Flight Controls of Otto Lilienthal's Experimental Monoplane from 1895

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Nomenclature

A_f	=	flight altitude (A_f equal to 0 corresponds to straight legs with feet on the ground), m
c_D	=	aircraft drag coefficient in aerodynamic coordinate system
c_L	=	aircraft lift coefficient in aerodynamic coordinate system
c_l	=	aircraft rolling moment coefficient in aerodynamic coordinate system
c_m	=	aircraft pitching moment coefficient in aerodynamic coordinate system
c_n	=	aircraft yawing moment coefficient in aerodynamic coordinate system
E	=	glide ratio C_L/C_D
F_P	=	preload force on levers of leading-edge flaps, N
U_∞	=	freestream velocity, m/s
α	=	aircraft angle of attack, deg
η	=	geometric tail plane angle of incidence, deg
Θ	=	rudder deflection angle, deg
κ	=	opening angle of leading-edge flaps, deg

I. Introduction

IN 1889, Otto Lilienthal published his book *Birdflight as the Basis of Aviation*, containing the first lift-versus-drag data of cambered wings and other important information required for human flight [1]. In 1895, his experiences were regularly detailed in articles that were published not only in Germany but also in England, France, Russia, and the United States [2,3]. Many people from around the world came to visit him, including Russian Nikolai Zhukovsky, Englishman Percy Pilcher, and Austrian Wilhelm Kress. Zhukovsky wrote that Lilienthal's flying machine was the most important invention in the field of aviation. Lilienthal corresponded with many members of the Boston Aeronautical Society, of which he was an honorary member. Among them were Octave Chanute, author of *Progress in Flying Machines* [4]; James Means, who invited Lilienthal to perform flight demonstrations; Samuel Pierpont Langley, who visited Lilienthal in Berlin; and Greely S. Curtis, who even gained first-hand gliding experience during a visit with Lilienthal in 1895. On Wednesday, 29 May 1895, the *Verein zur Förderung der Luftschiffffahrt* did not hold its meeting in an auditorium in Berlin in the evening, as was customary, but at Otto Lilienthal's training hill *Fliegeberg* in Lichterfelde in broad daylight. The translated minutes note reads as follows ([5] p. 329):

> "A large number of members had accepted the invitation of Mr. Otto-Lilienthal yesterday, who demonstrated his widely known and famous flight experiments to those gathered there. Even though the low wind speed at that day didn't allow the flyer from fully developing his art, the experiments were all the more stimulating and instructive, since the vast majority of those present were only familiar with Mr. Lilienthal's experiments from descriptions."

Lilienthal demonstrated his 12th aircraft design, a monoplane with a wing area of over 20 m^2 to the visitors. Because of its wingspan of almost 9 m and wing chord length of 3 m, Lilienthal's largest monoplane can only be used in light winds. Lilienthal applied for a patent on the same day. The patent claim was submitted for the *front wing* (*Vorflügel*), a leading-edge flap used in a glider for this purpose for the first time. Because of the size of the apparatus, three profile rails were slid onto each wing instead of the usual two.

The patent was granted the following December by the German Imperial Patent Office as an addition to Lilienthal's first airplane patent from 1893. The patent specification states that "the front part of the wing surface is rotatable downward about the leading edge and is pressed downward by rubber bands so that it rotates downward when the air pressure acting from below is released, thereby producing a pitch-up moment on the apparatus" [6].

In practice, this translates to rubber bands pushing the moving wing section downward by about 30 deg when at rest. In flight, the wing surface is usually closed. However, when the soaring apparatus starts diving, cutting through the air with a low, or even negative, angle of attack, the wing flaps open due to the pretension of the rubber elements, thereby stabilizing the flight. Lilienthal did not have the vocabulary of modern flight mechanics at his time, yet aptly described that in certain flight attitudes the leading edge of the cambered wings of the patented monoplane can be subject to pressure from above at small angles of attack. Lilienthal noted the resulting danger to stable flight attitudes. He was convinced that the new leading-edge flap provided a nose-up pitching moment in such cases. The new apparatus was demonstrated to the visitors both on the ground and in flight. In the process, Dr. Neuhaus took a series of photographic pictures, in which the folded-down front wing section is clearly visible. It has just under 0.5 m chord length at the wing root and about 0.25 m chord length at the tips. The drawing attached to the patent is schematic, illustrating the patent claim without providing any details. Because the patent was filed as a supplement, the elevator (horizontal stabilizer) was depicted being in front of the fin (vertical stabilizer), as was the case in 1893, even though Lilienthal had positioned both stabilizers in a crosswise configuration at the end of the tail for quite some time at that point [7].

Figure 1 shows Lilienthal's large monoplane from above, which provides a good view of the vertical spoilers and wings' leading edges formed by flaps. The view from below in Fig. 2 shows the pilot

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Fig. 1 Otto Lilienthal in his Experimental Monoplane with flight controls near Berlin in 1895 (photograph: P. W. Preobrashenski, 1895, © Archiv Otto-Lilienthal-Museum).

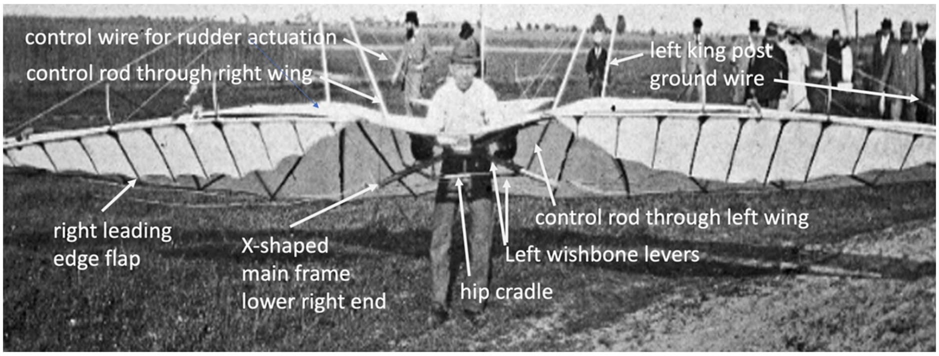

Fig. 2 Paul Beylich in the Experimental Monoplane with automatic balancing." Hip cradle, control levers, and rods transferring the control input to the strings above the wings can clearly be seen (adapted from the photograph by R. Neuhauss, 1895, © Archiv Otto-Lilienthal-Museum).

control linkage. These leading-edge flaps gave the apparatus the name *Vorflügelapparat (front wing apparatus).* In later publications Lilienthal also called it *Experimentiergerät (experimental apparatus)* as documented in his biography by Schwipps [5]. To follow Lilienthal's naming and to distinguish this apparatus from his experimental biplanes [8], it will be referred to as *Experimental Monoplane* for the remainder of this article.

