2 Flying Qualities—Some History

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What looks good, flies also good.

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2.1 Fixed-Wing Aircraft

Anyone who has ever watched a seagull, gliding effortlessly over the lake in the upwind along the bluff, is full of admiration of the ease and elegance with which he flies. The fine movements of wings and tail to correct the flight are not

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discernible. The bird is in an absolute balance with the wind, gravity, and lift. Thereby he conveys an impression of a perfect flier to the observer.

The first aircraft at the beginning of the last century were far away from such a perfection. Even the first aviation pioneers, who delved into flying 200 years back, had recognized what one must do to enable a flying vehicle cover a longer distance in an undisturbed gliding flight. To construct their models they oriented themselves mostly on the basic configuration of a bird with a wing in the front and an empennage arranged behind. With the center of gravity of the flight vehicle in correct position, these models flew stable and quite well. Technically, the expert then speaks of a "stable flight". In this case, stable does not mean "durable", but rather the ability of the aircraft to return automatically to its unperturbed initial condition in response to a disturbance. Also, the exotic tropical plant "Zanonia Macrocarpa", whose seeds show an extremely stable flight behavior, served as a prototype for a favorable aerodynamic design of a flying vehicle (see Fig. 2.1). The knowledge about what must be done to accomplish a stable gliding flight was essentially known to the aviation pioneers at the beginning of the last century. Design and numerical data required for construction of an aircraft, however, did not exist. One had to rather learn from the practical experience.

However, an airplane should not only fly straight and level in gliding flight, but must start from the ground, land again and above all fly in curves. With regard to the stability, one could rely on some existing knowledge. On the other hand, in the area of flight controls, the aviation pioneers had to tread unknown territories.

The Stork, whose flying skills *Otto Lilienthal* had studied intensively and had drawn his conclusions, served as a role model for his hang glider. Aerodynamic experiments by a specially constructed device provided him with the numerical data for the construction of his flying machine. His "normal apparatus" from the year 1894 even revealed the basic configuration of an aircraft. A horizontal and vertical surface were mounted some distance behind the wings. He needed both of these for the stability of his gadget about the vertical axis (directional stability) and about the lateral axis (longitudinal stability). The wings were mounted significantly upward (V-position), which provided sufficient inherent stability about the longitudinal axis (roll stability). However, *Lilienthal* steered his gadget by shifting of weight. As a consequence, the controllability was severely restricted and thus was the cause of his fatal crash in 1896.

The *Wilbur and Orville Wright brothers* followed another method. They had keenly followed the flight tests by *Lilienthal* and recognized that ensuring sufficient controllability about all the three axes is of pivotal importance. To achieve that, the flyer possessed aerodynamically effective elevator and rudder. For roll control about the longitudinal axis, which is necessarily required for coordinated curve flight, highly elastic wings were built and twisted. The horizontal tailplane was arranged in front of the center of gravity (see Fig. 2.2). Thereby the "Flyer" was no longer stable. Pilot had to intervene constantly in order to stabilize

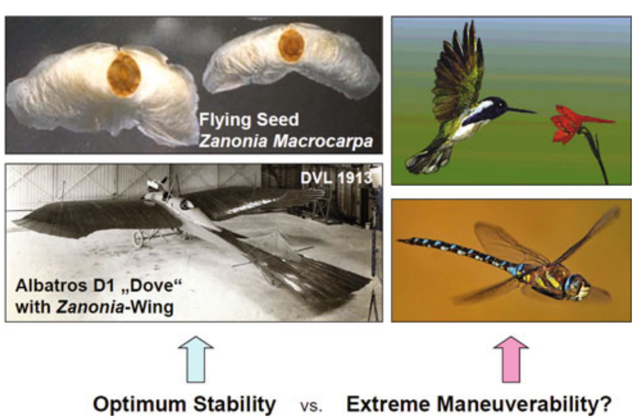


Fig. 2.1 Stability or controllability—where is the compromise? (*Credit* P. Hamel)

Fig. 2.2 The first fully controllable aircraft, the "Flyer III" in flight (1905), (*Credit* Deutsches Museum)

the flyer and keep it on the track. The *Wright* brothers believed that a skilled pilot must be in a position to continually balance the Flyer through an effective control. Too large an inherent stability is on the other hand more likely to be obstructive, when large disturbances must be compensated by control inputs. Probably the *Wright* brother had not adequately appreciated the importance of inherent stability for the flying [1].

With their desire for neutral stability, the *Wright* brothers were rather alone in the pioneer generation by aircraft manufacturers. Awareness was established that sufficient inherent stability is absolutely essential for safe flying. A pilot continuously struggling to stabilize the gadget can hardly perform any other task. Only much later the idea of reduced static stability (*Relaxed Static Stability*) was once again taken up during the development of highly maneuverable combat aircraft. These aircraft were, however, not stabilized by a pilot, but through a multi-redundant flight controller.

In the year 1909, *Louis Charles Blériot* had arrived at the classical basic configuration for the aircraft with his Type XI, which was mostly adopted for the aircraft construction thereafter, (see Fig. 2.3). This configuration is characterized by a front mounted motor with a tractor propeller and tailplane located at the rear for the longitudinal and lateral control. The roll control was not yet by ailerons, but through twisting the entire wing. The aircraft was apparently sufficiently stable about all the axes and allowed *Blériot* a smooth ride across the English Channel to England.

Aircraft development showed a rapid boom during the First World War. In Germany a variety of very different aircraft types were delivered to the Imperial German Army Air Service. Of course, there was no question of consistent and good flying qualities. It was a challenge for the pilots to fly many of these aircraft and they were hardly deployable. This diversity led the aircraft engineering department of the German Aeronautical Test Establishment (DVL) in 1917, to test several aircraft types for their flying qualities and to assess them by the pilots. Although it was not an objective assessment, a few characteristics emerged, which were then considered important and desirable [2]. These evaluations based on the pilot assertions, however, did not offer yet a reliable basis to improve the flying qualities through technical measures.

The aircraft which came closest in demonstrating the wishful good flying qualities was the biplane Fokker D VII constructed by Antony Fokker (see Fig. 2.4). Introduced in the year 1918, the Fokker D VII evolved as the most successful combat aircraft during the First World War. The aircraft was inherently stable, highly maneuverable and possessed good control surface effectiveness about all axes. One characteristic was particularly notable, namely, the aircraft recovered itself automatically from the dangerous spin as soon as the controls were released by the pilot. In the heat of an aerial combat, it was quite easy for the pilot to stall the aircraft and thereby enter into a spin.

