REDUCED STATIC LATERAL STABILITY IN AIRPLANES

A Thesis by

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I have examined the final copy of this Thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a Major in Aerospace Engineering.

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DEDICATION

To my wife, Julie, and my parents, Roger and Sara, for believing in me.
To my children, Marie, Jared, Sara, and Ben for their unconditional love.

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ABSTRACT

Recent flight test experience and simulator studies have shown that the traditional test for static lateral stability, the steady heading sideslip, in some cases may be overly conservative and place unnecessary restrictions on the aircraft operation or design. In addition, effective dihedral need not be positive in all areas of the flight envelope to provide acceptable handling qualities.

Positive static lateral stability is desired so that the aircraft will be safe and that the airplane handling characteristics will be "pleasant." The safety requirement stems from a desire for redundancy in the primary control system. However, safety analysis of modern aircraft often show this redundancy without effective dihedral through other means such as aileron trim, roll spoilers, etc. In terms of handling characteristics, positive static lateral stability usually provides for a more favorable rating of flying qualities by pilots. However, tests have shown that acceptable handling qualities are obtained in most areas of the flight envelope even with negative effective dihedral. Development flight testing on recent business jet aircraft have shown that the aircraft can be operated safely without use of the primary roll control system, even though the basic aircraft did not pass the traditional steady heading sideslip test in all configurations. Furthermore, the handling qualities of the aircraft were considered excellent.

Evaluations were conducted in a fixed base "iron bird" aircraft simulator by experienced pilots. Heading and bank capture tasks, crosswind landing, and engine-inoperative tasks were conducted with multiple values of effective dihedral from slightly positive to negative. Flying qualities data included pilot opinion quantified using the Cooper-Harper rating method. In addition, tests were conducted on a light business jet in a configuration which showed negative effective dihedral using the traditional steady heading sideslip method, but positive effective dihedral demonstrated by rudder turns from a wings level state. The handling qualities ratings of this same aircraft was very high in all phases of flight throughout the entire flight envelope, even to dive speed.

Test results support early flight test findings that positive static lateral stability is desirable, but contrary to the application of these early findings, neutral or slightly negative static lateral stability in limited areas of the operational envelope is allowable without sacrificing safety or good handling qualities. Furthermore, rudder turns from a wings level state are adequate in testing for effective dihedral.

PREFACE

Flight testing in the 1940's and 50's was often conducted for the sake of pure research - gathering data for application to future designs and furthering man's understanding of flight. As this knowledge grew, less time was spent in pure research and more effort was expended in refining aircraft destined for operational use. It has become a rare exception to design, build, and test an aircraft for pure research with no intention to produce more than the one or two test articles. Today, in the civilian world, this is truer than ever. Time to market is the key phrase, and reducing that time is the ultimate goal. As such, little time is available for development of new aircraft. The theme today is verification of the design so that certification can be completed as quickly as possible, placing the aircraft in the hands of the customer as quickly as possible, in order to begin that revenue stream back to the manufacturer (and share holders) as quickly as possible.

This is not necessarily a poor approach. The aircraft industry is not alone in it's effort to produce a safe and quality product with a minimum of time and effort. This is common in the American free enterprise system. But in order to accomplish this goal, it is necessary that significant design changes during the flight test program be reduced or eliminated. Changes to systems and aircraft configuration in the flight test phase can delay certification and customer delivery by months and even years, costing the company millions of dollars in interest and lost revenue, not to mention the loss of credibility within the industry and with its customers.

In order to avoid these late changes, or at least catch them as early as possible, it is necessary for the flight test team to thoroughly evaluate the aircraft early in the flight test program. This can be very difficult as there are many conflicting constraints on these tests. Some aspects of the aircraft handling qualities and performance are encountered at aft center of gravity, some at forward; some at high altitude and high Mach, some at low altitude and low Mach; and some even at mid altitudes and moderate speeds. This was the case on a recent business jet certification in which the static longitudinal stability was believed to be satisfactory, since it was tested at high and low altitudes, but was found to be unsatisfactory at a intermediate altitude, necessitating late design changes to the longitudinal control system.