From the very beginning, the Experimental Monoplane was designed to serve as a tool for control experiments. The actuating system can already be seen in photos (Fig. 2) [9]. It essentially consisted of the hip cradle, which was formed by two willow withies bent upward toward the rear and joined at the back near the vertical stabilizer, connected by an additional bar in front of the pilot's body. With wishbonelike levers linking the hip cradle to control rods on each side, a displacement of the hip fork will cause a deflection of the control rods passing through the wing surface near the rear cockpit ring. In pictures, these oblique control rods look like two additional king posts.[¶] At first, these rods were only used to deflect the vertical stabilizer laterally as a rudder. The movement of the control rods was transferred to the trailing edge of the tail via strings [7]. These strings ran from the king posts over the control rods to the lower part of the tailplane. It is not clear from the photos whether the flexibility of the tail boom or an articulated pivot provided the lateral deflection of the tail unit's trailing edge. However, in the main author's view, an articulated arrangement, which allowed for only moderate rudder deflections, is more likely. To increase the effect of the rudder, Lilienthal extended the vertical stabilizer by adding ribs and fabric to the top. Still, the size of the elevator stayed the same as with his patented monoplane *Standard Soaring Apparatus*, the world's first aircraft that was produced in series. The relatively small elevator likely helped to improve the glide ratio, but it also resulted in reduced longitudinal stability of the aircraft with closed leading-edge flaps, making the newly invented automatic pitch control even more important.

The photograph depicted in Fig. 1 also shows small vertical control surfaces attached at the outer ends of the wings, which rotate around short, upright posts resembling small sails. A string led from the front edge of such a wing-tip rudder, or roll spoileron, to the control rod, which had been shortened and moved back for this purpose. In normal flight, these control surfaces align themselves in the wind. When the pilot moved his body to the right, for example, the right control surface turned inward via the control rods and strings, while the left one remained unaffected.

The Bavarian flight pioneer Alois Wolfmüller had been an important correspondent of Lilienthal since 1893. In 1894, he acquired a copy of Lilienthal's patented Standard Soaring Apparatus and conducted flight experiments with it [10]. Wolfmüller also began experimenting with his own aircraft designs to improve controllability. In March 1895, Otto Lilienthal introduced his large Experimental Monoplane to Alois Wolfmüller in a personal letter [10]: "I am currently building a larger glider of about 20 m^2 wing area, which can only be used at calm winds." He wrote about the wing tip rudders: "Furthermore, I have attached a surface to each wingtip, which I can straighten up by pulling the string in order to bring back the leading wingtip." Because Lilienthal said "straighten up the surface," it is possible that, in addition to the devices visible in the photo, some experiments were performed with simpler spoilerons. These control devices are interesting, as they have the potential to avoid the problem of adverse yaw. If such a control surface is deflected to one side by moving the hip cradle, the drag is simultaneously increased on that wing while the lift is decreased. As an actuated spoiler increases drag, the yaw follows the same direction as the roll [11]. This asymmetric actuation of aircraft spoilers is still used by airliner pilots today, allowing aircraft designers to install smaller ailerons. This technique is prominently used during descending flight, when the drag increase is welcome to reduce altitude.

It is also noteworthy that both Wolfmüller and Lilienthal (and later also the Wright brothers) used warping of the wings. Wolfmüller

[¶]In contrast to modern hang gliders, which have one king post and ground wires to prevent the wing bending downward while being on the ground, Lilienthal's monoplanes usually had two vertical posts for the same purpose.

wanted to apply this control method manually, but Lilienthal most likely built a connection to the hip cradle, as did the Wright brothers with their 1902 glider and the 1903 flyer. In August 1895, Lilienthal wrote to Wolfmüller [12]:

> "You are entirely correct. The shift in center of gravity must be greater than a person can accomplish, when gliding in the wind with large wings. As the simplest method of balancing the lifting capacity of the two wings, I recommend rotating the wings around the longitudinal axis. I have found this to be the safest method compared to any others. It is also the method that is used by birds." After exchanging assurances of "mutual agreement to the protection of legitimate interests," a form of a nondisclosure agreement, Wolfmüller presented his thoughts and the results of his experiments on controlling flying machines, which were built using Lilienthal's design, in a long letter from 29 September 1895. This prompted Lilienthal to write more freely about his own attempts. Wolfmüller designed a wing warping device as well as an installation, that allowed pilots to sit within the flying apparatus. He argued that a sitting position would be advantageous, freeing up the pilot's hands to operate mechanical control systems such as two levers from his own design for twisting the wings. He proposed that other control elements could be operated using a strap around the upper body.

The same year in October, Lilienthal replied [13]:

> "I tested an arrangement similar to yours for moving and rotating the wings with outer tensioning wires running to different points of a lever mounted at the lower base point that can be pulled to give the wing profile the desired rotation. I also made it so that the tail could rotate to the right or left, making it easier to land. Furthermore, I have attached a surface to each wingtip, which I can straighten up by pulling the string in order to bring back the leading wingtip. These elements were operated by the hips, which press against a hip cradle, when the body is shifted sideways to shift the center of gravity." Lilienthal concluded by admitting that he had not yet achieved a decisive breakthrough in controllability:

> "These experiments, which I spent the entire summer investigating, have prompted me to make significant changes that I have not yet fully clarified and for which I regrettably have little time at the moment."

In the course of the investigations described in this paper, a full-scale replica of Otto Lilienthal's Experimental Monoplane was built, in addition to a 1:5 model. Both featured complete sets of control mechanisms: rubber-band activated leading-edge flaps for automatic pitch control, spoilerons, wing warping, and rudder for yaw and roll control, which were actuated by a hip cradle either individually or in combination. All structural materials relevant to the flying qualities were selected with great care in order to match the characteristics of the original.

II. Wind-Tunnel Tests

A range of parameter sets was investigated using the 1:5 model of the Experimental Monoplane in two different wind tunnels. The main focus of the investigation was on the aerodynamic effects of the various control elements. The first part of the aerodynamic investigation was carried out in the DLR-SWG (Side-Wind-Tunnel-Göttingen of the German Aerospace center), which is a closed-loop, low-speed wind tunnel. Isolated deflections of elevator and leading-edge flaps were compared to a reference configuration with undeflected control elements. A closed section with a length of 9 m, a width of 2.4 m, and a height of 1.6 m served as the test area. At the maximum power of $P = 0.5$ MW, it is possible to achieve a maximum flow velocity of $U_\infty = 65$ m/s in the empty test section. The lack of cooling requires an active flow velocity control system, which reduces the variations of the Reynolds number resulting from temperature changes. Each configuration was examined at up to 15 different angles of attack and at three mean flow velocities of $U_\infty = 5$, 7, and 8.5 m/s. It was not possible to investigate higher velocities in a safe manner due to insufficient structural stability of the model. Wind-tunnel effects on angle of attack, as well as lift and drag coefficients, and pitching moments were corrected using classic linear methods. The measurement system consisted of a six-component RUAG 796-6C strain gauge balance, a Prandtl tube, a Hottinger and Baldwin $\mathrm{MGC_{plus}}$ measurement amplifier system, and a computer network.