Since the beginning of the aircraft development, the above problem encountered in flight was also addressed scientifically in parallel. It was the British mathematician *George H. Bryan*, who in the year 1911 formulated the problem of aircraft motion on a sound mathematical basis. *Bryan* formulated the equations of motion and introduced the concept of "stability derivatives". However, it was not possible yet to solve this system of equations.

Based on Bryan's equations, the flight scientists *Leonhard Bairstow* from the National Physical Laboratory (NPL) in the UK provided the first rudiments of stability analysis. He realized that the complex system of equations could be decoupled into a "longitudinal motion" and in largely decoupled "lateral motion". Solutions to these now simplified equations resulted in the flight mechanical eigenmodes of motion, which are commonly known to today's aeronautical engineer such as "Phugoid", "short period" and "Dutch roll"

Fig. 2.3 Safely over the English Channel: Monoplane Blériot, Type XI (1909). *Louis Blériot* as pilot, (*Credit* Deutsches Museum)

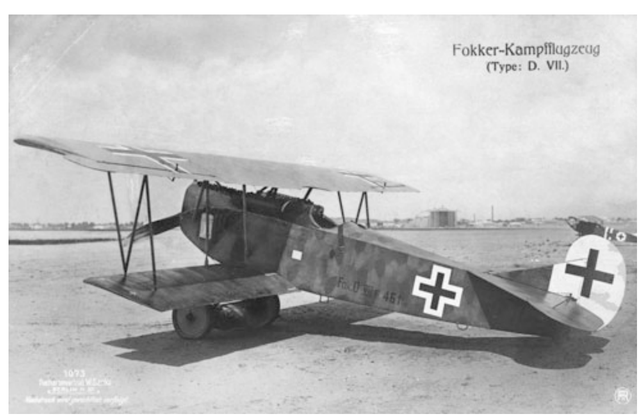


Fig. 2.4 The best fighter aircraft of First Word War, the legendary Fokker D VII biplane aircraft (1918), (*Credit* Deutsches Museum)

etc. To provide information about the order of magnitude of the stability derivatives, in the year 1913, *Bairstow* performed the first wind tunnel measurements on a model of Blériot-monoplane. A few years later, in the year 1916 commenced the wind tunnel measurements also with the same goal at the Massachusetts Institute of Technology (M.I.T.) in the United States under the leadership of *Jerome C. Hunsaker*. Although the measurements provided information about the static stability, predictions regarding the dynamic behavior and flyability were difficult to deduce. It was felt that a reasonable correlation between the wind tunnel measurements and flying qualities could be arrived at only through flight tests and in consultation with experienced pilots. These findings of the flight scientists were not utilized then by the aircraft manufacturers, as it was not possible yet to solve the mathematical problems without the aid of proper tools. The time was simply not yet ripe for that.

The lack of information about which parameters of an aircraft are most relevant to the flying qualities prompted the American aviation authority National Advisory Committee for Aeronautics (NACA) in 1919 to an extensive flight test program [3]. The objective was to establish a good correlation to the previous wind tunnel tests at M.I.T. The flight tests were performed mainly by the test pilot *E. T.* "*Eddie*" *Allen*, who later became one of the most distinguished test pilots of the USA. For these experiments, the aircraft were for the first time fitted with a simple measuring equipment to record the main parameters (control force, rudder position) during the flight. In this way, it was possible to determine reasons for the known poor flying qualities of Curtiss JN4H "Jenny". This laid the foundation stone for the flight test department of NACA, which excelled in the course of the following years with better and better instrumentation and excellent test pilots.

After the First World War, the flying qualities remained further on the topic of aeronautical research in Germany too. In the year 1926, the DVL Flight Department in Berlin-Adlershof dealt once again with flight performance tests. The aim was to gather reliable data for stability requirements. The tests pointed out the need for improving the stability characteristics of the then assembled aircraft and that the documents were not yet sufficient to predict, for example, duration of damping of oscillations. Nevertheless, a good balancing of elevator, rudder, and ailerons control forces was already demanded. The results of the DVL flying qualities experiments are reflected in the construction regulations for aircraft (BVF) published in 1928 [2].

Until the early nineteen-thirties, everything necessary was done to construct inherently stable, well controllable and safe aircraft. They were built on a wealth of experience and less on flight mechanical theories. The development engineers had then absolutely no options yet to predict the dynamic behavior of an aircraft. From the experience, one knew, however, what had to be done to suppress effectively such disturbing oscillations. For this reason, the development engineers hardly felt any need till mid-nineteen-forties for a detailed mathematical analysis of the flight performance.

Both civil and military aviation wanted aircraft to have flying qualities tuned to the respective requirements and with which an average pilot could cope well. For commercial aircraft, special emphasis was on instrument flight or the approach on a radio beam, whereas for military aircraft the maneuverability stood in the foreground. These are sufficient reasons for aircraft procurer to enquire about the flying qualities of a particular vehicle.

This topic led in 1940 to a large-scale research program at the NACA. The flight departments of NACA research centers at Langley Field (Virginia) and Moffett Field (California) conducted flight tests, with which stability and controllability of aircraft regarding the "flying qualities" were to be evaluated based on the pilot comments. After the outbreak of World War II, this study was greatly expanded with the participation of U.S. Army Air Corps and the U.S. Navy. Numerous civil and military aircraft were investigated under the leadership of NACA flight test engineer *Robert R. Gilruth*. Based on the flight physics, *Gilruth* developed a series of quantitative flying qualities criteria, which he correlated with the flight tests. His investigations resulted in a collection of flying qualities criteria, which were then stipulated as mandatory flying qualities guidelines for the aviation industry [4].

Whereas the flight test at Langley Field concentrated on flight test programs with subsequent pilot survey, on the other side of the continent the focus was already on determining the flying qualities of a future aircraft from wind tunnel measurements, before the pilots pointed out the deficiencies, which could be corrected only through highly time-consuming and costly efforts [5]. A very detailed wind tunnel measurements were carried out on different types of aircraft and these were correlated with those from flight tests.

