History of Key Technologies

Evolution of Airplane Stability and Control: A Designer's Viewpoint

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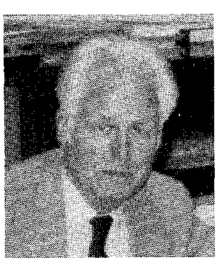
Nomenclature

A, B, C, D, E	= polynomial coefficients
b	= wing span, ft
C_L	= lift coefficient
C_{l_r}	= variation of rolling moment coefficient with yaw rate, 1/rad
C_{l_β}	= variation of rolling moment coefficient with sideslip angle, 1/rad
C_m	= pitching moment coefficient
C_{m_α}	= variation of pitching moment coefficient with angle of attack, 1/rad
C_{m_q}	= variation of pitching moment coefficient with pitch rate, 1/rad
$C_{m_{\delta_E}}$	= variation of pitching moment coefficient with elevator angle, 1/rad
C_{n_r}	= variation of yawing moment coefficient with yaw rate, 1/rad
C_{n_β}	= variation of yawing moment coefficient with sideslip angle, 1/rad
C_{y_p}	= variation of side force coefficient with roll rate, 1/rad
C_{y_β}	= variation of side force coefficient with sideslip angle, 1/rad
$\bar{c}$	= mean geometric chord, ft
F_A	= aileron wheel force (cockpit), lb
g	= acceleration of gravity, ft/s^2
I_{yy}	= pitching moment of inertia, slug ft^2
I_{zz}	= yawing moment of inertia, slug ft^2
K_q	= pitch rate feedback gain, rad/rad/s
L_p	= roll angular acceleration per unit roll rate, rad/s^2/rad/s
L_r	= roll angular acceleration per unit yaw rate, rad/s^2/rad/s
L_β	= roll angular acceleration per unit sideslip angle, rad/s^2/rad
M_α	= pitch angular acceleration per unit angle of attack, rad/s^2/rad
M_q	= pitch angular acceleration per unit pitch rate, = $C_{m_q}\bar{q}_1 S\bar{c}^2/2I_{yy}U_1$, 1/s
m	= airplane mass, slugs
N_β	= yaw angular acceleration per unit sideslip angle, rad/s^2/rad
P, p	= roll rate (X axis), rad/s
Q, q	= pitch rate (Y axis), rad/s
$\bar{q}_1$	= dynamic pressure, lb/ft^2
R, r	= yaw rate (Z axis), rad/s
S	= wing area, ft^2
T	= time constant, s
U, u	= speed component along X axis, ft/s
V, v	= speed component along Y axis, ft/s
$\dot{v}$	= side acceleration, ft/s^2
W, w	= speed component along Z axis, ft/s
$\bar{x}_{ac}$	= aerodynamic center location as a fraction of mean geometric chord
Y_p	= side acceleration per unit roll rate, ft/s^2/rad/s
Y_r	= side acceleration per unit yaw rate, ft/s^2/rad/s
Y_β	= side acceleration per unit sideslip angle, ft/s^2/rad
α	= angle of attack, rad
β	= angle of sideslip, rad
Δ	= incremental value for what follows
ζ	= damping ratio
Θ, θ	= pitch attitude angle, rad
δ	= control surface deflection, rad
Φ, ϕ	= bank angle, rad
Ψ, ψ	= heading angle, rad
ω_n	= undamped natural frequency, 1/s

Subscripts

1	= steady state
1, 2, 3, 4	= mode indicator
A	= aileron



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EDITOR'S NOTE: This manuscript was invited as a History of Key Technologies paper. It is not meant to be a comprehensive study of the field. It represents solely the author's own recollection of events at the time and is based upon his own experiences.

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c.g.	= center of gravity
E	= elevator
fus	= fuselage
max	= maximum
p	= phugoid
R	= rudder
sp	= short period

Introduction

THE purpose of this article is to present an overview of developments that contributed in a significant manner to the engineering field called airplane stability and control. Since the author's experience in this field is limited to fixed-wing airplanes, this article will be similarly limited. The author makes no claim for this to be an all-inclusive review of the world literature on this subject. Instead, the article represents the personal reflections of an aeronautical engineer who 1) has had the opportunity to apply stability and control theory to many airplane programs during his career, and 2) has been able to use his experience in the teaching of airplane stability and control, including its implications to design and development of airplanes.

Like most fields of engineering, airplane stability and control should be viewed as an applied science. It has taken contributions from a large number of other fields to reach a certain level of maturity as an indispensable tool in the design, development, and certification of safe airplanes. Fields that have contributed in a major way to the development of airplane stability and control are the following: 1) mathematics, 2) dynamics, 3) aerodynamics, 4) wind tunnel testing, 5) flight testing, 6) aeroelasticity, 7) flying qualities, 8) control theory, 9) simulation, and 10) flight control system design. To review each of these fields would fill several books. For that reason, this review will be further limited to those stability and control developments that had a major influence on airplane design. The narrative is presented in three parts: 1) the years before and through WWI, 2) the years between WWI and WWII, and 3) the years after WWII.

Years Before and Through World War I

Aeronautical vehicles have utility, providing they can be controlled (or guided). This fact was already recognized by Johnson[1] who wrote the following:

> We now know a method of mounting into the air, and, I think, are not likely to know more. The vehicles can serve no use till we can guide them, and they can gratify no curiosity till we mount them to greater heights than we can reach without, till we rise above the tops of the highest mountains.

From a practical viewpoint, it is widely accepted that the Wright brothers were the first to recognize that, in addition to the need for solving the lift-weight and thrust-drag problem, there is the problem of stability and, most importantly, controllability. Even today it is still not widely recognized that the Wrights built their "Flyer" consciously as a slightly unstable, but controllable machine. Draper[2] and Combs,[3] give an account of the solid engineering approach taken by the Wrights. What is also not widely recognized about the Wright brothers is that they did a lot of homework even before they began work on their airplane experiments. They reviewed most of the pertinent literature up to that point, including the pioneering work of Cayley, as discussed in Ref. 4. The theory of airplane stability and control appears to be rooted in the work done by Lanchester[5,6] and, more importantly, on the mathematical approach to the subject by Bryan.[7] Once Bryan had laid the groundwork for the description of aircraft motion using the general theory of rigid-body mechanics (as developed by Routh[8]), the first major problems to be solved were 1) finding acceptable ways to express the aerodynamic forces and moments that act on an airplane in terms of the variables of motion, and 2) finding acceptable ways to approximate and to interpret the solutions of the equations of motion.

Since the airplane equations of motion consist of six, simultaneous, nonlinear differential equations, solving them was beyond the practical possibilities in Bryan's time. A major contribution, therefore, was the recognition that any general flight state can be thought of as a superposition of two basic states: 1) a steady state, for which no accelerations of the fundamental motion variables exist, and 2) a perturbed state, for which all fundamental motion variables are described relative to a known steady state. These ideas are referred to as the perturbation substitution that, for three example variables, translates into the following:

$$U = U_1 + u \qquad P = P_1 + p \qquad \Theta + \Theta_1 + \theta$$

Since it is required in most airplanes that any perturbations are kept small, it turns out that the perturbed state equations can be linearized, which greatly facilitates their solution. As a result of the superposition of steady state and perturbed state (the perturbation substitution), the problem of total airplane motion is split into two simpler problems:

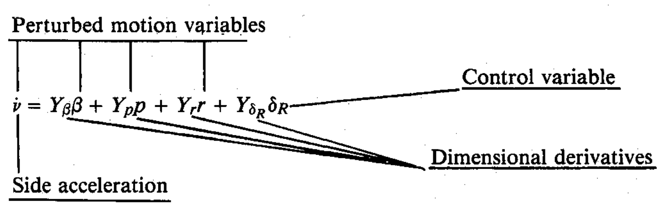
1) The steady state (or trim) problem. This allows the designer to address the following question: Can the airplane be trimmed into a steady state flight condition?

2) The perturbed state problem. This allows the designer to address the following questions: Is airplane response to externally generated disturbances (turbulence) acceptable? and Is airplane response to internally generated disturbances (pilot or failure induced) acceptable?

Both problems require that the essential motion variables be related to aerodynamic forces and moments. That was first done through the introduction of dimensional stability derivatives. Bryan[7] is also credited with being the first to introduce this idea, which is illustrated in Fig. 1. A very useful consequence of the introduction of dimensional stability derivatives is that all terms in the equations of motion have acceleration (linear or angular) as their physical unit. In any given flight condition, the engineer can therefore judge the relative importance of each term by inspection.

