenomena of four-engine Ar 234-type configuration with wing sweep (Fig. 25).

Challenging Junkers Ju 287

The Junkers Ju 287 with a forward swept wing (FSW) gets appropriate credit in this historical review. The performance increases caused by aft swept wings and jet engines were not easily blended in the overall transonic aircraft design. In moderately high-aspect-ratio swept-back wings, there is an outboard shift in aerodynamic span loading, which combined with an outflow of the boundary layer leads to wing-tip stall. Wing-tip stall results in nose-up pitch and undesirable wing drop. Several design techniques such as wing fences, leading-edge slots, and slats as well as vortex generators have been later installed to reduce wing-tip stall at low and at transonic speeds and to improve aileron control effectiveness at the wing tips.[21,22]

To alleviate the low-speed controllability problems of swept wings, the Junkers design bureau headed by Hans Wocke eventually decided to give a new aircraft project forward rather than aft-wing sweep.[23] Wing stalls caused by boundary-layer crossflow or shock-wave generation would very likely originate at the wing root and move outward rather than at the wing tip. On the other hand the FSW has a fundamental aeroelastic torsional divergence problem, that is to say, it bends under lift load and increases the angle of attack and the loads at the wing tip. Sometimes the deformation increases until the structural limits are exceeded.[22,24]

The Junkers swept-forward-wing aircraft prototype designated Ju 287 V1 (Fig. 26) was flown for the first time on 16 August 1944. Beforehand, wind-tunnel data on aerodynamic performance, controllability and aeroelastic divergence were gathered not only at the Junkers company in Dessau but also in the large subsonic wind-tunnel facility A-3 and high subsonic wind tunnel A-2 at LFA in Braunschweig during 1944/45 (Ref. 15; Blenk, H., "Geschichte des Instituts für Aerodynamik der LFA," unpublished monograph, 1945). From these LFA Ju 287-type aerodynamic and aeroelastic model tests only recently the author discovered a few photographic documents[24] (Figs. 27–29).

Further Ju 287 V1 flights (Fig. 30) until the armistice revealed increasing g loadings during tight turns without pilot inputs as a result of aeroelastic divergence tendencies and lateral-directional Dutch-roll-type flying qualities problems. Development and flight experiments were continued in the Soviet Union after World War II without a technical breakthrough.[25]

After World War II, H. Wocke again took up the swept-forward concept during the development of the corporate aircraft HFB-320 Hansa Jet, which took the air for the first flight on 21 April 1964 (Fig. 31, top right). Although only in limited series production, the HFB-320 aircraft had excellent handling qualities and provided 10 years later a most suitable host aircraft for the first fly-by-wire in-flight simulator at DLR Braunschweig.[26] About 20 years

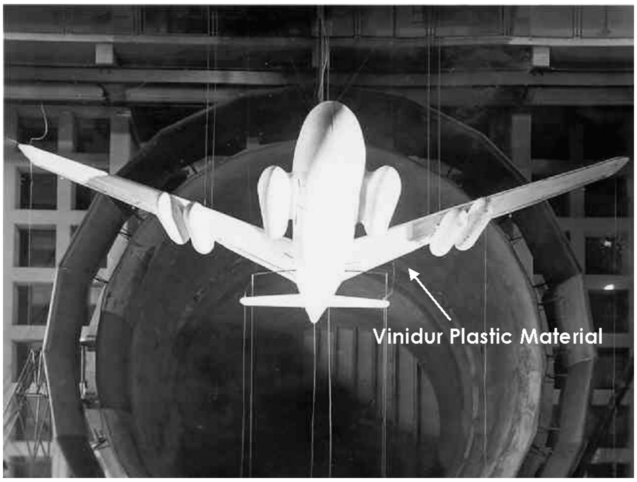


Fig. 28 Ju-287 FSW wind-tunnel model for flutter investigations in A-3.

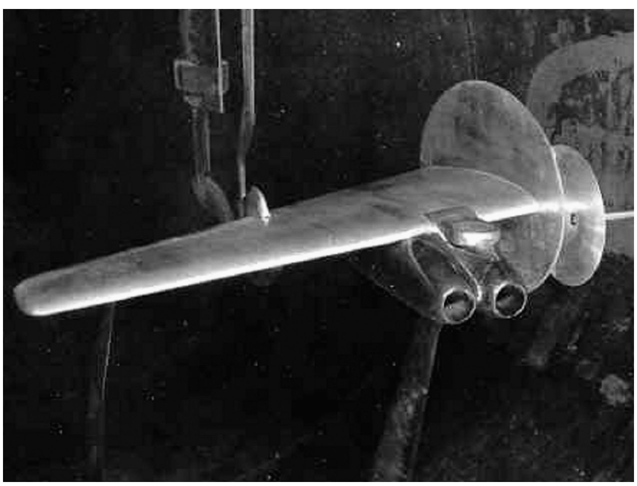


Fig. 29 Ju 287-type transonic half-model in A-2.

