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Flying Qualities of Otto Lilienthal's *Large Biplane*

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Nomenclature

A_f = flight altitude (equal to 0 equivalent to straight legs, feet on ground), m
C_D = drag coefficient of aircraft
C_L = lift coefficient of aircraft
C_M = longitudinal moment coefficient about aerodynamic center, 1/rad
C_P = pressure coefficient
c = chord length, m
E = glide ratio C_L/C_D
Q = pitch rate, deg/s
q_∞ = dynamic pressure, Pa
U_∞ = freestream velocity, m/s
α = aircraft's angle of attack, deg
Δs = flight distance, m
η = geometric tail plane angle of attack, deg
ρ = air density, kg/m^3
v_f = flight speed, m/s

I. Introduction

MORE than 125 years ago, the aviation pioneer Otto Lilienthal was the first person to invent, build, and publicly fly several aircraft. He received a United States patent for his monoplane glider [1] in 1895. Several copies of this *Normal Soaring Apparatus* were sold to customers in America and Europe. In the same year, he developed his designs further into two different biplane aircrafts, of which the *Large Biplane* (*Großer Doppeldecker*) showed the most promise. Lilienthal's idea behind the transition from his monoplane design to the biplane depicted in Fig. 1 was to increase the wing surface without enlarging the wing span, as this would have made controlling the aircraft in roll more difficult. Countless flights with both biplanes have been photographically documented, making them the first successful, man-carrying biplanes in history. Lilienthal's flight demonstrations and his theory of cambered wings, developed and published in his book [2], contributed to the epochal shift in the rapid development of aeronautics. Culick [3] also notes that he was the first aeronautical engineer to combine the accepted concepts of equilibrium and stability with his ideas of control in order to maintain equilibrium in the face of disturbances. Among other experts and flight enthusiasts, the American railroad engineer Octave Chanute corresponded with Lilienthal. According to Crouch [4], Chanute served as the focal point of the international community of aviation pioneers at the time by corresponding with leaders of the field such as Lilienthal and Langley. He supported the cause of aviation by spreading news, holding lectures, and establishing a baseline of shared

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Felix Wienke is an Aeronautical Engineer at DLR, German Aerospace Center. After receiving a M.S. in aerospace engineering from the Technical University of Munich, he performed load and stability analyses of wind turbine rotors with a focus on high-fidelity fluid–structure methods at the DLR, German Aerospace Center's Institute of Aeroelasticity. In 2017, he became a Ph.D. candidate at the DLR, German Aerospace Center's Institute of Aerodynamics and Flow Technology, working on the aerodynamics of porous wings with a special focus on its application to Otto Lilienthal's patented monoplane "Normalsegelapparat." His work includes small- and full-scale wind tunnel testing as well as numerical investigations.

Andreas Dillmann received a M.S. in mechanical engineering in 1986 from the Technical University of Karlsruhe and his Ph.D. in physics in 1989 from the Georg-August University of Göttingen. From 1990 to 1998, he worked as a Theoretical and Experimental Researcher in high-speed aerodynamics at DLR, German Aerospace Center. He received his postdoctoral lecturing qualification (habilitation) from the Leibniz University of Hannover in 1995 and became a Full Professor of theoretical fluid mechanics at the Technical University of Berlin in 1998. Since 2003, he has been the Director of the DLR, German Aerospace Center's Institute for Aerodynamics and Flow Technology and a Full Professor of aerodynamics at the Georg-August University of Göttingen.

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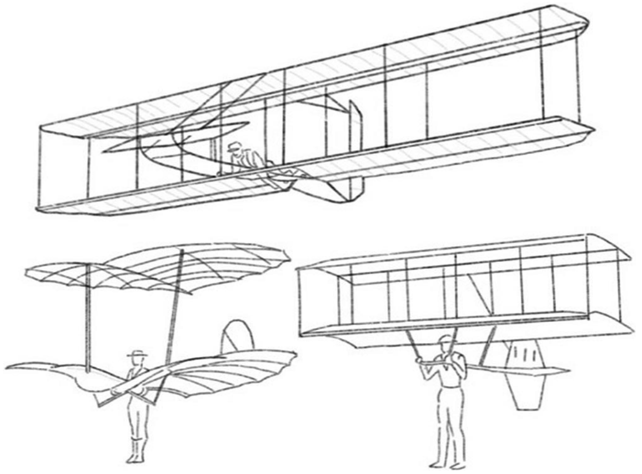


Fig. 1 1902 Wright glider (top) and its precursors: 1895 Lilienthal's *Large Biplane* (left) and 1896/1897 Chanute–Herring glider (right).

knowledge through publications such as his classic book on flying machines [5]. In the period between 1894 and 1904, Chanute decided to begin his own experiments. By following Lilienthal's approach of carefully performing increasingly advanced flight tests, he guided several young men, among them Augustus Herring, toward successful flight performances. He introduced bridge building techniques to the truss structures of his bi- and multiplanes to improve their structural integrity as shown in Fig. 1. In his experiments in 1896, this biplane flew as stable as Lilienthal's biplane [6] with a larger wing span and improved structural rigidity. Chanute focused on maintaining equilibrium in flight by incorporating automatic stability in his designs, which led him to make first steps toward active controls.