Similarly, as in the case of NACA, the developments in Germany were directed towards quantitatively definable flying qualities guidelines. Essential experiments related to this aspect were carried out at the DVL in the nineteen-thirties by *August Kupper*. After *Kupper* passed away, *Karl-Heinrich Doetsch* was responsible for the continuation of the work. Though the use of instrumentation to measure important flight mechanical parameters, it became possible to obtain numerical data necessary for quantification. In the year 1943, the DVL, and almost at the same time the NACA, published a new draft of the flying qualities guidelines [6]. In these guidelines, special emphasis was placed on the verifiability of the stipulated flying qualities. Thus, the guidelines also contained a number of standardized testing instructions and directives for the assigned test pilots. As a result, the German aviation industry possessed a set of rules to design control surfaces and flight controls for a standardization the flying qualities to a large extent.

With the introduction of jet engines, the usable flight regime was extended up to the speed of sound. This resulted in new demands and requirements on the flight performance, flying qualities and on the flight safety. On approaching the speed of sound, the so-called compressibility effects were encountered, leading to hitherto unknown flight instability with reduced control capability. Although the new configurations such as sweptback and delta wing ensured acceptable flying qualities in the high subsonic range, they faced new problems at lower airspeeds, such as those during landing. The dilemma was how to manage the higher elevator and rudder forces resulting from the increased aircraft size and enhanced airspeeds

However, conventional aircraft configurations also showed occasionally stability problems during certain flight tasks. Already during the war, there were attempts to improve the deficient flying qualities with the help of a controller. Again, the fundamental contributions of *K.-H. Doetsch* on automatic control at DVL provided the practical basis for artificial stabilization of aircraft (see Chap. 4).

New aircraft configurations and the increasing air traffic forced an enhancement of flying qualities guidelines. The criteria should now be formulated task-specific (takeoff, landing, cruise flight, maneuvering, approach in a glide slope, etc.). Also, the different types of aircraft (transport aircraft, combat aircraft) should be evaluated differently. The military and the aeronautical establishments requested the NACA to deal with flying qualities of transport aircraft during instrumental approach and landing. The Navy needed specific criteria for a safe approach on an aircraft carrier. The US Air Force Air Materiel Command was interested in determining the stability derivatives of an aircraft from flight tests.

This also applied to the control forces. The control forces should be such that a safe "feeling" for speed and stability is conveyed to the pilot. Already in the nineteen-twenties, it was realized that the forces to be exerted by the pilots would no longer suffice to actuate the rudder of large aircraft. This problem was initially solved through the introduction of so-called auxiliary rudders. Auxiliary rudders, whether Flettner tab or spring-loaded auxiliary rudder (spring tab), were successfully installed worldwide in many aircraft types. The harmonization of control forces and adaptation on the prescribed guidelines led sometimes to serious problems. This resulted in numerous changes to the tailplane, until the desired characteristics was achieved. For some aircraft hundreds of flying hours were spent to adjust the rudder forces to the operational conditions [7].

The first aircraft with adjustable flying qualities (*Variable Stability Aircraft*) originated in 1947 out of this difficulty. Thereby the elaborate and expensive modifications to aircraft could be averted (see Chap. 5).

The development and the use of automatic course controls (autopilot) brought a new set of tools, attitude gyro, rate gyro, electrical and hydraulic servomotors, which could be used for other purposes as well. With such servomotors large rudder control forces could be exerted even without the help of auxiliary rudder. This was particularly important for the new generation of jet aircraft, which flew under high dynamic pressures and required large control forces. However, the pilot lost thereby the sensation for the control forces, which is an important criterion for handling qualities. This feeling had to be provided to him now artificially by a force feedback. Autopilot, stabilizing controller (*Stability Augmentation Systems, Response Feedback Control Systems*), servos, and artificial control forces contributed significantly to growing complexity of aircraft.

The correct designing of such complex systems needed a thorough flight mechanical analysis, before they could be integrated into a plane. Since the late nineteen-forties, new procedures for stability analysis and controller design were available in the USA. Using the root locus method developed by *Evans* and the *Bode* plots in the frequency domain one was able to model complex systems and carry out stability investigations. With the introduction analog computers, it became finally possible to investigate complex flight systems in a simulation. These methods were the result of years of research in the fields of electrical engineering, flight mechanics, and control engineering [8]. This way the errors and instabilities could be detected and eliminated at an early stage. The subsequent stability and system analysis on the digital computer was another important step towards flight safety and saved a lot of precious flight test time, and thereby avoided dangerous situations for test pilots [9].

The flying qualities analysis also benefited from the new procedures and methods of stability analysis. These advances and the outbreak of war in Korea forced the U.S. Air Force and Navy to a closer cooperation in the area of flying qualities. The result of these joint efforts was the newly revised flying qualities guidelines in the form of a "Military Specifications, Flying Qualities Piloted for Airplanes" during 1954 [10].

The initial flight controllers were still based on pure flight state feedback systems (*Response Feedback Control*). The controller is superimposed on the manual control through the pilot without affecting its function. As a result, the flying qualities could be improved and brought in accord with the guidelines.

New technologies and tasks led to significant expansion of flight domain. The flight at supersonic speed, intelligent weapons systems, challenging flight tasks such as flights close to ground-level (*Terrain-Following*) revealed the limits of mechanical manual flight control. Only with an elaborate flight controller, it was possible to meet the flying qualities guidelines. The complex flight controller could be readily realized, dispensing with the manual control through levers, push rods, and ropes. Instead of a mechanical connection to the inceptor, the hydraulically operated rudder actuation received now an electrical input. This new technology was termed as "Fly-by-Wire". New controller functions made possible the flight with reduced stability in order to achieve performance improvements. Security features, such as stick shaker and flight envelope limiter, ensured safety and avoided structural overloading. The pilot now flew a controller-aided airplane. An exhaustive account of national and international flight test demonstrators, which serve the purposes of testing, certification, and implementation of Fly-by-Wire technologies in the military and civil aviation, is provided in Chap. 6.