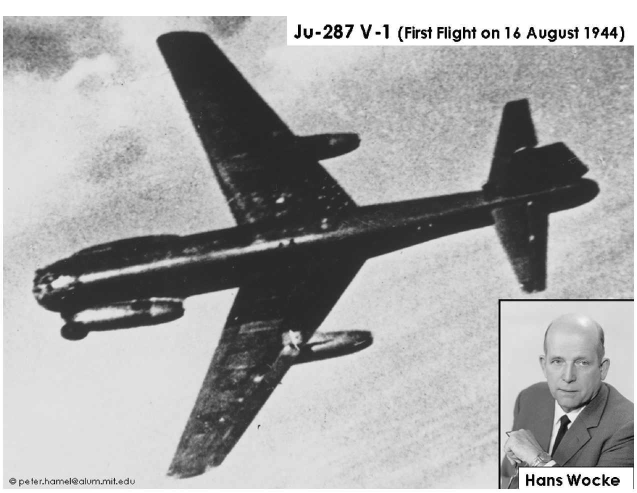


Fig. 30 Ju 287 V-1 FSW demonstrator vehicle.

later Grumman realized another swept-forward experimental aircraft configuration designated X-29 and embodying an innovative so-called aeroelastic-tailored composite wing. First flight was on 14 December 1984 (Fig. 31, bottom left[24]).

The former Soviet Union investigated the benefits and drawbacks of a metal swept-forward wing, which was flight tested on the Flying Laboratorium (LL-2) designed by Tsybin[25] as early as 1947/48. Fifty years later with the availability of composite structures in Russia, the Sukhoi S-37 Berkut began its flight-test program. First flight

Fig. 31 Unique FSW vehicles during 55 years.

Fig. 32 Interrogation of German scientists at LFA Braunschweig (May 1945) (© Hoffmann&Campe).

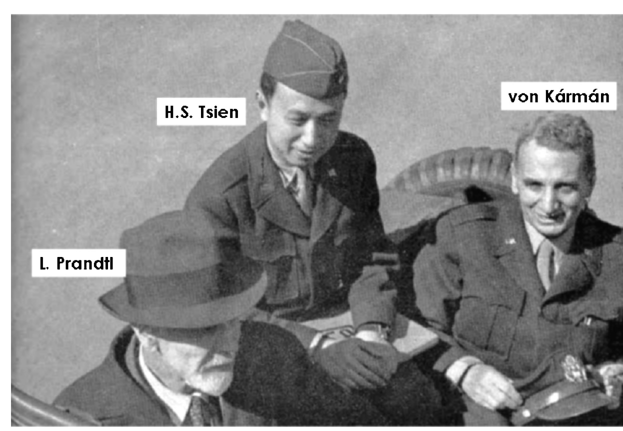


Fig. 33 Interrogation of von Kármán's former teacher Prandtl at AVA Goettingen (May 1945).

took place on 25 September 1997 (Ref. 25) (Fig. 31, bottom right). This aircraft project was later renamed Su-47.

Operation Lusty and Its Know-How Transfer

Since February 1945, Robert T. Jones from NACA had been actively looking for ways to increase the critical Mach number and independently predicted the drag-reducing properties of sweepback and the arrow wings.

In late April 1945 members of the U.S. Scientific Advisory Group headed by Th. von Kármán and assigned to the Commanding General H. H. ("Hap") Arnold of the Army Air Forces prepared to exploit the German Luftwaffe secret technology (Operation Lusty). On the day hostilities ceased in Europe, Th. von Kármán and members of the SAG team, H. Dryden, H. S. Tsien, G. Stever and besides others the Boeing chief aerodynamicist G. S. Schairer, were at LFA in Braunschweig—Voelkenrode (Figs. 32–34). The motivation and challenge for this advisory group was to directly talk to some key German scientific leaders rather than searching around and digging for drawings and data. First-hand information revealed the totality of the German scientific picture much easier.

Among the most surprising discoveries at LFA were high-speed wind-tunnel models with swept-back wings and unique associated masses of test data and documents in the library. It confirmed Jones' predictions as well as the outcome of Schairer's long discussions on the benefits of sweepback to solve the high drag problem with Tsien, which they had during their crossing of the Atlantic (Schairer, G. S., Letters to H. Schlichting, 4 Jan. 1978, 12 Dec. 1975)[6,27] and it caused Schairer's writing of an important letter to his Boeing parent company (Fig. 34).