For the investigation of the wing warping, spoileron effects, and hinge moments at the leading-edge flaps, an additional experiment was set up in DLR, German Aerospace Center's 1 m low-speed wind tunnel (1MG). The right half of the existing 1:5 model was mounted directly on a piezoelectric force and moment balance and exposed to the flow through the wall of the wind tunnel. Yaw and roll moments as well as leading-edge flaps hinge moments were recorded at a mean flow velocity of $U_\infty = 8.5$ m/s (Table 1).

A. Performance

The lift over drag polar of the glider is depicted in Fig. 5. The approximately quadratic shape with an offset toward positive lift coefficients is characteristic for a cambered wing. The glider enters the stalled flow regime for lift coefficients above $c_L = 1.1$ and achieves a maximum lift coefficient of $c_L = 1.25$ at an angle of attack of $\alpha = 22.3$ deg. A minimum drag coefficient of $c_D = 0.078$ was recorded. The influence of the freestream velocity is negligible, which indicates a minor Reynolds dependency of the results. It also suggests that the structural deformations are relatively small, because the shape of the wing does not change with the increasing dynamic pressure. Figure 6 shows the lift over drag glide ratio E as a function of the angle of attack. The glide ratio forms a distinct maximum in the range $6.8 \leq \alpha \leq 9.2$ deg. Because of the limited number of measured angles of attack, the maximum glide ratio and the angle of attack at best glide can only be determined approximately. The maximum glide ratio $E_{\mathrm{max}} = 5.55$ occurs at an angle of attack of $\alpha = 9.3$ deg.

To assess the flying qualities in manned flight conditions, the lift coefficients required for pilot masses of $m_{\mathrm{pilot}} = 70, 80,$ and 90 kg are calculated using a lift curve, which is averaged across the three measured freestream velocities. The resulting trim points for an assumed flight velocity of $U_\infty = 11.5$ m/s are shown in Fig. 6. The trim angles of attack are located in the range $9 \leq \alpha \leq 12$ deg, well below the onset of stall and close to the maximum glide conditions. Lilienthal's reported weight of 80 kg results in a trimmed glide ratio of $E_{\mathrm{Trim}} = 5.3$ at an angle of attack of $\alpha_{\mathrm{Trim}} = 10.25$ deg, which is only about 5% below the best glide value. A previous investigation by Wienke et al. [14] on Lilienthal's first patented production aircraft, the Standard Soaring Apparatus, arrived at a trimmed angle of attack of $\alpha = 16$ deg at a significantly lower glide ratio below 4 for the same pilot mass and flight velocity. In

Table 1 Test matrix

Control input	Flow velocity, m/s		
	5	7	8.5
Rudder deflection Θ_0, deg	0	0	0
Rudder deflection Θ_1, deg	3.7	2.2	1.8
Rudder deflection Θ_2, deg	7.3	5.9	5.4
Rudder deflection Θ_3, deg	11.4	10	9.1
Elevator inclination η_0, deg	−11	−10.5	−9.5
Elevator inclination η_1, deg	−2.5	−2	−1.8
Elevator inclination η_2, deg	−22.8	−21.3	−19.6
Wing warping ww_0	±0	±0	±0
Wing warping ww_1	neg.	neg.	neg.
Spoileron deflection ϵ_0, deg	0	0	0
Spoileron deflection ϵ_1, deg	90	90	90
Leading-edge flap deflection κ_0, deg	0	0	0
Leading-edge flap deflection κ_1, deg	30	30	30

comparison, the best glide ratio of the Experimental Monoplane is about 40% higher, which is due to the considerably larger wingspan at identical pilot drag and horizontal stabilizer dimensions. It is questionable whether some experimental imperfections, such as the pilot dummy, which was slightly too small and without clothes, led to a bias toward higher values of the glide ratio. It is understood that the tests performed earlier with full-scale Lilienthal replicas delivered a higher accuracy. However, the main advantage of the Experimental Monoplane is its increased wing surface, which allows an 80 kg pilot to fly very close to the best glide ratio.

B. Stability

Because many early experimental aircraft designs were not stable with respect to their flight mechanics, the static longitudinal stability characteristics are discussed here based on the measured pitching moment curves. Several conditions have to be met in order to achieve steady, trimmed, and statically stable flight. The total mass of glider and pilot, along with the flight velocity, results in a trim angle of attack on the lift curve, which has to fall within the range of attached flow below maximum lift. At this trim angle of attack, the location of the combined center of gravity and the elevator incidence angle have to be chosen in such a way that the pitching moment around the combined center of gravity becomes zero. Such a flight condition is statically stable when the slope of the pitching moment curve around the combined center of gravity is negative, as it crosses the $c_m = 0$ abscissa from positive to negative pitching moments.

The Experimental Monoplane is controlled through weight shifts by the pilot and changes in the elevator incidence angle. An increasingly negative elevator incidence angle η shifts the pitching moment curve to higher values. As a result, the elevator can be used as a trim device before takeoff.

To give the pitching moment results a better context, they are now compared to data previously published by Wienke [16] for Lilienthal's preceding aircraft, the patented Standard Soaring Apparatus,

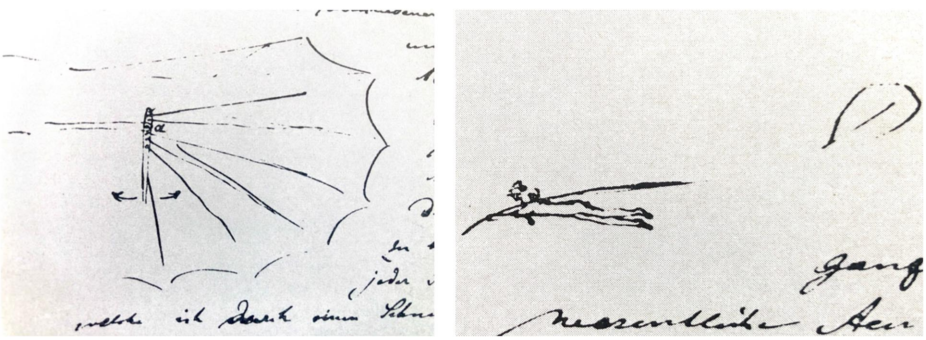

Fig. 3 Illustration of Lilienthal's wing warping mechanism (left) and the extreme pilot posture required (right) to counteract a diving flight attitude with weight shift control as sketched and described only in a letter (reprinted in part from O. Lilienthal: Letter to A. Wolfmüller, 1895/10/03, © archive Deutsches Museum München, Acc. 1932-1/11 source [15]: https://lilienthal-museum.museumnet.eu/archiv/objekt/15904).