Finally, the Wright brothers combined the existing body of experience and knowledge with their own innovations in the field of active pilot controls and aerodynamics in their extensive glider tests between 1900 and 1902. Applying Lilienthal's step-by-step approach, they were able to achieve the first powered flights in late 1903. Actually acquiring pilot skills before attempting powered flight, made the *airmen* so much more successful than the preceding attempts of the *chauffeurs*. Culick [7] states that most of the Wrights' predecessors focused on intrinsically stable aircraft and did not progress far enough to be concerned with the problem of maneuverability. According to Perkins [8], the Wrights believed from the beginning that powerful controls were mandatory and would allow the pilot to maintain the necessary equilibrium. Their breakthrough became possible because their designs exhibited reduced stability complemented by reasonably effective pilot controls around all three spatial axes.

The present Paper is intended to give insights into the aerodynamic and handling properties of Lilienthal's *Large Biplane*. The goal is to further the understanding of Lilienthal's achievements as one of the greatest of the precursors, as Jakab [9] calls him. The current work is a continuation of the authors' investigation into its monoplane predecessor presented in [10,11].

The AIAA 1903 Wright "Flyer" project [12] pursued similar goals of constructing and testing a full-scale model as well as performing manned flights with a minimally modified replica of the historic Wright flyer. Further research such as virtual reality simulations based on the test data followed [13]. Another investigation into the Wrights' 1901 and 1902 gliders was published by Kochersberger et al. [14,15], who evaluated the aerodynamic performance from full-scale wind tunnel tests. They were able to derive simulation models, which were used in preparation of manned flights in a replica of the 1902 glider. Lawrence and Padfield [16] performed further investigations into the handling qualities of the Wrights' 1902 glider and powered 1905 flyer 3 [17]. They derived simulation models from their reduced scale wind tunnel data to evaluate their flight dynamics behavior and maneuverability. A thorough discussion of the handling qualities was based on piloted simulation trials. They conclude that the flight control system was the Wright brothers' most important innovation in their early development, followed by continuous improvements toward the powered 1905 flyer.

II. Glider Reconstruction and Dimensions

Earlier DLR, German Aerospace Center wind tunnel tests demonstrated the influence of the permeability of the fabric, which has been woven on an original loom using a formula that was developed based on a careful analysis of a fabric sample taken from an original glider wing [10]. The lower wing of the *Large Biplane* is the exact same size as the one used in Lilienthal's patented monoplane glider. Unlike the lower wing, the upper one is not foldable but is divided in the middle. Besides increasing lift, the upper wing also changes the flight mechanical properties in comparison to the monoplane, which will be discussed in the following. The original *Large Biplane* glider did not survive. However, there are several preserved specimens of the original monoplane, on which the biplane was based. The authentic replica of the *Large Biplane* used for the tests described in this Paper was built by the Otto Lilienthal Museum in Anklam (Germany). It is reported that Lilienthal modified his gliders to a certain extent during his experiments [18]. In conjunction with the wood and fabric construction reinforced by steel wires, it can be assumed that the glider geometries were subject to various alterations. The geometry of the replica (main dimensions given in Table 1) is based on surviving drawings by Lilienthal [1] as well as on drawings by Nitsch [18]. Circular arc airfoils were manufactured with a thickness to chord ratio of 1/20, which is in line with the thickness ratios documented by Lilienthal (Ref. [7] p. 271). Special attention was paid to the tension of the steel wires connecting the willow longerons of the wings to the mainframe as depicted in Fig. 2. Their lengths greatly influence the overall trim of the glider. During all balance measurements and later flight tests, the wing fabric was sealed with a coating of diluted wood glue. This treatment resulted in a flexible coating, which was easier to apply than the collodion coating originally used by Lilienthal. Using glue instead of collodion for coating has no aerodynamic consequences because the remaining permeability to air of both treatments is negligible.