Figure 33 implies a certain tragic element as it mirrors three generations of scientific excellency and idiosyncrasy: Th. von Kármán being escorted by his former teacher L. Prandtl and by his former student H. S. Tsien. Von Kármán was furious that Prandtl, his former professor and mentor of his youth, did not know about German war atrocities committed in the name of science. On the other hand von Kármán was unable and helpless to protect and prevent his one time best student and brilliant Caltech and MIT professor Tsien from political suspicion, five-year house arrest, and deportation from the United States in 1955. The immediate access to LFA and AVA know-how after WWII was crucial for the start of the first generation of military and civil swept-wing aircraft in the United States, such as B-47 (Fig. 35), F-86 (Fig. 36), B-52, B 707, DC 8, and other countries (Schairer, G. S., Letters to H. Schlichting, 4 Jan. 1968, 12 Dec. 1975).[8,27,28]

R. T. Jones' life-long complementary contributions to swept- and oblique-wing aerodynamics and pivoting-wing aircraft after WWII have been given proper attention by H. Mark,[29] W. R. Sears,[30] and J. D. Anderson.[10]

It was already stated that the first true industry project utilizing an aft-swept-wing concept was the P 1101 designed by Messerschmitt in 1944/45 (Ref. 6). After the availability of German captured wind-tunnel test data and industrial design details, direct derivatives of this configuration were developed in the United States at Bell[23] (X-5) and in Sweden at SAAB (J-29) with the expertise of former

Fig. 35 First operational U.S. swept-wing bomber.

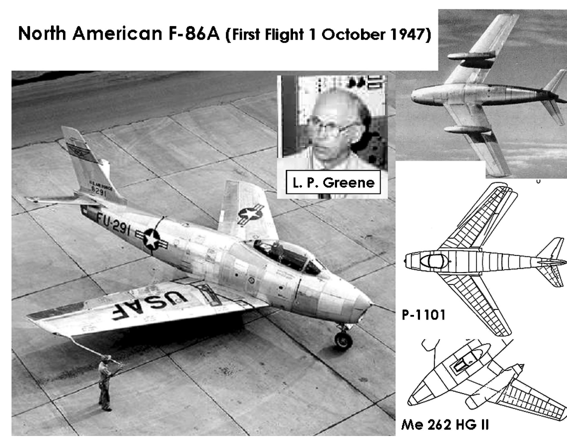
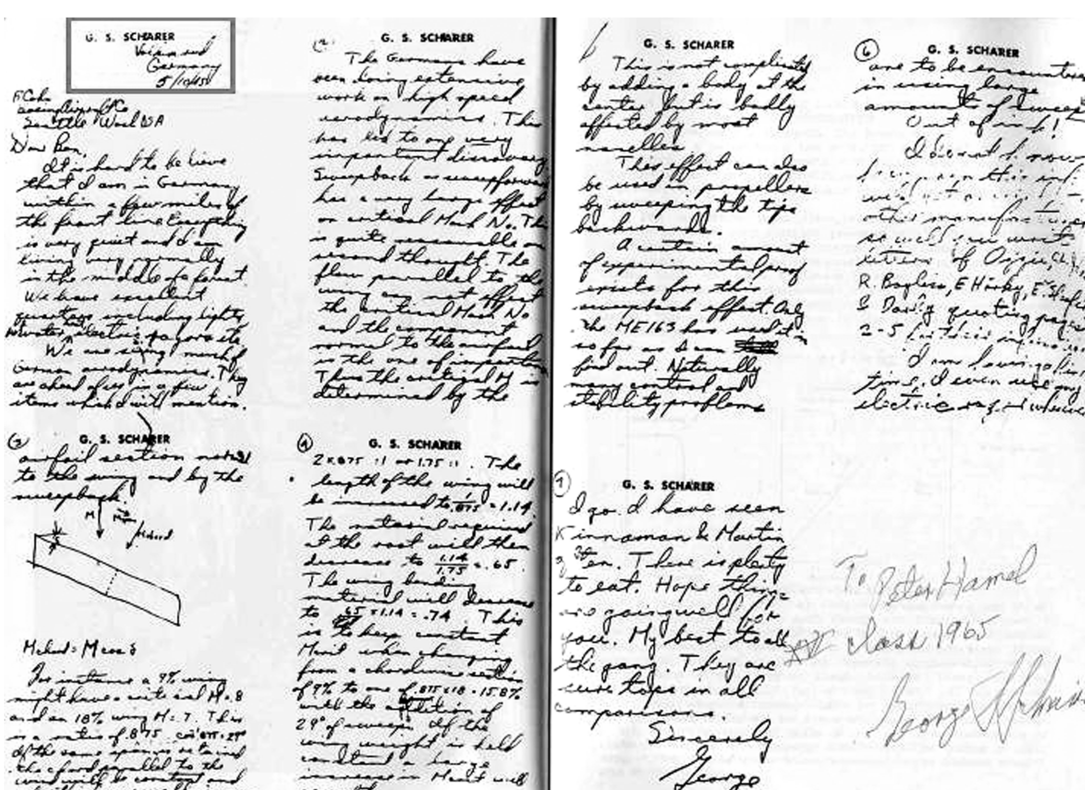


Fig. 36 First operational U.S. swept-wing fighter.