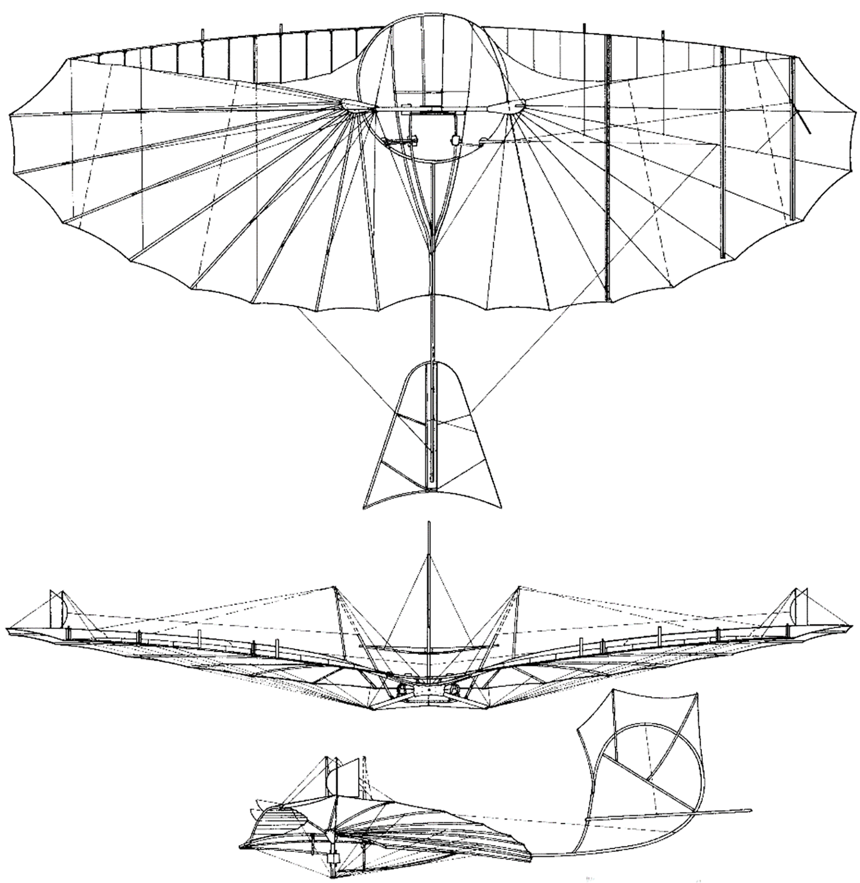

Fig. 4 Reconstruction drawing of the Experimental Monoplane (reprinted from [7], p. 104, © Archiv Otto-Lilienthal-Museum).

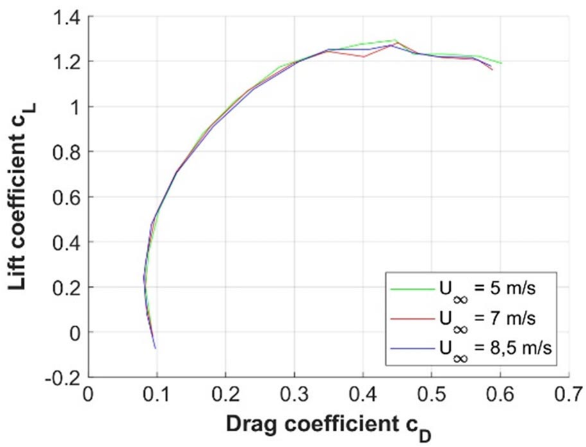

Fig. 5 Lift vs drag of the Experimental Monoplane with closed leading-edge flaps.

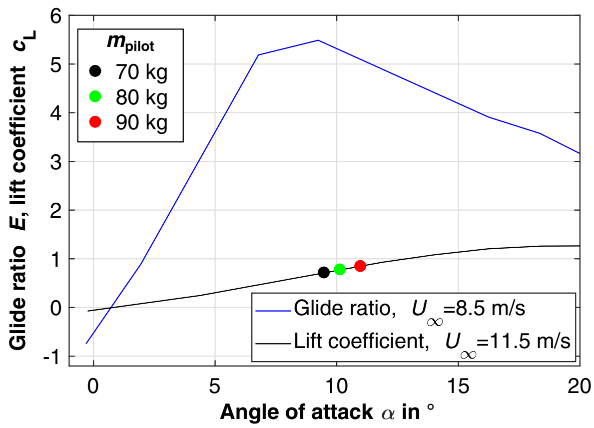

Fig. 6 Glide ratios and lift coefficients of the Experimental Monoplane with closed leading-edge flaps (dots indicate lift coefficients required for various pilot weights at 11.5 m/s).

trimmed for best glide ratio at $U_\infty = 11.5$ m/s. Figure 7 compares the pitching moments around the glide center of gravity for the Standard Soaring Apparatus with the results of the Experimental Monoplane at its most negative elevator incidence angle for both open and closed leading-edge flaps. The results of the present study are shown as linear approximations. They were derived from measured data of the attached flow region below $\alpha < 20$ deg in order to suppress measurement noise, which occurred when significant regions of the flow are separated.

The pitching moment curves of the two configurations are similar but exhibit different slopes and intersections with ordinate and abscissa. The zero-lift pitching moment coefficient c_{m0} at the zero-lift angle of attack of $\alpha = 0$ deg will be discussed first. The zero-lift pitching moment of $c_{m0} \approx 0.05$ of the Standard Soaring Apparatus is significantly higher than the one of the Experimental Monoplane at $c_{m0} \approx 0.03$ with closed leading-edge flaps of $\kappa_0 = 0$. From this lower zero-lift pitching moment, it follows that the pitching moment coefficients of the Experimental Monoplane are below those of the Standard Soaring Apparatus for the entire angle of attack range up to the trim angle of attack α_{Trim}. It can also be deduced that the slope of the pitching moment coefficient at the trim angle of attack is lower, which indicates less static stability. The zero-lift pitching moment of $c_{m0} \approx 0.05$ of the Experimental Monoplane with open leading-edge flaps of $\kappa_1 = 30$ deg is significantly higher and coincides with the one of the Standard Soaring Apparatus. This indicates similar statically stable flight characteristics for both aircraft in this configuration. Because of the more negative pitching moment slope at fully open leading-edge flaps, the trim angle of attack of the Experimental Monoplane for a given center of gravity is also smaller with the open configuration. The main frame position considered for the data analysis shown in Fig. 7 results in the trim angle of attack to be reduced from about $\alpha_{\mathrm{Trim}} = 17$ deg down to $\alpha_{\mathrm{Trim}} = 7$ deg. To fly the glider with open leading-edge flaps, the pilot would have to shift the center of gravity too far to the front for a sustainable pilot posture. However, the glider was flown with closed flaps that would only open automatically at very low angle of attack. Figure 8 illustrates the working principle of Otto Lilienthal's automatic pitch control system. The leading-edge flaps were pulled open by rubber bands, whose tension could be adjusted before takeoff. When the angle of attack was reduced, the direction of the net pressure force on the leading-edge flaps eventually changed from lift to downforce, which then opened the leading-edge flaps supported by the tension of the rubber bands. Figure 9 depicts color coded pressure coefficients and streamlines derived from two-dimensional computational fluid dynamics for closed (top) and open (bottom) leading-edge flaps. It can be seen that a closed leading-edge flap leads to a continuously higher pressure on the lower side of the wing and a lower pressure on the upper side. This indicates a relatively constant lift distribution in cordwise direction. For an open leading-edge flap, the flowfield shows a strongly increased lifting pressure difference on the leading-edge flap and a reduced lift force on the main wing due to the reduced pressure values on the main wing's lower side. The pitching moment is therefore considerably higher with an open leading-edge flap, at the price of a reduced overall lift and an increased drag.