There are some minor differences between the replica and Lilienthal's *Large Biplane*, which are intended to reduce the pilot's risk during the flight tests. To prevent the mainframe from digging into the ground during landing mishaps, skids were fitted to the ends of the mainframe. Their aerodynamic effect is negligible due to their small size. The original solid wires, bracing the wing longerons against the mainframe, were replaced by stainless steel cables. Their tension has been permanently fixed using compression sleeves instead of adjusting it using the custom tension locks, which Lilienthal patented for

Table 1 Glider dimensions

Length	5.25 m (17 ft 3 in.)
Wing span	6.60 m (21 ft 8 in.)
Wing area	24 m^2 (259 sq ft)
Empty weight	33.5 kg (74 lb)
Mean aerodynamic chord length	2.03 m (6 ft 8 in.)

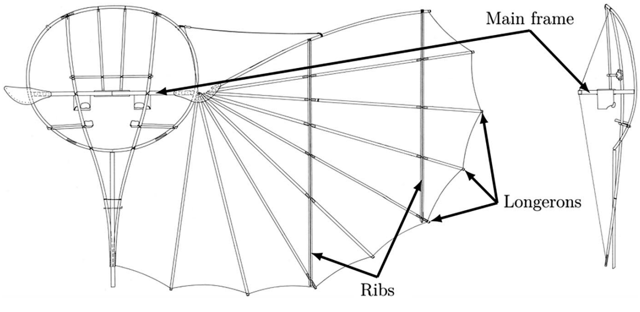


Fig. 2 Basic structure of the biplane's mainframe and lower wing.

Fig. 3 Balance force and moment measurements with the Lilienthal glider mounted on the supporting structure of the test vehicle of the German Hang Gliding Association.

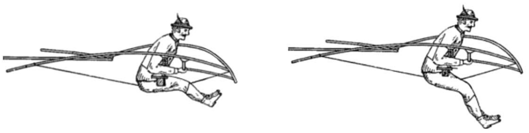
his gliders. The backrests were replaced by two parallel bamboo rods along the sides of the cockpit for safety reasons. They provide the pilot with a larger range of motion, while preventing him from leaning too far backward, allowing him to place some of his weight on them. The tube-shaped forearm supports of the original were reduced to sturdier, flat arm pads, located on the lower mainframe struts. The pilot used these as arm rests during flight, but he did not have any leverage to lift the rear of the glider during takeoff. During the final downhill flights, the head wind was always strong enough to lift the whole glider by itself after a short takeoff run of only a few meters. When low wind conditions persisted during the towed flights, the arm pads were supplemented with shoulder straps that bore most of the glider's weight, making the takeoff run less strenuous. The strongly curved parts of the glider structure, such as the cockpit frame, stabilizers, and longerons, were manufactured from willow, just as in the original. However, the three longerons closest to the leading edge were replaced by pine wood poles, which were presoaked and bent into shape. The improved structural stability at the cost of an increased glider weight of 33.5 kg was necessary because one of the test pilots was about 15% heavier than Lilienthal. In addition, tethered and towed horizontal flights added another 15% to the required lift forces when compared to free downhill flights at an incline.

III. Balance Measurements

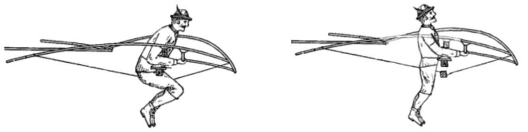
The full-scale balance tests of the *Large Biplane* were conducted with the help of the test vehicle of the German Hang Gliding Association in Fürstenfeldbruck, Germany, as depicted in Fig. 3. A three-component balance was mounted on a sting at the upper end of a supporting tower structure on top of the vehicle and clamped to the glider's mainframe.

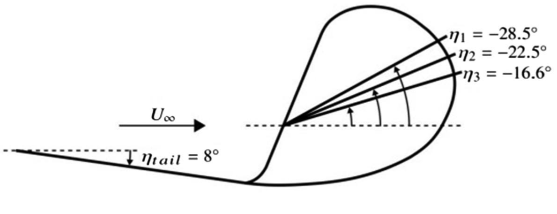
Data were recorded at freestream velocities of 20 km/h $\leq U_\infty \leq$ 45 km/h at angles of attack between $-17 \leq \alpha \leq 45$ deg. The influence of the pilot's drag was estimated by a drag penalty based on earlier tests, assuming the steady flight body posture shown in Fig. 4b. The elevator incidence angle was set to the middle position of $\eta_2 = -22.5$ deg of the three calibrated angles depicted in Fig. 4e. All data were recorded during measurement runs up and down the 2.7 km long runway. Continuous traverses in angle of attack were performed at a low angular velocity to obtain quasi-steady data. The test vehicle records freestream velocity and direction during the test runs to take current atmospheric conditions into account. The results were sorted into discrete angle of attack intervals and averaged. The influence of atmospheric disturbances was further minimized by repeating the test runs in both runway directions for each freestream velocity. During the tests, the glider exhibited structural vibrations, which manifested themselves as noise in the quasi-steady measurement curves. Because the sting and balance system was comparatively rigid, the majority of these elastic deformations originated from the glider's structure. The wing structure, made of wood and steel bracing wires, proved itself to be a well-designed truss structure, exhibiting small and continuous deformations in the form of wing bending. The tailplane structure was connected to the mainframe by a single bamboo rod of approximately 30 mm in diameter and braced with cotton chords against the main structure. This resulted in vertical up and down bending and longitudinal torsion of the whole tailplane structure during testing. The tailplane vibrations were strongest at high angles of attack, when they were triggered by turbulence from the stalled wing. Changes in the elevator incidence angle due to deformation of the tail structure under the aerodynamic load have not been measured. The digital filter described by Savitzky and Golay [19] was applied to the averaged forces and moments to reduce the small-scale variations introduced by noise and vibration.