Bryan's concept was based on the important assumption that all aerodynamic forces and moments that act upon the airplane are a function of the instantaneous values of the motion variables only. In addition, Bryan assumed that the exterior airplane shape was known: the so-called rigid airplane assumption.

Example Side Force Equation



Example Definitions for Dimensional Derivatives

$$Y_\beta = \frac{\bar{q}_1 S b C_{y_\beta}}{m}$$

$$Y_p = \frac{\bar{q}_1 S b C_{y_p}}{2mU_1}$$

where C_{y_β} and C_{y_p} are dimensionless derivatives, with

$$C_{y_\beta} = \frac{\delta C_y}{\delta\beta} \quad \text{and} \quad C_{y_p} = \frac{\delta C_y}{\delta(pb/2U_1)}$$

Fig. 1 Dimensional and dimensionless derivatives.

Figure 1 also illustrates the general nature of the relationship between aerodynamic forces and the motion variables according to Bryan. Bryan's method was extended by Bairstow et al.[9] In Ref. 9, a detailed account is given of the dynamic stability behavior of an airplane. Bairstow was first in rooting the airplane stability quartic in terms of its polynomial coefficients. He also was first in using Routh's stability criteria, which are summarized in Fig. 2. These stability criteria are still used today in setting dihedral angles and sometimes in vertical tail sizing.

An event with momentous consequences to the development of aeronautical science in general, and to airplane stability and control, in particular, was the creation of NACA. This occurred through the vehicle of the Navy appropriations Act, Public 273 by the 63rd Congress in 1915.

NACA was established to ensure that the USA would become and stay pre-eminent in aeronautics. Among NACA's first order of business was the development of methods (theoretical and experimental) to understand what makes airplanes statically and dynamically stable, to find out how much stability is needed, and to develop methods to help designers develop acceptable airplanes.

Later that year, in NACA's first annual report, Hunsaker[10] presented a concise analysis of the stability behavior of the Curtiss JN2, using Bairstow's method of Ref. 9. In 1916, Hunsaker[11] presents an analysis method that includes the lateral-directional dynamics. In it, he uses the term Dutch Roll to identify the oscillatory roots of the lateral-directional characteristic equation. It is of interest to note that Hunsaker proclaimed the longitudinal short period to be unimportant while the longitudinal phugoid was singled out as the major problem area.

In Ref. 12, the basic method of determining the motion of the airplane in gusts is outlined by Wilson. Credit goes to Wilson for recognizing the importance of rotational gusts. He could not follow up on the idea due to a lack of data on such gusts. In his summary to Ref. 12, Wilson makes the point that although the effect of constant, nonrotational gusts on the JN2 can be significant, a pilot should be expected not to have any problems in arresting such effects. Perhaps this represents the first formal appreciation for the problem of handling qualities? The use of the linear differential operator $D = \mathrm{d}/\mathrm{d}t$ in solving airplane dynamics problems was also introduced by Wilson.[12]

The first detailed study of the effect of airplane configuration (= relative arrangement of the lifting surfaces, including conventional, canard, and tandem) on airplane stability appears in Ref. 13 and is due to Marchis. After the Wrights, this is the first systematic use of wind tunnels by a major research facility.

It has already been seen that airplane reactions to gusts were an important point of concern to many investigators. It was also recognized that gusts are made up of components with different frequencies. A method for computing the reaction of airplanes to frequency-dependent gusts was worked out first by Wilson.[14]

Years Between World War I and World War II

During this period, largely under the influence of NACA (but with many major contributions from European organizations), many advancements were made in the field of airplane stability and control. Handley Page made a significant contribution to airplane controllability in stalls by his invention of the automatic slot (HP-slat) in 1919 (see Ref. 15 and Figure 3). This development was perfected in the wind tunnel and in flight test. The HP-slat saw extensive use even in the jet era: the F-86 and the Sabreliner are prominent examples.

With the fundamental solution to the problem of how to model and how to analyze airplane stability came the realization that methods would be needed to predict and determine stability and control derivatives of airplanes. Three paths were available to accomplish this: 1) theoretical, 2) wind tunnel, and 3) flight test. Sorely needed were a systematic series of methods for engineers to use in predicting stability and control derivatives. With that information as a base, theoretical, tunnel and flight test methods would have to be evolved to predetermine the flight characteristics (flying qualities) of airplanes. NACA went about this task in a very systematic manner, resulting in a flood of reports.

In 1923, Norton[16] carried out flight tests to determine the effect of flight controls (fixed or free) on airplane stability. In his conclusions he states the following:

> It is far more dangerous to have an airplane statically unstable than it is dynamically unstable. While dynamic stability is interesting from a scientific point of view, the designer may entirely disregard it unless the airplane is such a radical departure from the usual practice as to make an investigation of this property advisable.

Characteristic Equation

$$As^4 + Bs^3 + Cs^2 + Ds + E = 0$$

where A through D are functions of

Derivatives
Flight condition
Airplane geometry
Mass and geometry

s is the Laplace domain variable.

Routh's Stability Criteria

1) Roots are stable if (and only if)

$$A, B, C, D, E > 0$$

$$D(BC - AD) - B^2E > 0$$

2) Real root is stable if $E > 0$

Application to lateral-directional case:

$$E = g\cos\theta_1(L_\beta N_r - N_\beta L_r)$$

From this, the design condition for spiral stability is

$$(C_{l_\beta}C_{n_r} - C_{n_\beta}C_{l_r}) > 0$$

Fig. 2 Routh's stability criteria.

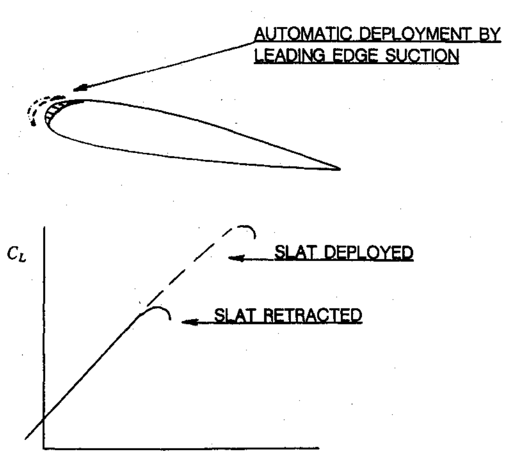


Fig. 3 Handley Page automatic slat.

One wonders if this is where the old (and wrong) saying "make sure that an airplane is statically stable and the dynamic stability takes care of itself," comes from?

Design of lateral controls of airplanes has always been recognized as a major problem.[3] In 1937, Weick and Jones[17] summarized the status of lateral control methodology. This type of research summary was to become a hallmark of NACA. Early dissemination of research and design data helped to advance American aeronautics technology.

A significant problem with aileron design was the associated adverse yaw and poor control force behavior. The Frise aileron was one solution to these problems. Cures to balance problems associated with Frise ailerons were reported in Ref. 18. Another solution was the invention by Jones and Nerken[19] of the differential aileron linkage. Figure 4 illustrates both solutions.

With today's computers, it is hard to imagine how difficult it was to do trade studies of dynamic stability behavior of airplanes. In 1937, Zimmerman[20] came up with a series of design charts enabling engineers to trade off the first- and the second-order lateral-directional modes: roll, spiral, and dutch roll.

The effect of lateral stability on the gust response of airplanes (handling and ride) was solved by Jones in the form of C_{n_β} vs C_{l_β} design charts in Ref. 21. (Fig. 5 is an example.)

