Henrich Focke's Helicopter Design Lecture at the Technical University of Stuttgart, Winter Semester 1955-56

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ABSTRACT

The biography of Henrich Focke is well known and documented. From October 1954 to February 1955, he lectured at the Technical University of Stuttgart during the winter semester. He returned to Brazil to continue his contract work on the "Convertiplane" (a quad-tiltrotor aircraft) and the "Beijaflor" (a small single rotor helicopter). The topic of Focke's lecture in the winter semester 1954-55 was "Design of Fixed-Wing Aircraft", but the lecture manuscript of it is unavailable. In the following year 1955-56 Focke lectured about "Helicopter Design" and that manuscript was recently found in the central archive of DLR. It provides deep insights into the helicopter design philosophy of Henrich Focke.

1. INTRODUCTION [1]

Henrich Focke, born 1890 in Bremen, Germany, wrote his memoirs in 1977, shortly before his death in his hometown in 1979.(1) This autobiography was published in 1996.(2) Another source on Focke's life, especially focusing on his aircraft of fixed- and rotating-wing type, is found in Enno Springmann's book, which briefly mentions Focke's 1955 lecture.(3) A few paragraphs about Focke's professorship in Stuttgart from October 1954 through March 1956 are found in a book about his Kolibri helicopter developed at Borgward in Bremen.(4) These provide insight into Focke's time at the THS (Technische Hochschule—Technical University) Stuttgart. Much more insight into the events at Stuttgart are found in the Archive of the University of Stuttgart by a collection of letters and other documents.(5-8)

Surprisingly, the website about the history of the University of Stuttgart Institute of Aircraft Design is surprisingly vague about Focke's role: "However, for around six months after the end of the war, the aircraft designer Heinrich Focke was the 'provisional' head of the institute. However, he declined the appointment to the Chair in order to develop a two-seater light helicopter in Brazil."(9) The website does not specify when Focke was in residence, and notes that the institute was newly established as late as 1959, ie, several years after Focke left and Ulrich Hütter was assigned as its Chair. The true story is quite different.

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1. Presented at the Vertical Flight Society's 81st Annual Forum & Technology Display, Virginia Beach, VA, USA, May 20-22, 2025. Reprinted with permission by the author.

After the Second World War aeronautical work, both in manufacturing and research, was forbidden in Germany – except for fundamental research – and most experts in aeronautics were invited (or forced) to work abroad. Henrich Focke and his team initially started in France on the SE 3000 (a replica of the Fa 223 helicopter) and the experimental SE 3101 (using one rotor of the SE 3000 and a newly designed V-tail with two tail rotors inclined by 90º to each other) until 1948 when their contract ceased. During the next few years Focke returned to Germany and offered engineering services while privately developing plans for a runway-independent aircraft with two wings and four tilt rotors. This drew attention of a Dutch industrialist, and in 1951 Focke and his core team were hired for its design, then named "Heliconair". However, the investors could not bear the cost of building a prototype. In 1952 the Brazil Ministry of Aeronautics bought all rights from the Dutch investors, hired Focke and his team, which continued the work (then called the "Convertiplane") in the Centro Technico da Aeronautico in Sao Paulo. This facility was a mixture of a Technical University, a center of aeronautical research, and experimental testing of aircraft. In 1955 an order for design of a small two-seat helicopter "Beijaflor" followed.

The hot and humid climate in Brazil, especially during summer was detrimental to Focke's health and his contract included a summer leave to Germany where it was winter. In 1952 the ban on aeronautical manufacturing and research in Germany was eliminated, and in 1953 universities started to re-establish their institutes. The German Bundesländer re-opened their aeronautical research institutions, such as AVA Göttingen and DFL Braunschweig. In Baden-Württemberg several Ministries initiated support for aeronautical research and industry in an effort to attract helicopter research and manufacturing into the country. The founding of the DSH (German Study Society for Helicopters) at the Stuttgart airport in 1953 was a first step. Its director became Professor Dr Walter Just, Focke's employee until 1943. (DSH was on the next floor to Bölkow Developments, which in 1969 merged with the Messerschmitt and Blohm companies to form MBB, which became famous with the Bo105 helicopter.) Professor Just published three DSH Reports about helicopter aerodynamics as a first activity and lectured for many years on the subject at the THS beginning with the summer 1954 semester.[(10-12)] Focke, in his lecture notes, refers to the rotorcraft theory that the students had learned in one such summer semester.[(13)] The students benefited from the synergy of Just's theory and Focke's design philosophy using the example of a real helicopter, the Brazil "Beijaflor".

As a second phase of the Baden-Württemberg Ministries' aeronautical initiative, THS created a new institute of aircraft design (the name changed several times) and sought a Chair. The THS's Faculty of Engineering formed a selection committee and on February 24, 1954 unanimously voted for Focke.[(5a)] He had previous experience from 1933 as a university lecturer in aircraft design at the TH Bremen. Some members of the committee were his former students, and they recalled his excellent and didactically outstanding presentation style. In a March 8 letter to the THS Director, the Dean of the Faculty nominated Focke, adding a 10-page justification.[(5a)] The THS Senate concurred, and on March 9 the THS Director submitted the decision to the Ministry for Culture for approval, which on April 4 sent an offer to Focke in Brazil for appointment as Ordinary Professor and Director of the new THS Institute of Aircraft Design.[(5b)]

Focke (now aged 64) felt deeply honored but was initially hesitant to accept. In his May 14 reply he worried that his existing contract with Brazil's Ministry of Aeronautics (which had two years remaining) might be prohibitive and which he considered it immoral to cancel. Moreover, Focke would not give up his interest in aircraft design and construction. Despite the liberalization of aeronautical research and industry in Germany, actual construction and manufacturing had yet to follow suit. He also noted that he felt responsible for his Brazilian team of 18 leading German engineers. Would it be possible, Focke asked, for him to return to Germany once construction and manufacturing were more widely developed? If so, would it be possible to stay there only during the winter semester teaching helicopter design and manufacturing, complementing the helicopter theory lecture by Professor Just during the summer semester? Focke also wondered what would be the latest starting date (assuming the Brazilian contract issue could be amicably resolved), and what sort of budget the new Institute would have.[5c]

Focke managed to modify his contracts with the Brazilian Ministry and THS such that during the summer he would work at the Centro Technico da Aeronautico in Brazil and during the winter teach in Germany. At the end of October, he moved to Germany, starting his first lecture in the winter semester of 1954-55 on "Design of Fixed-Wing Aircraft". However, nothing was prepared both in terms of offices, an institute building, and his nomination as Ordinary Professor. Consequently, the Institute's initial offices were in a former barracks. By the spring of 1955 the lack of facilities remained unchanged. Discussions with the Ministry of Transportation and with the airport Echterdingen in February 1955 failed to produce a decision of a location, preferably close to an existing airfield and far enough from populated area.[6a, 6b] Suitable buildings were found at Echterdingen, but these required considerabe renovation. It took until April 28 before the certificate of the Ordinary Professorship to be signed by the Ministry, effective 1 May 1955.[5d] Focke departed for Brazil without having learning of it.[5m] Focke was paid only for the month of March 1955 instead of for the entire semester.

When Focke returned to Germany in September 1955 for the 1955-56 winter semester to teach "Helicopter Design", the situation remained the same: no clarification of the Ordinary Professor assignment, missing back salary, his pension, and still no final location for the Institute. A mass of letters, phone calls and in-person meetings, all of which over-stressed Focke's patience, produced no results. At least he had some office space at "Geschwister-Scholl-Str. 34" in the heart of the city, near the Rectorate of the University.

On September 23, Professor Siegel sent a letter to the THS Director containing plans for the "Institute Professor Focke", including a description of a building "next to a forest" consisting of a two-story 683 m² office building, including library, offices for assistants, doctoral students, Focke's office, meetings rooms, and a lecture room.[7a] A large 819 m² hall with a workshop was attached. A November 12 letter from Focke described the proposed site as near the "Pfaffenwald" area of Stuttgart (today the University campus and a DLR location are there) as suitable. He attached a sketch of the area including the buildings and even a whirl tower (see Figure 1). [7b]

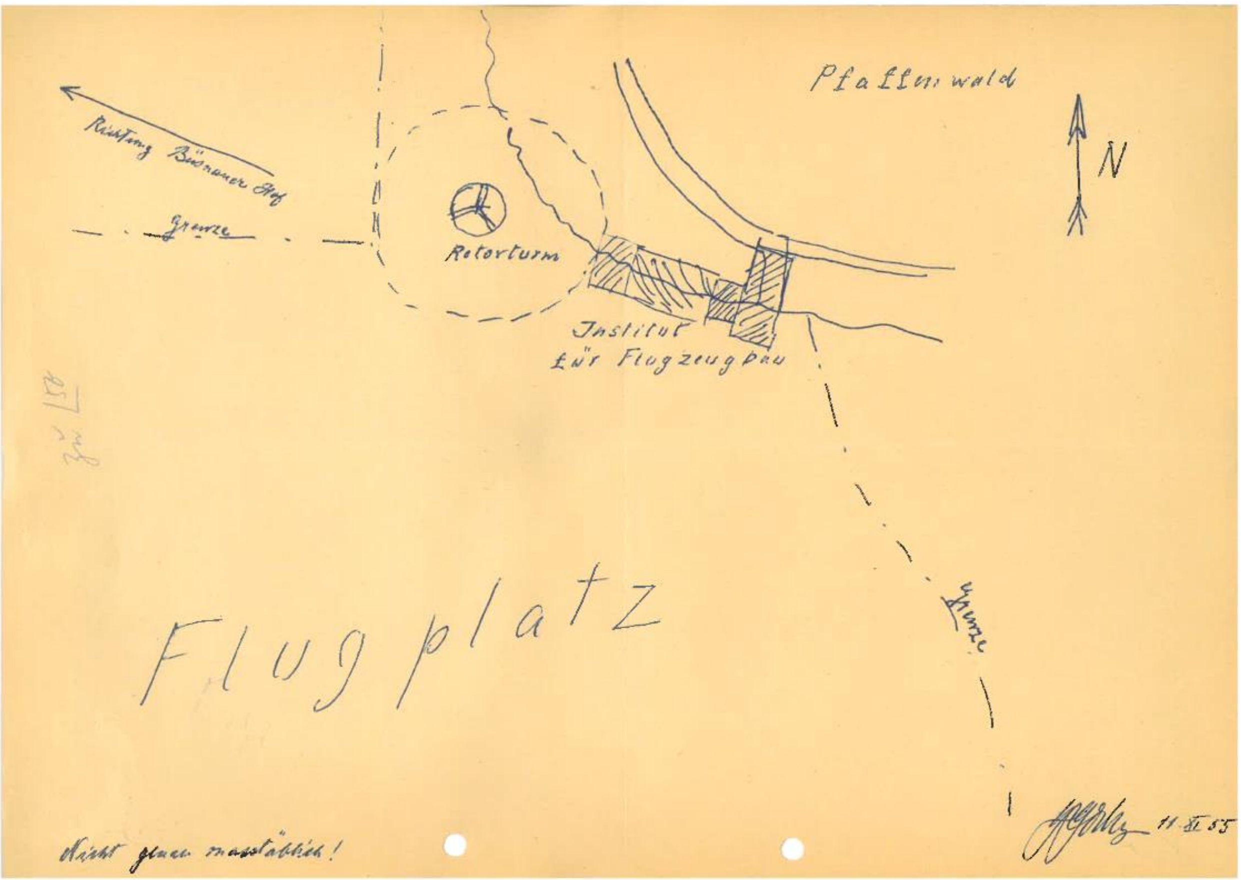

Figure 1. Sketch of the proposed Institute and whirl tower near Pfaffenwald

He emphasized that noise was to be expected and that his mechanic would apply special mufflers to the engine exhausts. However, he also expected to use jet engines in future with significantly higher noise levels, requiring a significantly farther distance from the populated area. Focke asked the Director for a commitment to progress as he expected it would take a few years to complete.

In the meantime, Focke was designing a helicopter as "flying test rig", the whirl tower, and a wind tunnel. He rented additional offices as the University had none, and requested a subsequent authorization by the Director on December 6, who submitted it to the Ministry for Culture on December 12. [8a, 8b] Unfortunately, nothing moved forward, and his certificate of assignment as Ordinary Professor was not signed until June 9, 1956, almost two years after his start as lecturer in 1954.[5e] In April 1956 Focke returned to Brazil disappointed without any knowledge regarding his status at the THS, the promised institute, his salary, or his pension.

Sometime in spring of 1956, the car manufacturer Borgward approached Focke with the offer to design a "Volks-Helicopter", similar to the successful "Volkswagen". Although Focke liked the work with the students at THS as well as the practical work of designing a helicopter again, after balancing all the unsolved issues of the THS (not least of which was being largely unpaid for his work there) with the new opportunities offered at Borgward he chose to transfer his efforts to Borgward in May.[3, 4] In a June 14, 1956 letter to the Ministry for Culture, he announced that he had taken another job in Germany, stressing that he had not been paid DM 10,500 for the 1954-

55 winter semester, had received just a single payment for March 1955, and he could barely pay the cost for the flights to Brazil and back.[5f (1)] A second letter to the THS Director provided more details of his unsuccessful attempts to resolve these issues with THS and the Ministry.[5f (2)]

Thereafter, the dispute accelerated, starting on July 5 with the THS Director's refusal to accept Focke's resignation.[5g] By October 4, the Ministry for Culture issued a Certificate of Dismissal for Focke, declaring the salary period to be paid from October 1, 1955 to March 31, 1956. Professor Madelung was nominated as provisional head and Chair of the Institute of Aircraft Design effective from August 6, 1956.[7c] The Stuttgart Institute of Aircraft Design was officially established in 1959 with Ulrich Hütter as its Director.[9]

Beginning August 1, 1956, Focke and his team developed the "Kolibri" helicopter at the Borgward company in Bremen that showed many features of the "Beijaflor" from Brazil. Borgward also allowed Focke to continue his work overseas, and the design of the Borgward-Focke Kolibri took shape. A day before its certification flights planned for February 1, 1961, Borgward became bankrupt, and the work on the Kolibri stopped and Focke, now age 71, retired soon after.[1 - 4]

2. HENRICH FOCKE'S HELICOPTER DESIGN LECTURE 1955-56

The lecture manuscript is in the form of a 123-page typewriter manuscript with 104 pages of text and hand-drawn sketches and 19 pages of graphs, many of which can be found in former Focke publications.[13] Photographs were mentioned by Focke, but they were only shown as slides. All following content is from this source material, so no further references are made to it. Some calculations for the design of components, eg, the engine cooling fan, reveal surprising inaccuracies when re-calculating them. These can be attributed to rounding error only in part; for example, Focke states a rotational frequency of 520 rad/sec and a rotor radius of 0.25 m to be 150 m/sec instead of 130 m/sec, a 15 % error. It must be kept in mind that in the early 1950s all computations were carried out manually using books with tables of mathematical functions such as logarithm, square roots, trigonometric functions, etc. Mechanical calculators for fundamental operations were available, but the most important computing tools were still paper, pencil and the slide rule. Focke uses the "German notation" of symbols used in equations, the conversion to today's symbols is given in the Appendix.

2.1 Introduction and History of Rotorcraft

It was by no means clear 50 years ago which of the dynamic types of flight would initially win the battle for the practical realization of vertical flight.[14] In 1955 helicopters were still very rare in Germany. Conceptually, helicopters were illustrated via an instructional sketch of two fixed-wing aircraft tied together by a 1km rope, flying in circles around each other without a rolling angle ϕ (Figure 2).

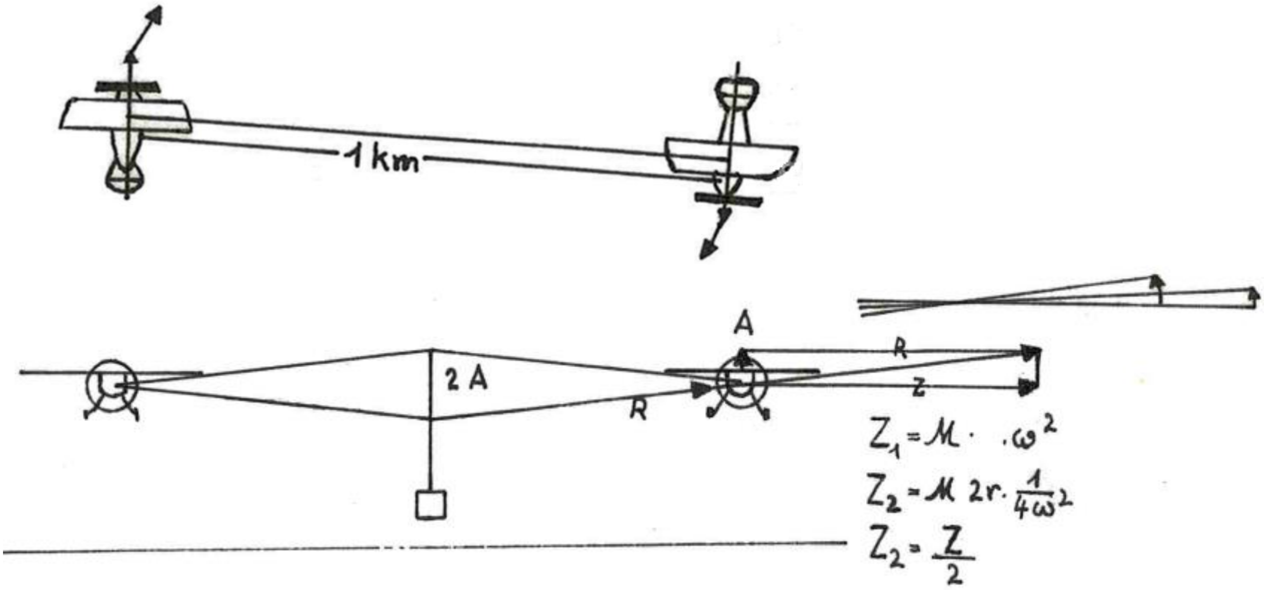

Figure 2. Two fixed-wing aircraft tied together by a rope.

An unrestrained aircraft has to keep a roll angle ϕ during the circular flight, so its lift must be greater than its weight by $1/\cos\phi$. When tied together as in Figure 2, the lift always equals its weight because the rope takes on the centrifugal forces of $Z = Mr\omega^2$. When fixing the rope's center point to the ground, the two aircraft resemble the equivalent of a two-bladed rotor of a helicopter. In this example, Focke assumed the individual aircraft's mass to be 2 tons and the aircraft flew at 360 km/h, resulting in a centrifugal force of 4,000 kg. Now let each aircraft have 1/5 of its weight as excess lift, so the balance of centrifugal force and excess lift results in a rope angle of about 6 degrees relative to ground, similar to the flapping angle of a helicopter rotor blade. This example illustrates Focke's approach to teach students the physical principles of the rotating-wing aircraft by means of simple physics already known from fixed-wing aircraft.

There is another, and in principle almost simpler, way to get from the fixed-wing aircraft to the helicopter; the so-called "Nasoben", or "nose-up" system, developed as early as 1910 by its spiritual creator Ferdinand Bendemann, an early 20th-century German engineer and scientist (Figure 3). He noted that it should have 2 counter-rotating screws to balance the torque and an overpowered engine. Vertical take-off fighters from Convair and Bell suggest that Bendemann was a good prophet.[2]

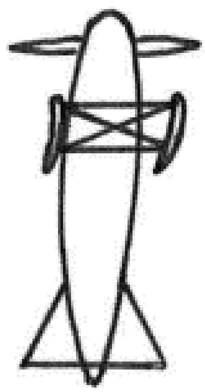

Figure 3. Bendemann's vertical take-off airplane.

2. For example, the Lockheed XFV-1 *Salmon* (1953), Convair XFV-1 *Pogo* (1954), or Bell Model 65 ATV (1954). Articles in WW1 Aero magazine are at https://www.secretprojects.co.uk/threads/dvl-bendemann-vtol-aircraft.24198/

Focke's lecture continued with a historical review of helicopters and photos of them (only shown by slides), beginning with Leonardo da Vinci and followed by those of Louis Breguet, Paul Cornu, Alphonse Papin and Didier Rouilly, István Petróczy/Theodore von Kármán/Vilém Žurovec, and Henry Berliner, all accompanied by a brief list of their deficiencies. Focke concluded by another list of more serious approaches between 1922 and 1933 by George De Bothezat and Ivan Jerome, Étienne Oehmichen, Raúl Pescara, Juan de la Cierva, Christian Hellesen and Louis Kahn, Albert Von Baumhauer, Oszkár Asboth, Corradino D'Ascanio, Breguet, and Nicolas Florine, concluding with the Focke-Wulf Fw 61, the first practical, fully controllable, and safe helicopter that was certified and which flew thousands of kilometers, while most of the other vehicles never left the experimental airfield.