Another complication is the certification requirements. Few other industries have the regulatory oversight and customer scrutiny as the aircraft industry. Unfortunately, many of these requirements are themselves subject to opinion and interpretation. The opportunity for a company test pilot to determine the level of rule compliance of a specific aspect of a new aircraft contrary to the regulatory agency's opinion is abundant. During development of the same business jet referred to previously, the static lateral stability testing was satisfactorily completed by company test pilots. The data was reviewed and determined to be compliant with the applicable Federal Aviation Administration (FAA) regulations (CFR 41 Part 25). However, during subsequent compliance testing conducted by FAA test pilots, it was determined that the static lateral stability was not satisfactory in some portions of the flight envelope. Weeks and months of discussions and negotiations between the company and the FAA followed. The interpretation of the rule was under scrutiny and what eventually followed was a specific interpretation by the local FAA office and a small change to the primary roll control system of the aircraft. The ironic part is that both the company and the FAA pilots agreed that the unmodified aircraft was safe and the handling qualities adequate, the issue was compliance with the interpretation of the regulation.

The specific issue in this case was that during steady heading sideslip tests in a single configuration - with gear extended, full flaps, and maximum continuous power from the engines, the aircraft initially exhibited slight positive static lateral stability, but then slowly rolled opposite the rudder input, exhibiting slight negative static lateral stability. It is believed that the change was caused by fuel migrating to the low wing during the steady heading sideslip maneuver. The interpretation of the rule was that the aircraft has to show positive static lateral stability for at least 30 seconds. The aircraft was unable to pass this test until a modification was made to the roll control system. However, in speaking with the company test pilots, it was evident that the aircraft could be safely maneuvered without the use of the primary roll control system in the very configuration that did not pass the FAA tests. Pilots were able to control the bank angle and maneuver the airplane solely through the use of rudder and sideslip. Obviously there was a disconnect between the letter of the law and its intent, the intent being the capability of the pilot to maneuver the aircraft in roll without the use of the primary roll control system, thus providing redundancy should the primary system fail.

Soon after this aircraft was certified, another new business jet prototype encountered similar issues early in the test program. Once again, the handling characteristics were determined to be satisfactory except for a small areas of the flight envelope in which it could not pass the steady heading sideslip test for static lateral stability. This aircraft was modified with the addition of small fences on the ailerons, which drove the ailerons in the proper direction in the presence of sideslip, thus allowing the aircraft to pass the FAA test.

Many other aircraft manufacturers have encountered similar difficulties in meeting the static lateral stability criteria set forth by the certificating agencies. These certification criteria are primarily meant to ensure a safe aircraft. The static lateral stability requirement is meant to provide the flight crew with a secondary means of roll control, should the primary roll control system become inoperative. It is ironic that one of the popular means of meeting this requirement is the so-called aileron-rudder interconnect. This system typically provides a full time mechanical connection between the rudder pedals and the ailerons, thus allowing the pilot to raise the low wing in the steady heading sideslip test and therefore meeting the rule, but defeating the purpose of the rule.

Discussions of these issues lead to the question: "is there a better way?" Could a better, more relevant test be developed for the safety feature desired by the certification agencies? Could the regulations be relaxed without compromising safety? What are the driving stability characteristics for controlling the aircraft using rudder alone? Hopefully some of these questions will be answered by this paper and substantial savings can be realized by aircraft manufacturers, as well as the regulatory agencies.