The described consequences of the different flowfields can also be found in the measured wind-tunnel data and can be seen in the linear trend of the pitching moment curve as depicted in Fig. 7. This likely extends below the zero-lift angle of attack of $\alpha = 0$ deg, resulting in the open leading-edge flap to produce a higher, nose-up pitching moment than the closed baseline configuration. As a result, the opening of the leading edge adds a returning moment toward positive angles of attack. The beauty of Otto Lilienthal's approach to gain automatic pitch control by leading-edge flaps lies in their variable deflection. Once the right tension of the rubber bands is set, the pitching moment curve potentially displays both: the relatively high pitching moments at low angles of attack with open flaps and a trim angle of attack around $\alpha = 10$ deg to achieve the required lift with closed flaps. Measurements of the leading-edge flaps lever forces are depicted in Fig. 10. It can be seen that a (closed-flap) pretension of 0.4 N opened the flap at 6.1 deg during the wind-tunnel experiment and led to its automatic closing at 6.9 deg aircraft angle of attack. The applied spring rate of 5 N/m deflected the flaps sufficiently (28 deg with respect to closed position). Considering increased flap areas (25:1) and lever lengths (5:1), as well as the increase air speed (11.5:8.5) during the full-scale flight scenario, this leads to a required pretension of the four rubber bands of approximately 1.8 N each.

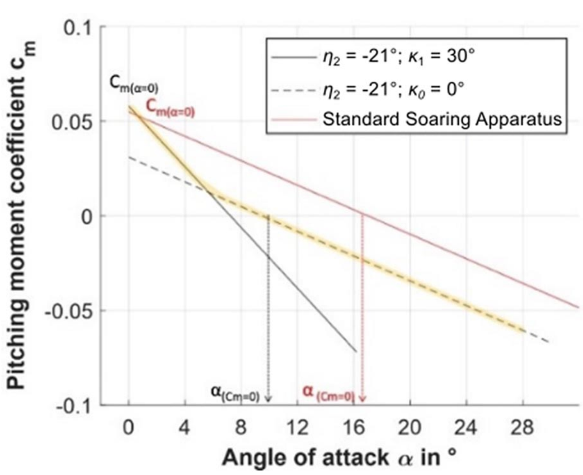

Fig. 7 Linearized pitching moment coefficient around the center of gravity of Standard Soaring Apparatus and Experimental Monoplane for two different settings of the leading-edge flap (at maximum elevator inclination) (partly adapted from [14]).

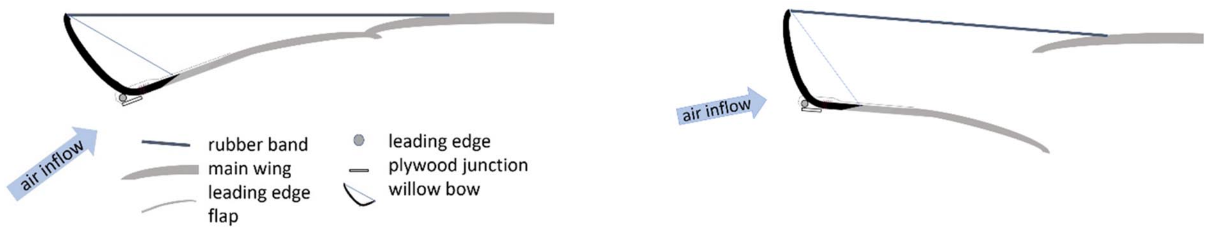

Fig. 8 Closed (left) and open (right) leading-edge flap positions depending on the angle of attack of the incoming flow.

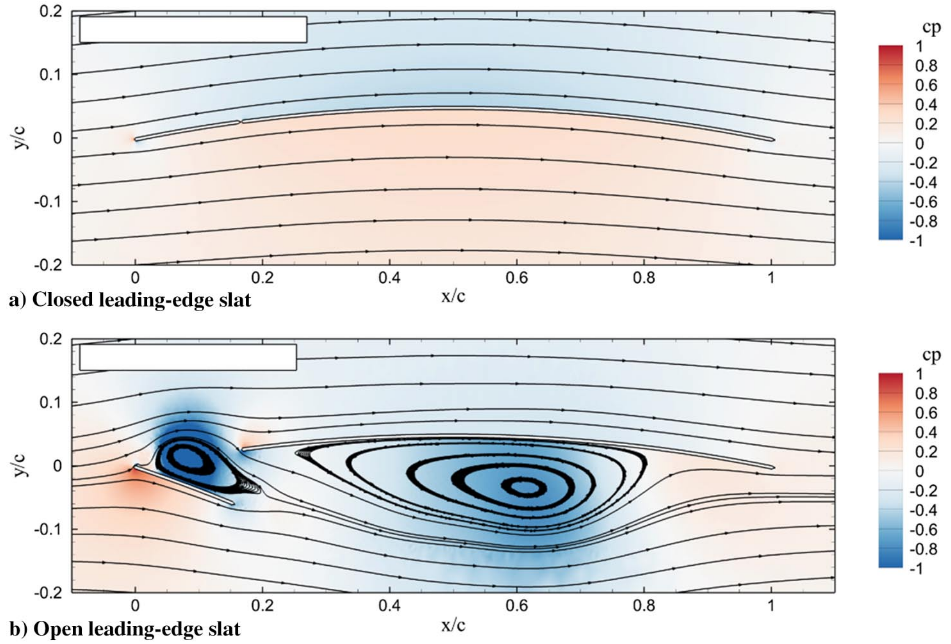

Fig. 9 Color-coded pressure coefficients and streamlines derived from two-dimensional computational fluid dynamics computations for closed (top) and open (bottom) leading-edge flaps.