Focker also mentioned the Flettner Fl 282 as a practical and successful vehicle at the end of the 1930s and highlighted the Focke-Achgelis Fa 223 as the largest machine of the time that got its type certificate in 1942 with series production thereafter. He then highlighted the most important post-war developments, including the Bell 47 and 61, Bristol 171 and 175, Hiller UH-12B, Kaman HTK-1, Piasecki YH-16, Sikorsky S55 and S56, SNCASE SE.3120, and SNCASO SO.1221. Focke concluded this historical parade with the Focke-Achgelis Fa 269 (Focke's tiltrotor concept of 1944), his "Convertiplane" (under development in Brazil) and the Transcendental Model 1-G.

2.2 Design, construction and manufacturing of rotorcraft

2.2.1 Main Rotor

Focke emphasized the importance of theory and comparison of its results with measured data from the wind tunnel and experiences from flight testing. While theory (the foundations of it were taken as granted) provides logical results on grounds of physics with many simplifications, its results must be triple-checked with data in order to come up with reliable coefficients.[3] Usual equations for thrust, torque and power of a propeller were given using thrust, torque and power coefficients based on $\rho/2$ instead of ρ as used today.[4]

$$S = k_n \frac{\rho}{2} F u^2 \qquad M_d = k_d \frac{\rho}{2} F R u^2$$
$$N_{req.} = M_d \omega = k_d \frac{\rho}{2} F u^3 \qquad u = R\omega \tag{1}$$

3. A lecture on helicopter aerodynamics which addressed this was given by Professor Just DSH during the 1954 summer semester at the THS
4. The notation $\rho/2$ is standard in fixed-wing aerodynamics. From 1908-33 Focke designed fixed-wing aircraft and therefore kept that notation for his rotating-wing developments. Just was supervisor of the aerodynamics group of the Focke-Achgelis company from 1938-43. Gunther Reichert was one of Just's students and was acknowledged as one of the "fathers" of the successful MBB Bo105 helicopter. In 1983 he became a lecturer at TU Braunschweig, still using this notation.

Here, $S \approx G$ = thrust or weight (German: Schub, Gewicht); $k_s \approx k_n$ = thrust or normal force coefficient; F = rotor disk area (German: Fläche); M_d = rotor torque (German: Drehmoment); k_d = torque coefficient; R = rotor radius; $N_{req.}$ = required rotor power; ω = rotational frequency; u = blade tip speed (German: Umfangsgeschwindigkeit). The unit of forces was given in kg instead of Newtons, moments in mkg instead of Nm, power in mkg/sec instead of Nm/sec. The difference is the gravity constant $g \approx 10$ m/sec².

Theoretically, from equation (1), for infinite F an infinite weight could be lifted by very little power.

Focke outlined the practical limits of this result (1) the maximum possible radius due to material strength and rotor weight increasing by the cube of the radius, and (2) the maximum blade tip speed due to adverse compressibility effect on airfoil drag and hence rotor power (Figure 4). The limit is about 230 m/sec (Mach 0.67) at sea level and less with increasing height above ground due to decreasing temperature and the speed of sound.

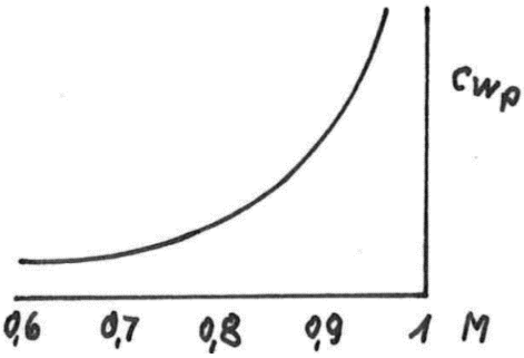

Figure 4. Compressibility effect on drag coefficient.

The hovering figure ζ_L given in equation (2) (instead of today's FM) in Focke's words "compares the desired (= thrust) with the unavoidable (= power)", similar to the glide (or lift/ drag) ratio C_l/C_d in fixed-wing theory because based on energy considerations given the ratio $C_l^{3/2}/C_d = \xi$.

$$\zeta_L = \frac{k_n^{3/2}}{2k_d} \qquad (2)$$

His interpretation of the ζ_L is the comparison of the power contained only in the axial direction of the rotor slipstream with the power transmitted by the rotor shaft. Losses due to swirl in the slipstream are mentioned as usually small and mostly negligible. ζ_L depends on blade shape, pitch angle, airfoil and its surface, but not on overall dimensions or power supplied. In order to become independent of helicopter size, the thrust in equation (1) is divided by the disk area and the power by the thrust or weight. The resulting power loading versus disk loading is shown as a graph in Figure 5 for the ideal rotor with $\zeta_L = 1$ and a real rotor with $\zeta_L = 0.675$, based on wind tunnel and flight tests of a 3-bladed rotor with taper ratio 2:1, a twist of -4 degree/R and NACA 23014 airfoil. One quantity will fall when the other rises.

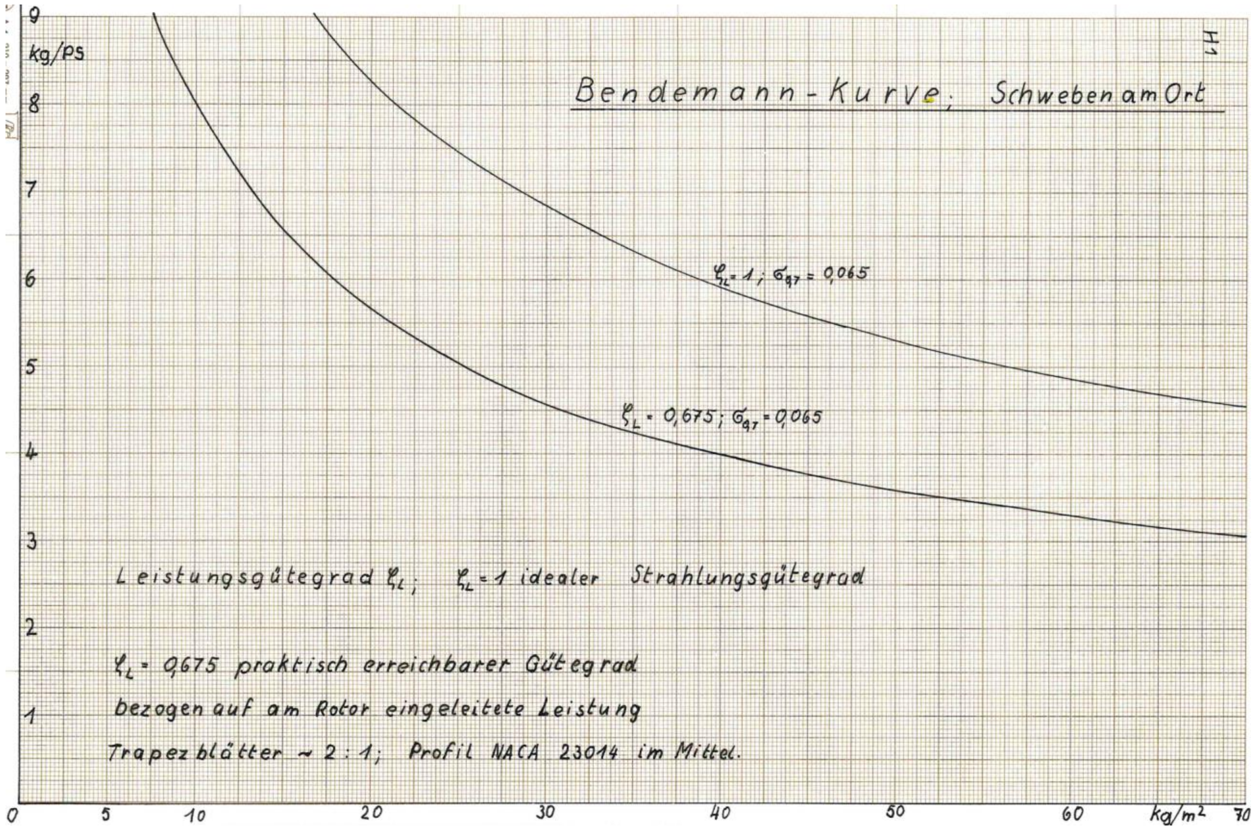

Figure 5. Bendemann-curve of an airscrew at zero flight speed (= rotor in hover) for different ζ_L.

In order to continue the theory as a practical example for a fixed-wing aircraft, Focke introduced the design goal as a small single-engine two-seat helicopter for use in Brazil, the "Beijaflor".[5] Its maximum takeoff weight is $G = 900$ kg, the rotor diameter is 9 m ($F = 64$ m², $S/F = 14$ kg/m²), and the emergency landing speed is $V = 45$ km/h $= 12$ m/sec. The required autorotating rotor lift coefficient then results in about $c_l = 1.4$, well between measured stationary values of 1 and 2 during unsteady maneuvers. From Figure 5 a power loading of about $S/N_{req.} = 6.8$ kg/HP can be allowed and the shaft power required in hover amounts to $N_{req.} = 900/6.8 = 134$ HP. Additional losses include engine cooling, gear box losses, hydraulics, avionics and other electric consumers, torque compensation rotors and their gears, as well as the influence of height above ground. Further requirements are a climb speed of 1-2 m/sec minimum and hovering capability at 1,500 m above sea level. Including all those, an engine power of 225 HP would be needed.

2.2.2 Additional losses

a. Engine cooling and losses of the drive train

Focke placed special emphasis on cooling and the power required to drive the ducted cooling fan. He derives the air mass flow required for the amount of engine power given above for cooling air by 28°C, resulting in 8.2 HP. When including the dual drivebelt (for redundancy = safety) losses,

5. This refers to Focke's first lecture "Design, Construction and Manufacturing of Fixed-Wing Aircraft" in the winter semester 1954-55

a total of 9 HP is assumed for cooling provided the design incorporates clean aerodynamic engine air inlets and outlets.

The detail design of the cooling fan is treated next, with application of blade element momentum theory. It includes the account of high lift coefficients near the hub due to centrifugal force effect on the boundary layer. The fan diameter is chosen as 0.5 m and a numerical example is given for two different RPM values.[6] Focke emphasizes that for the workshop, only 3-5 radial sections should be given in terms of pitch angle, chord length and airfoil because the craftsman will then take care of the smooth curvature from root to tip on his own. Finally, he refers to reference 15 that includes all these plus tip gap effects.

Focke warns that "we would not be good engineers if we do not account for the extent of the consequences of our simplifications and neglect."

He addresses the swirl at the fan blades due to the circumferential momentum added to the air by the backwards-tilted blade element lift (Figure 6). It reduces the in-plane velocity component, modifies the resultant velocity magnitude and direction, and hence the section airfoil angle of attack.

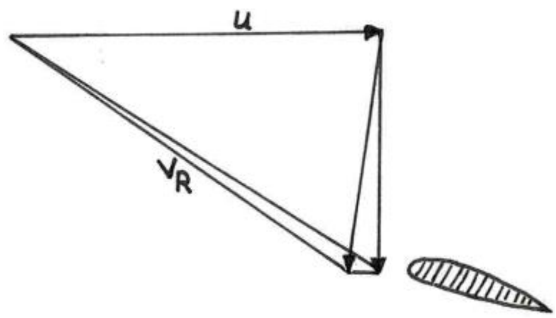

Figure 6. Velocity triangle without and with swirl.

The best method of cooling suggested by Focke is entirely without a fan by using an exhaust ejector (Figure 7 – see reference 16). Because most of today's engines come with a cooling device from the manufacturer, we need not care about its design, and the shaft power data already accounts for its losses. The power balance so far: Engine 225 HP – Fan 9 HP = 216 HP.

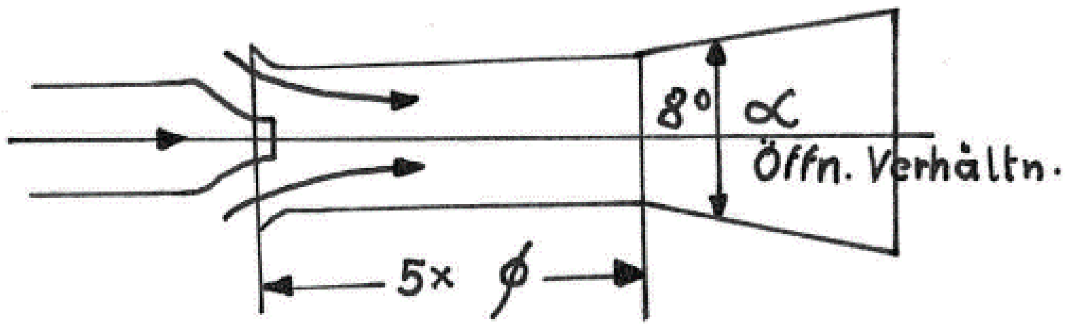

Figure 7. Velocity triangle without and with swirl.

b. Gear friction, couplings

Based on a 2-row 18-cylinder reciprocating engine the RPM reduction ratio of about 10:1 between motor and rotor requires a 2-stage gearbox. Turbines (which are much lighter but also

6. In this section of the manuscript, a number of computing errors cause erroneous results far beyond rounding errors

consume more fuel) require more, but they include a gearbox already and at their output shaft a reduction of about 10 is needed. A one-stage gear is judged as not useful because gear wheel diameter ratios above 3 are unsuitable for cylindrical gears and even more so for bevel gears. Undercutting at the tooth root, high local surface pressures and unfavorable friction path conditions when the teeth slide against each other impair safety against pitting and pressing, as well as efficiency and service life. Hardening distortion of tooth surfaces requires careful grinding, and small remaining disparities lead to "whining" from rotational noise as consequence of unwanted de- and accelerations, causing wear and service life. Therefore, Focke selected a 2-stage gearbox which (using the example of the Fa 61 and Fa 223) was even spatially separated (Figure 8).

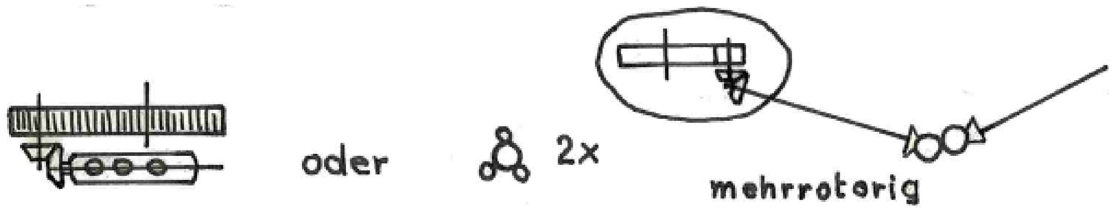

Figure 8. Two-stage gear in one or 2 locations.

Focke judges the loss of the best possible gear box at 1% of the power input per stage, but accounts for manufacturing tolerances in the order of 0.01 to 0.001 mm (considered as not very precise manufacturing) which leads to 4% as conservative estimate. For the example helicopter, 4% of 216 HP = 8.8 HP. Engines are elastically mounted. The connection to the gearbox and bearings of the rotor shaft cause additional friction due to their elasticity and oscillations. Altogether, they consume a little amount of power, rounding the above to 10 HP. Power balance: $216 - 10 = 206$ HP.

c. Auxiliary devices

Hydraulics and provision of electricity for equipment were estimated to be 2 HP for this small helicopter. New balance: $206 - 2 = 204$ HP.

d. Tail rotors: "the big chunk of losses"

The two tail rotors of Focke's example helicopter must provide the full main rotor torque compensation at takeoff power plus some margin for yaw control. To avoid collision of main and tail rotors they must be sufficiently separated (Figure 9). Since main rotor torque requires the knowledge of the main rotor power, which is not yet known, an estimate for it must be made then the tail rotor power can be calculated, compared with the power balance and the estimate for the main rotor, and iterated until convergence is obtained. Focke assumes 175 HP for the main rotor.

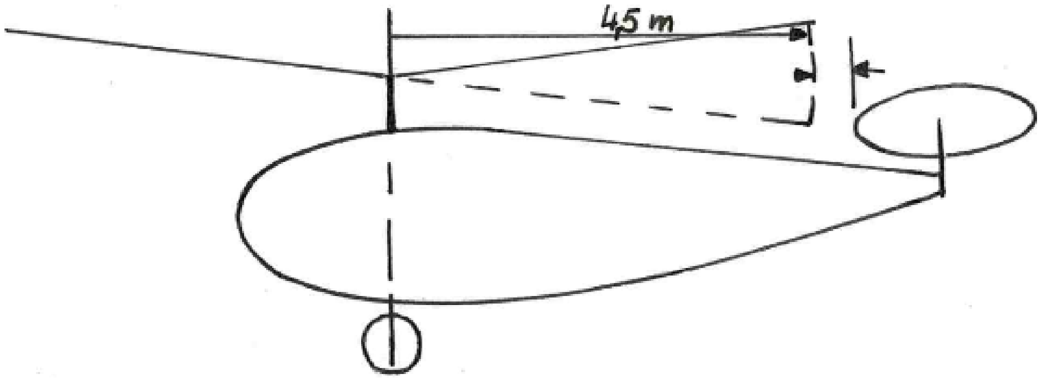

Figure 9. Estimation of main and tail rotor separation.

With a main rotor radius of $R = 4.5$ m and some additional space to the tail rotors they have a distance of 6 m between their rotor centers (Figure 9). To compensate, the maximum torque at takeoff power (175 HP), combined with 300 RPM ($\omega = 32$ rad/sec) of the main rotor results in a torque of $M_R = 415$ mkg, leading to a side force at the tail of $415/6 = 69$ kg. Adding a small contribution of 9 kg for yaw control results in a total side force of 78 kg.

A single horizontal axis tail rotor would do that job but does not provide any damping in pitching motions of the helicopter which is essential for the helicopter's steady and dynamic stability. Therefore, Focke had in 1938-39 already invented and patented the twin tail rotor arrangement as shown in Figure 10.[17,18] In this arrangement the tail rotors represent lifting surfaces both in vertical and horizontal direction, just as a conventional aircraft's elevator and rudder serve all three functions: torque compensation, elevator, rudder.[7] The streamlines indicate the flow deflections for different control purposes and are also shown in Figure 10.

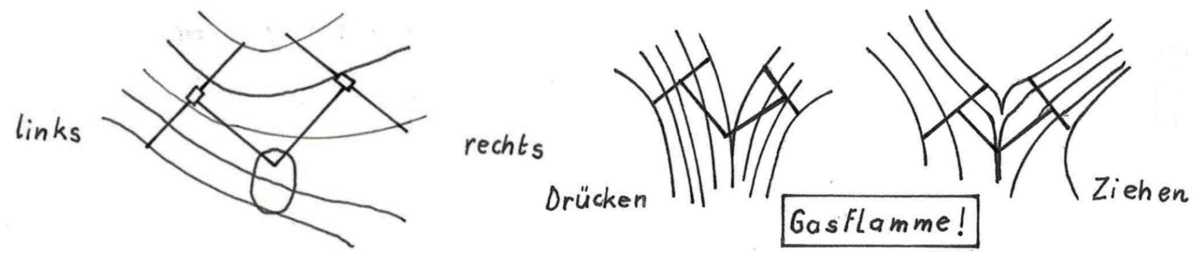

Figure 10. Twin tail rotor, left: in hover (differential collective), center: stick forward (collective up), right: stick back (collective down).

Measurements at the "Beijaflor" have shown that the efficiency in torque compensation (left sketch in Figure 10) is better than a single rotor because the left rotor sucks from the upper left and blows to the lower right, while the right rotor sucks from the lower left and blows to the upper right. The interference with the other rotor's wake increases the efficiency to 0.8, instead of 0.7 of the individual rotor. When pushing downward on the control stick, both tail rotors generate upwards lift and the aircraft experiences a larger nose-down pitching moment than from a single rotor with vertical axis due to slipstream interference (collision of both, center sketch).

7. Except for the Focke helicopters, all other manufacturers use horizontal tail rotors and must add an elevator and fin for getting sufficient longitudinal and lateral stability.