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LIST OF ABBREVIATIONS / NOMENCLATURE

AC	Advisory Circular
ATP	Airline Transport Pilot
AFHA	Aircraft Functional Hazard Assessment
AGL	Above Ground Level
AIR	Aileron-Rudder Interconnect
CAA	Civil Aeronautics Authority
CAR	Civil Air Regulations
CH	Cooper-Harper
EAS	Equivalent Airspeed
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FHQ	Flying and Handling Qualities
FL	Flaps
GR	Landing Gear
HDG	Heading
HQ	Handling Qualities
HQR	Handling Quality Rating
KIAS	Knots, Indicated Airspeed
LH	Left Hand
MCT	Maximum Continuous Thrust
MFD	Multifunction Flight Display
MSL	Mean Seal Level
NACA	National Advisory Committee for Aeronautics
OEI	One Engine Inoperative
PFD	Primary Flight Display

LIST OF ABBREVIATIONS / NOMENCLATURE (Cont.)

PSSA	Preliminary System Safety Assessment
RH	Right Hand
RWY	Runway
SE	Single Engine
SFHA	System Functional Hazard Assessment
SHSS	Steady Heading Sideslip
TLF	Thrust for Level Flight

LIST OF SYMBOLS

b	Wing Span
β	Sideslip Angle
C_L	Lift Coefficient
Cl_β	Rolling Moment Coefficient due to Sideslip
$Cl_\beta h$	Rolling Moment Coefficient due to Sideslip Acting on Horizontal Tail
$Cl_\beta v$	Rolling Moment Coefficient due to Sideslip Acting on Vertical Tail
$Cl_\beta wb$	Rolling Moment Coefficient due to Sideslip Acting on Wing/Body
$Cl_{\delta a}$	Rolling Moment Coefficient Due to Aileron Deflection
$Cl_{\delta r}$	Rolling Moment Due to Rudder Deflection
Clp	Rolling Moment Coefficient Due to Roll Rate
Clr	Rolling Moment Coefficient Due to Yawing Rate
Cn_β	Yawing Moment Coefficient due to Sideslip
C_{Yp}	Sideforce Coefficient Due to Roll Rate
δa	Aileron Deflection
δr	Rudder Deflection
L_A	Total Airplane Rolling Moment
L_β	Rolling Moment Due to Sideslip
p	Roll Rate
q	Dynamic Pressure
r	Yaw Rate
ρ	Air Density
S	Wing Area
U_1	Airplane Velocity
V_D/M_D	Maximum Design Dive Speed / Mach Number
V_{mo}/M_{mo}	Maximum Design Operating Speed / Mach Number

LIST OF SYMBOLS (Cont.)

V_{ref}	Reference Speed (Usually 1.3 * Vso)
Vs_o	Stall Speed in Landing Configuration
Vs_1	Stall Speed in Specified Configuration
ω_d	Dutch Roll Damping

CHAPTER 1

INTRODUCTION

Positive static lateral stability is required for by the Federal Aviation Administration for certification of airplanes. This requirement is also present in many military and other civilian design and flight test criteria. However, recent research and practical experience has shown that airplanes with neutral or even negative static lateral stability in some areas of the flight envelope are safe and exhibit adequate or even excellent handling qualities. This paper examines the history of this stability requirement and presents arguments for the change of the requirement.

1.1 Stability

Aircraft stability refers to the response of the aircraft to forces and moments in relation to an initial condition. Aircraft stability is divided into two main groups specific to the axes of the aircraft: longitudinal and lateral/direction. The later two are typically grouped together due to the strong coupling that often occurs between the lateral axis and directional axis of the aircraft. Stability can be divided further into dynamic and static. Dynamic stability describes the motion of an aircraft over some period of time following a disturbance from a steady state condition. Static stability describes the instantaneous force and moment behavior of the aircraft to disturbances from a steady state. [1]

For example, as the aircraft rudder pedal is depressed in flight, the rudder pedal force will increase proportional to the amount of rudder deflection. This indicates positive static directional stability: a tendency to oppose a disturbing force about the directional axes of the aircraft. If the rudder pedal is deflected then rapidly released, the nose of the aircraft will oscillate from side to side with the magnitude diminishing with each cycle. This indicates positive dynamic directional stability. In both of these examples, the aircraft tends to return to its initial flight condition. These stability characteristics are important to ensure an aircraft that is safe and controllable by the average pilot. If deflection of the rudder pedal caused the nose of the aircraft to continue to diverge from it's initial direction, or oscillate in a divergent manner, the pilot workload would increase significantly just to maintain the aircraft in the desired direction. Significant compensation on the part of the pilot would be required to maintain course.