The measured lift coefficients over the angle of attack are shown in Fig. 5 at several freestream velocities. Up to an angle of attack of $\alpha = 12$ deg, all lift curves exhibit a linear interval with differences in the order of $\Delta C_L = 0.12$ between the highest and the lowest freestream velocity. With increased velocity, the lift tends to increase at a given angle of attack. The stall behavior is benign, with a gradual departure from the lift curve and low gradients near the maximum lift



a) Dive **b) Glide**





c) Climb **d) Landing** **e) Elevator incidence angles**

Fig. 4 Pilot postures and elevator incidence angles.

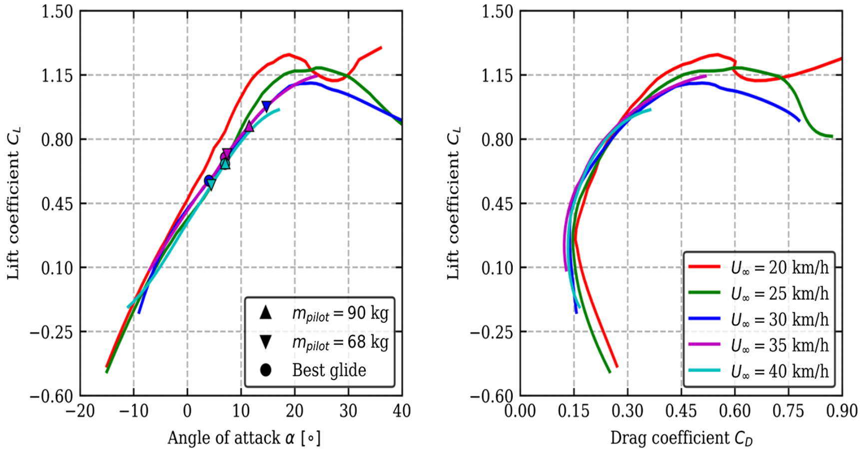


Fig. 5 Lift coefficients plotted against angle of attack (left) and drag coefficient (right) at different freestream velocities.

coefficient between $1.10 \leq C_L \leq 1.25$ at an angle of attack of approximately $\alpha \approx 20$ deg. The drag polar shown in Fig. 5 has a classical parabolic shape in the linear lift interval below $C_L = 1.1$. The minimum drag of $0.123 \leq C_{D\,\min} \leq 0.155$ occurs near $C_L \approx 0.25$. An increase in freestream velocity results in a reduction of the minimum drag.

The pitching moments around the glider's mainframe center are shown on the right-hand side of Fig. 6. They exhibit three distinct intervals. The first interval up to an angle of attack of $\alpha = 10$ deg coincides with the linear lift interval. All freestream velocities exhibit positive, pitch-up pitching moments around $C_M = 0.055$, with a tendency toward smaller values at higher velocity. The change in pitching moment in the linear interval is too small to confirm a linear dependency on the angle of attack due to the measurement uncertainty. For $10 \leq \alpha \leq 25$ deg, the glider transitions into full stall with a linear decrease in pitching moment and little variation between the freestream velocities. Above $\alpha = 25$ deg, the glider is fully stalled, and the pitching moment tapers off. Lower freestream velocities result in more negative, pitchdown moments. The glide ratio $E = C_L/C_D$ is shown on the left side of Fig. 6. The glider achieves a maximum glide ratio of $E = 3.5$ at a freestream velocity of $U_\infty = 35$ km/h. The lowest glide ratio of $E = 3.1$ was measured at a freestream velocity of $U_\infty = 25$ km/h.