Pulling the stick upward causes the two wakes to diverge from each other (right sketch) and the effect is less. Assuming a power loading of 5 kg/HP results in a disk loading of 25.5 kg/m² (Figure 5). Accounting for the lateral tilt of the tail rotors, a conservative estimate for the individual tail rotor thrust is $78/2 \cdot \sqrt{2} = 56$ kg of thrust. The disk area becomes $56/25.5 = 2.18$ m², resulting into a diameter of 1.65 m and a power consumption of 2 x $56/5 = 22.5$ HP altogether.

As with the main rotor, the tail rotors consume power due to their gear boxes and shaft transmissions, bearings, etc. Due to the higher rotational speed of the small diameter tail rotors (in our example: the ratio of diameters is 9 m to 1.7 m = 5.3 = equivalent to one stage of a gear box), a 1-stage gearbox is sufficient (adding 2% of 22.5 HP = about 0.5 HP), resulting in 23 HP of the tail unit. Power balance: 204 – 23 = 181 HP.

This leaves a margin of 6 HP to the estimated main rotor power of 175 HP, but this margin will not be fully available because now the torque to be compensated is a little larger. Increasing the tail rotor's diameter to 1.7 m still leaves a space of 0.65 m between the main and tail rotor blade tips (Figure 9) and increases the tail rotor total power by 3 HP, such that the power balance becomes 178 HP.

Climb ratio at sea level

The main rotor alone requires 134 HP as calculated before, leaving an excess power of $178 - 134 = 44$ HP = 3300 mkg/sec excess power for vertical climb. Division by the helicopter weight of 900 kg results in a climb speed of $V = 3.6$ m/sec, much larger than the 1-2 m/sec required. This is a very important measure for climbing performance, ceiling height, climb times and all parameters depending on it. Focke notes that some published theories predict a higher climb rate due to a factor of 2 involved, which becomes problematic for lower values of excess power, although he never experienced this in practice.[8]

Tip speed of main and tail rotors

The proper selection of rpm and with it the blade tip speed is a matter of principle, so we must be at the best point of $\zeta_L = k_n^{3/2}/(2k_d)$, equation (2). He recommends not to calculate thrust and torque coefficients k_n and k_d but use test curves, e.g. from Walchner, to find ζ_{opt}.(19) Then, within the limits of the airfoil polar, we can trade the number of blades z and the blade area f (or, when the radius is already given, the chord t) for the lift coefficient c_a, as all affect the thrust linearly in attached flow. t and z are combined in the representative solidity $\sigma_{0.7}$, equation (3)

$$\sigma_{0.7} = \frac{z \cdot t_{0.7} \cdot R}{R^2 \cdot \pi} \qquad (3)$$

It is practical to use $k_n/\sigma_{0.7}$ instead of k_n for ζ_L as it provides the insight as a c_a related to the blade area f_{blade} (Focke called it "Just formula") and then compare calculation with experimental

8. This happens when including only induced and climb power of the rotor but ignoring the parasite power of airfoil drag.

data.[10 - 12] Focke points out the important influence of the Mach number M, and uses charts to estimate the best RPM for given radius, take-off weight and blade design. Figure 11 summarizes ζ_L data from theory and various measurements, including different tip Mach numbers.

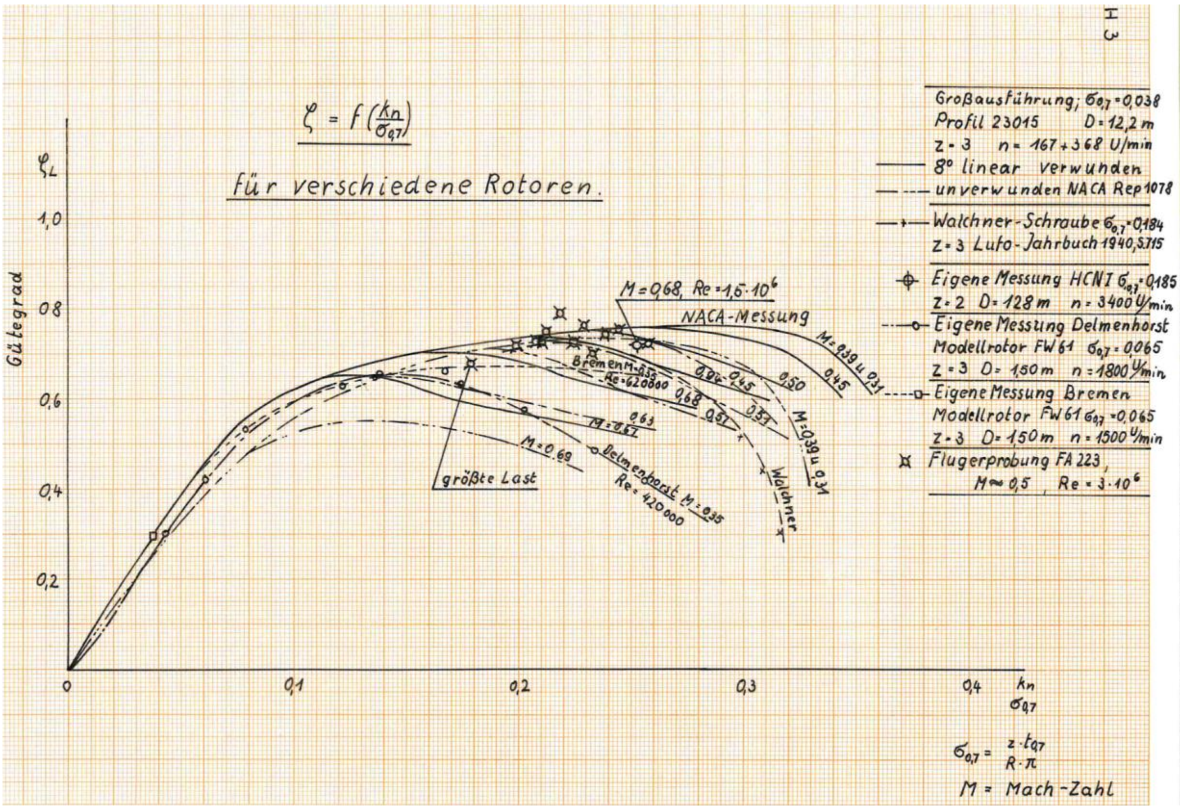

Figure 11. Figure of merit versus specific blade loading $\boldsymbol{k_n/\sigma_{0.7}}$.

The airfoil influence essentially is its drag coefficient growing with its thickness, and hence the calculated parasite power must be corrected proportionally. Also, the influence of solidity on ζ_L is proportional for a wide range of k_n (Figure 12).

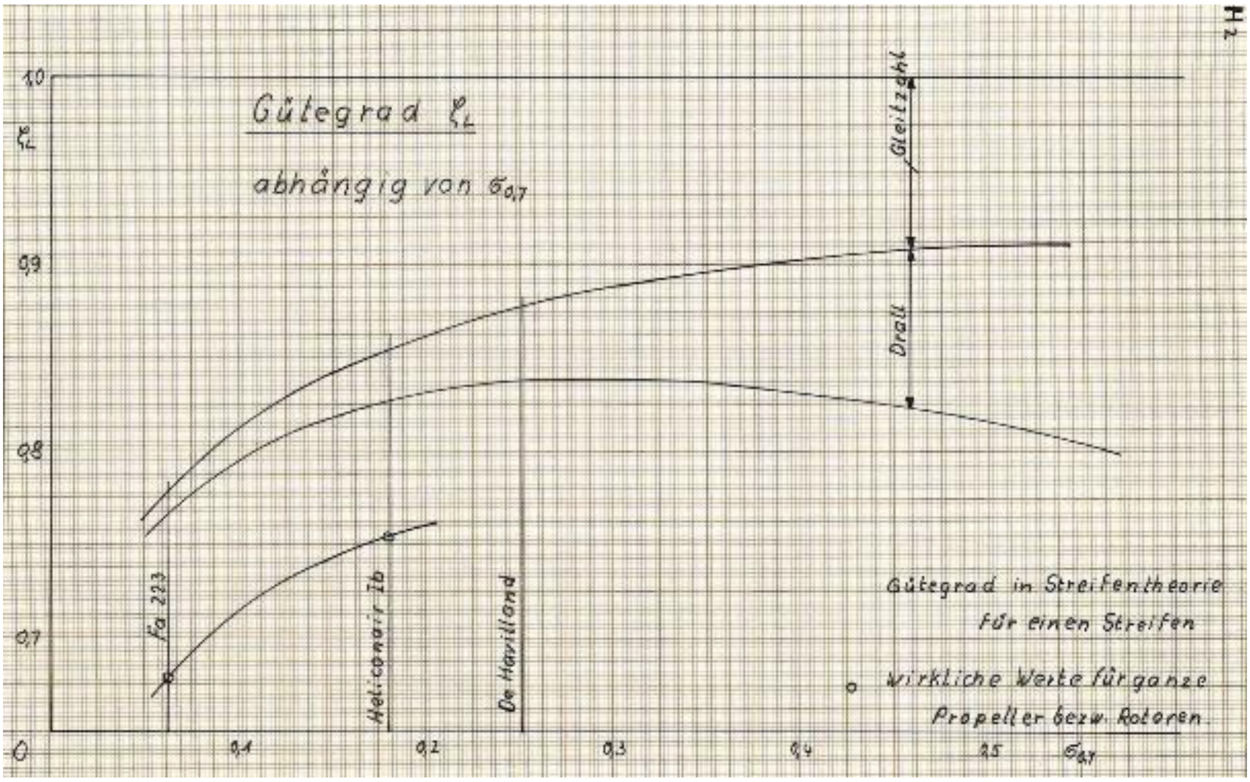

Figure 12. Influence of solidity $\boldsymbol{\sigma_{0.7}}$ on figure of merit.

Considering the radial station at $0.7R$ as representative for the entire rotor blade, the blade thrust simplifies to equation (4), left, and must equal the thrust coefficient form, right.

$$S = c_a \cdot \frac{\rho}{2} \cdot (0.7 \cdot u)^2 \cdot t \cdot R \overset{!}{=} k_n \cdot \frac{\rho}{2} \cdot \frac{t \cdot R}{\sigma_{0.7}} \cdot u^2 \tag{4}$$

Solving for $\overline{c_a}$ provides the representative lift coefficient, equation (5).[9]

$$\overline{c_a} = 2 \frac{k_n}{\sigma_{0.7}} \tag{4}$$

Although lift coefficients as high as 1.8 may be reached near the hub, a range of $0.75 - 0.85$ is useful in practice but better to continue with $k_n/\sigma_{0.7}$. Recall that k_n varies with flight condition. Computing equation (1) for rotor thrust and power, the best values for rotational speed ω and load factor n, assume takeoff with full throttle as the reference condition. From Figure 11 $\sigma_{0.7} = 0.065$ is selected for our example helicopter. Although a higher value of ζ_L, it is detrimental in high forward speed. The maximum of ζ_L for $M \approx 0.6$ is greater than 0.7 at $k_n/\sigma_{0.7} \approx 0.2$, leading to $\overline{c_a} \approx 0.5$ and $k_n = 0.013$. Solving the thrust equation in equation (1) for the tip speed provides $u = 132$ m/s and after division by the radius $\omega = 29.5$ rad/sec = 279 RPM, quite near

9. Note that $k_n = 2C_T$, then $\overline{c_a} = 4\, C_T/\sigma$.

to the initial assumption of 300 RPM.[10] An iteration of the design would be required until the goal is matched, and the same applies for the tail rotors. Considering a gear reduction ratio of about 9 leads to an engine rpm of 2,650, but for permanent operation only 2,400 would be allowed. This, in reverse, reduces the rotor rpm further, increases k_n to $0.013 \cdot 2{,}650^2/2{,}400^2 = 0.0158$, hence $k_n/\sigma_{0.7}$ becomes $0.0158/0.065 = 0.243$ and with it $\overline{c_a} = 2.5 \cdot 0.243 = 0.608$, sufficiently below the allowed limit of 0.85.

Now the torque coefficient can be calculated. The torque based on 300 rpm was $M_d = 415$ mkg, corrected for our 279 rpm: $M_d = 415 \cdot 300/279 = 446$ mkg. Focke notes that in an actual design the entire process must be iterated, but for purposes of the lecture this is a "waste of time". The power of course remains at $N = 134 \cdot 75 = 10{,}000$ mkg/sec and from equation (1) we solve for the torque coefficient and check for the figure of merit ζ_L.

$$k_d = \frac{N}{\rho/2 \cdot F \cdot u^3} = \frac{10000}{1/16 \cdot 64 \cdot 132^3} = 0.00109$$
$$\zeta_L = \frac{k_n^{3/2}}{2 \cdot k_d} = \frac{\sqrt{0.013^3}}{2 \cdot 0.00109} = 0.68 \qquad (5)$$

ζ_L is close to the initial assumption of 0.675. The same must be done for the tail rotor and Focke leaves it as homework to his students. It should lead to approximately 2,000 RPM.[11]

e. Furthermore: "do not forget that all this belongs to the sea level ISA"

The influence of height above ground lies in the variation of air density, and for each height the entire process needs to be repeated as as the climb velocity becomes zero. The power required increases proportionally to $1/\sqrt{\rho}$ and the motor power available decreases with height. As an example, at 6,000 m height ρ has halved, and to keep the dynamic pressure constant the tip speed u and with it ω must increase by $\sqrt{2} = 1.41$, as well as the power required which keeps aerodynamic coefficients at the airfoil near the optimum operational point. The power available from the engine at different height is obtained from the manufacturer. Without turbocharger the power loss is roughly proportional to the altitude. From practical experience, in agreement with theory, 1 m/s climb rate at sea level corresponds to a ceiling height of 600 m; 2 m/s result in 1,100 m and 8 m/s in 4,000 m. We had 3.6 m/s, leading to about 1,950 m.

The practical limit of today's helicopters is often a rough rotor operation due to $\overline{c_a}$ becoming too large, i.e. stall develops because the maximum allowed motor rpm is limited. For greater altitudes the collective control angle must be increased, exaggerating the stall which results in blade slap and vibration. In autorotation the rpm should also increase proportionally to $1/\sqrt{\rho}$, but at great

10. The blade tip Mach number is $M = 132/340 = 0.39$, significantly below 0.6 – it is typical for Focke designs to have it near that of autogyros to avoid large rpm differences when switching from helicopter to autorotation.
11. This leads to a tip speed of the tail rotors of 179 m/sec, or $M = 0.53$, higher than that of the main rotor

altitudes it does not. Focke emphasizes that his team was the only one testing it with the Fa 223. At heights above ground of 500 m with $\rho = 1.2$ kg/m³ 260 rpm developed, but at 7,000 m with $\rho = 0.45$ kg/m³ only 300 rpm instead of 420 rpm for an unknown reason. Eventually that was determined to be due to an excessively large and enduring descent rate developing at that height.

Twin engine helicopters are calculated in the same manner but will have more power-consuming components to be considered.

Focke also addresses ground effect, allowing takeoff in the case of no excess power available. Compared to hovering out of ground effect, at $D/4$ above ground the k_n rises by 46%, the k_d only by 10%. But he recommends not to rely on it and instead treat it as sufficient reserve in climb capability.

Focke's concluding remarks:

i.) Parts in the rotor's slipstream (airframe) are not yet considered. The slipstream contraction is completed much earlier than usually believed ($0.3D$).

ii.) Vortex ring state = vertical sagging: the entire rotor drag coefficient is about 1.2, equivalent to a circular disk.

iii.) In climb all airframe parts generate drag, though very small because of small climb velocity, for example 3 m/s leads to $q = 0.56$ kg/m².

iv.) Due to tip path plane tilt by flapping angle β_1, the vertical component of rotor thrust is $k_a = k_n \cdot \cos\beta_1 \approx k_n$.

2.3 Speed performances of the helicopter

This addresses the expected maximum and cruising speed, and the climbing speed in banked flight. In horizontal flight the equilibrium of forces shown in Figure 13 is given by equation (7), balancing the lift (A) with the weight (G) and the rotor horizontal force (W_{Rot}, which must be negative to become a propulsive force!) and the helicopter drag (W_S).

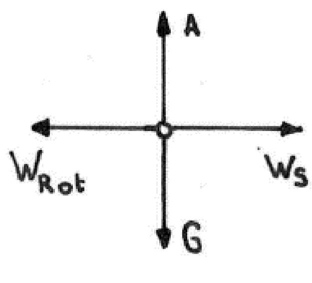

Figure 13. Balance of vertical and horizontal forces.

$$A = G \approx S \qquad -W_{Rot} = W_S \qquad (6)$$

We now need k_n and k_d values in the presence of a tangential advance ratio and introduce the old symbol μ, which was already used by Glauert and Lock, not to be confused with the axial advance ratio λ.[20, 21] For vertical climb k_n, k_d as functions of λ from Walchner were already shown.[19] Our thrust and torque coefficients k_n, k_d are now extended by a drag coefficient k_w, equation (8).

$$W_{Rot} = k_W \cdot \frac{\rho}{2} \cdot F \cdot u^2 \qquad (7)$$

Instead of calculating these coefficients in forward flight, Focke recommends the use of charts of measured data complemented by calculated data, which have the value of giving us the expected character of the curves and thus help inter- and extrapolating measured data. He obviously showed and discussed graphs that were not contained in the lecture notes but are taken from reference 14. Beginning with k_n versus μ^x, the tangential advance ratio, the solid lines of $K_{sv\infty} = 100k_a \approx 100k_n$ in Figure 14 represent the measurement, and the dashed lines are from theory for a range of rotor angles of attack α_π. For small angles the agreement is good but deviates for large angles due to growing stall areas.

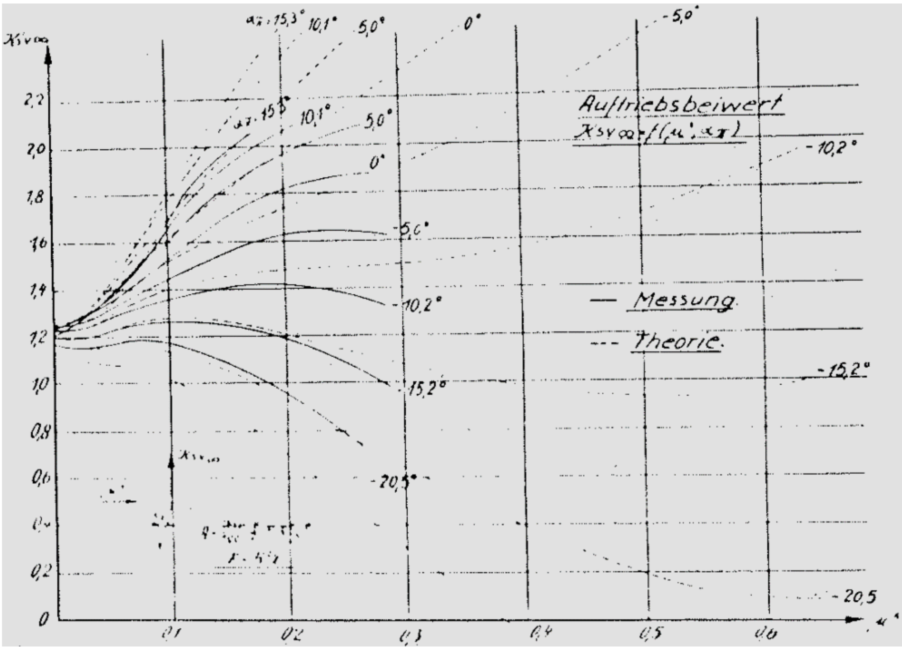

Figure 14. Vertical thrust coefficients versus tangential advance ratio $\mathbf{\mu^x}$, $\boldsymbol{\vartheta} = \mathbf{11}$ degrees, Figure 8 from reference 14.

For forward flight we need $\alpha_\pi < 0$ where the agreement is better. With a sufficient number of such tables the thrust can be interpolated for any combination of λ, ϑ und α_π.

Especially interesting is the behavior of k_n for $\alpha_\pi = 0$: with increasing μ^x the thrust rises considerably, though less than predicted by theory. If the torque does not rise as strongly as well, then less power will be expected (consider Figure 15, again from reference 14 and not yet made nondimensional) here for $\vartheta = 6$ degrees. After a small increase, a sharp drop of required power follows. Plotting for constant thrust the effect is even more pronounced. Increasing thrust and decreasing power consumption must result in considerable savings in forward flight, and that is actually the case.