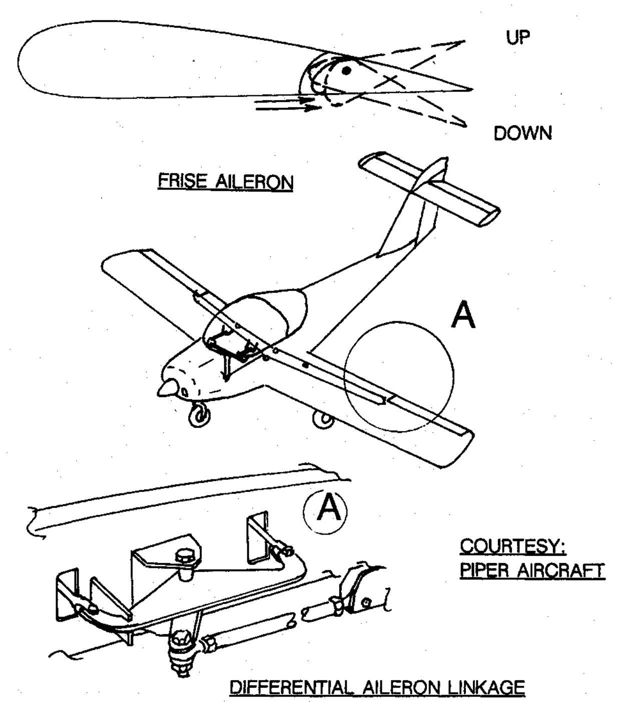
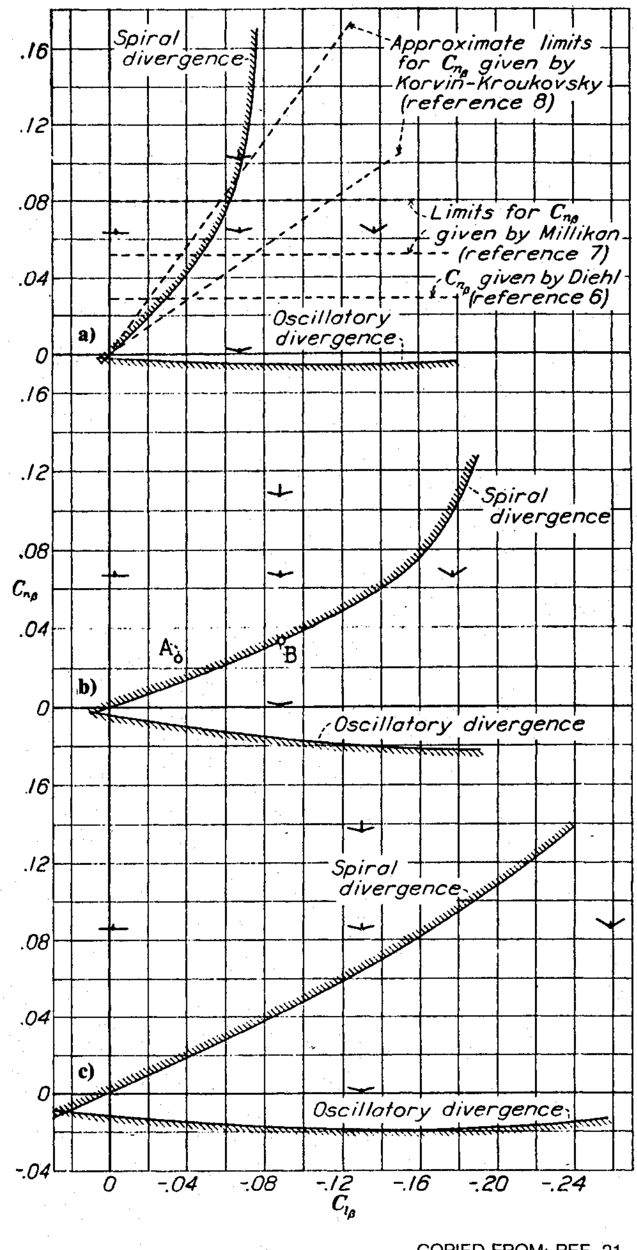


Fig. 4 Example of a Frise aileron and a differential linkage.



a) $C_L = 0.35$; $U_0 = 150$ f. p. s.
b) $C_L = 1.0$; $U_0 = 88.5$ f. p. s.
c) $C_L = 1.8$; $U_0 = 66$ f. p. s.

Fig. 5 Effect of lateral and directional stability on dynamic stability behavior.

The spin characteristics of airplanes form a topic of research even today. Following pioneering work by Gates and Bryant[22] in 1926, NACA investigated fighter spin behavior in flight. The result was Ref. 23. This was followed by the first systematic investigation of the effect of center of gravity, mass distribution, and aircraft geometry on airplane spin behavior by Seidman and Neihouse.[24] Reference 24 is the last of their four reports on this topic.

In 1935, Volume V of Ref. 25 was published. In it, Jones gave a summary of the state of the art of airplane dynamic stability and response theory. Reference 25 also included a remarkably clear discussion of airplane spin characteristics.

An investigation of the effect of wing geometry on airplane stability derivatives was reported by Pearson and Jones[26] in 1938. This report can be seen as the first in a long series of derivative estimation applications that (after WWII) culminated in the well-known United States Air Force (USAF) Datcom.

Static longitudinal stability of airplanes is dominated by wing downwash behavior at the tail. Predicting this downwash behavior was made easier when Silverstein et al.[27,28] published their still useful downwash design charts of 1939.

Problems with airplane handling qualities were recognized to be a significant contributor to accidents.[29] An accident classification committee of NACA, which wrote this report, concluded in Ref. 30 that over 50% of aircraft accidents were caused by pilot error. Some committee members speculated, however, that handling qualities were a part of the problem. It was also recognized that handling qualities depend to a large extent on the aerodynamic balance of flight control surfaces. The tailoring of control surface hinge moments is done by shaping (nose, gap geometry, hingeline location, trailing-edge angle) and by tabs. Hartshorn[31] and Garner,[32] in 1929, pioneered the use of powerful geared tabs (also called balance tabs) in the United Kingdom. Harris introduced them to the USA in 1935 through Ref. 33, which is still useful as a control-

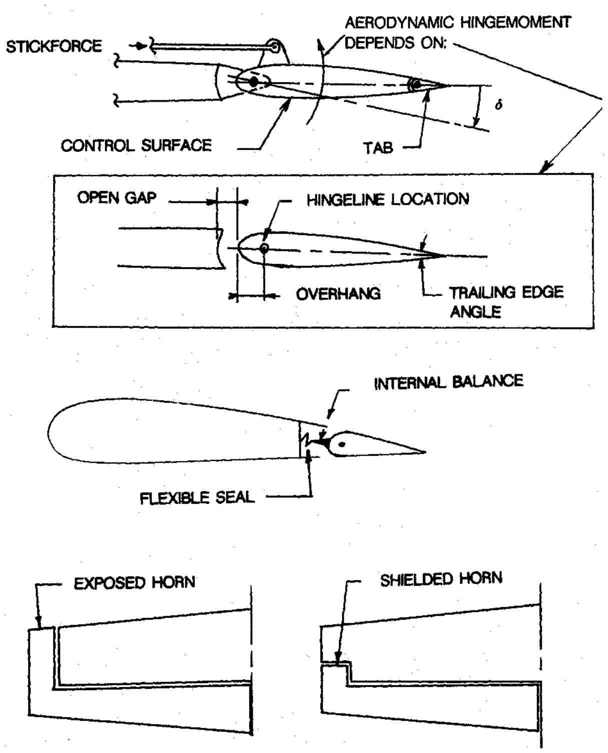


Fig. 6a Example control surface configurations.

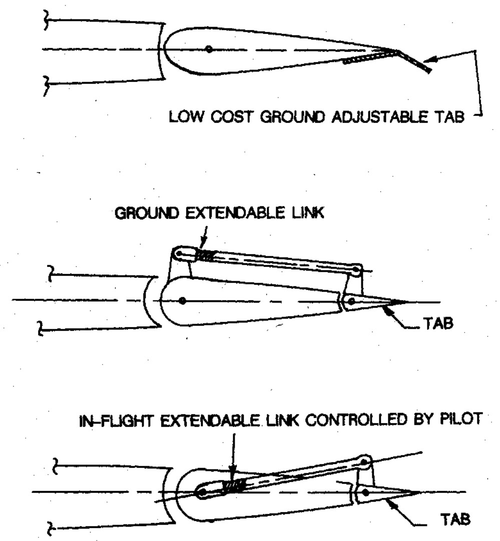


Fig. 6b Example tab applications.