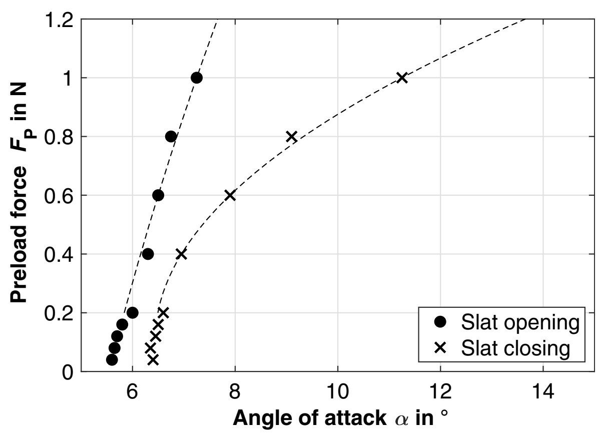

Fig. 10 Preload on leading-edge flap levers; spring rates 2 N/m (F_P < 0.2 N) and 8 N/m (F_P > 0.2 N).

Wind-tunnel and flight-test data of the investigated Standard Soaring Apparatus, the Large Biplane, and the large Experimental Monoplane all show that Otto Lilienthal managed to design flying machines that allowed stable flight within their individual flight envelope. The pitching moment data presented in this article demonstrate the potential of his invention for automatic pitch control and prove how well he understood the necessity to apply control surfaces to a monoplane with a wingspan of nearly 9 m in order to complement his type of weigh-shift control. However, the stability, which was even higher than in some later aircraft designs, was only present for flight attitudes in steady flight, which ensured largely attached flow on the wings. Once the aircraft stalled, the stability vanished, and the pilot had to react rapidly by shifting his weight to the rising front and, in case the stall occurred asymmetrically, to the rising wing's side. The reason for this limitation lies mainly in the design of the horizontal stabilizer and the tail. It was designed for flights in the vicinity of the ground and for flare landings, which were Lilienthal's preferred way of landing. In Lilienthal's American patent description from 1895, which describes the world's first serial production aircraft, the Standard Soaring Apparatus, he wrote the following [2]:

> "... on the latter is pivoted the tail in such a manner that it can freely turn upward, but finds downward a point of support on the fixed rudder. This mode of attaching the tail has the advantage that the tail will have no carrying action when the machine is employed like an ordinary parachute, thereby preventing from turning downward."

This ability of the horizontal stabilizer to freely turn upward and thereby to have no carrying action when the airflow acts from below is wonderful when flying in ground vicinity but can become deadly when flying at higher altitudes. In case of a flare landing, which is also commonly used with modern hang gliders, and stall that occurs near the ground, the result is a pancake landing, a vertical fall that sees the wings leveled and acting "like an ordinary parachute" [2]. However, high flight altitudes require the aircraft to start diving in order to accelerate and recover. On 9 August 1896, the day of his fatal crash at age 48, Otto Lilienthal flew his patented monoplane for the first time in several weeks, after concentrating on flying his Large Biplane in the meantime. At an altitude of approximately 15 m above ground, he was stopped by a wind gust and, in spite of his experience, did not manage to lower the rising leading edge of his left wing by weight shifting, as he had frequently done before. His deadly crash on that day confirmed the risk of flying at higher altitudes and outside the flight envelope at high angles of attack. His more than 2000 gliding flights, however, had shown the stability and safety of gliding flights in calm air and ground vicinity.

C. Controllability

Considerable measurement noise was introduced by the long sting, which connected the 1:5 model to the measurement balance in the initial test setup in the SWG. This caused difficulties with isolating the aerodynamic effects of the control devices. Only the yaw moments due to the deflection of the rudder could be extracted reliably. Therefore, a second test setup in DLR, German Aerospace Center's 1MG was devised to investigate the wing warping and spoileron effects. The right half of the existing 1:5 model was mounted directly on a force and moment balance and exposed to the flow through the wall of DLR, German Aerospace Center's 1MG. Yaw and roll moments were recorded for a single flow velocity of $U_\infty = 8.5$ m/s. In addition to the measurement noise, the elasticity of the scaled model introduced unwanted aeroelastic effects. This was resolved by replacing the elastic nylon lines, which braced the wing against the main frame, with steel wires. This change reproduced the elastic properties of the full-scale original more closely, which proved to be essential for capturing the effect of wing warping and spoileron deflection.

The analysis of the glider's controllability focuses on the roll and yaw moment coefficients resulting from the deflection of the control elements. The moments due to a deflection of the control elements were isolated by subtracting the results of the baseline configuration from the results of individually deflected control elements. It can be seen in Figs. 11 and 12 (x symbols) that adverse yaw occurs when wing warping is applied. For the depicted wing warping, the leading edge was pulled inward to reduce the wing's angle of incidence along its span, which decreases both lift and drag. The resulting roll and yaw moments act contrary to each other and have opposing signs in the investigated range of incidence angles from $6 \leq \alpha \leq 14$ deg.

The yaw moment coefficients for wing warping range from $c_n = -0.12$ to $c_n = -0.32$. The yaw moment coefficients of different rudder deflections are shown in Fig. 12 (□ symbols). For the investigated set of deflections, a larger magnitude in yaw moment can be reached with the rudder up to an incidence angle of about 14 deg. It could therefore be used to compensate for the adverse yaw of wing warping control actuation. The yaw moment curves depicted in Fig. 12 also show a lower effectiveness of the deflected rudder at the higher the angle of attack. This is caused by the increasing influence of the main wing wake at high angles of attack, which reduces the local flow velocity and therefore the side force generated

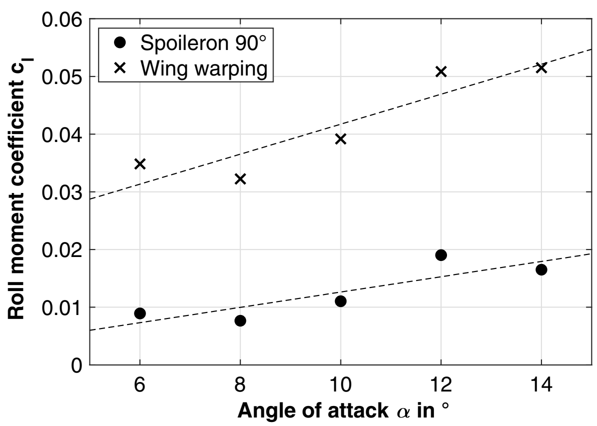

Fig. 11 Roll moment coefficients due to wing warping and spoileron deflection.