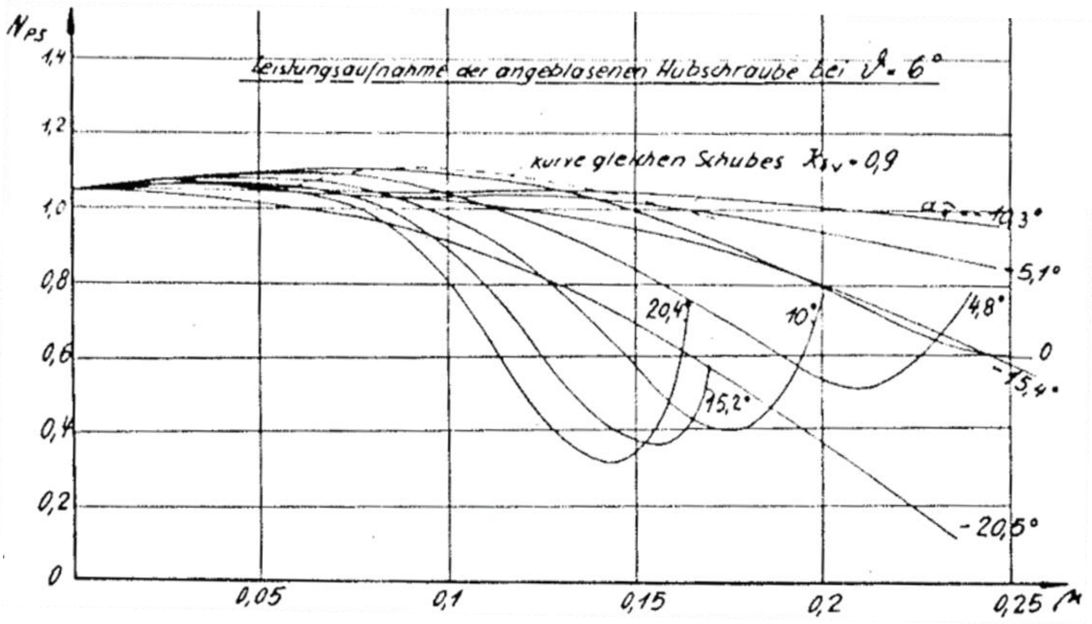

Figure 15. Power consumption of a rotor versus tangential advance ratio $\boldsymbol{\mu^x}$, $\boldsymbol{\vartheta = 6}$ degrees, Figure 26 from reference 14.

Using the calculated values of our example helicopter (same weight as the Fw 61), the power required in forward flight is shown in Figure 16 from reference 14. The lowest power amounts to 69% of the hovering power here, but on average, with all existing helicopters, it is in the range of 62 - 65%. For higher speeds the power grows with parabolic character due to the increasing drag coefficients k_w of the helicopter that we need to address next. It is overcome by forward tilting of the rotor. Two curves are plotted in Figure 16 for $c_{ws} = 0.022$ and 0.028. For a maximum of 72 HP at the rotor and the higher fuselage drag coefficient we obtain a maximum horizontal speed of 121 km/h, which officially was measured as 122.2 km/h.

We therefore must generate negative rotor drag by tilting the rotor downward with negative α_π such that the rotor drag becomes negative (= propulsive), i.e. the lower part in Figure 17 is of interest. The airframe drag is represented by its drag coefficient c_{ws} based on the speed of flight $u \cdot \mu$ and referenced to the rotor disk area. The rotor's forward thrust coefficient is k_w and the balance of forces leads to Equation (9).

$$c_{ws} \cdot \frac{\rho}{2} \cdot F \cdot u^2 \cdot \mu^2 - k_w \cdot \frac{\rho}{2} \cdot F \cdot u^2 = 0; \quad c_{ws} \cdot \mu^2 = k_w \tag{8}$$

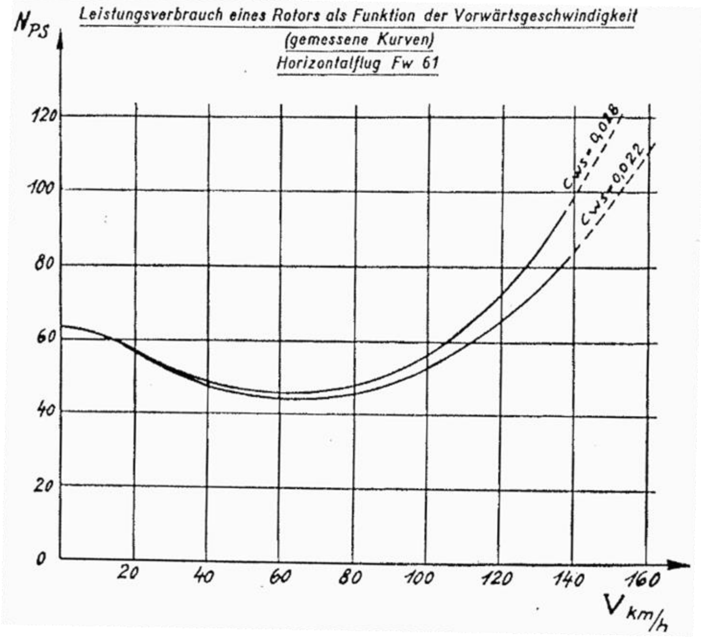

Figure 16. Power consumption of a rotor versus flight speed $\boldsymbol{V}$, $\boldsymbol{\vartheta} = \mathbf{6}$ degrees, Figure 25 from reference 14.

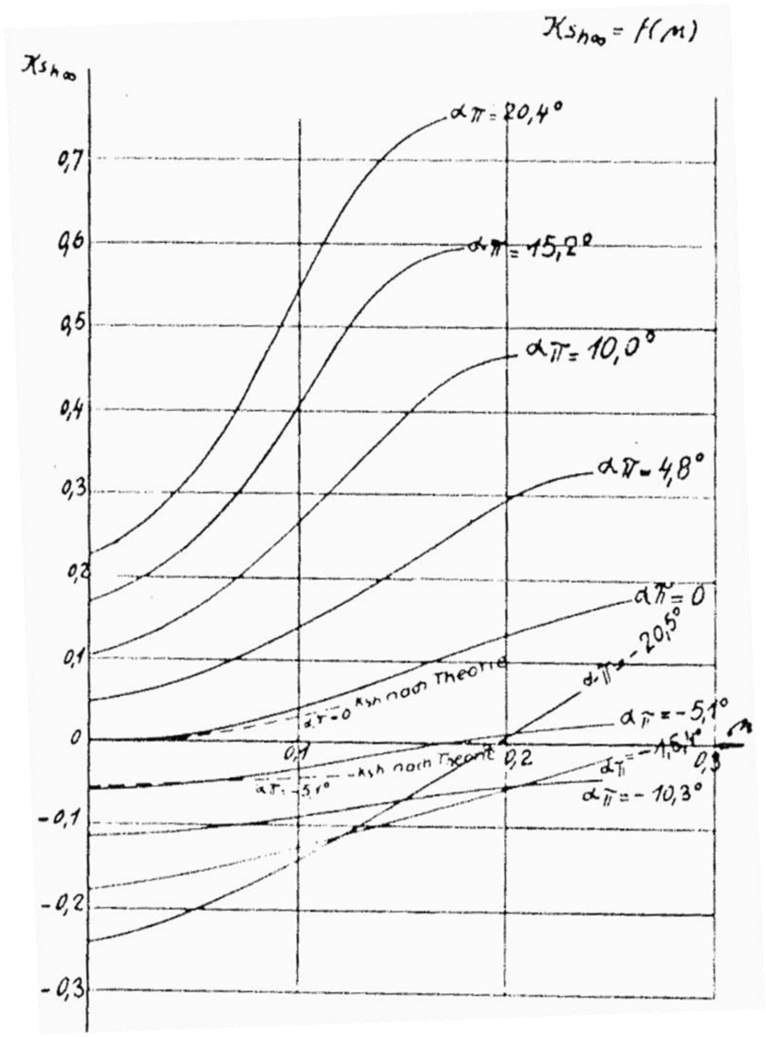

Figure 17. Propulsive force coefficients of a rotor versus tangential advance ratio $\boldsymbol{\mu}^{\boldsymbol{x}}$ for $\boldsymbol{\vartheta} = \mathbf{11}$ degrees, Figure 9 from reference 14.

Now having all curves k_n, k_w, k_d versus μ at hand in the form of data sheets incremented in 5 degree steps of α_π Focke used the following scheme indicated in Figure 18. For a given rpm the k_n remains the same as in hover. In an arbitrary sheet k_n vs. μ we select a μ therein and get the respective $\vartheta_{0.7}$ (left part of Figure 18).

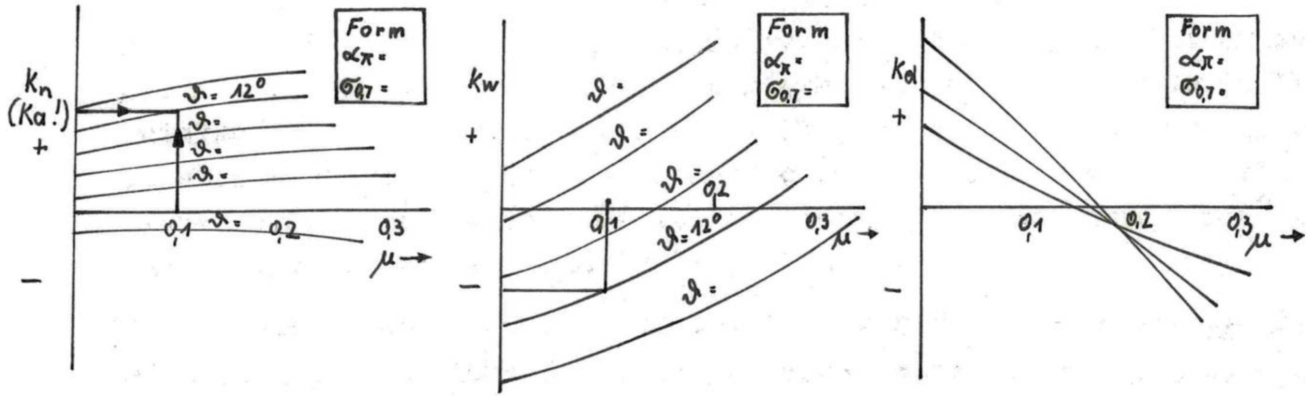

Figure 18. Scheme.

After calculation of the c_{ws} the respective k_w is obtained by equation (8). For the same α_π as before we take a data sheet k_w vs. μ and check for the same μ and $\vartheta_{0.7}$ whether the k_w fits to the calculated one (center of Figure 18). If not, restart with a different μ and get a new $\vartheta_{0.7}$ and iterate until convergence is obtained. Finally, the sheet k_d vs. μ for the same α_π we go from μ to $\vartheta_{0.7}$ and find k_d, with which we can also easily calculate the required power at this operating point. The flight speed is determined by μ and u and we can enter the first point to generate our power curve as indicated in Figure 19.

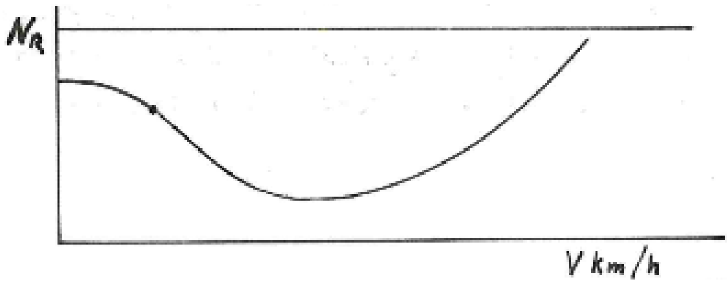

Figure 19. Power versus flight speed for $\vartheta_{0.7}$ = ...

Focke excuses the mathematical inelegance of the method, because we have to iterate the advance ratio in the first phase of the calculation. It is much more important to have reliable numerical values supported by theory *and* practice, and above all a transparency of the calculation process throughout its course than simple elegance of procedure.

He also drafts another purely mathematical so-called η_H-method. η_H is a speed coefficient used in a graph versus the efficiency factor ζ_L (Figure 20) which indicates the order of magnitude of the speed for all reasonably normal helicopters, but somewhat optimistically. It is based on Equation (10).

$$V_H = \eta_H \cdot 270 \cdot \frac{N}{G} \qquad (9)$$

The number 270 must include everything that makes up c_{ws} etc. The highest point of the curve is $\eta_H \approx 3.5$. We can see that the maximum speed depends solely on the reciprocal value of the power loading G/N. Both branches of the curve end at the origin, but in hover with $V_H = 0$ we should end at $\zeta_L \approx 0.7$, such that the transition must be estimated. Three examples were elaborated and compared to measurements (
Table **1**).

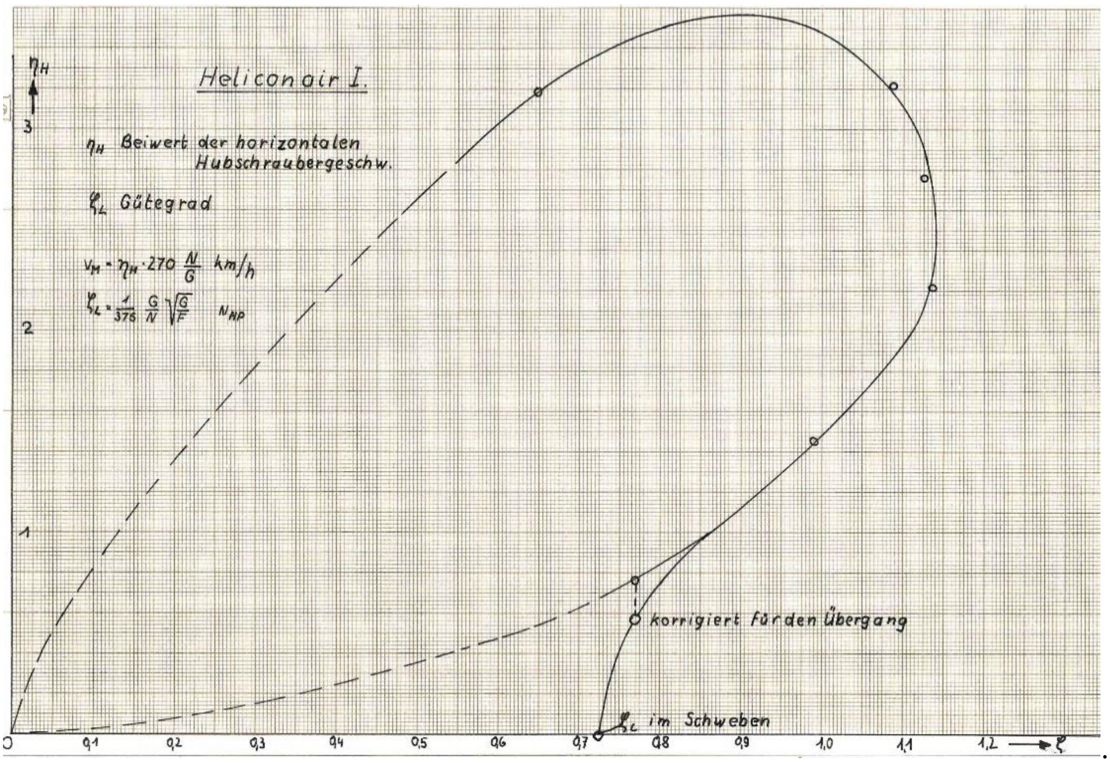

Figure 20. $\boldsymbol{\eta_H}$-method.

Table 1. Application of the $\boldsymbol{\eta_H}$-method.

Helicopter	N, HP	G, kg	V_{max}, km/h, calculated	V_{max}, km/h measured
Beijaflor	170	900	179	168
Fa 61	130	950	129	122.5
Fa 223	840	4300	185	182

The power saving at medium speeds, as an apparent ζ_L goes up to 1.13 are also seen in Figure 20. This is because it is based on momentum theory in hover where the momentum is only given by its own induced velocity, but in forward flight larger air masses are captured and this means a power saving.

The final subject is climbing in forward flight along a flight path angle γ, which is very important as the climb performance is much better than vertically from a hover. The power curve in Figure 19 already indicates larger excess power available in forward flight than in hover. We need to split the weight into its components in γ direction and normal to it, and the balancing equation (6) is modified to equation (11).

$$A = G \cdot \cos\gamma \approx S \qquad -W_{Rot} = G \cdot \sin\gamma + W_S \tag{10}$$

The weight has a significant component added to the aircraft drag and a new torque coefficient k_d results. The process with the curve sheets from Figure 18 then is the same as before. However, the power difference method also immediately provides the climb rate by the amount of excess power. A maximum of 178 HP is available and in hover we needed 134 HP, leaving 44 HP for climb, which resulted in 3.6 m/s. At speed of minimum power, we assume 65% of 134 HP = 87 HP required, the excess power then amounts to 91 HP, which results in 7.6 m/s climb speed. A real helicopter design of course requires all calculations being carried out at different altitudes and the respective air density.

2.4 The outcome of all before: an offer to a customer

Description: Helicopter "Beijaflor" with 225 HP Continental 225-4 engine, two-seater with side-by-side seats, closed Plexiglas canopy, single-rotor, with double tail rotors, ready to fly with certificate of approval from the German federal testing authority[12]

Dimensions:
Rotor ø = span = 9 m; length 9 m; height 2.3 m
Dual control, removable, included in delivery

Weights:

Empty weight:	700 kg
Payload:	
Pilot	75 kg
Companion	75 kg
Fuel	45 kg (1½ hour journey)
Oil	5 kg (1½ hour journey)
Cargo	200 kg
Flight weight:	900 kg

Performances:

Maximum speed	160 km/h
Cruising speed	130 km/h

12. Luftfahrt-Bundesamt (LBA) = Federal Aviation Office, Founded in Bonn 1953, since 1954 in Braunschweig, until 1980 also air accident investigation board (Flugunfalluntersuchungsstelle, FUS)

Backward speed	20 km/h
Take-off speed	0 km/h
Landing speed	0 km/h
Landing speed in autorotation in the event of engine failure	45 km/h
Vertical climbing speed out of ground effect	3.6 m/s
Climbing speed diagonal	7.6 m/s
Vertical ceiling height out of ground	1,300 m
Ceiling height diagonal	3,500 m
Price: net cash without discount etc.	DM 80,000.—[13]

2.5 Construction and manufacturing

2.5.1 Load assumptions

Certification of this theoretical helicopter must fulfill requirements of the newly established post Second World War German authorities. Specifications with load cases were under preparation in the mid-1950s in Germany so those from abroad were in use. In Brazil there were none and Focke was acting according to his own conscience. For the "Beijaflor" he used the old German regulations and those of the leading countries of the day and, as Focke states, "cooked our own simplified soup of all". The most important load cases are outlined in the following.

A. Airframe

I. Maximum loads, largest forces normal to the flight path

This case covers short-period peak loads due to gusts, pull-up maneuvers and the combination of events causing the highest loads, and their impact must be traced through all parts of the aircraft, e.g. airframe bending. At $k_{n,max}$ with largest rpm and largest flapping β_1 the most undesirable direction of the resulting force must be determined for all components. Also, periodic oscillations about the mean will further increase peak loads. As an example, Focke provides a sketch with a low frequency high amplitude and high frequency of low amplitude (Figure 21).

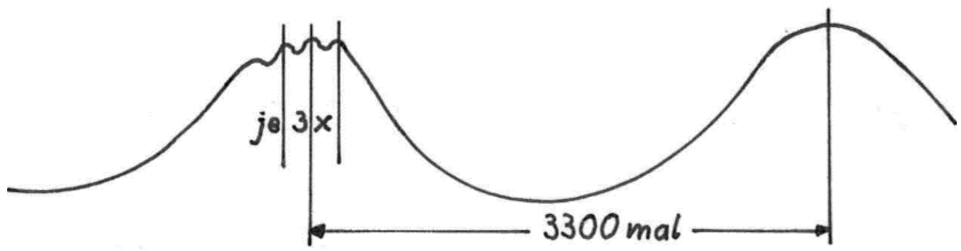

Figure 21. Example load time history.