G. S. SCHARER
[illegible] Germany
5/10/45

B. Cohn
Boeing Aircraft Co
Seattle Wash USA

Dear Ben,
It is hard to believe that I am in Germany within a few miles of the front line. Everything is very quiet and I am living very normally in the middle of a forest. We have excellent quarters including lights, hot water, electric razor etc.
We are studying much of German aerodynamics. They are ahead of us in a few items which I will mention.

(2) G. S. SCHARER
The Germans have been doing extensive work on high speed aerodynamics. This has led to one very important discovery. Sweepback or sweepforward has a very large effect on critical Mach No. This is quite reasonable on second thought. The flow parallel to the wing may not affect the critical Mach No and the component normal to the surface is the one of importance. Thus the critical M is determined by the

(3) G. S. SCHARER
airfoil section normal to the wing and by the sweepback.
[illegible]
Method: M cos δ
For instance a 9% wing might have a critical M=.8 and an 18% wing M=.7. This is a ratio of .875 [illegible] If the same spar is used and the chord parallel to the wind will be constant and the thickness will increase not by 2:1 but by

(4) G. S. SCHARER
2×.875 :1 or 1.75 :1. The length of the wing will be increased to 1/.875 = 1.14. The material required at the root will then decrease to 1.14/1.75 = .65. The wing bending material will decrease to .65×1.14 = .74. This is to keep constant Mcrit when changing from a chordwise section of 9% to one of .875×18 = 15.8% with the addition of 29° of sweep. All the wing weight is held constant [illegible] in Mcrit will result.

(5) G. S. SCHARER
This is not complicated by adding a body at the center but is badly affected by most nacelles.
This effect can also be used in propellers by sweeping the tips backward.
A certain amount of experimental proof exists for this sweepback effect. Only the ME163 has used it so far as I am able to find out. Naturally many control and stability problems

(6) G. S. SCHARER
are to be encountered in using large amounts of sweep.
Out of ink!
[illegible]
R. Bayless, E Hartley, [illegible]
[illegible] quoting pages 2-5 [illegible]
I am [illegible]

(7) G. S. SCHARER
I go. I have seen Kinnaman & Martin [illegible]. There is plenty to eat. Hope things are going well for you. My best to all the gang. They are sure tops in all comparisons.
Sincerely
George

To Peter Hamel
[illegible] 1965
George Schairer

Fig. 34 George S. Schairer's historic letter from LFA Braunschweig to his Boeing aircraft companion B. Cohn dated 10 May 1945 (Ref. 9).

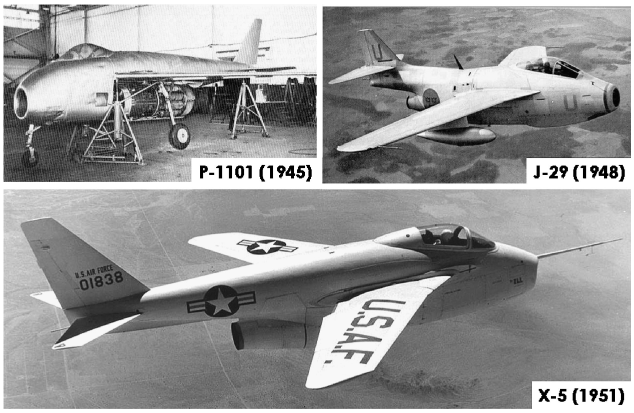


Fig. 37 Messerschmitt P 1101 swept-wing prototype and its direct derivatives.

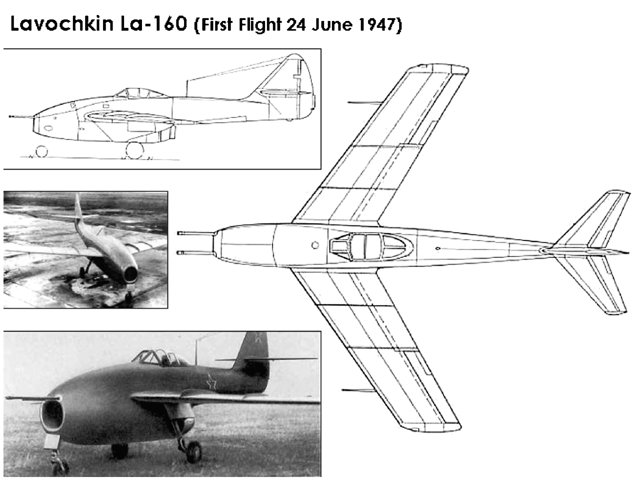


Fig. 38 First Russian swept-wing test aircraft.