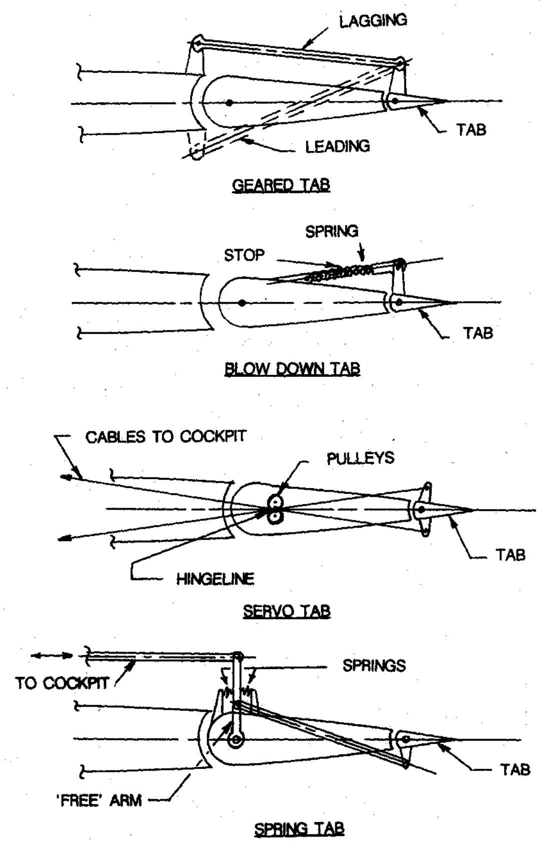


Fig. 6c Example tab applications.

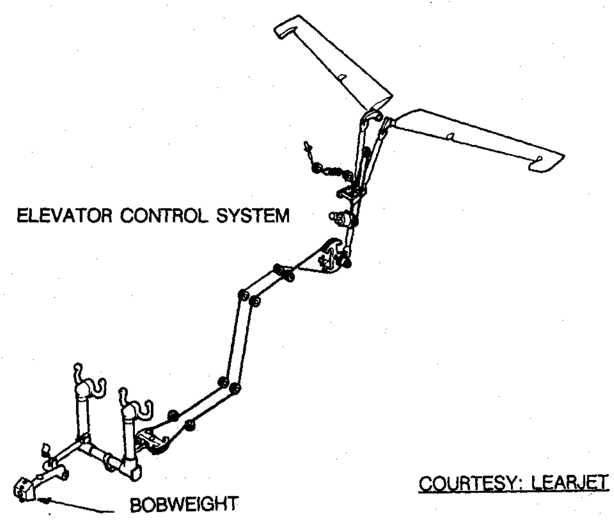


Fig. 7 Example of a bob-weight installation.

tab design report. Figures 6a–6c illustrate the various types of control and tab configurations as seen even today in many airplanes with reversible flight controls.

Airplanes with reversible flight controls (and the controls left free) can have dynamic stability behavior much different from that predicted for an airplane with the controls fixed. The effect of free aileron and rudder controls on dynamic stability was analyzed by Bartsch[34] in 1938. His method was extended by Jones and Cohen[35] in 1941 to include the elevator controls.

In England, Spitfire fighters developed the problem of pilots pulling the horizontal tail off in recoveries from dives. The problem was traced to very light stick forces per g. It was solved by Miles[36] with the use of a bob weight in the control system (see Figure 7).

In 1941, Gilruth and Turner[37] discussed the use of Lanchester's pb/2V (wingtip helix angle) as a criterion for satisfactory roll control. The famous pb/2V = 0.07 rule is promulgated in Ref. 37. That report also recognizes the important effect of elastic and aeroelastic deformations in lateral control systems.

Compressibility effects were already recognized to be important in some very early NACA technical reports that dealt with the aerodynamic characteristics of propeller blades. In 1939, a significant theoretical discovery was made by Kaplan[38] in which he showed that for thin airfoils the center of pressure shifts very little with increasing Mach number.

Up to the early 1940s, longitudinal control in most airplanes had been obtained through the use of elevators. For any given tail surface area, there are various limitations to the size elevator that can be employed. It was to be expected that the idea of using the entire horizontal tail (flying tail or slab tail) for control was only a matter of time. Mostly because of compressibility problems with elevators in pullouts from dives, did Jones[39] suggest the use of a "flying tail." The idea was backed up with an analysis and a flight test as early as 1943.[39]

A problem in the prediction of longitudinal stability of airplanes has always been the effect of the fuselage and nacelles on the aerodynamic center of wing-fuselage-nacelle combinations. The problem was first tackled theoretically by Munk[40] in 1923. A systematic series of tunnel tests led to considerable clarification by Jacobs and Ward[41] in 1935 using data obtained in the NACA Langley Research Center variable density tunnel on no fewer than 209 models. Figure 8 shows the importance of this effect on several recent airplanes.

Criteria for longitudinal stability from a pilot's viewpoint were introduced by Gilruth and White[42] in 1941. The criterion used was the variation of elevator deflection with angle of attack.

The effect of propeller tilt angle on longitudinal stability was delineated by Goett and Delaney[43] in 1944. A complete analysis of these and other effects, useful for designers, appeared in the widely used textbook by Perkins and Hage.[44]

During WWII, Germany, the United Kingdom, and the USA developed a keen interest in tailless configurations. An analysis of the stability and control characteristics of such configurations was performed by Jones[45] in 1941. A summary of stability and control characteristics of tailless designs was compiled by Donlan[46] in 1944. This work was in support of efforts at Northrop toward developing tailless fighters and bombers. These designs had plenty of stability and control problems.

As airplane flight envelopes grew toward higher speed and higher altitude while airplane size also increased, more and more problems developed with their still reversible control systems. The spring tab offered a temporary solution. The spring tab was first proposed and analyzed by Gates[47] in 1941. A concise analysis of the spring tab was developed by Phillips[48] in 1944. Figure 6c shows a spring tab schematic. A major problem with spring tabs is their potential for flutter. That problem was addressed by Frazer and Jones[49] and Collar[50] in 1943.

Steady state aeroelasticity had become troublesome in its effect on lateral controls in the early 1930s. Based on the pioneering work by Pugsley,[51] Pearson and Aiken[52] prepared charts for designers to determine the required torsional stiffness in the achievement of prespecified roll performance. Figure 9 illustrates this problem.

Airplane performance increased rapidly during WWII. Compressibility was now affecting longitudinal stability in a frightening manner: pulling out of high speed dives had become questionable. Hood and Allen[53] addressed these problems and came up with some solutions. One of their solutions was the all-flying tail. (It is of interest to note that the list of references in Ref. 53 does not include Jones' Ref. 39 of the same year.)

During WWII, flying qualities became very important both as a research topic and as a regulatory topic (flying quality specifications). In 1943, Gilruth[54] formulated a set of requirements for satisfactory handling qualities from a designer's viewpoint. This, in turn, led to Ref. 55, which defined a very useful wind tunnel test procedure for determining critical stability and control characteristics.

The military specifications of Refs. 56 and 57 are typical of the early flying quality specifications based on NACA work.

Of major importance to airplane stability, control, and performance engineers was the appearance of Ref. 58 of 1945 by Abbott and Von Doenhoff. This magnificent achievement resulted in Ref. 59, a textbook that is still popular with engineers, students, and professors in 1990.

Years Since World War II

In 1947, Toll[60] published an extensive lateral control research summary. It contained 91 references and dealt with such topics as ailerons of all types, spoilers, lateral control force tailoring, system lag effects, and control surface distortions (control surfaces were still largely canvas covered). This report also included extensive design methodologies.

As a result of the introduction of jet powered fighters and, later, bombers, airplane mass distributions began to change. Masses were now concentrated along the X axis more than ever before. In 1948, Phillips[61] predicted the occurrence of roll rate induced coupling that could lead to severe instabilities. Such instabilities were indeed found to occur in early F-100 fighters in the mid 1950s. The problem was thoroughly researched in flight tests of the NACA X-3. Figure 10 shows the well-known roll coupling stability boundaries according to Phillips.[61] These boundaries are still used in tail-sizing procedures for high performance airplanes today.