13. In 1955, US \$ 1 = DM 4.2. Therefore, DM 80,000 = US \$ 19,000; today that would be US \$ 224,000

Care must be taken when selecting the material. Steel bears 10,000 load cycles during the lifetime of the helicopter as if they are steady loads, but Dural decreases in tensile strength from very few load cycles on.

The US currently uses a load factor of $n = 2$ as a minimum and also if it is proven that higher values are physically impossible. By calculating the maximum possible $k_{n,max}$ of the flight regime and relating it to the k_n in hover, a factor of about 1.8 will result, and with small exceedances the US factor of 2 is well justified.

The autorotation must also be checked. Prescribing the maximum rpm and V_{max} limits the number of stress conditions, but in this mode the rpm is out of our hands. An overload will increase the rpm by its square, i.e. to the maximum motor $\cdot \sqrt{2}$. All rotating parts subjected to the centrifugal force must therefore be calculated with twice the safe load.

In autorotation there is no clear limit of the possible load factor, due to a larger margin between $\overline{c_a} \approx 0.2$ usually occurring in fast forward flight and 1 as possible from the airfoil polar, suggesting a load factor of $n \approx 5$. During flight tests and despite the pilot's best efforts no more than $n \approx 1.7$ could be achieved. Focke's hypothesis for this low value includes:

1. The hinged rotor blades yield immediately;
2. Due to high rotational inertia the rpm cannot build up quickly;
3. Most important: Most helicopters have ϑ that decreases with β for reasons later to be discussed, causing an automatic reduction of blade lift, hence rotor thrust.[14] Theoretically the load factor can be eliminated that way, but that would also eliminate the controllability of the helicopter.

Concluding, $n = 2$ for Case I is sufficient and the safety factor against breakage from US regulations is $j_{Br} = 1.5$ and as precaution we add safety against yield stress of $j_{0.2} \geq 1.2$.

II. Defects or adjustment errors in the control unit, imbalance

Imbalance forces can be very large, though do not necessarily cause large load factors in normal direction. If one of the blades has a different ϑ than all others, it will take a different flap and especially lag angle, and the 3-star is disturbed, its center of gravity outside the hub. Our helicopter blades may have a weight of 16 kg each, all together about 50 kg. A shift of center of gravity by only 1 % R due to the single lagging blade cause a revolving imbalance force of equation (12).

$$Z_{imbalance} = 0.01R \cdot \frac{m}{g} \cdot \omega^2 = 0.045 \cdot \frac{50}{9.8} \cdot 30^2 = 206 \text{ kg} \qquad (11)$$

14. Pitch-flap coupling

In autorotation ω may become 42 rad/s, resulting in 410 kg. This force revolves with the rotor rotational speed and are quite uncomfortable and strength must be ensured in all directions. This is combined with a load factor of $n = 1.2$ normal to the flight path plus all possible flapping up to $V_{H,max}$. Focke also addresses a serious defect, e.g., the blade fully transverse with $\vartheta = 90$ degrees, a $c_{wp} > 1$ (100 times of the attached flow value of 0.01) where the lag angle of our helicopter may reach a position opposite to its preceding blade. Then the mass of the entire third blade is $Z = 2.25 \cdot 16/9.8 \cdot 30^2 = 3{,}300$ kg, impossibly large.

III. Permanent case

This covers permanent oscillations due to periodic air loads, engine and gearbox vibration, etc. that have to be carried by respective components. During cruise the load factor is 1, but fatigue strength of the material becomes important. Foreign countries permitted a service life with parts replacement after a certain period of operation at the cost of the owner. Focke does not recommend it for psychological reasons: consider a pilot flying a helicopter in the 290th hour of the rotor shaft's service life of 300 hours! Instead, Focke suggests considering a load factor of 1, normal rpm, $V_{H,max}$, and $j_{0.2} = 1.2$ against fatigue strength, i.e. infinite cycles of oscillation. In normal flying $V_{H,max}$ is limited to just minutes at a time because of the engine operational power limits defined by the manufacturer.

Focke comments that defining load cases is easy, performing the strength calculations for all parts of the helicopter with rigor is very, very difficult, extremely time consuming and one of the most responsible problems of all, so is therefore omitted in this lecture.

He then addresses stresses from rare maximum loads. A fortunate circumstance is that they relate to the alternating stresses in the same way as the static strength of the materials to their fatigue strength, in a ratio between 2 and 3. Therefore most parts designed for maximum static loads usually also prove to be fatigue resistant. Another issue is resonances to the multiple harmonics of the rotor rpm. As an example, a strut serves to subdivide the buckling length of another main strut and usually carries no load at all. If it oscillates in resonance with large amplitudes the bending stress may reach the fatigue limit and it breaks. The main strut then has no support and may first buckle, then break at the next high loads. Such cases cannot be predicted and require careful observation. Further, all periodic air forces are transmitted by the blades to the hub where they accumulate and transmit permanent vibration to the airframe.

Focke then explains such a failure with the example of a crashed Fa 223 helicopter near Mont Blanc. Poor material with less fatigue strength and resonance loads caused a push rod to break. After investigation and lab tests, the part was intentionally weakened (!) to get out of the resonances by shifting its natural frequency away from those of excitation.

IV. Negative load factors

Negative load factors of significant magnitude occur when switching from helicopter to autorotation and are especially strong in fast forward flight when α_π is negative and ϑ is large. Now ϑ is suddenly switched down, the lift at the blades becomes negative, causing the β to go negative, hopefully not touching the hard stops and stress must remain within permissible limits.

This can be approximately measured but is better measured in flight. Based on this, we demand $n = -0.5$ at normal rpm.

V. The tail unit cases

The absolute highest k_n of the tail rotor(s) is again decisive in combination with the normal rpm, and safety factors of $j_{break} = 1.5, j_{0.2} = 1.2$ apply. The non-rotating parts, elevator and rudder, are treated like those in fixed-wing aircraft. A force of $0.55 \cdot q_h \cdot f_{tail\,unit}$ is to be distributed over the chord according to US regulations without tip loss.

75 % superposition in case of elevator and rudder forces (Figure 22) that is required for fixed-wing aircraft must also be considered, beginning with horizontal flight $n = 1$ and j as before.

Figure 22. Elevator and rudder.

VI. Landing cases

US load cases should be assumed, but they leave open the possibility of absorbing the required working load to a large extent by plastic deformation. Helicopter and autorotation landings can usually be carried out softly and without speed. Therefore, today rigid skid landing gear are often used that may be replaced after hard landings. Nose wheel arrangements are found to be too weak despite meeting regulations, so their loads should be assumed to be larger.

VII. General cases

German pre-war fixed-wing regulations regarding head injuries in a rollover should be used for operational and occupant safety reasons because these can also occur with helicopters and gyroplanes. Focke cited the example of an accident near Bösel at the end of 1943 when an Fa 223 tried to pull parts of a crashed Do 217 out of a bog in strong winds. To avoid stalling, the pilots, using their fixed-wing experience, pushed the control stick downward, which caused the Fa 223 to crash. Instead, Focke argued, they should have applied more power and kept the nose up.

B. The transmission forces

For our small helicopter two very basic requirements must apply throughout the vehicle.

1. For the gearbox itself, the actual moments and forces resulting from the maximum possible engine power must be applied with a load factor dependent on the number of cylinders in the engine. This is for more than 5 cylinders: $n = 1.5$.

Within the range of operational rpm, the torsion and bending oscillations must either be sufficiently well separated from resonances, or the amplitudes remain within the fatigue diagram of the respective materials, or the resonance rpm’s must be marked in red on the instrument panel (only if regular operation is granted when avoiding these rpm). Since calculation of the amplitudes is vague, measurements are needed with several sensors along the element to avoid being trapped in an oscillation node that does not show stress. Form factors to be considered as large as 2 or 3 are not rare. Calculating oscillations of a larger gearbox takes an enormous effort and unfortunately it happens again and again that some calculated resonance points do not appear at all or, what is worse, a completely different one appears instead. Some orders of magnitude are given for torsion and bending.

2. All parts through which *airframe and gearbox forces* pass must be calculated for all possible *simultaneous* forces with the prescribed n and j for the airframe and gearbox with superposition of static and alternating loads.

This applies to the housing of the rotor hub, through which the often-high tooth and bearing pressures pass, but also, depending on the type of mounting, the entire thrust of the rotor must be transferred to the fuselage by means of the housing fastening bolts.

Focke concludes by repeating that no regulation can relieve the designer of responsibility. At best, normal designs can be calculated throughout the helicopter. For unusual or new designs, the attention and thinking of the actual technical-physical design process must be doubled. In considering liability, Focke notes, many countries, including Germany, have exonerated the inspection authorities who have elevated this principle of the sole responsibility of the designer to a legal principle and absolve them of all responsibility, even if they cause an accident through an official but technically incorrect order. While the former principle of the designer's responsibility can still be approved, rejection of the certification authority’s responsibility for the consequences of an incorrect order given by it must, in Focke’s opinion, be condemned as immoral.

2.6 Entering the design phase

The rotor hub can be subdivided into rotor blades and rotor. It is a piece of precision engineering like the gearbox and often contains part of the reduction gear and mainly contains the control elements that transmit the desired changes in blade pitch angle ϑ, periodic and constant, to the blades. In a helicopter with a single tail rotor (its plane of rotation is vertical) it can only take over yaw control. The main rotor must then perform longitudinal and lateral control and the switching to autorotation. Because the rotor thrust is always normal to its tip path plane we need to tilt it by variation of the blade pitch angle ϑ and use the natural reaction of blade flapping in response to it, as Glauert and Lock suggested 30 years before.[20,21] Consider a rotor with a horizontal tip path plane with the blade tip front position at B and in back position at D (Figure 23). Now introduce a periodic (sinusoidal) ϑ with maximum on the advancing side at 90º azimuth and minimum on the retreating side at 270º azimuth.

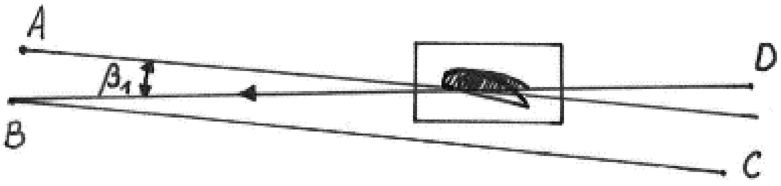

Figure 23. Flapping response to pitch control.

Increasing α by $\vartheta_{max} > 0$ on the advancing side causes the blade to flap upwards and thus reduce its angle of attack there, reaching the highest flap angle β_1 at the front of the rotor at 180º azimuth, A in Figure 23, which is 90º after our input. On the retreating side at 270º azimuth, $\vartheta_{min} < 0$ and the opposite happens, the blade flapping down to alleviate the decreasing α and reaches the lowest flap angle $-\beta_1$ at the rear position 360º, again 90º later. Therefore, to obtain whatever desired flapping reaction (or tip path plane tilt), we have to introduce the pitch control for it 90º beforehand. Focke cites the German poet Wilhelm Busch, who wrote:

"Beatings are effective indeed,

especially before misdeed."

In hover, a constant ϑ results in a horizontal tip path plane. In forward flight the advancing blade experiences more lift due to increasing dynamic pressure and the blade will flap upwards, reaching β_1 at the front, while on the retreating side a reduction of it and the blade will flap downwards, reaching $-\beta_1$ at the rear. To eliminate this, we need to introduce $\vartheta = -\beta_1$ on the advancing and $\vartheta = \beta_1$ on the retreating side. At the time of Glauert and Lock (mid 1920s) no helicopter existed, but autogyros by Cierva did exist, which mechanically tilted the rotor hub (and with it the shaft = material axis of rotation), an equivalent to our blade pitch control by ϑ. The mechanical solution to periodical pitch control is the swashplate to run a push rod with a roller on it and connect it to a lever that turns the blade by ϑ (Figure 24) one for each blade.

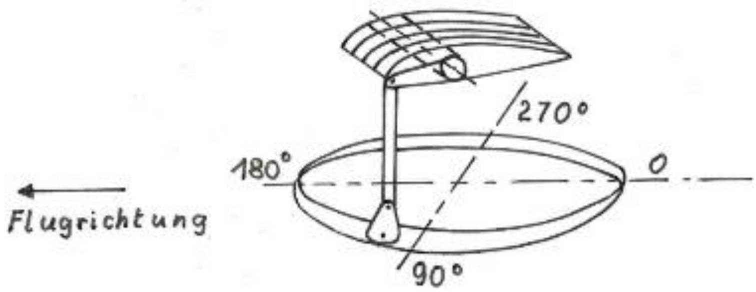

Figure 24. Blade pitch control linkage.

The swashplate consists of a non-rotating part with a complete ring rotating around it with ball bearings between both. The push rods to the blades then are mounted to the ring by joints designed as adjustable roller bearings with the smallest possible play. This is very important because everything depends on precise compliance with the basic ϑ. If a blade deviates 5 ft in the ϑ, you will feel a constant quiet oscillation with the speed in flight; with a 10 ft error, you can tell the on-board mechanic to readjust the blades; and no sensible pilot will fly with a 20 ft error.[15] Roller bearings on a bushing made of the best phosphor bronze are best suited because of their smallest manufacturing tolerances.

For flight control the rotor disk must be tilted in any direction, hence the swashplate as well, which is achieved by the classic gimbal as sketched in Figure 25. A drawing from a real design is shown in Figure 26 and Focke explained all parts of it in detail. In case of a single tail rotor with vertical tip path plane the main rotor also has to perform the elevation control, i.e. the entire swashplate must also be shifted up and down on the shaft to increase or decrease ϑ everywhere, but in our twin tail rotor design we do not need it since the elevation control is executed by the tail rotors instead.

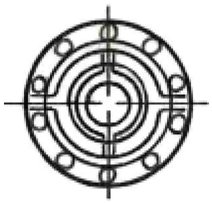

Figure 25. Swashplate and gimbal.

The swashplate ring is connected to the nonrotating part by dual ball bearings (upper and lower) that must be carefully centered and its play minimized. Special care is required for the blade needle bearings for pitch control and roller bearing to carry the centrifugal forces with high pressure. Their lubrication must be ensured.

15. Minute of arc, 1’ = 1/60° = 0.0167°; 20’ = 0.333°

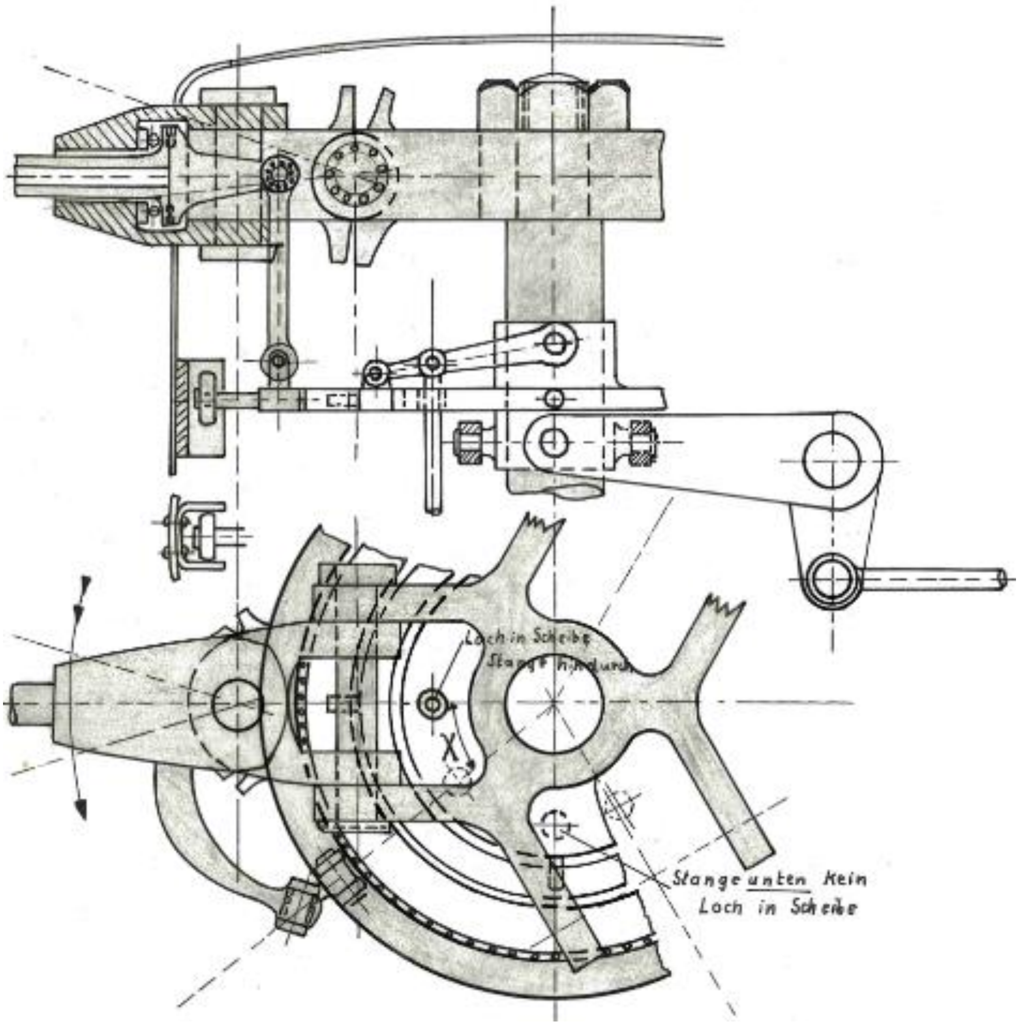

Figure 26. Complete swashplate design.

2.6.1 Geometric and dynamic relationships of rotor hubs

A. Cone angle

a. The maximum and minimum mean flapping angle, β_{max} and β_{min}, are computed from positive ($n = 2$) and negative (-0.5) load factors. Start with $n = 1$ and use the theoretical aerodynamic load distribution at a number of azimuth stations, take that of the maximum loads near the blade tip, then calculate the distribution of centrifugal forces using the real mass distribution, and β_{max} is obtained when the moments about the hinge are equal.[16] Repeat with negative peak load for β_{min}.

b. In addition to this mean value, the dynamic flapping β_1 is additive, which increases linearly with μ. As approximation for $n = 1$: $\beta_1 \approx 7.8^{\circ}$. From theory β_1 depends on $\mu \cdot k_n/\sigma_{0.7}$ and $\mu \cdot \vartheta_{0.7}$ and is proportional to $\sqrt{n}$, such that $\beta_{1\,max\ (n=2)} \approx \sqrt{2} \cdot \beta_{1\,max\ (n=1)} = 11^{\circ}$, if the load is obtained by pulling, i.e. increase of the rotor disk angle α_{π}. **Error! Bookmark not defined.** If it is obtained by an increase of $\vartheta_{0.7}$ instead of α_{π}, both $\vartheta_{0.7}$ and k_n go up and generate n. Because $k_n/\sigma_{0.7}$ and $\vartheta_{0.7}$ are optimized they fluctuate little and the β_1 as well. Then, the overall

16. This refers to the helicopter aerodynamics lecture of Professor Just in the summer semester

maximum flapping angle is the sum of the former β_{max}, plus the latter β_{1max}, plus 1° to 3° margin.

B. Control angles

For the highest μ we must eliminate the β_1 developing by the longitudinal control angle, such that the resulting thrust again passes through the helicopter center of gravity: at $\psi = 90°: \vartheta = -\beta_{1max}$ and at $\psi = 270°: \vartheta = +\beta_{1max}$. The swashplate must therefore be tilted by β_1, or by a transmission ratio of it, and again add some margin of 1° to 3° for control about this condition. This is the stick "push" condition for fast forward flight. For "pull" – to allow for slow rearward flight – about -2° are required. Due to the equivalence of periodic control angle and periodic flapping we can write $-\vartheta_S = a_1 = \beta_1$.

Focke criticizes here an error of reasoning that has repeatedly appeared in serious helicopter literature even in recent times, as if reaching the highest and lowest tip path point with a delay of 90° after the greatest ϑ change has anything to do with any dynamic processes such as damping or mass forces that are supposed to cause this "phase shift".[17] The true angles of attack simply have to be made smaller or larger where the air forces would become too large or too small due to the combination of velocities. If we do not do this using the control amounts just calculated, the rotor itself does it using β_1.