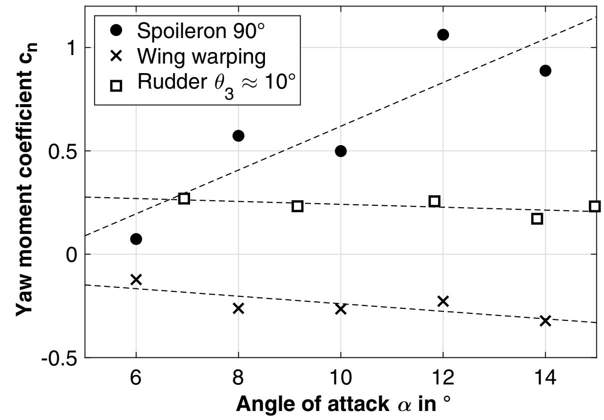

Fig. 12 Yaw moment coefficients due to wing warping and spoileron deflection.

by the deflected rudder. However, large rudder deflections in the range $10 > \Theta > 6$ deg create enough yaw moment to compensate the adverse yaw of the wing warping and should thereby allow for coordinated turns when a correct combination of rudder deflection and wing warping is applied.

When the spoileron is actuated, the lift decreases while the drag increases. As a result, roll and yaw moments with the same sign are created for a spoileron deflection of 90 deg relative to the flight direction, as shown in Figs. 11 and 12 (● symbols). This proverse yaw behavior, with the effects of roll and yaw acting in the same turn direction, may nevertheless require the additional use of rudder and, possibly, wing warping to properly coordinate turns because the required ratio between roll and yaw depends on the turn rate. Otto Lilienthal sketched an actuated elevator the day before his fatal crash (see Fig. 13), but, to the author's knowledge, this variant was not flown by him.

III. Flight Tests

In 2021, flights were performed at Jockey's Ridge State Park close to Kitty Hawk, North Carolina, in order to gain practice and first-hand experience with the exact replica of the glider. The effect of control surface actuation was limited for safety reasons by tethers attached to the wings. Although the wing tethers were frequently kept free of tension during the practice flights, they had to stabilize the glider during the early attempts to control the glider by actuating the control mechanisms via the hip cradle and in case of gusts. An additional towing line was used on several occasions to pull the glider forward when the slope of terrain in the wind direction was too shallow for pure foot launches.

Free downhill flights without any string or rope attached were performed by five test pilots (Andrew Beem, Billy Vaughn, George Reeves, and Jan and Markus Raffel) at Marina Beach State Park north of Monterey, California, in 2022. These flights lasted up to 7 s and

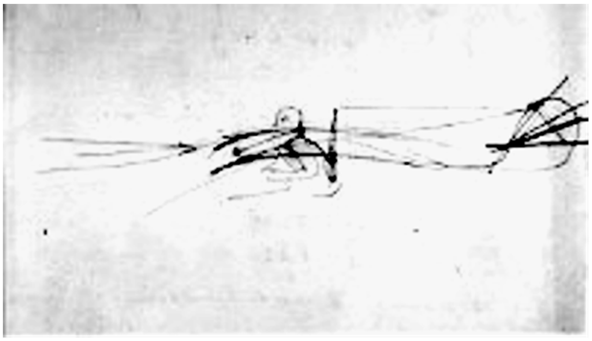

Fig. 13 Sketch for an elevator actuated by the pilot's lower back via lever and control wire [5] (reprinted from [7], p. 140, © Archiv Otto-Lilienthal-Museum).

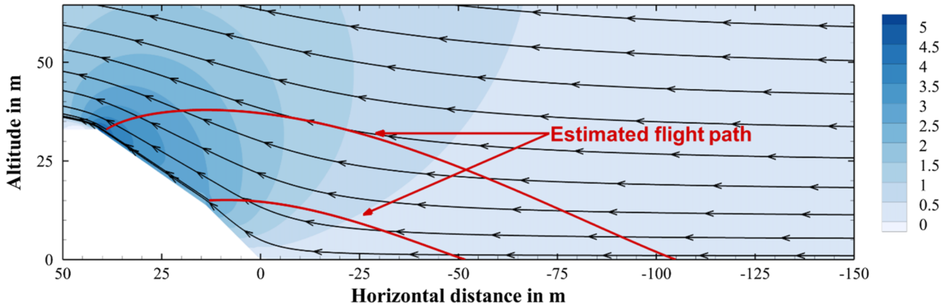

Fig. 14 Estimated dune cross-section and predicted wind situation at Marina Beach, California, with the vertical wind component shown as contours.

achieved flight distances of up to 72 m. For safety reasons, the majority of these free flights was performed with weight shift control only because the use of tethers was not possible due to the hill slope and flight altitudes. The launches with actuated controls focused on the investigation of the rudder and spoileron actuation via the hip cradle and were performed by Andrew Beem.

A two-dimensional computational fluid dynamics simulation of the flow over the dune for an onshore wind of 11 kt was performed in order to gain a better understanding of the site conditions. Figure 14 shows a simplified cross-section of the dune at the takeoff site along with the stream traces and the vertical velocity component resulting from the simulated wind conditions. In addition, two estimated flight paths are plotted in red. It is assumed that the glider travels at a flight speed of 11.5 m/s at a lift to drag ratio of 4.5. The deflection of the wind results in a strongly upward velocity component in front of the top of the dune. This provides additional lift to the glider and allows it to climb above the takeoff position under these idealized conditions. For the higher takeoff position near the top of the dune shown in Fig. 14, the vertical component of the flow over the dune lifts the glider above its takeoff altitude of 33 m and allows flight distances in the order of 100 m. The supporting effect of the wind is diminished when taking off from the lower position at 15 m. In addition, the glider experiences a gradual change from strong to weak vertical wind velocity along the upper flight path, which results in a slow change of the trimmed angle of attack. On the lower flight path, the wind velocity gradients are stronger, which requires a quicker change of the pilot's center of gravity toward the rear in order to prevent the glider from lowering its nose and entering a quick descent. It is concluded that the ideal takeoff position is close to the top of the dune. The possible flight distances under these idealized conditions also give an indication as to how high the takeoff position should be chosen in order to safely land on the beach and to avoid the shoreline.

Fig. 15 Practicing lateral and longitudinal control with limited control authority: tethered flight tests on the Outer Banks 2021.

Fig. 16 Otto Lilienthal flying his Experimental Monoplane on the Fliegeberg 1895 (photograph: R. Neuhauss, 1895, © Archiv Otto-Lilienthal-Museum).

Fig. 17 A flight with low angle of attack. Lilienthal is countering the dive by shifting his weight strongly backward (photograph: R. Neuhauss, 1895, © Archiv Otto-Lilienthal-Museum).

Fig. 18 A similar flight position, shortly before landing. Andrew Beem is turning the glider to flare by shifting his weight strongly backward.