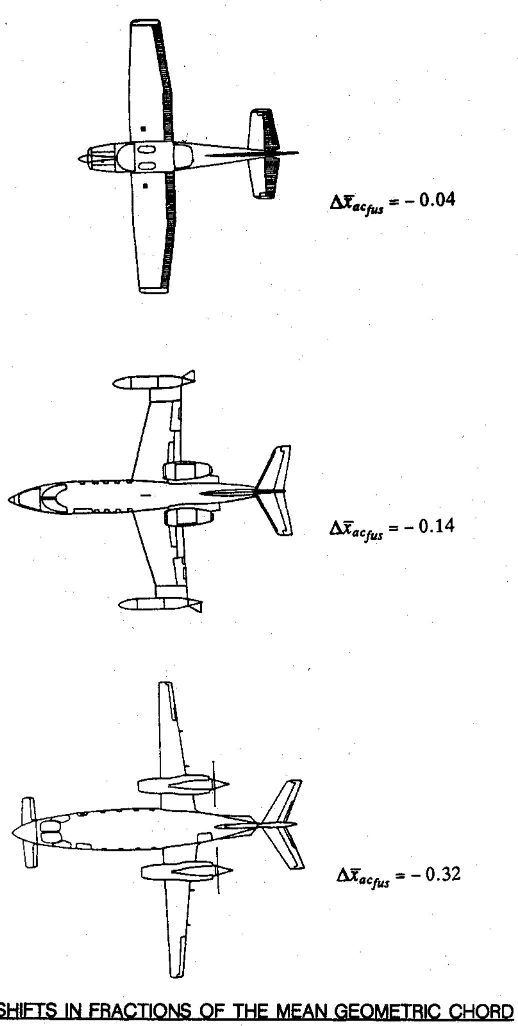


Fig. 8 Effect of configuration on fuselage induced shift of aerodynamic center.

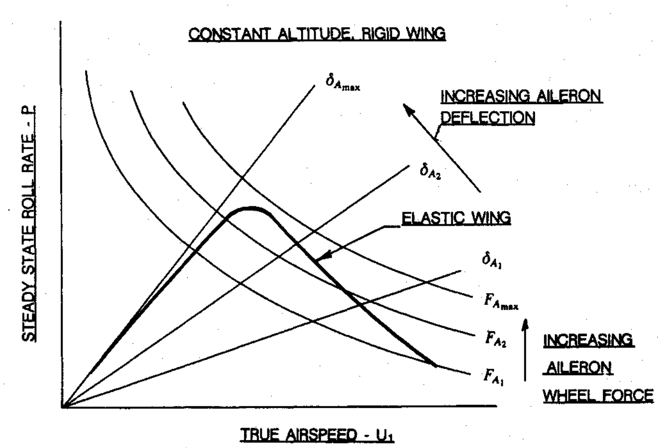


Fig. 9 Effect of aeroelasticity and wheel control force on roll performance.

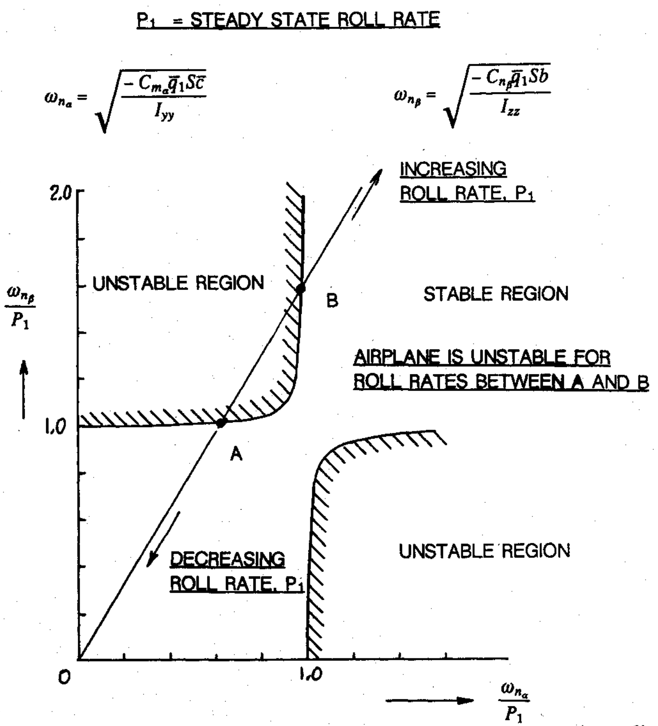


Fig. 10 Roll coupling stability boundaries according to Phillips.[61]

In 1949, Phillips[62] produced another milestone in the development of theory and application of flying qualities. This very useful work contained 41 references. The military flying qualities specification of 1948[63] was based largely on NACA work. This was, however, to change. The USAF and the U.S. Navy began to rely more and more on their own flying qualities research. Much of that early work was done through contracts with the Cornell Aero Laboratory and through the use of variable-stability airplanes. The era of variable-stability airplanes can be said to have begun with Refs. 64 and 65.

An event that had significant consequences to the development of stability and control at the international level was the creation of NATO in 1949 and, subsequently, the establishment of AGARD in 1950. AGARD sponsors international conferences dealing (among others) with airplane stability and control problems and solutions.

NACA continued its series of derivative estimation methods with Ref. 66. This report dealt with methods for estimating derivatives in supersonic flight. It was aimed at delta wing configurations and heralded the coming of the F-102, F-106, and B-58.

Aeroelastic effects became even more important with the introduction of the first supersonic airplanes. Reference 67 dealt with the effect of wing aeroelasticity on static longitudinal stability. In a sense, this report represents the last of an era: it still uses the so-called closed-form solution methods. This changed in 1951 with Diederich's Ref. 68, which introduced the use of matrices in solving aeroelastic problems with roll controls.

This work was based on the earlier introduction of matrix methods in the United Kingdom by Frazer et al.[69] The introduction of digital computers made the use of matrix methods economical.

In retrospect, it is amazing that it took so long for the most elegant Laplace transform method to gain a foothold in airplane dynamic theory. As pointed out before, Wilson[12] already used the $D = d/dt$ operator notation. In 1931, Bryant and Williams[70] introduced Heaviside's method of operators to the solution of an airplane dynamics problem. Jones[71] introduced the method in the USA. Engineers involved in the development of servomechanisms were using Laplace transforms (which is closely related to Heaviside's method) in the early 1940s. Despite this, the use of Laplace transforms did not appear in the airplane dynamics literature until 1950.[72] The

Equivalent Stability Derivative Concept

$$C_{m_{q_{\text{SAS-on}}}} = C_{m_{q_{\text{inherent}}}} + \Delta C_{m_{q_{\text{SAS}}}} \quad (1)$$

$$\zeta_{\text{SP}} = \frac{-[M_q + (Za/U_1) + M_{\dot{\alpha}}]}{2\omega_{n_{\text{SP}}}} \quad (2)$$

where

$$M_q = \frac{C_{m_q}\bar{q}_1 S\bar{c}^2}{2I_{yy}U_1} \quad (3)$$

Preliminary Damper Sizing Steps

1) Find required ζ_{SP} from MIL-F-8785C

2) Find inherent ζ_{SP} from Fig. 12

3) Find $\Delta C_{m_{q_{\text{SAS}}}}$ from (1) and/or from Fig. 12. Set this equal to

$$\Delta C_{m_{q_{\text{SAS}}}} = (2U_1/\bar{c})C_{m\delta_E}K_q \quad (4)$$

4) Solve pitch damper gain K_q from Eq. (4)

5) If $K_q > 2$ deg/deg/s, the airplane needs more control power $C_{m\delta_E}$ for the SAS to function.

Fig. 11 The equivalent stability derivative concept.

method gradually became a standard tool in the solution of open- and closed-loop airplane stability and control problems. The simultaneous introduction of digital and analog computers helped push this development.

The work of Bode[73] and Evans[74] made the use of Laplace transforms and transfer functions even more convenient. Their work was extended and made popular in aeronautics by the appearance of the famous Northrop Volumes[75] developed by McRuer and Ashkenas under U.S. Navy Bureau of Aeronautics sponsorship, guided by Leo Chattler. The seven Northrop volumes formed the basis of modern stability and control methodology. This work resulted directly in Ref. 76, which still is a standard textbook for those wishing to become proficient in stability and control. Reference 76 is extremely well documented with footnotes and references dating all the way back to 1759. McRuer and Ashkenas also developed the first useful models of the human pilot. Their pilot transfer functions[77,78] allowed the use of feedback control theory in predicting flying quality behavior. This, in turn, required the introduction of an appropriate pilot-to-airplane rating scale. That was first done by Cooper and Harper.[79]

Methods for estimating stability and control derivatives of highly elastic airplanes were put in closed, matrix format by Roskam et al.[80] in 1968.

NACA continued its work in developing methods for estimating stability and control derivatives. Important reports in this regard are Refs. 81–84, the latter foreshadowing the development of the USAF Datcom[85] which first appeared in 1970.