German engineers and scientists from industry and research organizations (Fig. 37). Most impressive is the early first flight date of the first operational Swedish jet fighter SAAB J-29 ("Flying Barrel") on 1 September 1948. Further details about the history of these two aircraft projects can be found in a book about advanced Messerschmitt projects.[31]

The first Soviet swept-wing test aircraft La-160 ("Strelka") was developed as early as 1947 by Lavochkin's Design Bureau, one of Russia's most innovative aircraft design teams at that time. The La-160 was again an equivalent of the P-1101 development and had a thin wing with 35-deg swept leading edge. During the design stage, captured German swept-wing data were available, but further extensive wind-tunnel studies were performed at Russian aeronautical research institute TsAGI. The necessity of upper-wing fences at subsonic speeds was revealed. Such fences were installed on the La-160, two on each wing (Fig. 38). Its RD-10F turbojet engine could gain extra 50% of thrust by using an integrated afterburning chamber designed by I. A. Merkulov.

The RD-10 was a copy of the German Junkers Jumo 004A turbojet engine designed in 1940, and a later version Jumo 004E, designed by Anselm Franz in 1941, was the world-first turbojet engine equipped with an afterburner. One-hundred hour test runs with several engines were accomplished until 1944, and series production was planned for 1945. A nonafterburning version of the Jumo 004 was also used in the Ju 287 V-1 swept-forward prototype.

The La-160 took the air for the first time on 24 June 1947. Flight trials during June–September 1947 provided the designers with reliable data on stability and handling characteristics of swept-wing aircraft. It was perhaps the most important database for all future Soviet swept-wing aircraft projects. Near sonic speeds (Mach 0.92) were achieved. But this experimental aircraft was still too small to have sufficient range and carry large weapon load, and it was not accepted for series production.

Fig. 39 First operational Russian swept-wing fighter (© Naval Institute Press).

Also based on TsAGI wind-tunnel test data, which clearly indicated that swept wings with boundary-layer fences will probably be a right answer to overcome stability and control problems and to master airflow breakdown at low speeds, the MiG 15 of the competing Mikoyan Design Bureau was developed. It would become one of the best combat aircraft in the early 1950s (Fig. 39). A short maiden flight was on 30 December 1947, but the real first flight without engine problems was accomplished on 27 May 1948 with the second prototype (I-310-S-02).

Because of the mass of captured German data on the advantages of a swept or delta wing for transonic flight, the advanced British straight-wing supersonic project Miles M.52 was cancelled on 31 January 1946 by the Voelkenrode "tourist" Ben Lockspeiser. Ironically, M.52 project documents went finally to the United States in order to complete the Bell X-1 database and contributed to the famous success of the world first supersonic flight on 14 October 1947 piloted by Ch. E. Yeager.

As already discussed, German industry and research organizations were becoming increasingly concerned with certain detrimental effects of wing sweep on handling qualities at low and transonic speeds (at low speeds, outboard shift in aerodynamic span loading in combination with an outflow of the boundary layer leads to wing-tip stall; and at transonic speeds; reduced aileron effectiveness and shock-induced flow separation and pitching). The industrial favored solution was the introduction of leading-edge slats and slots. Also, alternatives such as the addition of wing fences were investigated by W. Liebe at the DVL offshoot FVA in Prag. A. Busemann contributed by suggesting all-movable tail planes for improved pitch control effectiveness at transonic speeds instead of hinged control surfaces.

Area Rule and Artificial Stability

This short account on early wings sweep research and aircraft design challenges will be concluded with some observations about the beginnings of area ruling and artificial stability.

For the first time Frenzl from Junkers patented and applied the principals of area ruling to their Ju 287 V-1 prototype (e.g., prevent sudden increases/decreases in cross-sectional areas along the longitudinal body axis) in order to minimize engine-airframe interference effects by mounting the engine nacelles at optimum wing and fuselage stations[32] (Fig. 40).

Maybe by intuition if not by intention, the then innovative Martin XB-51 swept-wing bomber clearly exhibited some kind of area ruling (Fig. 40) by forward locating the fuselage-mounted engine nacelles. First flight was on 28 October 1948. The former German aerodynamicist and designer of the T-tail Ta 183 aircraft project at Focke-Wulf, H. Multhopp (Fig. 41), contributed to the XB-51 design. He joined the Martin Company a few years after WWII. He knew all about the German area-rule experience at Junkers and other projects at Messerschmitt and others, and at least he exercised