Lateral control stick deflection tilts the swashplate about an axis 90° to the longitudinal stick and therefore generates a control angle $\vartheta_C = b_1$ at 0º azimuth and tilts the tip path plane in lateral direction. The moment of rotor thrust times its arm to the helicopter center of gravity gives the rolling moment M_Q, opposed by the helicopter rolling inertia J_H. The roll acceleration then is $d\omega/dt = M_Q/J_H$. For the intended lateral speed: calculate as in longitudinal, but without β_1 as it is 90° to it, and add ±2° to ±6°.

Switching from helicopter to gyroplane motion requires a parallel movement of the swashplate by a considerable amount of 6° to 8° and still all longitudinal and lateral controls need to be fully available. No linkages must run into a hard stop. To avoid hitting anything, the blade lever should be placed on the blade spar so that it is horizontal in the middle of this total stroke, the various contributions are sketched in Figure 27. For example, if $\vartheta_{0.7} = 14°$ is required for helicopter position, the blade lever should be 0.5° below it and this is then symmetrical in the range. The blade rib at $0.7R$ must be set to $\vartheta_{0.7} = +13.5°$ and the blade lever to 0° in the jig during blade assembly.

17. Unfortunately, no reference given. Textbooks 1950: Stepniewski, Laskowitz; 1951: Morris, Nikolsky; 1952: Gessow & Myers, Harris, Lynn; 1953: Dommasch; 1954: Ginoux, Levellen, Liberatore, Fay; 1955: Liptrot, Taylor, Shapiro

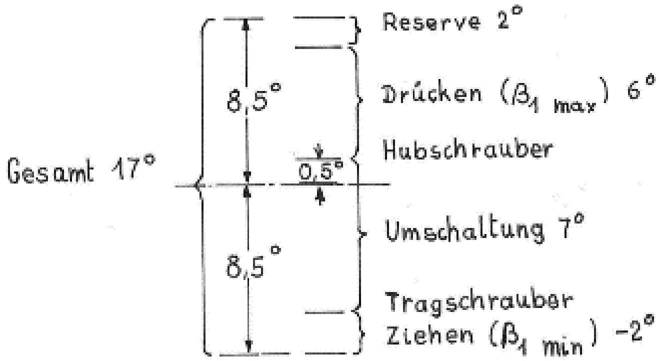

Figure 27. Total range of pitch control angles.

C. Control moments

For rotors with a central hinge ($a = 0$ in Figure 28) the thrust direction passes directly through the hub center even with β_1 such that thrust times arm l_0 to the helicopter center of gravity is the moment generated.

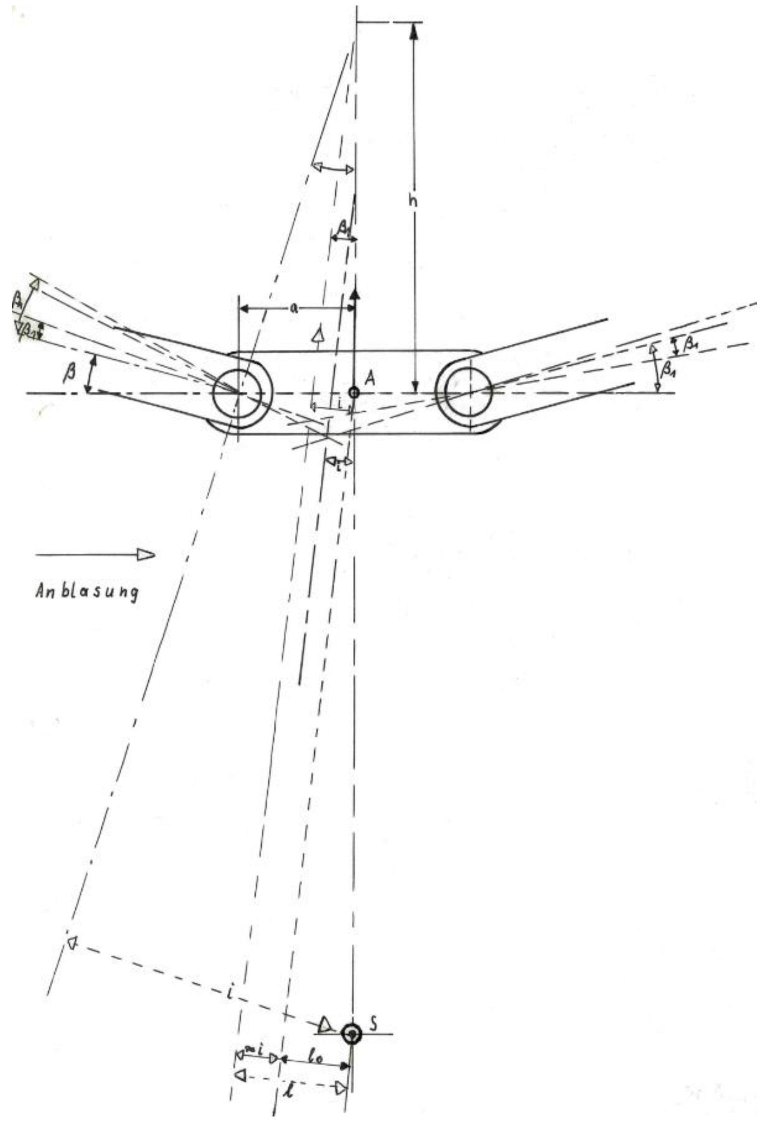

Figure 28. Thrust direction with flapping hinge offset.

With hinge offsets of $a > 0$, as is the case for the majority of helicopters, the resulting thrust must lie in the bisector of the blades with the important result that the point of intersection with the axis of rotation (Focke calls it the "Zentralpunkt" = central point Z) comes to lie considerably above the plane of the flapping hinge, h in Figure 28, and has a larger arm l to the helicopter center of gravity S. Increasing β with $\beta_1 = const$ leads to a smaller h, while increasing β_1 with $\beta = const$ keeps $h = const$, but the thrust is more inclined and hence the arm $l = l_0 + i$ grows. Therefore, for a given helicopter of constant rotational speed and constant weight, all thrust directions of the rotor always pass through this central point, even with all control movements $\Delta\vartheta$ or the occurrence of β_1. We can derive h from theory or from Figure 28, and it is $h = a/(2\beta) = a/(2a_0)$, where a_0 is the constant control angle.

D. Further conclusions

The rotor shaft defines the axis of rotation, here called the "material axis" with the blades flapping up and down, while the axis normal to the tip path plane tilted into any direction represents the "virtual axis", as if the entire hub was tilted into that direction without any flapping motion. Glauert has proven through lengthy calculations that the inclination of the entire rotor hub for the control moments of the head is identical to a periodic change of ϑ.

In hover, we only have constant control angle and no flapping motion, just a mean flapping angle, see Figure 29(I). To fly forward, we push the control stick, the swashplate tilts, a sinusoidal control angle $\Delta\vartheta_{sin} < 0$ is applied to the rotor blades, the entire rotor disk tilts forwards by β_1 and the helicopter starts to gain speed because the thrust is also tilted forward by β_1 (II). With increasing speed, β_1 starts to build up until it eats up all we have put in and the rotor cone is horizontal again (III). Flying faster requires more pushing of the stick.

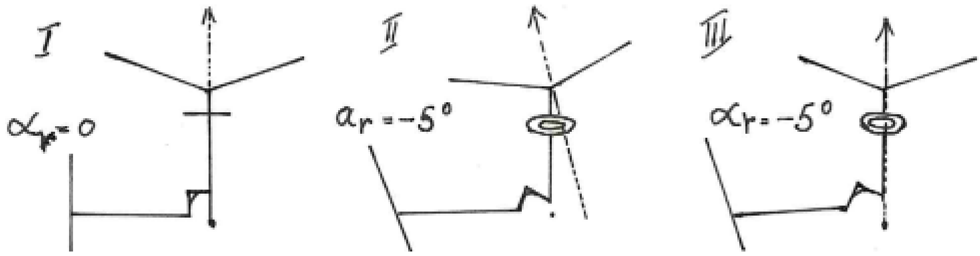

Figure 29. Longitudinal control for forward flight.

Of course, the engine throttle also has to be operated appropriately following the power curve: transitioning from hover to forward flight needs to throttle back, for high speeds add throttle after the power minimum.

Focke warns about incorrect representations in the contemporary literature and even earlier in the 1930s. In our theoretical helicopter k_n can only increase by increase of α_π due to pulling the altitude control which causes a download of the tail rotors so the helicopter pitches up and increases α_π. $\vartheta_{0.7}$ is not increased and therefore β_1 does not increase proportionally to the load factor, but considerably less. It is different when using the collective control angle $\vartheta_{0.7}$ for altitude control, then β_1 actually increases in proportion to the load factor.

E. Coriolis moments with lag angle about the virtual and material axis. Necessity of the lagging hinge.

Assume flapping hinges in the hub center rotating with constant ω and the blades flapping with β_1. The blade center of gravity receives periodic changes of its distance to the material axis. Coriolis accelerations act and considerable inertial forces lead to periodic lead-lag bending moments about the material axis that the flapping hinges have to carry. Focke emphasizes that changes in lagging angle due to inertial forces almost always far outweigh those due to changes in aerodynamic forces that oppose them. The bending moments at the root can reach 100s of mkg, demanding high strength of the blade spar. Therefore, we use lagging hinges but also have to deal with lag angles, and values of $\pm 15° - 20°$ have not produced any issues in practice.

One of the strangest and most surprising phenomena we will discuss with rotor hubs is the following static instability that remained unknown until 1939 and occurred during the first test runs of the Fa 223 rotors. When the throttle was applied a little more strongly for spinning up the rotors, the blades of both rotors suddenly folded upwards like an inverted umbrella already at low rpm values, resting against the upper flapping angle stops and rotating without any other disturbances or damage. Only at very low engine speeds did they feel comfortable going down. Focke puzzled for nights until he found that the ordinary right-angled cardan joint changes the pitch angle ϑ of the blade when β and δ are changed at the same time. Figure 30 shows why: when the flap angle goes up, a lag angle against rotation due to drag effectively increases the pitch angle, which generates more lift, the blade flaps up further, drag increases, the lag angle grows etc. Consider a lag angle of $\delta = 90°$, then $\Delta\vartheta = \beta$; a lead angle of $\delta = -90°$, then $\Delta\vartheta = -\beta$. The relation is $\Delta\vartheta = \beta \cdot \sin\delta$, or for small angles $\Delta\vartheta = \beta \cdot \delta$.

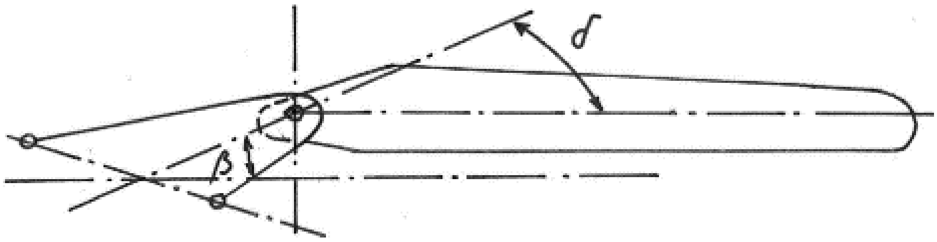

Figure 30. Flap-lag divergence.

Focke derives the kinematic relation as given in equation (13), which for small angle assumption also results into the above $\Delta\vartheta = \beta \cdot \delta$.[18]

$$\sin \Delta\vartheta = \tan\beta \cdot \sin\delta \qquad (12)$$

The centrifugal forces act to stretch the blade, more so in flapping than in lagging. Lift and drag are related to each other by the glide ratio ϵ, the lag moment can then be expressed by the flap moment, the lag angle calculated by the moment equilibrium with centrifugal moment and the

18. This must be erroneous, because for $\beta = 90°, \tan\beta = \infty$. With $\delta = 90°, \sin\delta = 1$ and the $\sin\Delta\delta$ in maximum can be 1, but not ∞. Because $\sin\delta \approx \delta$ holds for up to 45° with just 10 % error the small angle assumption can be applied even for relatively large lag angles, while the flap angles were limited to a hard stop, plus elastic flap bending above that.

additional pitch angle from equation (12), or its simplified form, fed back into the lift moment. From kinematic relations, $\delta \approx \epsilon \cdot \beta \cdot (r_S - a)/a$, such that $\Delta\vartheta = \epsilon \cdot \beta^2 \cdot (r_S - a)/a$ grows with the square of the flap angle. Divergence stability requires fulfilment of equation (14).

$$\frac{dM_Z(\beta)}{d\beta} > \frac{dM_L(\beta)}{d\beta} \quad \text{and} \quad \frac{dM_Z(\delta)}{d\delta} > \frac{dM_L(\delta)}{d\delta} \qquad (13)$$

Instead of calculating the differentiation, the solution is also found graphically, comparing the curves of the aerodynamic moments with those of the centrifugal moments as in

Figure **31**. The quadratic term β^2 in the lift via the lag-pitch coupling $\Delta\vartheta$ is the destabilizing effect, caused by the right-angle cardan hinge.

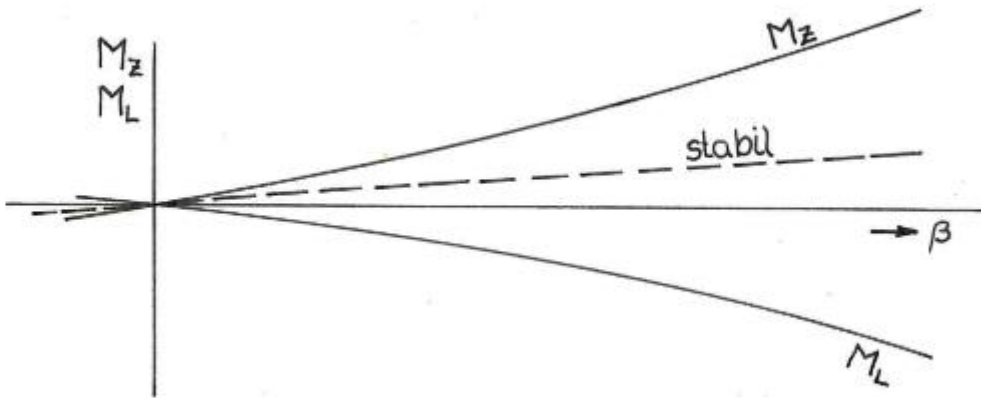

Figure 31. Graphic solution.

Focke concludes by noting that a given rotor and blade arrangement can only absorb limited motor power, and suggests methods to address this problem:

1.) Heavier blades – undesirable.
2.) Increase hinge offset a and with it also the restoring lag moment of centrifugal forces, but this increases the lag natural frequency and may get too close to the rotational frequency or cause ground resonance.
3.) Kinematic feedback of β on ϑ by an offset of the end of the blade lever from the flapping hinge axis as is shown in Figure 32, which is called "pitch-flap coupling" or δ_3-hinge in the US.[19]

In this arrangement, any flap deflection automatically reduces ϑ in proportion to β. Due to the kinematics of the linkage also a lag angle will change ϑ, but much less.

This section of the lecture ends with the control of different rotor arrangements.

1. Single main and tail rotor

Longitudinal: tilt swashplate about longitudinal axis
Lateral: tilt swashplate about lateral axis

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19. Can also be achieved by an inclined flapping hinge axis.

Yaw: tail rotor

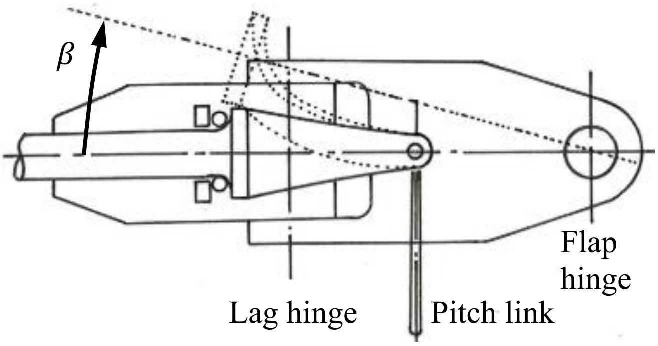

Figure 32. Pitch-flap coupling.

2. Coaxial rotors

Longitudinal: tilt both swashplates about longitudinal axis
Lateral: tilt both swashplates about lateral axis
Yaw: shift one swashplate up, the other down or opposite

3. Side-by-side rotors (blades must advance inside)

Longitudinal: tilt both swashplates about longitudinal axis
Lateral: shift one swashplate up, the other down or opposite
Yaw: both swashplates tilt in the same direction about the longitudinal axis

4. Tandem rotor (no tail rotor)

Longitudinal: shift one swashplate up, the other down or opposite
Lateral: tilt both swashplates opposite about the lateral axis
Yaw: both swashplates tilt in the same direction about the lateral axis

2.6.2 Rotor blades

Due to the very different speeds and angles of attack that occur, the airfoils should have good glide ratios for very different parts of the polar curve. This can best be met with airfoils of medium thickness, 12-15%, and perhaps even 20% in the future, as the tests of laminar airfoils and calculations of Wortmann have shown.[24,25] Thick airfoils give us a reasonable amount of space for the load-carrying elements of the blades.

Small movements of the center of pressure result in small aerodynamic moments, therefore the spar can carry all torsion and bending moments. The latter become zero in the hinges and the blade tips, a drawing shows its components, Figure 33.

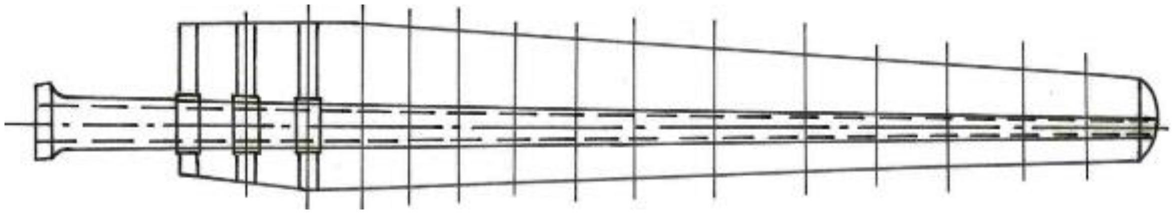

Figure 33. Components of a rotor blade.

a. Spar

In theory and practice the airloads acting on the rotor blade vary greatly with azimuth ψ and also versus the radius, while the centrifugal forces do not. We ignore the bending oscillations here as they are too extensive for [Focke's] lecture and confine us to the static treatment. From root to tip the centrifugal forces at a section of interest decrease and therefore the tensile cross-section of the spar can decrease as well. The conicity follows the taper of the blade and with it the absolute airfoil thickness. Bending stress results in its maximum from the load distribution of moments of the centrifugal forces minus the moments of the air forces (Figure 34). The maximum and minimum must be extracted from analysis throughout the revolution not only for flap and lag bending, but also for torsion moments.

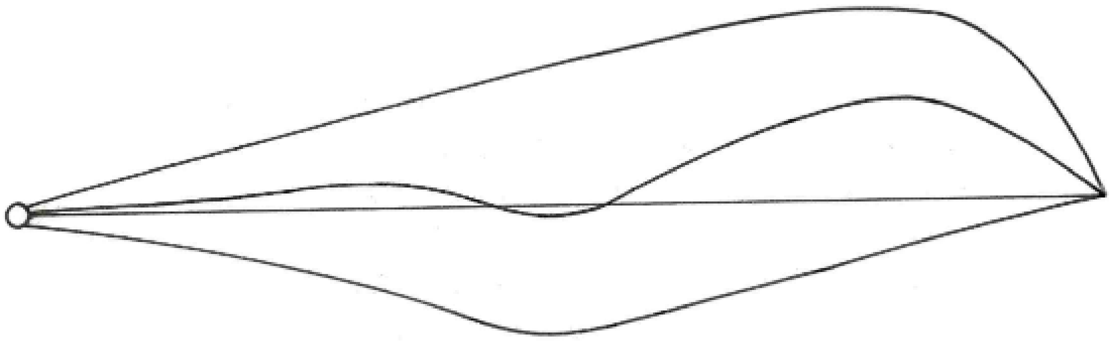

Figure 34. Bending moments in a rotor blade.

Sectional lift A and drag D of a blade element with width dr are always normal to the blade surface and act at the center of pressure (CP), but from the centrifugal forces we need to take the component normal to the blade, $Z' = Z \sin \beta$, acting at the center of gravity (S) with distance l to the CP. A torsional moment of $M' = A' \cdot l = Z' \cdot l$ results (Figure 35).