Based on the weights of the two test pilots and the glider, trim conditions are calculated for the five measured freestream velocities. They are listed in Table 2, along with the conditions for best glide and maximum lift, and included as markers in Fig. 5 for freestream velocities $U_\infty \geq 30$ km/h. The required freestream velocity for flight at $C_{L,\max}$ with a given pilot weight determines the minimum takeoff velocity $U_{\infty,\min}$. The lighter pilot (68 kg) is able to take off at velocities above 28 km/h, while the heavier pilot (90 kg) requires at least 31 km/h. The best glide ratio is achieved at lift coefficients of $0.57 \leq C_L \leq 0.7$ at velocities above 30 km/h. The lighter pilot is able to fly the glider in its best glide state at 35 km/h, which is only 25% faster than the takeoff velocity, whereas the heavier pilot has to fly slightly faster. The glider operates close to the stall region with both pilot weights.

Table 2 Trim and best glide conditions

U_∞	[km/h]	25	30	35	40
E_{opt}	[-]	3.14	3.30	3.50	3.44
$C_{L,\mathrm{opt}}$	[-]	0.74	0.57	0.70	0.66
$C_{L,\max}$	[-]	1.19	1.11	1.14	0.96
$C_{L,\mathrm{trim},90\,\mathrm{kg}}$	[-]	——	——	0.87	0.67
$U_{\infty,\min,90\,\mathrm{kg}}$	[km/h]	30.0	31.1	30.6	33.4
$C_{L,\mathrm{trim},68\,\mathrm{kg}}$	[-]	——	0.98	0.72	0.55
$U_{\infty,\min,68\,\mathrm{kg}}$	[km/h]	27.2	28.2	27.7	30.3

IV. Acquiring Lateral Control Skills: Winch Flights

Initial experiments quickly showed that the lateral control skills of the pilot are the deciding factor for keeping prolonged flights safely level because of external disturbances such as gusts. Asymmetric lift occurred especially at low pitch rates or initial high angles of attack as depicted in Fig. 7. The influence of the leading edges' vortices inherent to dynamic stall at flare landings will be described later. Lilienthal himself describes the pilot input, which counteracts roll disturbances, as a lateral shift toward the rising wing in Ref. [20]. The measured data of the winch supported flights is summarized in Table 3.

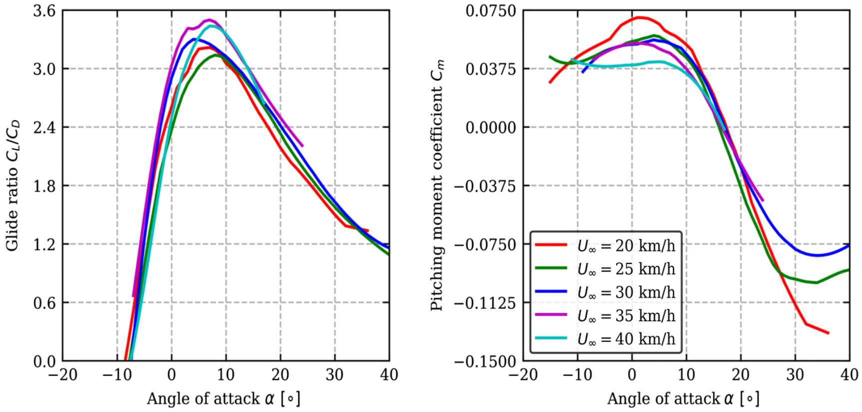


Fig. 6 Glide ratio (left) and pitching moment coefficients (right) at different freestream velocities.

a) Limited longitudinal control authority due to the attachment of the towing rope in front

b) Counteracting unintended roll motions

Fig. 7 Practicing lateral control during winch tests.

Table 3 Winch flights: August 2018

Flight parameters	Measured range
Distance flown Δs, m	119–380
Altitude while airborne A_f, m	−0.1–3.8
Speed while airborne v_f, m/s	7.5–8.9
Average wind speed U_∞, m/s	0.5–0.9

V. Acquiring Longitudinal Control Skills: Free Flights

After practicing lateral control near Moringen, Germany; Marina Beach, California; and on the dunes near Kitty Hawk, North Carolina, the *Large Biplane* replica has now been flown by three pilots: Markus Raffel (DLR, German Aerospace Center), Andrew Beem (Windsports), and Billy Vaughn (Kitty Hawk Kites). Foot launching gliders in gusty wind conditions requires some practice. However, by acquiring those skills, it was eventually possible to fly the glider safely. Strong wind gusts were consequently avoided because it was assumed that they can lead to a stall, which can exceed the pilot's capability to maintain the posture required for a balanced, controlled flight.