McRuer and Ashkenas[75] introduced the powerful idea of equivalent stability derivatives to the USA. Historically, this idea should probably be credited to Gates[86] and Garner.[87] The equivalent stability derivative idea allows the designer to arrive at a first-order estimate of tail size and control power requirements for airplanes with deficiencies (intentional or not) in inherent stability. This concept, illustrated in Fig. 11, should be coupled with that of derivative sensitivity plots. These latter were first introduced in Ref. 75. A modern example of a derivative sensitivity plot is given in Fig. 12. These plots allow the designer to quickly determine whether a new airplane design

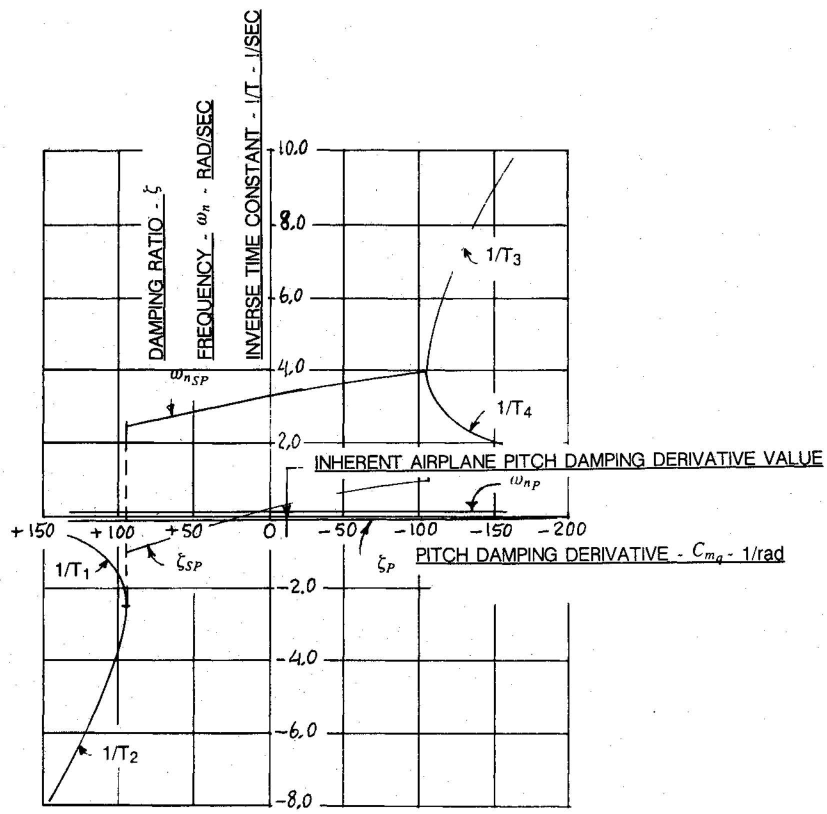


Fig. 12 Example of a derivative sensitivity plot.

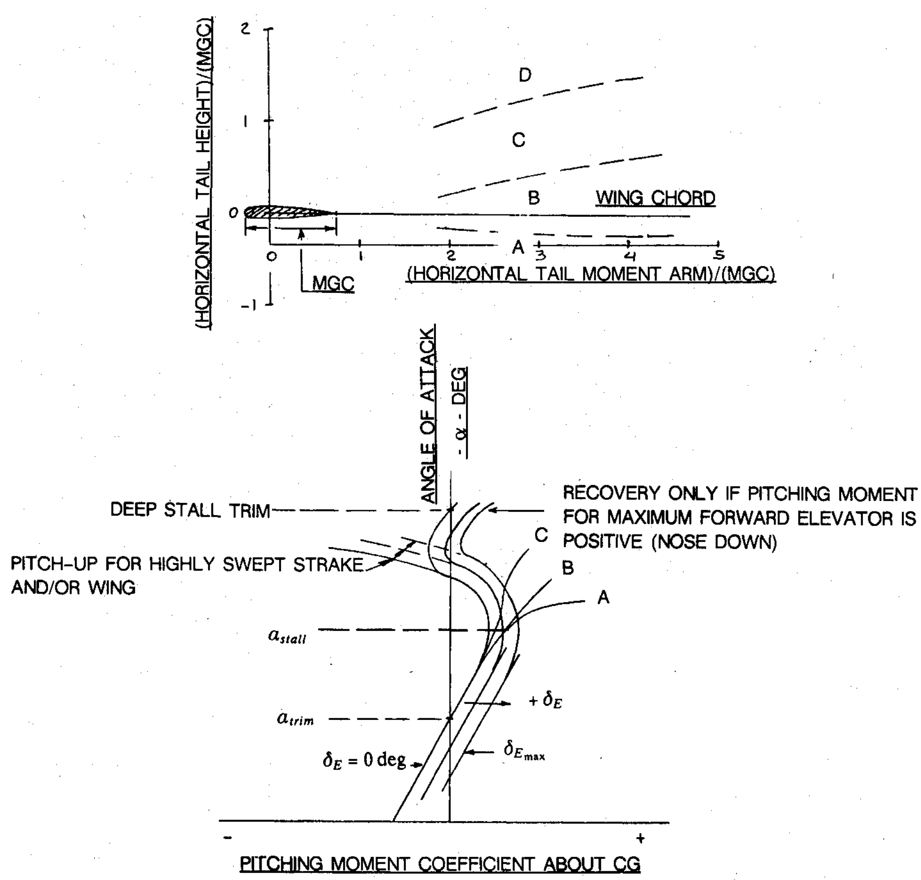


Fig. 13 Pitch break behavior as a function of horizontal tail location.

has sufficient control power to allow its stability augmentation functions to work at all. They also allow a rapid evaluation of the relative importance of a derivative. This is helpful in deciding where to put the engineering resources during the early development of an airplane.

Because of increases in the size and speed of airplanes in the 1950s, the design of flight control systems began to change. Hydraulic boost became a standard feature with airplanes such as the B-29.[88] Complete mechanical backup was still used.

The use of actuators for automatic flight controls goes way back to 1912. For details, the reader should see Table 1-1 in Ref. 76. Electric, pneumatic, and hydraulic servos all were already used in the 1912-1928 era.

With the introduction of powered flight controls came the need to develop artificial feel systems. Reference 89 was one of the first reports dealing with this subject. Reference 75 also contributed significantly to the development of artificial feel systems.

The 1950s saw the introduction of T-tails in high performance airplanes. The case for T-tails was argued by Multhopp.[90] At high angles of attack, many T-tail configurations developed serious control and stability problems: pitch-up and deep stall! With the help of high-α tunnel data and engineering simulators, Refs. 91 and 92 were very helpful in making the configuration design community understand the root causes of the early T-tail problems. Out of this work came design guides, as shown in Fig. 13. These allow configuration designers to quickly judge T-tail layouts.

Determination of stability and control derivatives from flight tests had been an important research topic at NACA for many years. References 93 and 94 are examples of the introduction of matrix methods in solving these problems. However, these methods were still cumbersome and affordable only by research organizations. Improvements in sensor accuracy and the availability of fast digital computers provided new stimuli to the development of modern parameter identification methods. Iliff et al.[95-97] made the enabling contributions.

In 1978, the Numerical Aerodynamic Simulator (NAS) facility was established at NASA Ames Research Center. This facility rapidly developed the capability for dense grid solutions of various approximations and exact versions of the Navier-Stokes equations. These equations had been unsolvable (from a practical viewpoint) until the development of very high speed computers such as the early Crays at NAS. The NAS foreshadows the days of the paper wind tunnel, where most stability and control problems can be analyzed very early in the design stage of airplanes. This will prove essential in the development of hypersonic designs.

Designing airplanes with good flying qualities was made much easier with the publication of "Mil-F-8785B" in 1969.[98] The introduction of the idea of levels of handling qualities from the Cooper-Harper scale and the tie-in between degradation of handling qualities with probability of flight control system failures made a rational approach to irreversible flight control system design possible. The extensive backup document[99] that accompanied Ref. 98 provided much needed insight into the connection between design parameters and specification parameters.