Static lateral stability refers to the ability to raise a wing with the use of rudder only. This is unlike any other stability conditions and some say that by strict interpretation it is not a true static stability condition at all [2]. In the previous example of static directional stability, in response to a gust upset that creates a right sideslip, the nose of the airplane will to yaw to the right, eliminating the sideslip and restoring the initial flight condition. However, an aircraft with so-called positive static lateral stability, when upset with that same right sideslip, will roll to the left, taking the aircraft further from the initial steady state condition. Unlike other static stability characteristics, it is not immediately intuitive why positive static lateral stability is necessary, whether for safety or any other purpose.

1.2 Effective Dihedral

The terms "effective dihedral" and "static lateral stability" may be used interchangeably. Effective dihedral will be used in this paper and as stated for static lateral stability, refers to the ability to raise a low wing with the use of rudder only. This assumes a normal configuration airplane as shown in Figure A-1[1] with conventional flight controls consisting of rudder, aileron, and elevator. These assumptions are made for the sake of simplicity. They represent the vast majority of aircraft flying today and a large amount of data, both theoretical and practical, exists for this configuration. However, the conclusions and recommendations of this paper are equally applicable to all configurations of airplanes since they focus on the acceptance criteria for handling qualities of airplanes, not the design or analysis methods. Therefore, whether roll control is accomplished via ailerons, spoilers, elevons, etc., the criteria remain the same.

This definition differs somewhat from others. For example, Perkins and Hage [2] define dihedral effect as rolling moment due to sideslip. The former definition is used because it highlights the control used to cause the sideslip, whereas defining dihedral simply in terms of sideslip may imply a static condition. The term "effective" is used because the stability derivative Cl_{β} is often used interchangeably with "dihedral effect." However, the term "effective dihedral" is meant to address the ability of the pilot to raise a wing by rudder alone, as stated, regardless of the reason or cause of this capability.

1.3 Steady Heading Sideslip

The most common test method used for determining effective dihedral is the steady heading sideslip (SHSS). This test is conducted by establishing a steady, trimmed condition in a specific

[1] See Appendix A for all Figures.

configuration; for example, gear down, flaps up, power set to idle. Once the aircraft is trimmed in all axes, the pilot lowers a wing in the same manner as entering a turn. However, opposite rudder is applied simultaneously to hold the heading constant and thus the airplane is held in a sideslip condition. The amount of sideslip is dependent upon the angle of bank being held and the rudder authority of the airplane. Very large sideslip angles are neither necessary nor required. Typically, bank angles between 10º- 30º are utilized. Once the SHSS condition is established, the roll control is released, while the rudder control is held constant. If the airplane begins to roll in the direction of the rudder input, the airplane is said to exhibit positive effective dihedral. If the airplane rolls opposite, it is said to exhibit negative effective dihedral. If the airplane maintains the bank angle after release, it is said to have neutral effective dihedral. This test has been in common use since the 1920's. Since the control inputs necessary for a SHSS on an airplane with positive effective dihedral are identical to the inputs necessary for landing in a crosswind, it is a logical test method as an extension of this everyday maneuver.

Another common requirement for lateral and directional stability requires that the control deflections and forces are substantially proportional while establishing a SHSS. This test is nearly identical to the previous method: the roll and yaw controls are input gradually, using care to hold the heading of the airplane steady. However, the sideslip is carried out to a larger degree, typically until a control force or travel limit is reached within a reasonable airplane attitude. Although it may be obvious to the test pilot whether or not the deflections and forces are proportional, often a data review following the flight is necessary for validation, especially if the stability is very close to neutral. The adequacy of these two maneuvers will be discussed in Chapter 2.