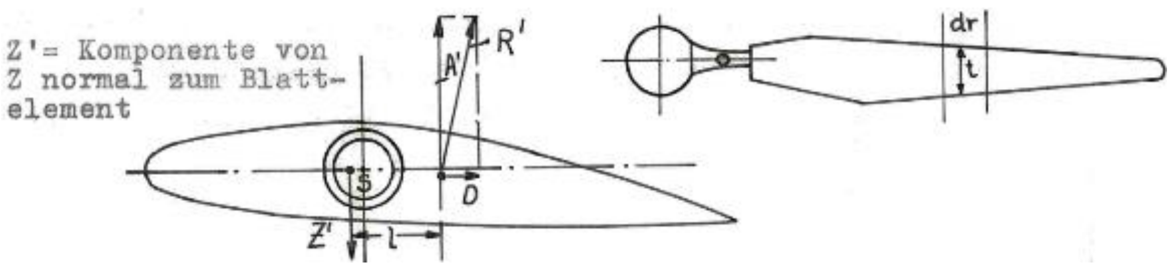

Figure 35. Contributions to torsion moments.

To keep torsion to a minimum, S should coincide with the CP, e.g. in a symmetrical airfoil at 25%. However, when the stall occurs, the CP shifts to approximately half airfoil chord $0.45 -$

$0.5t$ and the moment becomes considerable.[20] At a cross-section of the spar, it has tension from the centrifugal force and stress from flap and lag bending, which can be combined using the Müller-Breslau formula

$$\sigma_{virtual} = \sqrt{\sigma_b^2 + 3.5\tau^2} \qquad (26).$$

The centrifugal force can be regarded as constant, but for the bending stresses the range from maximum and minimum must be considered for fatigue strength. Endurance tests must be carried out to test with the determined tension, preferably with the entire spar oscillating at frequencies approaching 10^6 or $2 \cdot 10^6$. Only very high-quality pure and slag-free chromium-nickel or chromium-nickel-molybdenum steels with a tensile strength of 110-130 kg/cm² meet the requirements. A fatigue bending strength of 30 kg/cm² can be achieved from the Sandviken company in Sweden, no German steel has achieved this value. The surface must be smooth and groove-free.

b. Ribs

Plywood ribs with solid wood straps are mostly used and attached to the spar by clamping devices; even roughening the spar is prohibitive. For large moments, the clamps need to be glued to the spar by the Redux method (2-component glue: polyester) which requires heating of 165°C. A cross-section with a rib is shown in Figure 36.

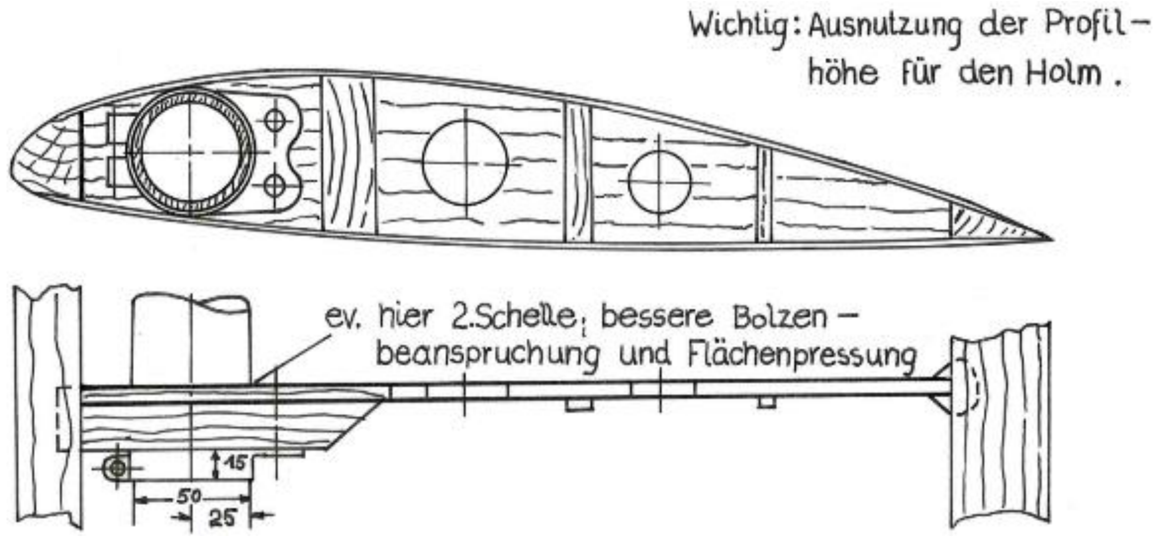

Figure 36. Blade cross-section with a rib.

From this, the surface of the clamp covered by glue is $f = 1.5 \cdot 5 \cdot \pi \cong 23$ cm². With a shear tension of 100 kg/cm² this can carry a peripheral force of $23 \cdot 100 = 2{,}300$ kg. The radius of the spar here is 25 mm = 0.025 m and the breaking moment can be calculated as $2{,}300 \cdot 0.025 = 57$ mkg.

20. Focke does not mention the CP shift aft of quarter-chord in compressible flow at high subsonic Mach numbers because his relatively low tip speeds will not reach these.

Light metal ribs are not proven because they are destroyed by concave-convex bending.

c. Miscellaneous

Solid wooden leading and trailing edge spars; nose mass weight compensation in chord direction; solid wooden blade tip caps; internal air pressure due to centrifugal loads $= 0.5 \cdot \rho \cdot r^2 \cdot \omega^2$ requires small trailing edge air holes for pressure relief.

The skinning requires waterproof plywood glued and nailed to the ribs, needs careful shafting of 1:20. Fabric is possible, but requires more ribs especially near the tip to ensure the airfoil shape. It must be sewn very tightly and needs a leading-edge protection, e.g. a second layer of plywood, but this is not used anymore.

Solid wooden blades without spar are possible, as are Dural extruded profiles with the trailing edge glued to it.

The lifetime of blades should be the service life of the helicopter without replacement regulations.

The blades must be balanced by pendulum, the aerodynamic shape checked, and whirl tower tested for balancing a set of blades.

Blade manufacturing requires a jig, templates for the ribs, angular placement of ribs and the blade lever as mentioned earlier. An example of a blade jig is drawn in Figure 37. The spar and the trailing edge are therefore the lines that determine the pitch angle and must therefore be defined very precisely, requiring a very precise measurement of the angles by technical monitoring beforehand. Due to the air holes, the inside must be varnished as well. A very good weatherproof exterior paint finish is a matter of course. The leading edge should be specially protected by a hard varnish.

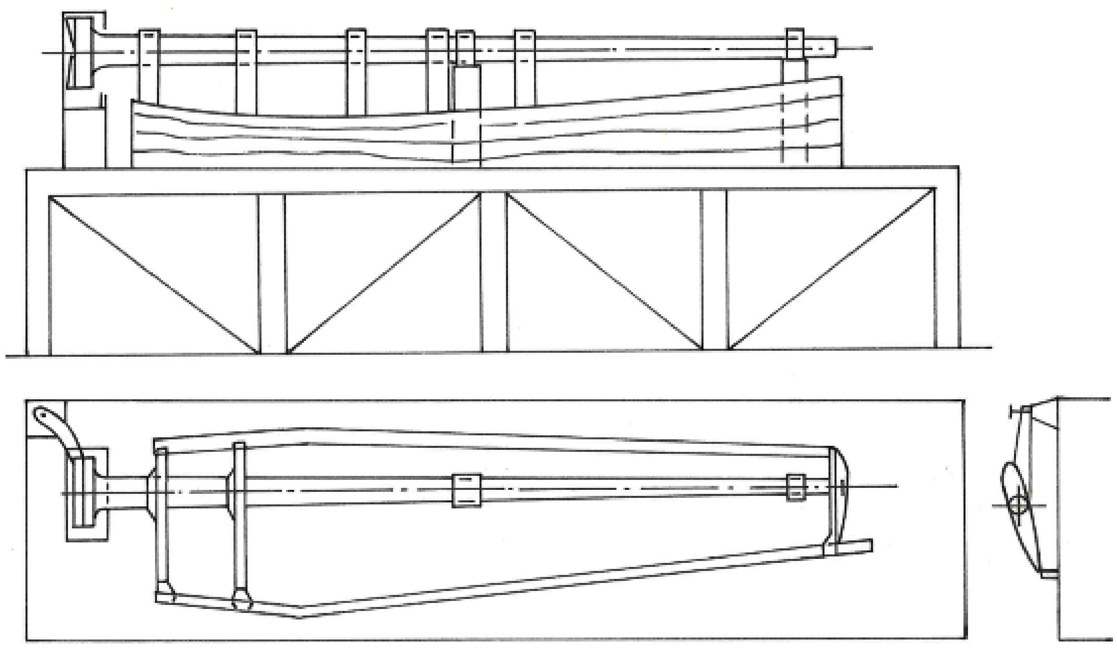

Figure 37. Blade jig for manufacturing.

In Germany it was taken to be granted that all parts subject to alternating stresses should have infinite service life and if it turned out it was not then remedial action was immediately taken. Unfortunately, this approach has currently been abandoned abroad and unlimited lifetime traded in for a limited life, i.e. after a defined time of operation needs replacement.

2.6.3 Tail rotors

A. Ordinary tail rotors with horizontal axis

They are essentially variable pitch propellers and can only be used for lateral control and to balance the torque. Like the main rotor they develop a β_1 and have a flapping hinge, often also a lagging hinge, and stiff propellers with a gimbal joint have also been used. Symmetrical airfoils are often used for simplicity although the torque compensation justifies an asymmetric airfoil. Only collective control is applied by pushing or pulling a rod through the hollow drive shaft. Flap-pitch coupling is applied to prevent excessive flapping. It is connected to the engine by a long drive shaft with several intermediate support bearings (Figure 38). Protection against contact with the ground must also be ensured with skids, due to the large angle to the ground during autorotation landings.

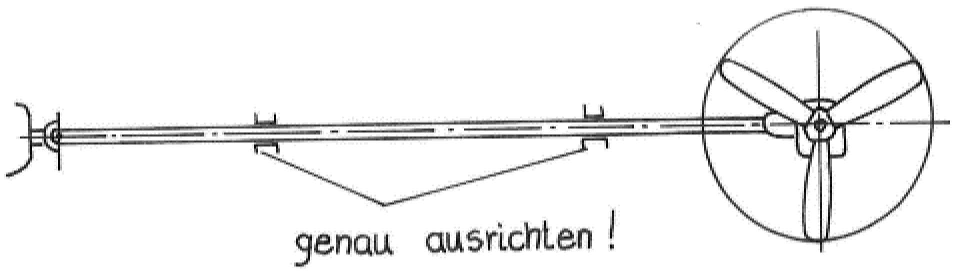

Figure 38. Single tail rotor arrangement.

The transmission shaft is fast-running to keep the tail rotor torque small and the remaining 1-stage gear is integrated in the tail rotor hub. The other end is connected to the main rotor shaft behind the clutch for keeping control during autorotation. The bearings need to be narrow enough to avoid bending resonances. Fuselage bending is usually not critical due to the soft transmission shaft and cardan connections at both ends allow for angular misalignments. Due to thermal expansion and installation difficulties, longitudinal movement of the shaft must be considered, for example by means of serration at one of the shaft's ends.

Tail rotor blades often are glued from wood in thin layers and then well protected from the weather and they are very light in weight. Plastic blades are also said to have been successfully tested recently, but I [Focke] cannot comment on this from my own experience.[21] Since centrifugal forces of the order of 100 kg arise and Coriolis moments of the order of 10 mkg in the absence of lagging hinges, great care must be taken with the connection of the wooden blade to the flapping hinge bolt. Wide sheet metal fittings and well-spaced bolts are recommended.

21. This refers to the glass fiber reinforced plastic blades for main and tail rotors in development at Bölkow at the airport of Stuttgart, next door to the DSH.

Twisting the blades is hardly worthwhile and of course makes production more expensive. Trapezoidal planform is useful, as we know from the main rotor, and the cost increase is not significant.

B. Double tail rotors

In our design we chose a double tail rotor arrangement tilted by 45º to the airframe and 90º to each other in a V-shape. The two-fold control linkage is more complicated also due to the little space in the gear box (Figure 39). For the different control purposes, they must be operated independently.

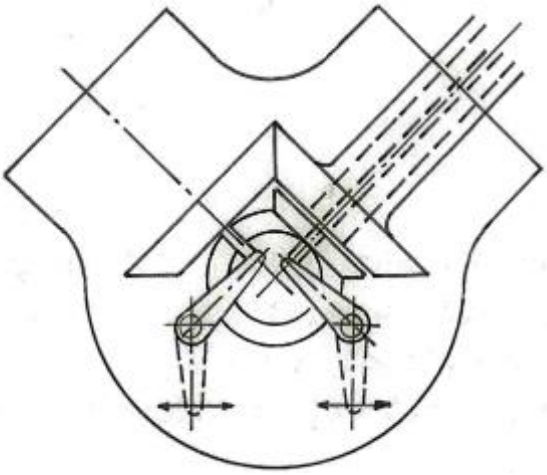

Figure 39. Double tail rotor gearbox and control linkage.

Control, auxiliary and connecting devices

The control levers in the cockpit are arranged intuitively, as in a fixed-wing aircraft. Stepping on the pedals initiates a turn to the respective side. The elevator control can be seen in two ways:

1. Pushing the stick is intended to increase speed. From hover, due to the power curve, this also results in a climb instead of a descent and requires a throttle down for maintaining the height.

2. This fact and the unfamiliarity of foreign countries with our German helicopter practice in the years 1936-45 led Sikorsky, as the first to achieve considerable success abroad in 1942, to take a different path: from the beginning he used a horizontally positioned “collective pitch” lever, which in itself corresponded to the intuitive movement (climb = pull up; descend = push down), but had and often still has another major flaw: with the increase of ϑ, the engine speed fell sharply if the throttle lever was left unchanged, but certainly if full throttle had already been applied beforehand. But with it also the engine power, and the climb, which was initially strong due to the inertia of the rotor also fell, and when only a slight excess of power was present it turned into descent, which is very dangerous especially near the ground (“throttled down rotational speed”). Another shortcoming of this method meant that with hands on stick and control lever no hand is free for the throttle, therefore the throttle is attached to the pitch lever by a rotary throttle knob like on a motorcycle.

Focke was concerned about the risk that the ϑ lever could become standard by way of world standardization and he strongly recommend resisting this and retaining the German procedure. In our design the ϑ lever is next to the throttle lever so that at first glance the arrangement looks like the throttle lever of a 2-motor model (Figure 40). The transmission of throttle and ϑ movement is carried out in such a way that the torque input of the rotor, when the levers are gripped together, is approximately equal to the torque output of the motor. Both grips can be operated with one hand only, pushing both forward or back, and adjusting small discrepancies by turning the hand.

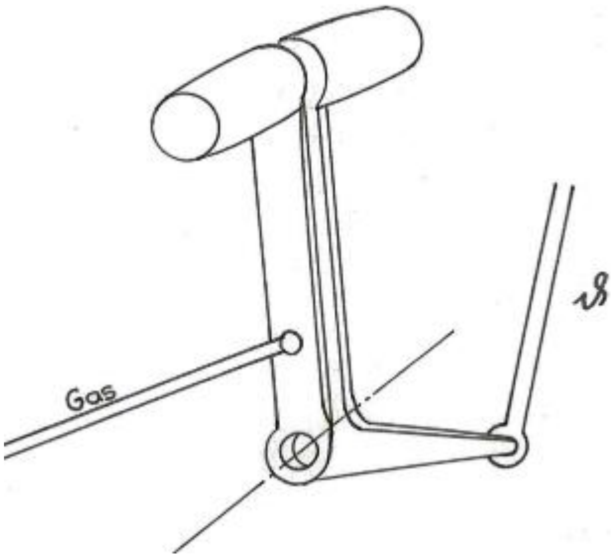

Figure 40. Collective control lever and throttle arrangement.

Independent of this, the automatic switching to autorotation occurs by means of a centrifugal governor that releases a lock when the rpm drops below a certain threshold and a spring pulls back both levers: the ϑ down to autorotation and the throttle to idle. All in all, altitude control using ϑ and throttle is suitable for hovering in place and vertical climb and descent, while normal longitudinal control is suitable for forward flight.

The vertical stick is used for longitudinal and lateral control by tilting the swashplate into any desired direction. The control forces transmitted to the pilot reveal some unpleasant character, because the blade torsion moments are transmitted to the swashplate. Where attached flow acts on the blades, the torsion moment is small. But in the occurrence of stall around 330º azimuth, the pressure center moves to mid-chord and generates a strong nose-down moment, that is transmitted to the swashplate by the blade's pitch link push rod. Because of 3 blades, this happens 3 times per revolution and is felt as stick force by the pilot (Figure 41).

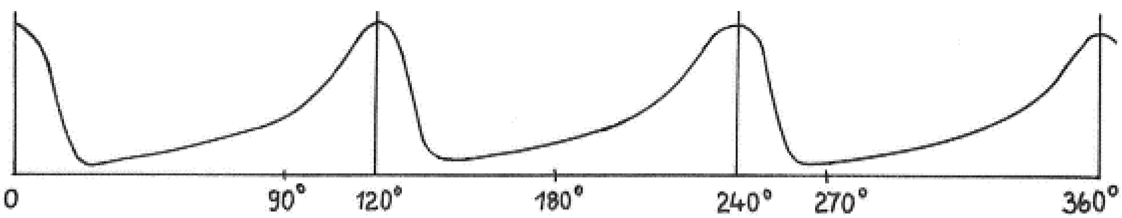

Figure 41. Schematic of control forces due to stall.

Components in the rotating frame must be designed for fatigue strength. Within the load path to the pilot a damper could be attached but this may cause blockage or hinder rapid motions.

Attaching a mass with inertia, as was done in the Fa 223, reduced the large vibration to a small tremor in the stick. A steady force is also transmitted to the stick, which is not unpleasant, but its source not known yet and Focke hoped to reveal the reason in the new institute to be created.

2.6.4 Overall control scheme

The control displacement ranges are similar to those of fixed-wing aircraft: push-pull of the stick ±225 mm, yaw ±150 mm, pedals ±100 mm to ±150 mm. The overall control scheme is sketched in Figure 42. Because the tail rotors have two functions

1. generate lift up or down, requiring the increase or reduction of ϑ of both rotors;
2. generate a sideward force to the right or left by differential ϑ control of the rotors;

a mixer must be installed that merges both functions before transmitting the control motion to the pitch levers of the tail rotors (Figure 43).