Forgoing the natural stability with the objective of improved flying qualities placed high demands on the integrity of the flight control system. A multiple redundant flight controller now ensures stability and makes sure that all functions required as per the flying qualities guidelines are restored. Aircraft which were designed for a spectrum of specific tasks and which could only be flown with the aid of a flight controller were the so-called *Control Configured Vehicle* (CCV) [11]. With the CCV Technology, the foundation stone was laid for all modern combat aircraft (see also Chap. 6).

Mathematical analysis, ground simulation, in-flight simulation, and flight test were the tools used in the nineteen-sixties and nineteen-seventies to investigate and to optimize the flying qualities of new aircraft types. The MIL-F-8785 provided a set of criteria, which allowed to verify objectively the flying qualities from flight test data. This alone was, however, not enough. Subjective evaluation by an experienced test pilot was additionally demanded (see Fig. 2.5). To account for this aspect a new policy "MIL-STD-1797" was published [12]. This guideline was based substantially on the MIL-F-8785, but contained additionally flight test methods and an evaluation table for a subjective evaluation by the test pilot. The *Cooper-Harper* Rating Scale [13] allowed a differentiated assessment of flying qualities and was a good supplement to the objective evaluation by the MIL.

To be more specific, the *Cooper-Harper* Rating scale is the subjective but structured measure to evaluate the handling qualities, in other words, the controllability of an aircraft in terms of pilot workload. For all practical purposes, it is the standard procedure employed over more than four decades. Basically, it aims at determining "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role" [13]. In general, it is intended

Fig. 2.5 NACA test pilot *George E. Cooper* with *Hugh L. Dryden*, the Director of NACA Ames Research Center (1951)

for pilot-in-the-loop tasks. As such design and definition of appropriate tasks to be flown and evaluated is critical in the application of this rating scale. It is based on the pilot assessment immediately after performing a particular task, the rating varying from 1 to 10. The highest rating of "one" implies fulfillment of task with very little effort, whereas the lowest rating of "ten" implies cases which were not controllable in all the test phases, because major deficiencies were encountered and that improvements are absolutely necessary. The standard *Cooper-Harper* Rating scale is presented in Fig. 2.6.

New tasks, expansion of flight operations, monitoring systems were also reflected in the cockpit. As a result, the pilot behavior, his way of response, mental and physical ability to withstand workload gained importance. It was particularly a trait of digital flight control systems that resulted, as a consequence, in a new kind of flying qualities problem. Computational and signal transmission times led to time delays in the control system. After the input of a command by the pilot, the aircraft reaction did not result immediately, rather only after a certain delay. Thereupon the pilot intensified his input and retracted the command immediately once the aircraft reacted vehemently to the control commands. The now developing oscillation (*Pilot Induced Oscillation*—PIO) was very difficult to control and has led to accidents with a few of the latest generation of combat aircraft. Even in the case of commercial aircraft, the PIO problems were not unknown (see also Sect. 9.2.12).

Investigations of flying qualities involving the pilots were the order of the day. Also, however, well-equipped ground simulators were not adequate enough to reproduce the environment of a modern control-assisted aircraft in totality. Only the in-flight simulation offered the possibility of replicating the flight control of another aircraft and to investigate under real workload conditions. Concomitant with the flight tests, the PIO problem was analytically

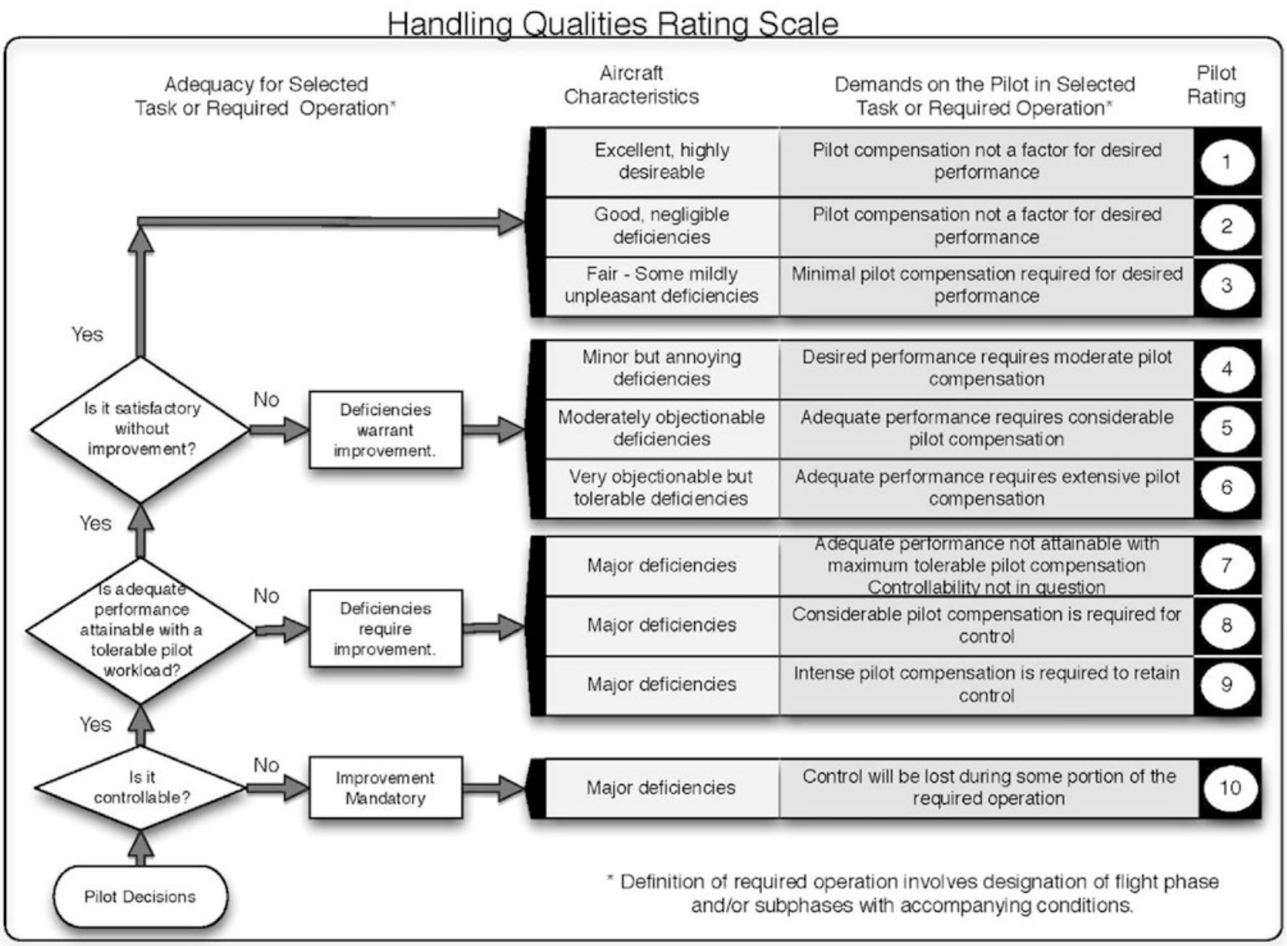


Fig. 2.6 Cooper-Harper Rating Scale

investigated. From the results of these investigations, strategies to adjusting the flight control could be derived so that PIO could be avoided.