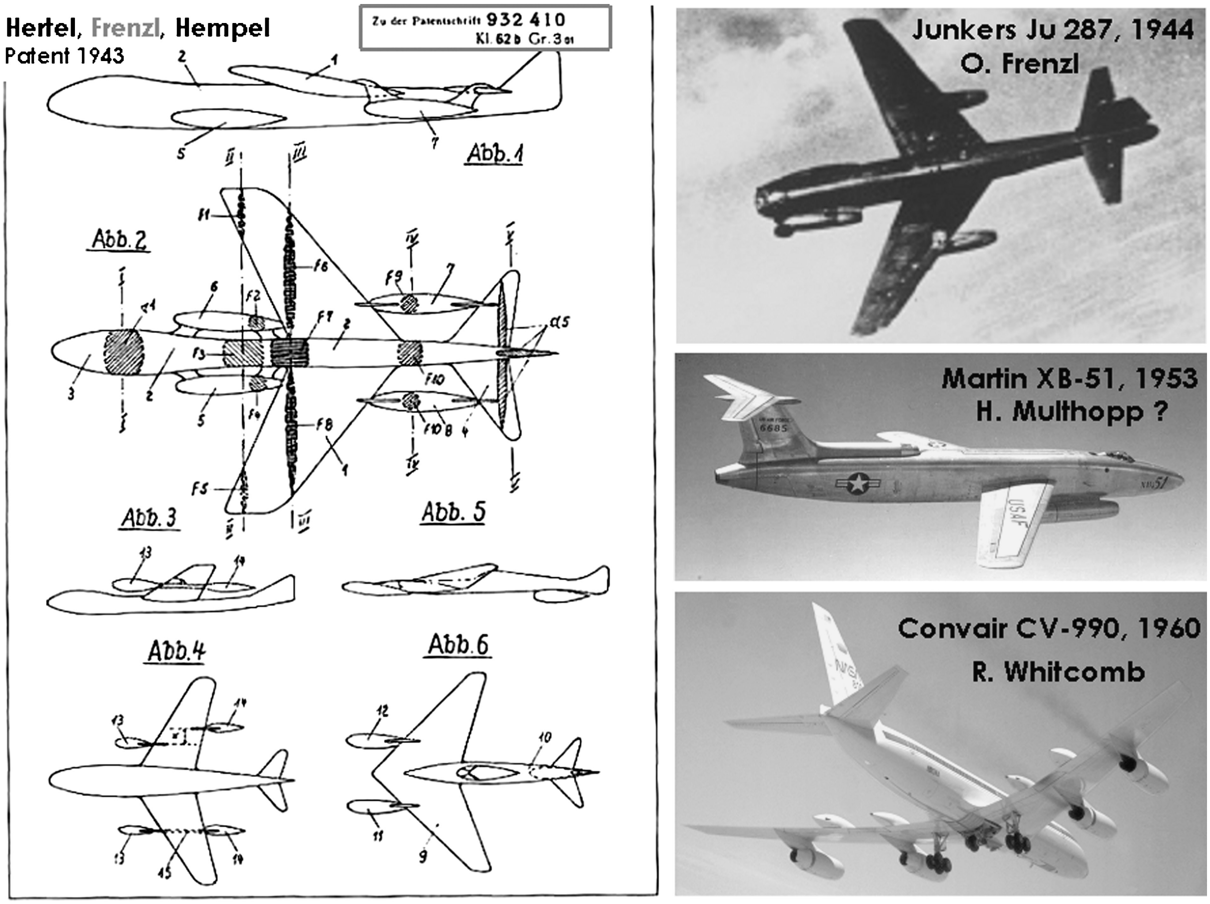


Fig. 40 Beginnings of transonic area ruling.

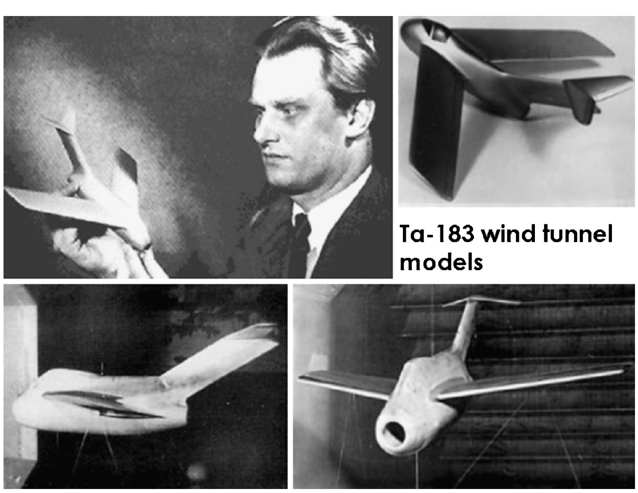


Fig. 41 Multhopp handling a Focke-Wulf-TA-183 "Huckebein" model.

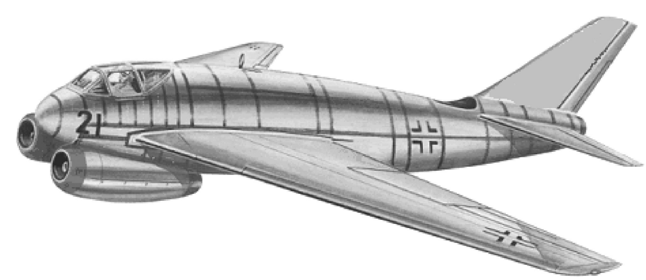


Fig. 42 Messerschmitt Project Study P-1102.

a certain influence on Martin's various T-tail aircraft designs. Interestingly, the XB-51 also shared the same engine arrangement as the Messerschmitt project P-1102 (Fig. 42).