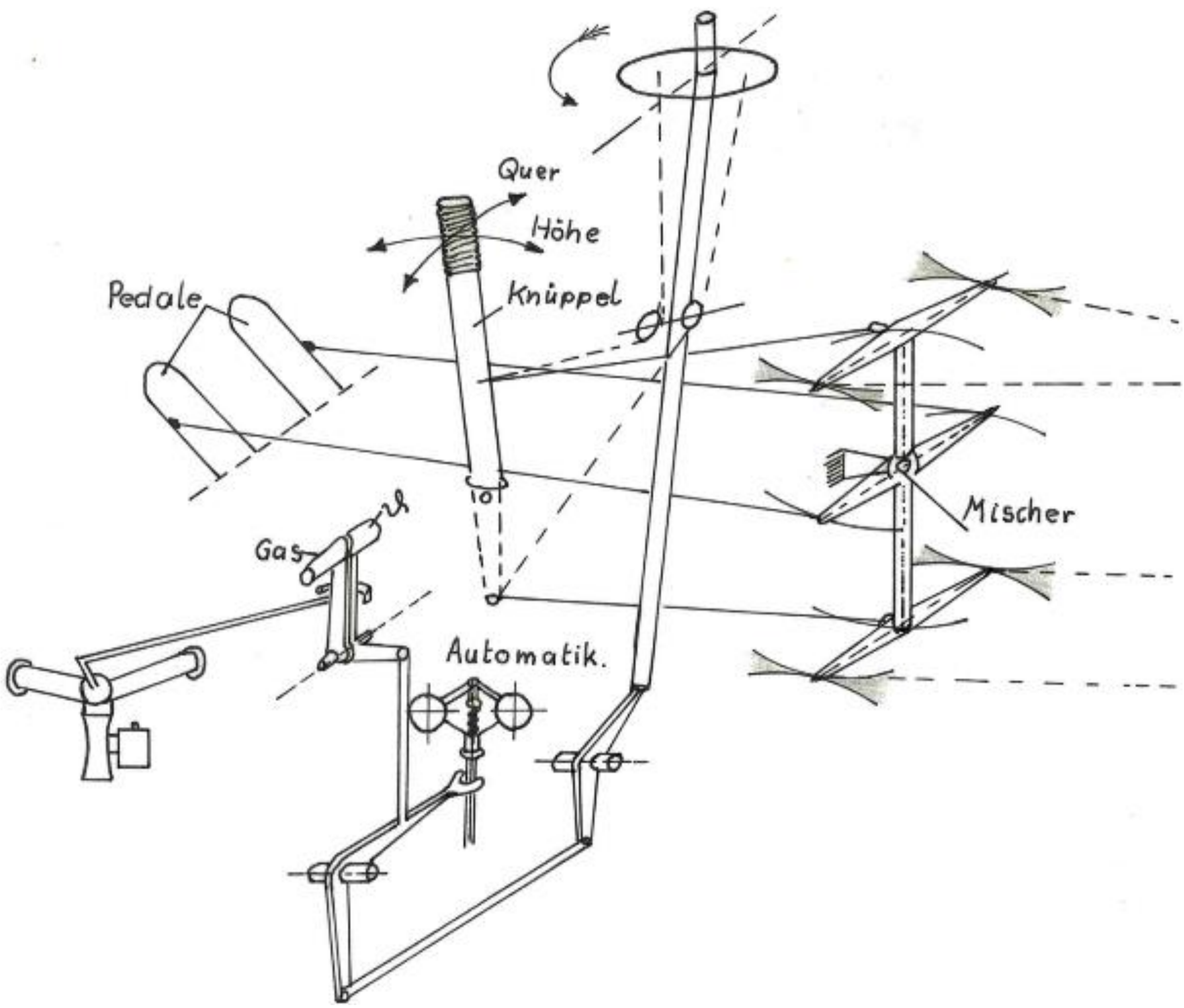

Figure 42. Scheme of all control elements.

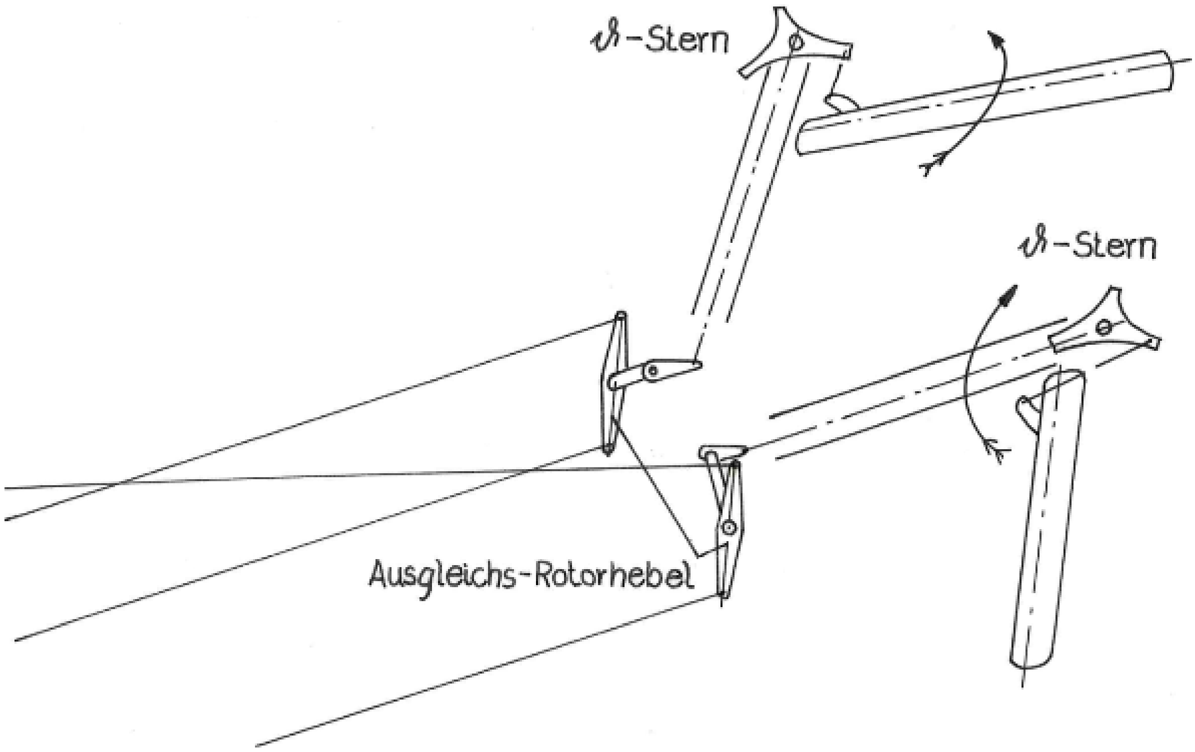

Figure 43. Tail rotor control cable diagram.

The control forces are treated thereafter. Focke comments that on foreign helicopters such as the Sikorsky, Bell, and Hiller there is some very unpleasant stick wobble, against which only such inadequate measures are taken that it is recommended to press the right knee firmly against the stick, grasp the handle very tightly and then place the fist firmly on the knee! However, I have occasionally seen that this is not done at all and the pilot simply follows a not too strong wobbling movement with his hand. You could see this recently in the movie *History of the Helicopter*.[27]

2.6.5 Clutch

This component of the helicopter must be handled with particular care to ensure unhindered autorotation. Two main types have proven themselves.

Steel disk clutches (Figure 44) are reliable at 1000 HP and 2900 rpm and are fully proven. However, they stick in oil when cold but this can be remedied by switching off in the evening when parking and idling for a short time. Risk of blade damage due to jerk in δ is otherwise high.

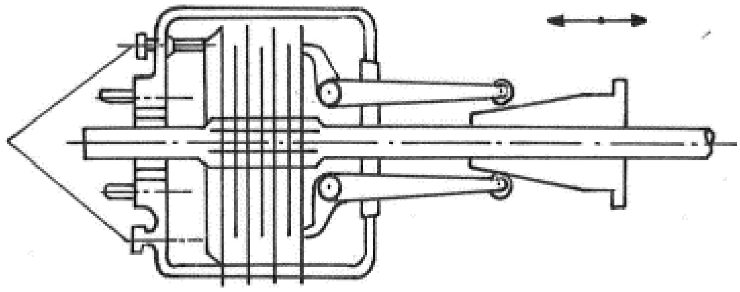

Figure 44. Sketch of a steel disk clutch.

Centrifugal clutches (Figure 45). Advantage: Automatic autorotation, if ϑ also down. Our experience to date has only been with smaller units, in the order of 200 - 300 HP at 2,000 to 5,000 rpm. Release in the event of engine failure by appropriately selected bolt position!

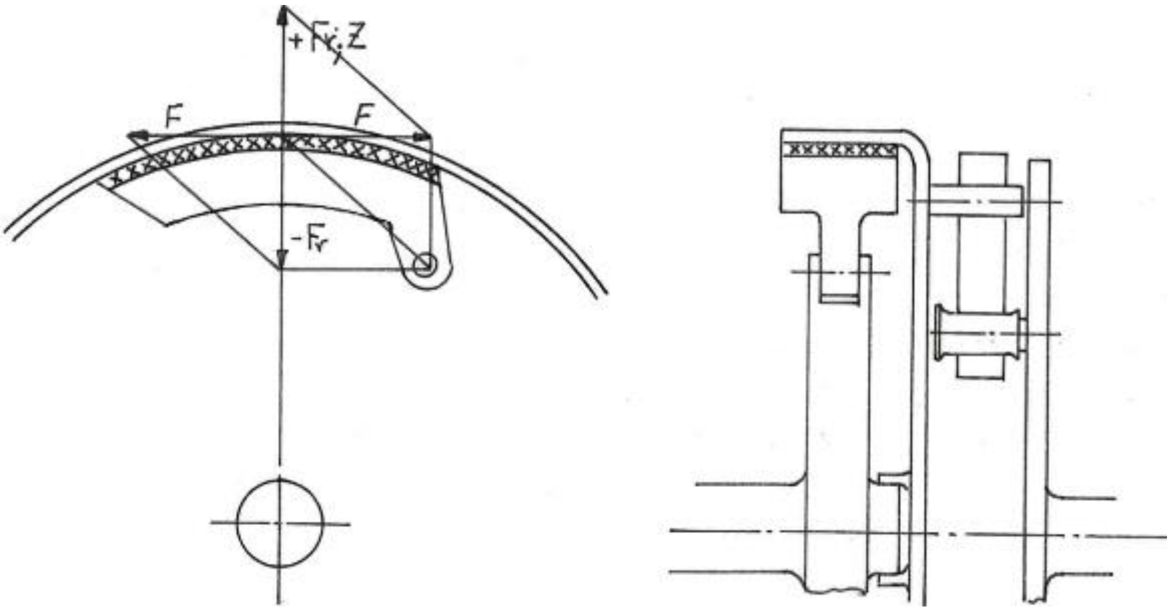

Figure 45. Sketch of centrifugal clutch.

2.7 Practical information about stability

The behavior of a helicopter without specific precautions is characterized by phase lags and excessive feedback moments because of their dependency on flight speed, resulting in growing amplitudes of motion. The oscillation period is important, large ones of more than 30 seconds are considered as an apparent dynamic stability. Large surfaces underneath the center of gravity could alleviate the large static feedback moment and increase the oscillation period but is only possible in lateral control. Today the lateral stability is insufficient and the longitudinal stability is bad. Methods to improve stability were developed by Bell ("Stabilizer bar"), which Sissingh had analyzed.[28]

Yaw stability is not difficult to obtain because the tail rotor represents a vertical stabilizer, but also generates torque which for the helicopter is a pitching moment. To all stabilities, but mainly to longitudinal stability, it can be said that they are better with flight speed than in hover or low speed. For longitudinal stability a trimmable fin would be beneficial. Finally, a schematic overall picture of our hypothetical design (Figure 46).

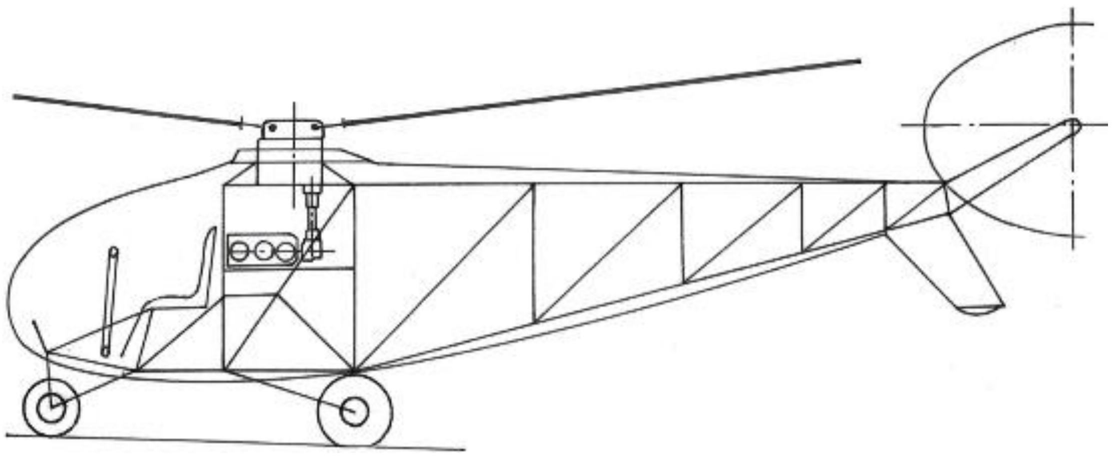

Figure 46. Overall picture of our design.

A photo of Henrich Focke from 1960 at an age of 70 years during his employment at Borgward in Bremen is shown in Figure 47, quite similar as his students would have seen him.

Figure 47. Professor Dr. e.h. Henrich Focke, 1960 (1).

3. CONCLUDING REMARKS

The lecture of Focke in 1955 significantly differs from today's rotorcraft lectures, as he addressed all aspects and components of helicopter design from an engineering point of view, with all theory as *a priori* knowledge and all his practical experiences of the preceding 20 years. It must be kept in mind that computers were not then in use and all computations had to be performed manually, therefore charts for rotor performances were used instead of lengthy numerical evaluations. He still followed his proven concept of rotor control, rotor blade design and self-stability of the helicopter from the Second World War without electric stability augmentation, and continued so with his last helicopter "Kolibri" designed at Borgward from 1956 until 1961, which was very similar to the Brazil "Beijaflor". With the data of the "Beijaflor" his students gained deep insight into all the aspects of designing a helicopter of the time.

Aerodynamic theory of the helicopter is not the main subject of Focke's helicopter design lecture, this is taken as *a priori* knowledge of the students from Professor Just's lecture at the same university. Therefore, Focke reduces aerodynamic theory mainly to momentum theory and eventually to a representative radial section, which Focke selects as the 70% radius location instead of radial distributions. The beneficial impact of blade twist and taper are therefore only side notes in Focke's lecture. Refined theory such as vortex wakes were completely beyond contemporary capabilities. Therefore, Focke emphasizes the importance of knowing the limits of theoretical methods and the need to validate them by experimental data. Flight limits due to, for example, retreating blade stall, are not directly computed by load distributions but are instead determined by maximum practical limits of generalized parameters, such as the mean lift coefficient at the representative section, or thrust coefficient limits as function of the advance ratio – all based on experimental data from practical experience.

Similar to the simplification in aerodynamics, the load cases could not be treated by computer application of finite element methods that were not yet at hand in the 1950s. Also, certification rules were not yet fully established and Focke followed a mixture of best practice and regulations where existing, with the priority of "safety first". Hard landings as load cases were only considered important for rigid landing skids but were not treated in his lecture because he proposed a classical landing gear with springs, dampers and wheels.

Compared to today's helicopter design, virtually all components of a helicopter have significantly changed. After a period of full-metal rotor blades that replaced the wooden blades design, fiber composite materials dominate the modern rotorcraft market. Welded steel frames for the fuselage are replaced by shell structures, increasingly replaced by fiber composite material designs. Turbine engines with automatic controllers widely replaced combustion engines with pilot controls at the throttle, but Focke already coupled some pilot controls to the throttle for alleviation of pilot work load in his helicopter design. An interesting aspect for helicopter static and dynamic stabilization by use of the Focke's invention of canted twin tail rotors did not find its way into today's helicopters, both due to its additional mechanical complexity and due to the applications of stability augmentation controllers.

Henrich Focke was especially remarkable in that he had an enormous amount of knowledge in theory, physical understanding and practice of all aspects needed in helicopter design that is reflected in his lecture. His impact on international rotorcraft design was mainly seen in the French Aerospatiale series of Alouette I and II helicopters that Focke considered "his grandchildren" emerging from his period with SNCASE in 1945-1948. It was also seen for a short period in the Brazil "Beijaflor", but never came to fruition in his latest design, the Borgward-Focke "Kolibri". His lecture at the technical university in Stuttgart was only given once and hence could not influence many students and the technical development in all areas of helicopter theory and its design progressed quickly in the 1960s, replacing traditional design concepts. The availability of computers significantly revolutionized the theory and design in all aspects, replacing the methods of Henrich Focke that were developed in the 1930s. However, many of the issues he raised are still fundamentally important, although now the subject of more sophisticated and capable methods. One would have to marshal a cross-disciplinary team of subject experts today to cover the same breadth of material as Focke did in his 1956 lecture.

APPENDIX

Table Conversion of symbols.

German	English	Focke	Multiplier	Today
Auftrieb	Lift	A, kg	g	L, N
Auftriebsbeiwert des Profils	Airfoil lift coefficient	c_a	1	c_l
Mittlerer Auftriebsbeiwert	Mean lift coefficient	$\overline{c_a} = 4\,k_n/\sigma$	$3/4$	$\overline{c_l} = 6\,C_T/\sigma$
Widerstandsbeiwert des Profils	Airfoil drag coefficient	c_{wp}	1	c_d
Durchmesser	Diameter	D, m	1	D, m
Blattelementbreite	Blade element width	dr, m	1	dr, m
Fläche des Rotors	Rotor disk area	F, m²	1	A, m²
Fläche des Blattelements	Rotor blade element area	f, m²	1	$c \cdot dr$, m²
Fläche des Rotorblattes	Rotor blade area	f_{blade}, m²	1	A_b, m²
Gewicht	Weight	G, kg	g	W, N
Gravitationskonstante	Gravity constant	g, m/s²	1	g, m/s²
Drehmomentkoeffizient	Torque coefficient	k_d	$1/2$	C_Q
Normalkraftkoeffizient	Rotor lift coefficient	$k_n \approx k_S$	$1/2$	$C_L \approx C_T$
Schubbeiwert	Thrust coefficient	k_S	$1/2$	C_T
Machzahl	Mach number	M	1	M
Drehmoment	Torque	M_d, mkg	g	Q, Nm
Leistung	Power	N, mkg/s	g	P, W
Drehzahl	Speed of rotation	n, T/min	1	n, rpm
Staudruck	Dynamic pressure	q, kg/m²	g	q, N/m²
Radius	Radius	R, m	1	R, m
Radiale Koordinate	Radial coordinate	r, m	1	r, m
Schub	Thrust	S, kg	g	T, N
Profiltiefe	Chord length	t, m	1	c, m
Umfangsgeschwindigkeit	Blade tip speed	u, m/s	1	V_{tip}, m/s
Geschwindigkeit	Velocity	V, m/s	1	V, m/s
Steiggeschwindigkeit	Climb velocity	v_s, m/s	1	V_c, m/s
Widerstand	Drag	W, kg	g	D, N
Blattzahl	Number of blades	z	1	N_b
Anstellwinkel	Angle of attack	α, deg	1	α, deg
Schlagwinkel	Flapping angle	β, deg	1	β, deg
Rotoranstellwinkel	Rotor angle of attack	α_π, deg	1	α_R, deg
Bahnwinkel	Flight path angle	γ, deg	1	γ, deg
Luftdichte	Air density	ρ, kgs²/m²	g	ρ, kg/m³
Drehfrequenz	Rotational frequency	ω, rad/s	1	Ω, rad/s
Gütegrad	Figure of merit	ζ_L	1	FM
Blatteinstellwinkel	Blade pitch angle	ϑ, deg	1	Θ, deg
Flächendichte	Solidity	σ	1	σ
Tangentialer Fortschrittsgrad	Tip speed ratio	μ	1	μ_x
Axialer Fortschrittsgrad	Inflow ratio	λ	1	μ_z

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Berend G. van der Wall joined the German Aerospace Center (DLR) in 1986 as research engineer and developed a rotorcraft simulation by engineering simplified approaches for blade flexibility, unsteady aerodynamics and vortex wake approaches. His PhD in 1999 demonstrated the usefulness of such approaches by validation with data from wind tunnel tests. Berend led the international HART I wind tunnel test and successive activities, honored by the American Helicopter Society (renamed Vertical Fight Society in 2018) Gruppo Agusta Award 1996, AHS Howard Hughes Award 2004, AHS AgustaWestland International Helicopter Friendship Award 2012, and became DLR Senior Scientist in 2011.

Berend is author of two textbooks on helicopter aerodynamics and rotor dynamics and a book about German helicopter developments during 1939-1945 (AIAA). He authored/coauthored eight book contributions, many journal articles and conference papers and holds several patents. The AHS/VFS Bernard Lindenbaum Award for the best paper in the History session of the Annual Forum was given to him in 2016 and 2020. In 2023 he received the VFS Technical Fellow Award for his career-based technical accomplishments.

Berend was also co-developer of the patented DLR-ONERA ERATO low noise rotor, that found its way into the Airbus H160 helicopter as “Blue Edge” rotor blade, and the respective paper was awarded by the AHS best Test & Evaluation paper 2016 and also as the EREA best paper 2016, and finally by the DGLR Honorary Pin of German Aviation 2019. A novel patented multi-swashplate individual blade control system development was nominated for the German Future Prize of the Federal President’s Award for Technology and Innovation in 2009.

Berend is a lecturer at TU Braunschweig since 2007 and became Honorary Professor there in 2014. He is member of the AHS (now VFS), the German Helicopter Museum and the Bremer AirBe. He serves in the Test & Evaluation and the History committees of the VFS and acted as associate editor of the Journal of the AHS and as reviewer for several other Journals.