2.2 Rotorcraft

The idea of rotary wing vehicles is almost as old as for the fixed-wing aircraft. In this case, too, a few paragons existed in nature, which provided orientation. The seeds of the sycamore (see Fig. 2.7), rotating in the presence of wind, can cover long stretches in a stable flight, whereas dragonflies and hummingbirds demonstrate the possibility of hovering flight in principle. The realization of a functioning rotorcraft, from the first ideas of *Leonardo da Vinci* (Fig. 2.8) to a viable helicopter, however, presented significantly more difficulties than those for the fixed-wing aircraft. After the maiden flight of the *Wright* brothers in the year 1903, another twenty years were needed until a so-called Autogyro or gyrocopter was built, flown and marketed by the Spaniard *Juan de la Cierva* (see Fig. 2.9). *De la Cierva* had solved two fundamental problems, namely (1) the control of high moments at the rotor blade root through an articulated connection of the rotor blades, the so-called flapping hinge, and (2) the steering of the Autogyro about the longitudinal and lateral axes by tilting the rotor head in the desired direction of flight (tilting hub control). However, in the case of the gyrocopter, the rotor is driven by the airflow, as such the flight vehicle requires an additional propulsion, for example via propeller, as in the case of fixed-wing aircraft. A hovering flight was therefore not possible and it took more than 10 years until the first halfway usable helicopter could demonstrate the hover and forward flight.

For a fixed-wing aircraft, a configuration (with front mounted engines, the lift-generating wings and the tailplane located at rear), which provided stability and good controllability was crystallized quite fast. In the case of helicopter, everything had to be principally accomplished via the rotating rotors. The rotor, the rotating wing, produces the lift as well as propulsion and control forces and moments which

Fig. 2.7 Sycamore seed (Acer pseudoplatanus)

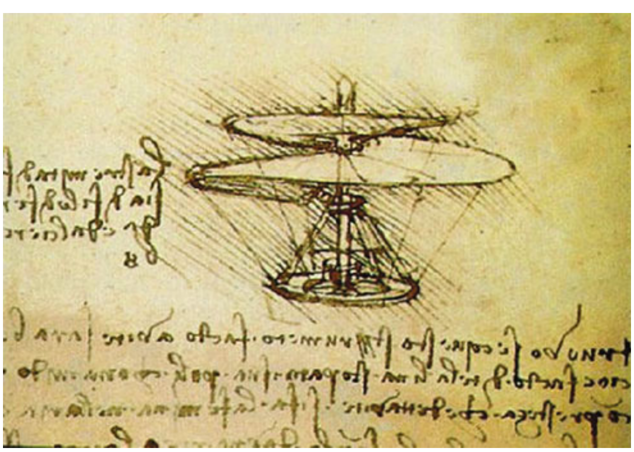


Fig. 2.8 Sketch of helicopter by *Leonardo da Vinci* (1490)

Fig. 2.9 Autogiro C 19 Mk IV of *Juan de la Cierva* (1926)

are needed for maneuvering. Not an easy task for a designer. The aviation pioneer *Wilbur Wright* saw this, however, quite differently, when he stated in 1909 that it is easy to build a helicopter, but otherwise it is a worthless device.

Unquestionably *Wilbur Wright* was not informed about the activities pursued at that time by many constructors to build a helicopter. Otherwise, he would not have come to such a misjudgment.

In addition to stiffness and vibration problems at the rotor and the lack of a light and high-performance motor for the high power, which is needed for hover, the flight mechanical problems, in particular, were in the foreground. It was necessary to cope with the turning moment on the fuselage, the reaction to the torque of the rotor drive. The problem of steering the helicopter for variations in lift and directions, with acceptable control forces, was not resolved for a powered rotor. The flight dynamics of the devices was highly unstable; the pilot had to intervene constantly to damp the arising oscillations and to keep the helicopter stable in the air. It is, therefore, not a surprise that the constructors arrived at quite different solutions.

For the development of an airworthy device, the evolution of scientific principles of rotor aerodynamics, rotor dynamics, vibration behavior and flight dynamics was essential and the developed theories had to be validated through experiments. In this respect, pioneering work has been carried out in Germany, which led to the construction of the first operational helicopter over here before the second World War [2, 14].

One of these pioneers was *Henrich Focke*. He drafted some important criteria that a practical helicopter design had to meet:

1. The ability of a safe landing after engine failure by means of autorotation.
2. Ensuring stability and control through the pilots, whereby the demands should not be higher than those for fixed-wing aircraft.