It is well appreciated that Richard Whitcomb from the former NACA conducted a series of systematic transonic wind-tunnel tests in the early 1950s on various configurations in order to demonstrate the beneficial effects of transonic drag reduction as a result of area ruling. It is also internationally recognized that Whitcomb's experimental database at NACA Langley came just in time to be convincing to the former Convair company to area rule the fuselage of the "problem" fighter YF-102 in order to get it finally supersonic[10] (Fig. 43). After this U.S. industrial area-rule debut, further applications found their way to other civil (Fig. 40, right bottom) and military transonic aircraft projects (Fig. 44).

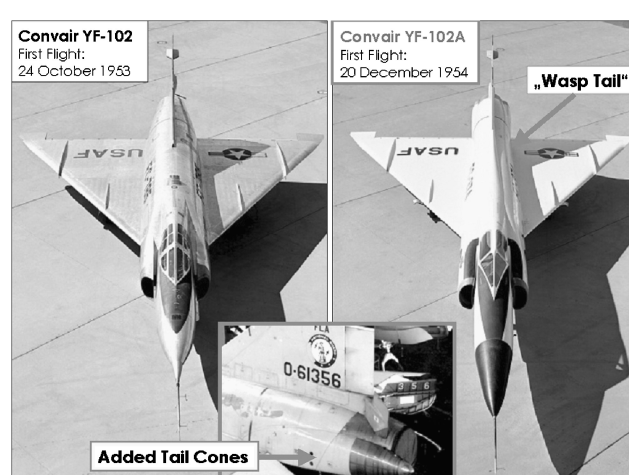


Fig. 43 First area-ruled U.S. fighter.

Fig. 44 Art and science of area ruling.

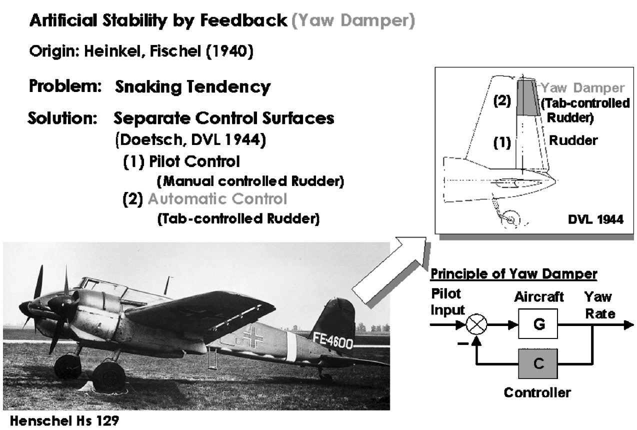


Fig. 45 German yaw damper research (Hs 129).

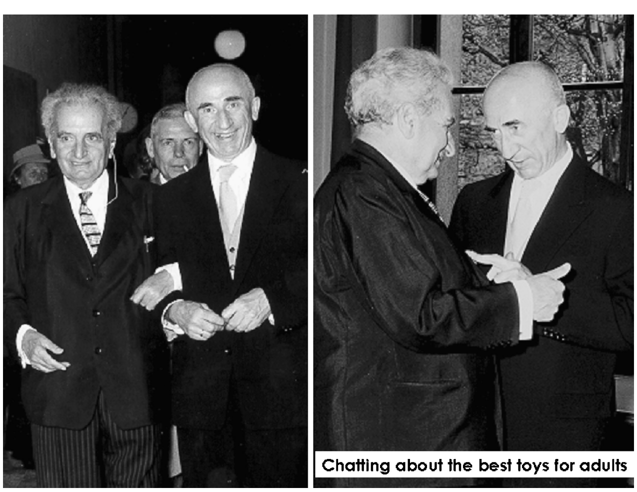


Fig. 46 Th. von Kármán (left) and H. Blenk during the Gauss-Medal award ceremony in Braunschweig (1960).

The earliest recognition of the need for stability augmentation was given by E. Heinkel on 20 September 1940 while introducing two lectures on the subject. He briefly remarked that longitudinal stability of very fast airplanes will diminish and that the transition to artificial stability produced by an automatic pilot will become an inevitable necessity in the near future.[33] One of the lectures on this subject was presented by E. Fischel, who for the first time discussed analytical methods by which it is possible to predict the benefits of artificial stability.[34]

One of the first applications of artificial stability was concerned with the reduction of directional snaking oscillations, which were

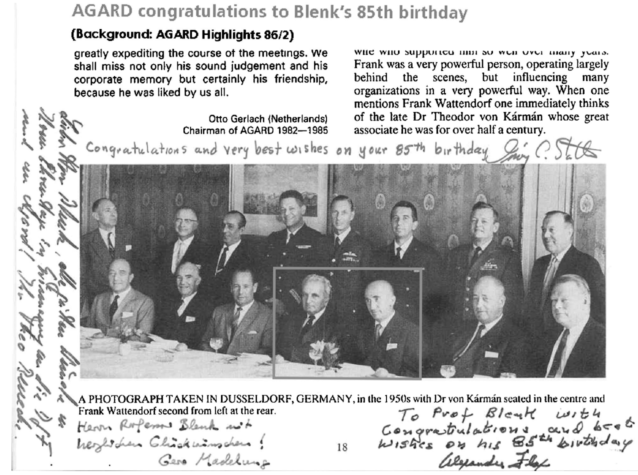


Fig. 47 U.S.–German postwar gestures of respect to H. Blenk (1986).