With the introduction of highly augmented airplanes and, in particular, digitally controlled airplanes of the same ilk came the problem of judging higher order system effects that are introduced by such systems. This resulted in problems with interpretation of Mil-F-8785B: the closed-loop root structure of the airplane no longer matched that on which the handling quality specifications were based. As a result, the so-called equivalent system approach was proposed[100] and developed. This, in turn, led to Mil-F-8785C.[101]

The author decided to end this review with the year 1980. It is left to future writers to assess the significance of developments since that time. Airplane stability and control has come a long way since Johnson's statement[1] in 1759 and since the first flights by the Wrights in 1903, which demonstrated practical controllability for the first time. The field of stability and control has developed into an indispensable component of aeronautics technology.

References

[1]Johnson, S., "Dissertation on the Art of Flying," *History of Rasselas,* published first in 1759, reissued by Clarendon, England, 1931, Chap. 6.

[2]Draper, C. S., Flight Control (1955 Wilbur Wright Memorial Lecture), *Journal of the Royal Aeronautical Society*, July 1955, p. 451-477.

[3]Combs, H. B., *Kill Devil Hill,* TernStyle Press, 1979.

[4]Pritchard, J. L., "The First Cayley Memorial Lecture: Sir George Cayley, Bart., the Father of British Aeronautics, the Man and his Work," *Journal of the Royal Aeronautical Society,* 1955.

[5]Lanchester, F. W., *Aerodynamics,* Constable, London, 1907.

[6]Lanchester, F. W., *Aerodonetics,* Constable, London, 1908.

[7]Bryan, G. H., *Stability in Aviation,* Macmillan, London, 1911.

[8]Routh, E. J., *Dynamics of a System of Rigid Bodies,* Macmillan, London, 1860.

[9]Bairstow, L., Jones, B. M., and Thompson, B. A., "Investigation into the Stability of an Aeroplane," British Aeronautical Research Council, R&M 77, 1913.

[10]Hunsaker, J. S., "Experimental Analysis of Inherent Longitudinal Stability for a Typical Biplane," NACA TR 1, Pt. 1, 1915.

[11]Hunsaker, J. C., "Dynamic Stability of Airplanes," *Smithsonian* Miscellaneous Collection, Vol. 62, No. 5, June 1916.

[12]Wilson, E. B., "Theory of an Aeroplane Encountering Gusts," NACA TR 1, Pt. II, 1915.

[13]Marchis, L., "Experimental Researches on the Resistance of Air," NACA TR 12, 1916.

[14]Wilson, E. B., "Theory of an Airplane Encountering Gusts, II," NACA TR 21, 1917.

[15]Barnes, C. H., *Handley Page Aircraft Since 1907,* Putnam, London, 1976.

[16]Norton, F. H., "A Study of Longitudinal Dynamic Stability in Flight," NACA TR 170, 1923.

[17]Weick, F. E., and Jones, R. T., "Resume and Analysis of NACA Lateral Control Research," NACA TR 605, 1937.

[18]Hartshorn, A. S., and Bradfield, F. B., "Wind Tunnel Tests on (i) Frise Ailerons with Raised Nose, and (ii) Hartshorn Ailerons with Twisted Nose," British Aeronautical Research Council, R&M 1587, 1934.

[19]Jones, R. T., and Nerken, A. I., "The Reduction of Aileron Operating Forces by Differential Linkage," NACA TN 586, 1936.

[20]Zimmerman, C. E., "An Analysis of Lateral Stability in Power-Off Flight with Charts for Use in Design," NACA TR 589, 1937.

[21]Jones, R. T., "The Influence of Lateral Stability on Disturbed Motions of Airplanes with Special Reference to the Motions Produced by Gusts," NACA TR 638, 1938.

[22]Gates, S. B. and Bryant, L. W., "The Spinning of Airplanes," British Aeronautical Research Council, R&M 1001, 1926.

[23]Soule, H. A., and Scudder, N. F., "A Method of Flight Measurement of Spins," NACA TR 377, 1931.

[24]Seidman, O., and Neihouse, A. I., "Free-Spinning Wind-Tunnel Tests of a Low-Wing Monoplane with Systematic Changes in Wings and Tails, IV. Effect of Center-of-Gravity Location," NACA TR 672, 1939.

[25]Durand, W. F., et al., *Aerodynamic Theory,* Vol. I-VI, Julius Springer, Berlin, Germany, 1935-1936.

[26]Pearson, H. A., and Jones, R. T., "Theoretical Stability and Control Characteristics of Wings with Various Amounts of Taper and Twist," NACA TR 635, 1938.

[27]Silverstein, A., and Katzoff, S., "Design Charts for Predicting Downwash Angles and Wake Characteristics Behind Plain and Flapped Wings," NACA TR 648, 1939.

[28]Silverstein, A., Katzoff, S., and Bullivant, W. K., "Downwash and Wake Behind Plain and Flapped Airfoils," NACA TR 651, 1939.

[29]"Aircraft Accidents, Method of Analysis," NACA TR 308, 1928.

[30]"Aircraft Accidents, Method of Analysis," NACA TR 357, 1930.

[31]Hartshorn, A. S., "The Application of the Servo Principle to Aileron Operation," British Aeronautical Research Council, R&M 1262, 1929.

[32]Garner, H. M., and Lockyer, C. E. W., "The Aerodynamics of a Simple Servo-Rudder System," British Aeronautical Research Council, R&M 1105, 1928.