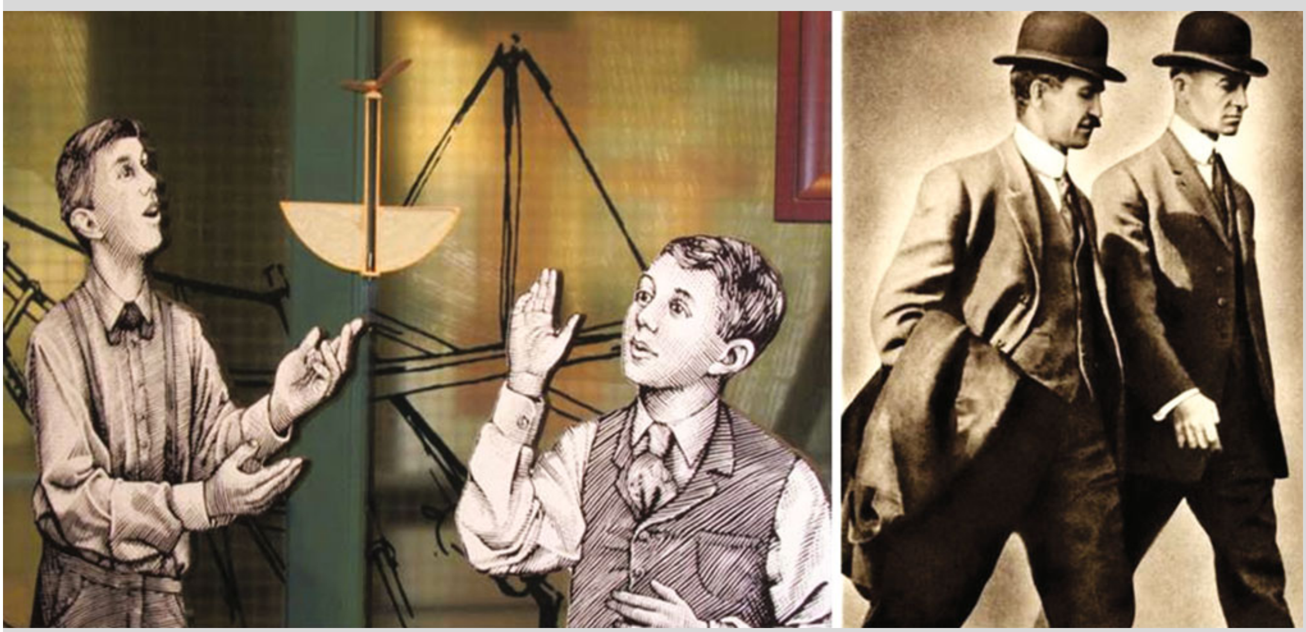
Fig. 2.10 The first ready for use helicopter Focke-Wulf Fw 61 (1936)

3. Ease of using the inceptors. Also, the control forces should be similar to those in the case of fixed-wing aircraft.
4. Acceptable flight performance in hover and forward flight.
5. Operational safety should be comparable to that of fixed-wing aircraft.

After numerous considerations and experiments, *Henrich Focke* opted for a largely symmetrical construction, with two counter-rotating rotors on cantilever arms, arranged right and left of the fuselage (see Fig. 2.10). With this the torque balance about the vertical axis was assured. To control the flight vehicle the incidence angle of the rotor blades was adjusted through a so-called swashplate on both rotors. Through raising and lowering the swashplate the incidence angle of the blades could be jointly adjusted (collective blade pitch control). In this way, climbing and descent, and through oppositely adjusting the swashplates the rolling motion of the helicopter could be controlled. By tilting the swashplates horizontal forces and moments could be generated for the longitudinal, lateral and yaw control of the helicopter. The requirements for a maneuverable helicopter were fulfilled for the first time with the Focke-Wulf Fw 61.

Here Wilbur Wright was wrong

Already as children, Wilbur and Orville Wright were interested in flying. Wilbur was 12 and Orville 8 years old when their father brought them a toy helicopter with rubber motor, a brand new invention then. Soon they built their own copies of the toy and these were actually their first motorized flying gadgets. When they were asked later what had triggered their fascination for flying, they always re-called this toy helicopter.



But soon they were looking for new challenges and Wilbur later was cited as follows:

> *Like all novices, we began with the helicopter (in childhood) but soon saw that it had no future and dropped it. The helicopter does with great labor only what the balloon does without labor, and is no more fitted than the balloon for rapid horizontal flight. If its engine stops it must fall with deathly violence, for it can neither float like the balloon nor glide like the aeroplane. The helicopter is much easier to design than the aeroplane but it is worthless when done.*
> *Wilbur Wright, Dayton, Ohio, January 15, 1909*

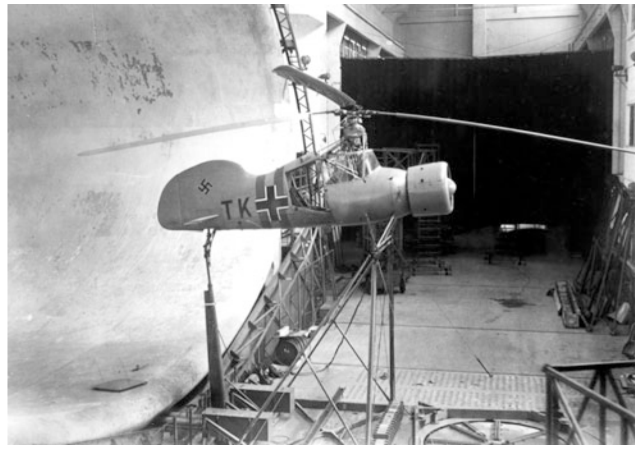


Fig. 2.11 Flettner Fl 265 helicopter in large wind tunnel at Chalais-Meudon (1941)

In April 1937, *Henrich Focke* together with *Gerd Achgelis* founded the company Focke-Achgelis. In 1938 the first major contract came from the German Lufthansa to develop a large transport helicopter with a payload capacity of 700 kg. Built on the Fw 61 concept, the Fa 223 was the first helicopter manufactured in serial production. During the war, it was deployed to transport operations in high mountains, for rescue operations, and for submarine surveillance.

In the year 1938, the inventor and aircraft designer *Anton Flettner* started with the development of helicopters. Like *Focke's* Fw 61, the successful *Flettner* helicopter had two counter-rotating rotors in a mostly symmetrical configuration. Unlike the Fw 61, these rotors were not mounted at cantilever arms, rather they were mounted directly on the fuselage at an angle of inclination of 12°. Because of the small distance, the two-bladed rotors were intermeshing. Collisions between the rotor blades were avoided through gearing. Similar to the Fw 61, the blade control was ensured by swashplates.

Prior to the flight tests, extensive wind tunnel tests were performed during August 1940 in the great French wind tunnel of Chalais-Meudon (see Fig. 2.11).

The Flettner helicopter showed high maneuverability and good controllability about all three axes and in all directions. With the Fl 265 a total of 126 flight hours were flown and over one thousand takeoffs and landings performed. No other helicopter worldwide at that time had achieved those hours in operation. Starting 1941 this helicopter was built as Fl 282 on a small scale and deployed by the armed forces for many different tasks (see Fig. 2.12). After the war, American pilots availed the opportunity to fly the Fl 282. Following this, they praised the stability and controllability of this helicopter, as being better than all other helicopters they had flown until then.