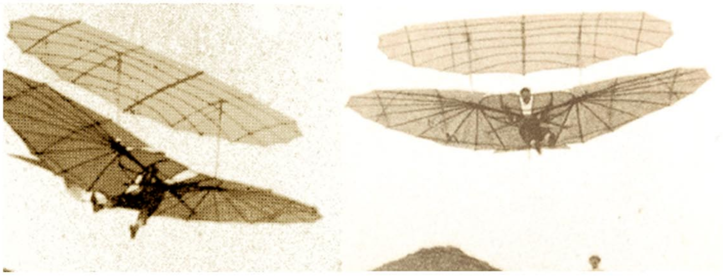
The angle of incidence of the horizontal tailplane was adjusted along the three angles shown in Fig. 4e to achieve longitudinal trim for a given pilot mass. A steeper angle of $\eta_2 = -22.5$ deg was suitable for the heaviest pilot (Raffel) at 90 kg, while the lightest pilot (Beem) at 68 kg achieved the best flights at a shallower angle of $\eta_3 = -16.6$ deg. The glider responded promptly and predictably to the pilot's input in these configurations. As a result, the pilots were able to easily direct the glider against the wind. This proved valuable during takeoffs from a sand dune, as shown in Fig. 8a. If one wing descends (here, for example, the left wing), the intuitive reaction of an untrained pilot is to also shift the legs to the left in order to land safely on his feet. However, because the torso is fixed in position with respect to the Lilienthal glider, this motion moves the center of gravity to the left, which amplifies the leftward roll angle. This can result in a flip of the aircraft, potentially causing a dangerous crash with the arms stuck in the framework of the glider. The correct, but counterintuitive, response is to shift the legs toward the rising wing. This is visible in the takeoff from the sand dune (Fig. 8a), where shear winds initially pushed the left wing down. After the training in Germany and California, the pilot instinctively shifted his legs toward the rising wing, leveling the glider (Fig. 8b).

The lateral control of the roll angle is similar to a modern hang glider, with two important differences. With a modern glider, the entire pilot mass is shifted relative to the wing. In addition, the roll moment is amplified by warping the wing through a shift of the wing keel [21]. With the historic glider, only the legs can be laterally repositioned. As a consequence of the smaller shifted mass, the legs need to be moved farther to the side to achieve a sufficient response by the glider. Because of the comparatively low control effectiveness

a) Accelerating before takeoff (pilot A. Beem)

b) Shifting the legs to the right (pilot A. Beem)

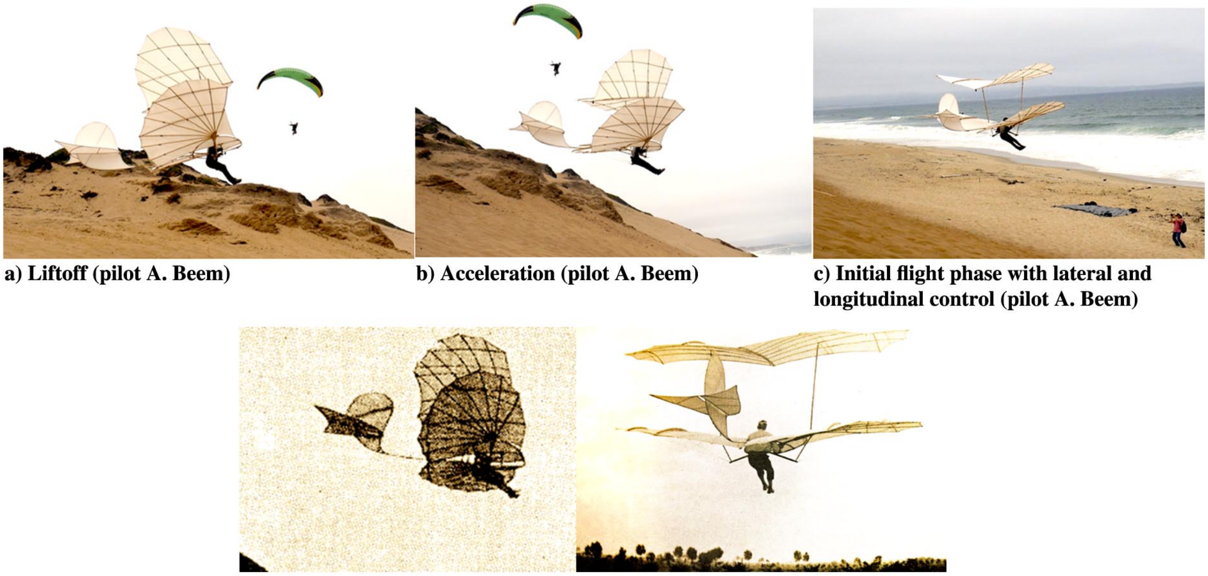
c) Establishing straight flight (pilot A. Beem)



d) Shifting the legs to the right (pilot O. Lilienthal)

e) Establishing straight flight (pilot O. Lilienthal)

Fig. 8 Foot launch with counterintuitive leg shifting towards the descending wing compared to historical photographs.



a) Liftoff (pilot A. Beem) **b) Acceleration (pilot A. Beem)** **c) Initial flight phase with lateral and longitudinal control (pilot A. Beem)**

d) Acceleration (pilot O. Lilienthal) **e)Initial flight phase (pilot O. Lilienthal)**

Fig. 9 Free flying glider in contemporary and historical photographs.