aircraft configuration dependent, annoying the pilots extremely during tracking tasks. K.-H. Doetsch and E. G. Friedrichs of DVL-Berlin flight tested in 1944 the first dedicated yaw damper by replacing the rudder of a Henschel Hs 129 with two separate yaw control surfaces, one for pilot manual control and the other for rate-gyro-controlled yaw damping (Fig. 45).[35,36]

Similar electromechanical aids to aerodynamics were implemented by Richard Vogt to the longitudinal and lateral axes to make the very large flying boats BV 222 and BV 238 with large control forces more pleasant to fly for the pilots. These activities represented also the beginnings of control systems with artificial feel.[37]

In the United States first yaw dampers were designed in the late 1940s for the already discussed Boeing XB-47 Stratojet swept-wing aircraft and the Northrop YB-49 Flying Wing with considerable success.[38,39] Since then, the notions stability augmentation or augmented aircraft are in aeronautical colloquial usage.[40]

Complementary information about the history of sweepback and German research and industrial contributions to aircraft aerodynamic design, flying qualities, and flight control can be extracted from further documents.[41–43]

Conclusions

From this limited historical survey on German aeronautical and vehicle-oriented research, the following conclusions or facts can be drawn or reinstated by taking also other references[6,41–43] into account:

1) German AVA/LFA/DVL wind-tunnel data gave proof in 1940 that Busemann's 1935 supersonic swept-wing theory is also applicable for subsonic compressibility effects.

2) The beginnings of area ruling can be traced back to Junkers' patent in 1943.

3) Artificial stability (philosophy, Heinkel; theory, Fischel, 1940) was first demonstrated by DVL's rate gyro controlled yaw damper (1944).

4) The existence of LFA Voelkenrode came as a complete surprise to the Americans and British after WWII.

5) Only after von Kármán and his scientific advisory team arrived in Germany was the totality of the German aeronautical research and design effort revealed.

6) German swept-wing wind-tunnel data dispelled U.S. doubts regarding the validity of R. T. Jones' theoretical work.

7) To preserve that scientific picture of LFA and AVA, every hardware and technical data were boxed up and shipped off mainly to Wright Field and to Bedford, United Kingdom.

8) Fairly extensive German wind-tunnel data were used for future swept-wing designs in the United States, Russia, United Kingdom, France, and Sweden.

Tribute

The presented material is also understood to be a tribute to German scientific aeronautical work in politically difficult times.

The managing director of LFA, the scientist Hermann Blenk, was unpolitical and never a member of the Nazi party. Blenk was able to ascertain until the end of World War II a maximum of basic aeronautical research and to be a supporter of scientists in distress.

Special tribute must be given to Theodore von Kármán who for a second time (after World War I) brought together scientists whose personal contacts had been destroyed by World War II. As a consequence, von Kármán established in 1952 the Advisory Group for Aerospace Research and Design (AGARD) and in 1957 the International Council of the Aeronautical Sciences (ICAS). Hermann Blenk was the first German member of the ICAS Executive Committee. Von Kármán received 1960 from the Braunschweig Scientific Society the Karl-Friedrich-Gauss-Medal in recognition of his scientific contributions in the field of applied mechanics and his efforts of fostering international collaboration.

Citing the late Hermann Blenk, the former honorary president of the German Aerospace Society (DGLR), the international aeronautical societies rendered homage to von Kármán being the "Lord of the Empire of Flight Sciences."

During this time, this author still was a student living in a simple room without heating, kitchen, or bathroom. He was not aware that von Kármán was residing some hundred meters from his apartment in the historic Braunschweig Hotel Deutsches Haus. On the right of Fig. 46, the warm personal relationship between von Kármán and Blenk can be anticipated. As both were enthusiasts of innovative toys, it can be imagined what they were talking about.

Another 26 years later leading aeronautical scientists and managing directors from the United States and Germany, such as the former AGARD Chairmen Theodore Benecke (1970–73), Alexander Flax (1973–76) and Gero Madelung (1985–88) and former AGARD Director Irving C. Statler (1985–88), spontaneously delivered some very personal congratulations to Hermann Blenk at his 85th anniversary in recognition of his modest but essential contributions to the post-war integration of aeronautical sciences within the NATO/AGARD community (Fig. 47).

From a scientific historical but also transatlantic social standpoint, it must be deeply regretted that the scientific AGARD family was destroyed in the late 1990s when national NATO authorities amalgamated the scientific-oriented AGARD structure with the Defense Research Group to form the Research and Technology Organization.

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