Independent of the development in Germany, the work was pursued on the construction of helicopters in other countries too. Already before the First World War, the French aircraft pioneer *Louis Charles Breguet* dealt with the construction of helicopters [15]. However, his preliminary designs, called Gyroplane, had difficulties even to takeoff from the ground. After that, he turned his attention to aircraft manufacturing. Not until 1930 his interest in the helicopter was rekindled.

Fig. 2.12 Flettner Fl 282 helicopter in operation (1943)

Together with a young engineer named *René Durand*, he developed a helicopter with two superposed rotors. The two rotors rotated in opposite directions, thereby the torque on the fuselage due to the rotors could be compensated. With the coaxial arrangement of the rotors, *Breguet* had arrived at another, almost symmetrical configuration, on whose basis a stable to fly and a controllable helicopter could be developed.

The rotors were designed two-bladed. Both featured a swashplate adjustable cyclic blade pitch control. The control around the vertical axis was effected by means of collective blade pitch control of the two rotors in opposite directions, thereby generating different amounts of torque moment, resulting in the desired yaw moment. For a straight level flight and for lateral motion, as in the case of other helicopter configurations, the rotor disks were inclined accordingly with the swashplates. To improve the stability, the helicopter was additionally equipped with a tailplane.

In the years 1934 and 1935, the helicopter was an object of numerous modifications. In June 1935 the helicopter took off for the successful maiden flight (see Fig. 2.13). In December 1935, with a flight time of 62 min the hitherto endurance record for helicopters was broken. The French aviation authority was impressed and placed in the year 1936 a contract with *Breguet* to develop a helicopter suitable for operation. The development progress was, however, slow and was interrupted repeatedly due to repairs and modifications. One difficulty was the ability for autorotation, an important requirement for the client. In the year 1939, the helicopter was damaged severely in an autorotation test.

The impending World War II put an end on the further development. The "Gyroplane Laboratoire" was destroyed by a bomb attack.

Born in Ukraine, American aircraft designer *Igor I. Sikorsky* had already commenced in 1930 to engage himself with the development of a usable helicopter. In the year 1931, he filed a patent for a helicopter, that already had all the essential features of the later model VS-300, namely a main rotor and a small vertical tail rotor for torque compensation and for control about the vertical axis. This asymmetrical configuration promised significant performance benefits; the technical capabilities available at that time, however, did not allow a successful construction [16].

After many attempts *Sikorsky* began in spring 1939 with the construction of an airworthy helicopter denoted VS-300 (Vought-Sikorsky) (see Fig. 2.14). The three-bladed main rotor was equipped with a cyclic rotor blade pitch control for vertical, longitudinal and lateral helicopter control. Besides

Fig. 2.14 Experimental helicopter Sikorsky S-46/VS-300 (1941), (*Credit* Igor I. Sikorsky Archives)

the torque-compensation, the tail rotor provided also the yaw control. The first flight took place in September 1939 and was flown by *Sikorsky* personally.

Many alterations followed, mostly because of poor controllability. Among other things, the rotor control was replaced, in the meantime, by small rotors on side arms for pitch and roll control; whereas only the vertical motion was controlled by the main rotor. With this configuration the world record for longest flight duration, that was hold since 1937 by the Fw 61, could be broken in May 1941 with a flight time of one hour and 32 min. In December 1941 the helicopter attained its final configuration with one main rotor and only a single tail rotor, which is adopted in many helicopter designs till today.

The success of the VS-300 convinced the US Army. Early 1943, they placed an order for production of 100 helicopters of the type R-4 developed meanwhile (see Fig. 2.15). During the war, the R-4 helicopter was successfully deployed for rescue operations and for passenger transportation.

Henrich Focke, *Anton Flettner*, *Louis Breguet* as well as *Igor Sikorsky* have independent of each other arrived at

Fig. 2.13 Experimental helicopter Breguet-Durand Coaxial "Gyroplane Laboratoire" (1941), (*Credit* American Helicopter Society)

Fig. 2.15 Production version of Sikorsky S-47/R-4 in operation (1941), (*Credit* Igor I. Sikorsky Archives)

technical solutions for a workable and "easy" to fly helicopter. Their ideas were incorporated in numerous successful helicopter developments after the war.

While *Focke*, *Flettner* and *Breguet* concentrated on configurations with two main rotors, Sikorsky concentrated on the design based on one main rotor and tail rotor. The advantages of this configuration over the dual rotor helicopters became readily apparent: higher performance, greater flexibility in rotor design, cost-effective construction. But the drawbacks weighed heavily, namely asymmetrical flying vehicle with poor flying qualities, complicated aerodynamic and dynamic conditions on main rotor and tail rotor. Particularly because of the better performance, the configuration main-rotor tail-rotor was largely preferred for small and medium helicopters, whereas other configurations were adopted only for heavy helicopters and special flying vehicles (see Fig. 2.16). The request for better flying qualities was of secondary importance during the first few decades of the development. Top priority was to meet the demands, mostly higher flight performance, for the military and civilian operations of helicopters. As a result, recent activities are characterized by constant efforts toward acceptable flying qualities and reduction of undesired oscillations and vibrations. It is estimated that in many helicopters about 25–50% of the development time was needed to deal with these shortcomings in the flying qualities [2, 17].

Based on the research work at NACA, the first flying qualities guidelines for helicopters were published during 1951 in the American *Civil Air Regulations Part 6-Rotorcraft Airworthiness; Normal Category.* Under the heading *Flight Characteristics* it is stated there: "*It shall be possible to maintain a flight condition and to make a smooth transition from one flight condition to another without requiring an exceptional degree of skill, alertness, or strength on the part of the pilot,…*", in the section *Controllability*: "*The rotorcraft shall be safely controllable and maneuverable during steady flight and during the execution of any maneuver…*", and in the section *Stability*: "*It shall be possible to fly the rotorcraft in normal maneuvers…*" [18]. These general qualitative statements have been made more precise in the first quantitative specifications for flying qualities of military helicopters MIL-H-8501 from the year 1952 [19]. Without sufficient database and without detailed explanations, numerous quantitative requirements were formulated, amongst others for static and dynamic stability, for control forces and the helicopter behavior in autorotation. In the year 1961, MIL-H-8501 was revised and this specification was effective as MIL-H-8501A in US and other countries for over 30 years.