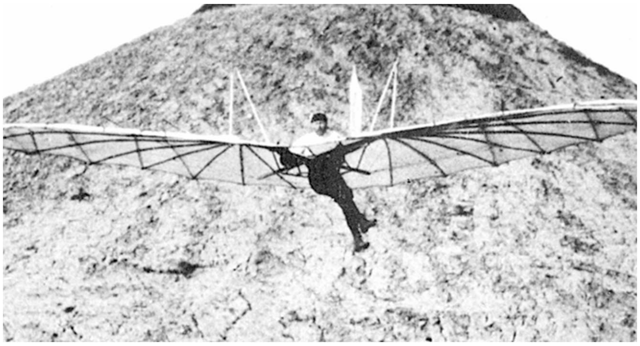

Fig. 19 Practicing yaw control with the rudder actuated via the hip cradle (Otto Lilienthal) (photograph: R. Neuhauss, 1895, © Archiv Otto-Lilienthal-Museum).

Fig. 20 Practicing yaw control with the rudder actuated via the hip cradle (Andrew Beem, 2022).

Lilienthal stated that for landing, similar to turning, the glider requires a counterintuitive pilot motion (see Fig. 3, right-hand side). He reported during his lectures and in his written flight reports that the pilot has to move his legs backward to pitch up and decelerate, even if his instinct advises him to position his feet forward when approaching the ground at higher speeds. However, the trim of the glider strongly influences this behavior. In the case of our test flights with the Standard Soaring Apparatus and the Large Biplane, it was sufficient to lean backward with the upper body and thereby transfer the weight of the whole body to the rear.

In comparison to the Standard Soaring Apparatus, the rearward weight shift of the Experimental Monoplane had to be much more pronounced because the leading-edge flaps were kept closed. All test flights featured the glider with firmly closed leading-edge flaps only, as the correct tension of the rubber bands for opening at the right airspeed was not measured at that time, and the complexity of the tests was limited for safety reasons. From time to time, this resulted in situations, in which the pilot had to shift his body weight drastically backward (see Fig. 18). Otto Lilienthal, quite obviously, made similar experiences during his flights in 1895, when he experimented with the automatic pitch control system (see Fig. 17).

The use of a deflecting rudder was successfully demonstrated by Otto Lilienthal in 1895. Figure 19 shows the lateral deflection of the rudder while Otto Lilienthal pushes the hip cradle to the left. This also results in a center of gravity shift, which causes a roll moment, whereas the resulting rudder deflection in the same direction produces a yaw moment and thus allows coordinated turns. The weight shift to the left by Otto Lilienthal and the rudder actuated by the hip cradle in the same direction can be seen in Fig. 19. The same feat was demonstrated by Andrew Beem in California in early 2022 (see Fig. 20). Wing warping was tested during a very limited number of short flights in the Outer Banks in 2021 but turned out to be a very difficult skill to acquire in just a very limited amount of time. The wing warping lever ends were connected to the main frame with tension locks during the majority of flights. This made it possible to trim the wings between flights, while they were not attached to the hip cradle.

IV. Conclusions

The scaled 1:5 model used during the wind-tunnel tests had a wingspan of 1.76 m. Balance tests showed that a freestream velocity of 11.5 m/s was sufficient to lift the glider plus a person of Otto Lilienthal's weight of 80 kg with a lift-to-drag ratio exceeding 5 : 1. The measured pitching moment coefficients, corrected for the influence of the pilot's weight and location, proved that the longitudinal stability of this glider was adequate across a wide range of incidence angles. As long as the flow is attached, the longitudinal flight stability is sufficient. Differences between the measurements of default configurations and activated control surfaces made clear that the wing warping generates adverse yaw. However, a simultaneously activated rudder has the potential to counteract this effect.

Lilienthal tested many modern control methods on his 1895 experimental aircraft: wing warping for effective roll control, rudder deflection for yawing, and the control of both by means of unilaterally actuated spoilerons (used later as the primary control, for example, on the *Easy Riser* ultralight aircraft). However, Lilienthal's experiments may not have had a direct influence on the later development of powered flight because he opted to not widely published them. The combination of rudder deflection and wing warping is the

Fig. 21 Trimmed flights of 72 m maximum distance without tethers; flight distances limited by high tide (Markus Raffel, Marina Beach, California, 2022).

control technique for which the Wright brothers received a patent in 1906 [17]. Because Lilienthal described the method in detail only in his private correspondence with Alois Wolfmüller and scientific publications merely proposed turning the wings along their longitudinal axis, it must be assumed that the Wright brothers developed the principle independently after reading the available literature of their days. In addition, the Wrights were the first to be successful in applying a well-tuned combination of wing warping and rudder control and to the mechanics of the biplane. They succeeded in designing, building, and flying an aircraft with three axis controls by a manually actuated elevator and by wing warping and rudder actuated simultaneously by a hip cradle in 1902. It might therefore be interesting to recall what they thought about Lilienthal's contributions to flight. In 1912, Wilbur Wright concluded his assessment on Lilienthal's progress in this respect with the following sentences:

> "Although he experimented for six successive years 1891–1896 with gliding machines, he was using at the end the same inadequate method of control with which he started. His rate of progress during these years makes it doubtful whether he would have achieved full success in the near future if his life had been spared, but whatever his limitations may have been, he was without question the greatest of the precursors, and the world owes to him a great debt" [18].

It is true that Otto Lilienthal had limitations and many other time-consuming responsibilities, like a family with four children, his own company with more than 30 employees, and a theater for members of his community, which he owned and operated. Nevertheless, he designed, built, and flew at least 12 different aircraft types in little more than five years, and, in contrast to the Wright brothers, who could rely on flight reports, aerodynamic data, and Chanute's biplane wing design, which had already been flown successfully years before their start, Lilienthal based his successes mainly on his own experiments. When Lilienthal attempted to build his first powered aircraft in 1893, the only automobile that was produced in series, the Benz patent motor car *Velo*, featured power specifications of 1.5 hp. In 1903, when the Wright brothers built their first powered aircraft, automobiles such as the Ford Model A already had five times the power (8 hp). It took the technical advancements of the preceding years, the talent of Charlie Taylor to build a 110 kg internal combustion motor with 12 hp, and some very advantageous weather conditions for the Wrights to fly in 1903. By 1908, the Wright Model A had 35 hp.

However, the rapid progress in the development of internal combustion engines was made years after Lilienthal's flight experiments. Therefore, Lilienthal flew mostly without or, in some limited cases, with a self-designed, super-light-weight two-cylinder carbon dioxide engine. At the end of his experiments regarding control methods, he stayed with the control method most adequate for hang gliders, which is still in use by tens of thousands of pilots today: the weight shift control [19]. In October 1895, Lilienthal wrote to Wolfmüller, "But in truth I am not convinced of these innovations—if the body is free to shift the center of gravity quickly enough, the same result can ultimately be achieved by other, simpler means. As always, practice remains key" [20].

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