[33]Harris, T. A., "Reduction of Hinge Moments of Airplane Con-

trol Surfaces by Tabs," NACA TN 528, 1935.
[34]Bartsch, E., Wende- und Rollschwingungen eines Flugzeugs, DFVLR, Jahrbuch, Germany, 1938.
[35]Jones, R. T., and Cohen, D., "An Analysis of the Stability of an Airplane with Free Controls," NACA TR 709, 1941.
[36]Brown, D. L., *Miles Aircraft Since 1925*, Putnam, London, England, 1970.
[37]Gilruth. R. R., and Turner, W. N., "Lateral Control Required for Satisfactory Flying Qualities Based on Flight Tests of Numerous Airplanes," NACA TR 715, 1941.
[38]Kaplan, C., "A Theoretical Study of the Moment on a Body in a Compressible Fluid," NACA TR 671, 1939.
[39]Jones, R. T., NACA WR L-496.
[40]Munk, M., NACA TM 1036, 1923.
[41]Jacobs, E. N., and Ward, K. E., "Interference of Wing and Fuselage from Tests of 209 Combinations in the NACA Variable-Density Tunnel," NACA TR 540, 1935.
[42]Gilruth, R. R., and White, M. D., "Analysis and Prediction of Longitudinal Stability of Airplanes," NACA TR 711, 1941.
[43]Goett, H. J., and Delany, N. K., "Effect of Tilt of the Propeller Axis on the Longitudinal Stability Characteristics of Single-Engine Airplanes," NACA TR 774, 1944.
[44]Perkins, C. D., and Hage, R. E., *Airplane Performance, Stability and Control*, Wiley, New York, 1949.
[45]Jones, R. T., "Notes on the Stability and Control of Tailless Airplanes," NACA TN 837, 1941.
[46]Donlan, C. J., "An Interim Report on the Stability and Control of Tailless Airplanes," NACA TR 796, 1944.
[47]Gates, S. B., "Notes on the Spring Tab," Royal Aircraft Establishment, Rept. BA1665, 1941.
[48]Phillips, W. H., "Application of Spring Tabs to Elevator Controls, NACA TR 797, 1944.
[49]Frazer, R. A., and Jones, W. P., "Wing-Aileron-Tab Flutter," (Pt. I, II), British Aeronautical Research Center, R&M 5668, 1942.
[50]Collar, A. R., "The Prevention of Flutter of Spring Tabs," Royal Aircraft Establishment, Rept. SME3249, 1943.
[51]Pugsley, A. G., "The Aerodynamic Characteristics of a Semi-Rigid Wing Relevant to the Problem of Loss of Aileron Control Due to Wing Twisting," British Aeronautical Research Council, R&M 1490, 1932.
[52]Pearson, H. A., and Aiken, W. S., Jr., "Charts for the Determination of Wing Torsional Stiffness Required for Specified Rolling Characteristics or Aileron Reversal Speed," NACA TR 799, 1944.
[53]Hood, M. J., and Allen, H. J., "The Problem of Longitudinal Stability and Control at High Speeds," NACA TR 767, 1943.
[54]Gilruth, R. R., "Requirements for Satisfactory Flying Qualities of Airplanes," NACA TR 755, 1943.
[55]Goett, H. J., Jackson, R. P., and Belsley, S. E., "Windtunnel Procedure for Determination of Critical Stability and Control Characteristics of Airplanes," NACA TR 781, 1944.
[56]"Specification for Stability and Control Characteristics for Airplanes," Specification No. C-1815, Army Air Forces, 1943.
[57]"Specification for Stability and Control Characteristics of Airplanes," Specification No. SR-119, Bureau of Aeronautics, Navy Dept., 1942.
[58]Abbott, I. H., Von Doenhoff, A. E., and Stivers, L. S., "Summary of Airfoil Data," NACA TR 824. 1945.
[59]Abbott, I. H., and Von Doenhoff, A. E., *Theory of Wing Sections*, Dover, New York, 1949.
[60]Toll, T. A., "Summary of Lateral Control Research," NACA TR 868, 1947.
[61]Phillips, W. H., "The Effect of Steady Rolling on Longitudinal and Directional Stability," NACA TN 1627, 1948.
[62]Phillips, W. H., "Appreciation and Prediction of Flying Qualities," NACA TR 927, 1949.
[63]"Flying Qualities of Piloted Airplanes," United States Air Force, Specification No. 1815-B, 1948.
[64]Milliken, W. F., Jr., "Progress in Dynamic Stability and Control Research," *Journal of the Aeronautical Sciences*, 14, No. 9, Sept. 1947, pp. 493–519.
[65]Heilenday, F., and Campbell, G., "Artificial Stability and Control of Longitudinal Motion of the B-26 Aircraft," Theoretical Investigation, Cornell Aeronautical Laboratory, Rept. TB-757-F-2, 1951.
[66]Ribner, H. S., and Malvestuto, F. S., "Stability Derivatives of Triangular Wings at Supersonic Speeds," NACA TR 908, 1948.
[67]Frick, C. W., and Chubb, R. S., "The Longitudinal Stability of Elastic Swept Wings at Supersonic Speed," NACA TR 965, 1950.
[68]Diederich, F., "Calculation of the Lateral Control of Swept and Unswept Flexible Wings of Arbitrary Stiffness," NACA TR 1024, 1951.
[69]Frazer, R. A., Duncan, W. J., and Collar, A. R., *Elementary Matrices and Some Applications to Dynamics and Differential Equations*, Macmillan, New York, 1946.
[70]Bryant, L. W., and Williams, D. H., "The Application of the Method of Operators to the Calculation of the Disturbed Motion of an Aeroplane," British Aeronautical Research Council, R&M 1346, 1931.
[71]Jones, R. T., "A Simplified Application of the Method of Operators to the Calculation of the Disturbed Motion of an Airplane," NACA TR 560, 1936.
[72]Mokrzycki, G. A., "Application of Laplace Transformation to the Solution of the Lateral and Longitudinal Stability Equations," NACA TN 2002, 1950.
[73]Bode, H. W., *Network Analysis and Feedback Amplifier Design*, Van Nostrand, New York, 1945.
[74]Evans, W. R., "Servo Analysis by Locus of Roots Method," North American Aviation, Rept. AL-787, 1948.
[75]McRuer, D., Ashkenas, I., et al., "Fundamentals of Design of Piloted Aircraft Flight Control Systems," U.S. Navy, Bureau of Aeronautics, Rept. AE-61-4:
Volume 1: Methods of Analysis and Synthesis of Piloted Aircraft Flight Control Systems, 1952.
Volume 2: Dynamics of the Airframe, 1952.
Volume 3: The Human Pilot, 1954.
Volume 4: The Hydraulic System, 1953.
Volume 5: The Artificial Feel System, 1953.
Volume 6: Automatic Flight Control Systems for Piloted Aircraft, 1956.
Volume 7: Methods of Design and Evaluation of Interceptor Fire Control Systems, 1959.
[76]McRuer, D., Ashkenas, I., and Graham, D., *Aircraft Dynamics and Control*, Princeton University Press, Princeton, NJ, 1973.
[77]Ashkenas, I., and McRuer, D., "The Determination of Lateral Handling Quality Requirements from Airframe-Human Pilot Studies," Wright Aeronautical Development Center, Air Force Flight Dynamics Lab., TR 59-135, 1959.
[78]McRuer, D., and Krendel, E. S., "Mathematical Models of Human Pilot Behavior," AGARDograph No. 188, 1974.
[79]Cooper, G. E., and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," AGARD-R-567 and NASA TN D-5153, 1969.
[80]Roskam, J., Holgate, T., and Shimizu, G., "Elastic Wind Tunnel Models for Predicting Longitudinal Stability Derivatives of Elastic Airplanes," *Journal of Aircraft*, Vol. 5, No. 6, 1968.
[81]Jones, A. L., and Alksne, A., "A Summary of Lateral Stability Derivatives Calculated for Wing Plan Forms in Supersonic Flow," NACA TR 1052, 1951.
[82]DeYoung, J., "Theoretical Antisymmetric Span Loading for Wings of Arbitrary Plan Form at Subsonic Speeds," NACA TR 1056, 1951.
[83]DeYoung, J., "Theoretical Symmetric Span Loading due to Flap Deflection for Wings of Arbitrary Plan Form at Subsonic Speeds," NACA TR 1071, 1952.
[84]Campbell, J. P., and McKinney, M. O., "Summary of Methods for Calculating Dynamic Stability and Control Response and for Estimating Lateral Stability Derivatives," NACA TR 1098, 1952.
[85]Hoak, D. E., et al., "USAF Stability and Control DATCOM," Flight Control Division, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, OH, 1970.
[86]Gates, S. B., "Notes on the Aerodynamics of Automatic Directional Control," Royal Aircraft Establishment, Rept. BA 487, 1924.
[87]Garner, H. M., "Lateral Stability with Special Reference to Controlled Motion," British Aeronautical Research Council, R&M 1077, 1926.
[88]Mathews, C. W., Talmage, D. B., and Whitten, J. B., "Effects on Longitudinal Stability and Control Characteristics of a Boeing B-29 Airplane of Variations in Stick-Force and Control-Rate Characteristics Obtained Through Use of a Booster in the Elevator-Control System," NACA TR 1076, 1952.
[89]Brown, B. P., Chilton, R. G., and Whitten, J. B., "Flight Investigation of a Mechanical Feel Device in an Irreversible Elevator Control System of a Large Airplane," NACA TR 1101, 1952.
[90]Multhopp, H., "The Case for T-Tails," *Aero Digest*, Vol. 70, No. 5, 1955.
[91]White, M. D., and Cooper, G. R., "Simulator Studies of the Deep Stall," NASA SP-83, 1965.
[92]Taylor, R. W., and Ray, E. J., "A Systematic Study of the Factors Contributing to Post-Stall Longitudinal Stability of T-Tail Transport Configurations," AIAA Paper 65-737, 1965.

[93]Donegan, J. J., and Pearson, H. A., "Matrix Method of Determining the Longitudinal Stability Coefficients and Frequency Response of an Aircraft from Transient Flight Data," NACA TR 1070, 1952.

[94]Donegan, J. J., "Matrix Methods for Determining the Longitudinal Stability Derivatives of an Airplane from Transient Flight Data," NACA TR 1169, 1954.

[95]Iliff, K. W., and Taylor, L. W., "Determination of Stability Derivatives from Flight Data Using a Newton-Raphson Minimization Technique," NASA TN D-6579,1972.

[96]Iliff, K. W., and Maine, R. E., "Practical Aspects of Using a Maximum Likelihood Estimation Method to Extract Stability and Control Derivatives from Flight Data," NASA TN D-8209, 1976.

[97]Gerlach, O. H., "A Regression Method for Determining Stability and Control Derivatives in Nonsteady Flight Maneuvers," (in Dutch) Delft University of Technology, Delft, The Netherlands, Rept. VTH-117, 1964.

[98]"Mil-F-8785B," Military Specification, Flying Qualities of Piloted Airplanes, 1969.

[99]"Background Information and User Guide for Mil-F-8785B," Military Specification, Flying Qualities of Piloted Airplanes, 1969.

[100]Hodgkinson, J., "Equivalent Systems Approach for Flying Qualities Specification," Society of Automotive Engineers, 1979.

[101]"Mil-F-8785C," Military Specification, Flying Qualities of Piloted Airplanes, 1980.