1.4 Handling Qualities

Airplane flying and handling qualities, abbreviated FHQ, "are those properties which describe the ease and effectiveness with which it responds to pilot commands in the execution of some flight task" [3]. These tend to be formulated by pilot opinion and are rather subjective. The two qualities (flying and handling) are interdependent and practically speaking, probably inseparable. The flying qualities are response related, the handling qualities are task related. For example, roll response to control input is a measure of flying qualities. The adequacy of roll control during landing in a crosswind is a measure of handling qualities. Obviously the two are closely related and as such, the single term "handling qualities" (HQ) will be used henceforth.

Pilot opinion is critical in the evaluation of handling qualities and was instrumental in the development of legacy and modern aircraft acceptance criteria. Theory and wind tunnel tests can only carry the design so far. Ultimately, it is the actual flying of the airplane that determines its acceptability. There is a number of different HQ rating scales available [4]. A universally accepted method for organizing and quantifying pilot opinion is the Cooper-Harper (CH) rating [5] and will be used throughout this paper. See Appendix B for further explanation of this method.

1.5 Historical Background

The necessity of positive dihedral effect has been presumed for many years, but it is important to examine where that requirement originated. Bryan (1911) and Lancaster (1908) are usually credited with laying the first secure foundations for aircraft stability and control. Lancaster accomplished this by practical observation and analysis and Bryan, as a mathematician, by developing equations of motion of a rigid body with six degrees of freedom. Forms of these equations are still in use today [3]. However, mathematical models of motion do not prescribe acceptable motion. In other words, being able to predict how an airplane moves in flight is not the same as specifying what kind of airplane motion is acceptable. This was to come later with the development of HQ specifications.

1.5.1 NACA

The root of modern HQ specification can be traced to the early years of handling qualities testing accomplished by the National Advisory Committee for Aeronautics (NACA) in the 1930's and 40's and from miscellaneous handling qualities reports even prior to this. President Woodrow Wilson chartered NACA in 1915 in an effort to raise American aeronautical research to the European level. It's mission was to "direct and conduct research and experimentation in aeronautics, with a view to their practical solution" [6]. This "practical solution" meant that the research should lead to improvements in future aircraft design. In order to accomplish this, it was necessary to establish common means of testing aircraft and acceptance criteria.

In the late 1930's, NACA began an investigation specifically on the flying qualities of airplanes [7]. This was conducted in 3 phases carried on nearly simultaneously. Phase 1 was the determination of what factors can be measured to define, quantitatively, the flying qualities of the airplane. Phase 2 was the development of instruments and test procedures for making those measurements. Phase 3 was the accumulation of data on existing aircraft to serve as a basis for constructing quantitative specifications. The first work, Phase 1, was done by the Chief Physicist of NACA's Langley test facility, E.P. Warner, while preparing a specification for the DC-4 airplane. Phase 2 and 3 were conducted by other NACA staff members. The aircraft used initially in Phase 2 and 3 was the Stinson SR-8E (Figure A-2), a large cabin class monoplane. Tests were later extended to other types of aircraft.

The Stinson aircraft was a high-wing design with a 2 degree positive dihedral. Flight tests revealed that the Stinson was laterally unstable (spiral mode) with flaps up below 140 mph and with flaps down was unstable above 110 mph. However, the aircraft exhibited positive effective dihedral throughout the operating envelope. Spiral instability was considered undesirable at that time, as was negative effective dihedral. Later specifications dropped the requirement for spiral stability since the period of this instability is typically long enough to be transparent to the pilot [3].