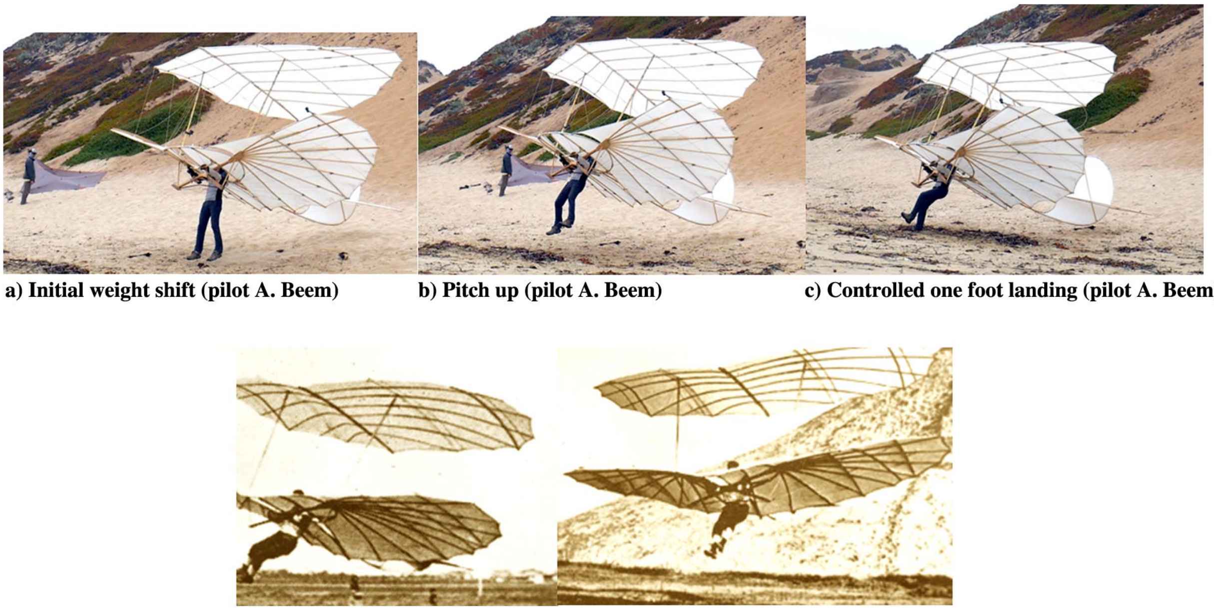
in roll, it was deemed unsafe to perform turns at low altitude and in close proximity to a hillside. Therefore, the feasibility of steep turns could not be investigated during the free flight experiments, although Lilienthal demonstrated 180 deg turns at higher altitudes. However, even Lilienthal tried to avoid such maneuvers because he asserted that safe landings could only be conducted against the wind.

After steady downhill flight depicted in Fig. 9, the pilot initiated the landing phase by shifting his weight rearward to pitch the glider up and slow it down when it comes close to the ground. The biplane glider exhibited a similar sensitivity to longitudinal weight shifts as the monoplane so that the pilot only had to lean his torso backward, as shown in Fig. 10. A premature and tentative weight shift resulted in a slow but pronounced stall of the flow over the wings. Because massively separated flow is always unsteady and three dimensional in nature, the glider rolls toward the wing, which stalls first and creates less lift and more drag. The resulting, involuntary turn at touchdown is well known in the case of modern hand gliders as well.

To achieve a good landing of Lilienthal's biplane, the pitch rotation needed to be delayed, and the pitch rate increased to have the wings stall dynamically. The result was a short lift overshoot coupled with an additional pitch-up moment [22], which was caused by the two-dimensional flow over the wings due to dynamic stall vortices along their leading edges [23,24]. With these lessons learned, Otto Lilienthal's 125 year old feat of landing the glider on one foot was reproduced by Andrew Beem, as depicted in Fig. 10b. Different pilots were able to perform smooth and safe flights followed by gentle landings in the replica, thereby achieving flight durations of up to 15 s over distances given in Table 4.

Table 4 Free flights: July 2019

Flight parameters	Measured range
Distance flown Δs, m	20–104
Altitude while airborne A_f, m	0.1–5.5
Speed while airborne v_f, m/s	4.5–7.6
Average wind speed U_∞, m/s	1.8–6.9



a) Initial weight shift (pilot A. Beem) **b) Pitch up (pilot A. Beem)** **c) Controlled one foot landing (pilot A. Beem)**

d) Pitch up (pilot O. Lilienthal) **e) Controlled landing (pilot O. Lilienthal)**

Fig. 10 Comparison of contemporary and historical of landing procedure.