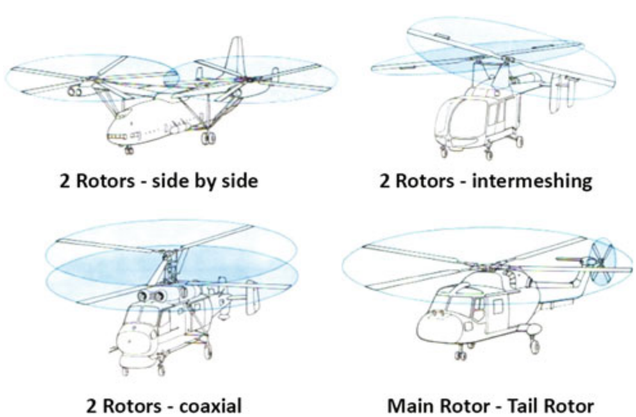


Fig. 2.16 Helicopter configurations

In the civil sector, essentially the qualitative criteria were retained and further developed (FAR 27 and FAR 29, EASA CS-27 and CS-29). However, the quantitative military criteria were often adopted as guidelines for design and certification.

For a long time, the specifications were considered as the targeted goal and not as indispensable requirement. This was partly due to the unavailability of design tools to meet soundly the stipulated criteria in the case of a new development, and on the other hand due to technical improvements, which made some criteria to appear as obsolete. As such, for example, the helicopter Bo 105 could not fulfill a few criteria related to dynamic stability or control coupling. The exceptional control-characteristics, namely fast control response and high effectiveness, of the newly developed hingeless rotor led, however, to flying qualities, which were rated by the pilots as very good. The helicopter was certified by the civil and later by the military authorities in many countries, despite its "shortcomings" compared to the valid criteria.

The expansion of the range of tasks, particularly for the military helicopters, the inadequacies of the flying qualities guidelines, and the availability of electronic systems for pilot assistance strongly necessitated new criteria. In order to compile a systematic database required for this, the US Army together with the NASA launched in 1975 a research program to which research organizations and institutions from Canada, England, and Germany (DLR) provided important contributions (see Sect. 8.4.1). Based on the data from ground-based simulations, especially, however, from flight tests, new flying qualities specifications for military helicopters, *Aeronautical Design Standard 33* (*ADS-33*), were finally published in the year 1988, and in the following years further refined [20].

The acceptance and applicability of the new, in many aspects revolutionary, flying qualities specification is based essentially on the systematic and reliable data base, whose evaluation led to new criteria and important insights about the relationships between subjective pilot handling qualities assessment ratings and quantified flying qualities parameters [21].

The in-flight simulator ATTHeS was a modified Bo 105 that, because of the Bo 105's control effectiveness, gave it the flexibility making it particularly well suited to make significant contributions to the currently available data base (see Chap. 8). As a result, important prerequisites were established for design and certification of helicopters, which are safe and "easy" to fly under all operating conditions and in all possible missions.

References

1. Perkins, C.D.: Development of airplane stability and control technology. J. Aircraft **7**(4), 291 (1970)
2. Herb, H.: The development history of flight mechanics, In German, Deutsche Luft- und Raumfahrt, DLR FB 67–44, July 1967
3. Perkins, C.D.: Development of airplane stability and control technology. J. Aircraft **7**(4), 293 (1970)
4. Gilruth, R.R.: Requirements for satisfactory flying qualities of airplanes, NACA Report 755, (1943)
5. Hartman, E.P.: Adventures in research—a history of Ames Research Center 1940–1965, p. 80. NASA History Series, Washington (1970)
6. Doetsch, K.-H., Friedrichs, G., Höhler, P., Lugner, H.: Redesign of flying qualities guidelines, in German, DVL-Bericht, March 1943
7. Ashkenas, I.L.: Twenty-five years of handling qualities research. J. Aircraft **21**(5), 290 (1984)
8. McRuer, D., Graham, D.: Eighty years of flight control: triumphs and pitfalls of the systems approach, J. Guid. Control. **4**(4) (1981)
9. McRuer, D., Graham, D.: A flight control century: triumphs of the systems approach. J. Guid. Control Dyn. **27**(2), 161–173 (2003)
10. Anon.: Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785 (ASG), September 1954
11. Wünnenberg, H. (Ed.): Handling Qualities of Unstable Highly Augmented Aircraft, AGARD AR-279, May 1991
12. Anon.: MIL-STD-1797, Department of Defense, March 1987
13. Cooper, G., Harper, R.: The Use of Pilot Rating in the Evaluation of Airplane Handling Qualities, NASA TN D-5153, April 1969
14. Knobling, K.: First helicopters and rotor systems. In: Hirschel, E. H., Prem, H., Madelung, G. (eds.) Aeronautical Research in Germany, pp. 293–309. Springer Verlag, Berlin (2004)
15. Leishman, J.G.: A history of helicopter flight. University of Maryland, www.terconnect.umd.edu/Leishman/Aero/history.html
16. Sikorsky Historical Archives, www.sikorskyarchives.com
17. Padfield, G. D.: Rotorcraft handling qualities engineering, managing the tension between safety and performance, 32nd American helicopter society. Alexander A. Nikolsky Honorary Lecture, May 2012
18. Anon.: Civil aeronautics board: civil air regulations part 6-rotorcraft airworthiness. Normal Category, Washington DC, USA (1951)
19. Anon.: Military specification: helicopter flying and ground handling qualities; general requirements for, MIL-H-8501, November 1952
20. Anon.: ADS-33E-PRF, Aeronautical design standard, performance specification, handling qualities requirements for military rotorcraft. United States Army Aviation and Missile Command, Aviation Engineering Directorate, Redstone Arsenal, Alabama, March 2000
21. Pausder, H.-J., Ockier, C.: Flying Characteristics specifications for helicopters. In: Hirschel, E.H., Prem, H., Madelung, G. (eds.) Aeronautical Research in Germany, pp. 480–482. Springer-Verlag, Berlin (2004)

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