VI. Conclusions

Free flights from hillsides as well as winch tows close to the ground were performed using an authentic replica of Otto Lilienthal's *Large Biplane* glider, achieving free flight distances of up to 104 m. The structural integrity of the design has been verified through balance measurements using a hang glider test vehicle, which demonstrated that the glider can lift and sustain loads of more than 240 kg.

Some modifications to the historic original were made to increase pilot safety. The increased takeoff weight and the reduced wing flexibility due to the use of pine wood for some of the longerons proved an acceptable compromise. Changing and improving the various adjustment options of the glider gave new insights into the likely learning process of Lilienthal and reinforced the authors' respect for his ingenuity. For example, changing the inclination of the support posts of the upper wing can increase the dihedral of the wings as well as the static margin of the glider [25]. This improved the control behavior and helped less experienced pilots to cope with pitch and roll disturbances. However, the alignments used to achieve this might have led to reduced performance during flight and balance tests of the replica, compared to the flight performance obtained by Lilienthal in 1895/1896.

Longitudinal trim was achieved for pilot weights between 68 and 90 kg by adjusting the elevator incidence angle. The lateral control required athleticism from the pilots because they had to be able to keep their legs extended to the side to have control input through weight shift. This limited the use of the glider to wind conditions of only moderate gusts because the lateral control authority was deemed too low for strong wind gusts.

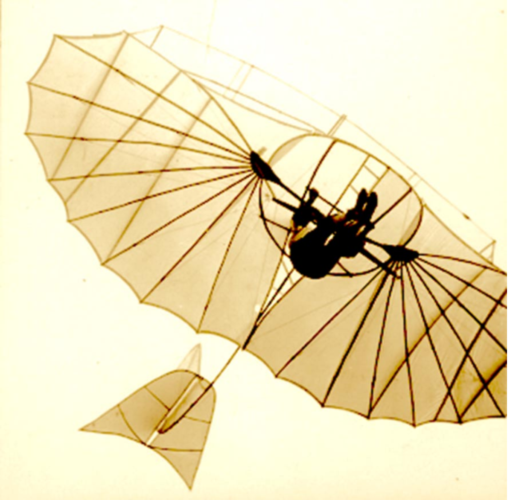


Fig. 11 1896 Otto Lilienthal, Fliegeberg near Berlin [26].

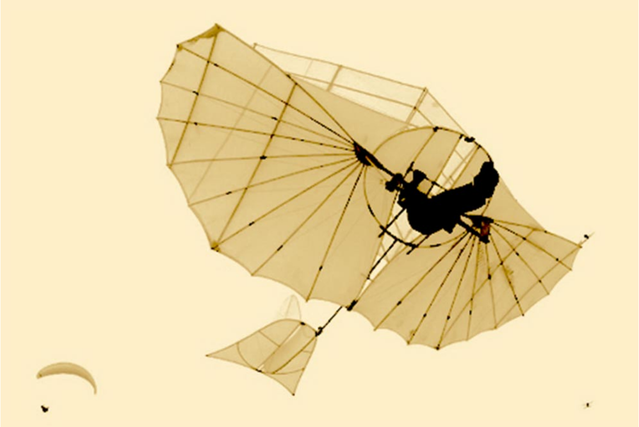


Fig. 12 2019 Andrew Beem, Sand City near Monterey, California.

A comparison of photographs from [26] of Lilienthal's Large Biplane from 1895 (11) to its replica from 2018 (Fig. 12) suggests that Lilienthal's original glider had a little less dihedral, a stronger wing curvature in the center of the lower wing, and less wing washout on the upper wing. The aerodynamic center of Lilienthal's *Larger Biplane* is higher than that of his patented monoplane, increasing the flight stability while reducing the lateral control authority. Therefore, the biplane's stability is greater, but flight speed and agility are higher in the monoplane.

Acknowledgments

The staff of the Otto-Lilienthal-Museum in Anklam, Germany, built the biplane from authentic materials after Otto Lilienthal's patent drawing and photographs. Andrew Beem (Windsports, Los Angeles, California) flew the biplane in California and gave extremely valuable input and support. Markus Krebs's help during the winch experiments is greatly appreciated. Many thanks are due to Simine Short, biographer of Octave Chanute, and Bernd Lukasch, director of the Otto-Lilienthal-Museum. The team of the German Hang Gliding Association helped passionately and competently during all phases of the balance tests. The project was strongly supported by many flight enthusiasts of the German Aerospace Research Establishment DLR, German Aerospace Center.

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