1.5.2 Lateral Stability

One of the earliest reports to come from NACA's effort to quantify handling qualities was NACA Report 589, "An Analysis of Lateral Stability in Power-Off Flight with Charts for Use in Design", by Charles H. Zimmerman, published in 1937. In this report, NACA begins to identify the factors that impact effective dihedral such as wing taper, sweepback, vertical tail size, and angle of attack. It is recognized here that rolling moment due to sideslip plays a large role in both dynamic and static lateral-directional stability characteristics of the airplane. It is seen that Cl_β (roll due to sideslip) must be negative for lateral stability, but that there is strong interaction between the lateral-directional modes. Although increasing the negative magnitude of Cl_β makes a divergence in spiral stability less likely and increases the ability to raise a wing with the use of rudder alone, it also has the undesirable effect of decreasing dutch roll damping and shortening the dutch roll period.

It was concluded that Cl_β should be small and negative, while Cn_β (yaw due to sideslip) should be small and positive. Although these and other recommendations were made in this document, they were far from conclusive: “The present state of knowledge does not justify positive assertions as to the desirability of any given set of stability characteristics.” Zimmerman goes on to say “A systematic correlation of stability characteristics with riding and handling qualities is needed ” [8].

Following on this recommendation, another early study that attempted to quantify satisfactory handling qualities based upon flight data, and one of the most successful, was accomplished in 1940-41 by Soule′ and Gilruth [7, 9]. Sixteen aircraft of varies types were tested and results quantified using recorded data and pilot opinion. It is important to note that these aircraft varied significantly in size and capability, ranging from large transport to small pursuit, size being relative to aircraft of that day. The systems redundancy and handling characteristics were significantly different at that time compared to modern aircraft. Designs that were acceptable in the 1940’s, such as the Stinson, would have little chance of complying with today’s civilian regulatory environment. Nevertheless, findings from this study, shown below, paved the way for modern handling qualities requirements.

Lateral-directional requirements determined by Soule′ and Gilruth were relatively simple and stated that lateral oscillations should be highly damped and that spiral stability was not required since lack of stability did not detract from the pilots’ ability to fly efficiently. The requirements of primary interest (requirement II-D) stated: “the rolling moment due to sideslip as measured by the variation of aileron deflection with angle of sideslip should vary smoothly and progressively with angle of sideslip and should everywhere be of a sign such that the aileron is always required to depress the leading wing as the sideslip is increased.” Also, “the variation of aileron stick force with angle of sideslip should everywhere tend to return to aileron control to its neutral or trim position when released.” [9]
The stated reason for the first requirement was to insure that the roll due to rudder will always be in the “correct” direction and any lateral divergence will not be of a rapid type. The stated reason for the second requirement was to ensure that the rolling moment due to sideslip has the “correct” sign with controls free. In other words, effective dihedral should be positive, but small in magnitude - identical to the findings of Zimmerman. However, no definitive reason is given for the requirements other than the stability should be in the “correct” direction. In addition to the requirements above, the cross wind force characteristics

required that there be a right bank for a right sideslip, and vice versa. The primary concern here being that a bank into the wind was necessary to correct for a crosswind landing. This is a reasonable conclusion and will be discussed in Chapter 5.

1.5.3 Variable Stability

Beginning in 1948, an on-purpose evaluation of the impact of effective dihedral on handling qualities was conducted by NACA [10, 11, 12]. Prior to this period, HQ requirements were based on evaluations of existing aircraft with vastly different characteristics. It was difficult, if not impossible, to separate the coupling effects that often occur between various stability parameters. However, with the advent of variable stability, scientists and engineers could isolate a particular parameter while maintaining continuity in the other characteristics of the test aircraft. The first of these tests involved a World War II vintage F6F-3 fighter aircraft (Figure A-3) equipped with a roll control system which allowed simulation of various dihedral values. These tests were later supplemented by Cornell Aeronautical Laboratory with another variable stability airplane, the F4U-5 Corsair [13].

To a large extent, these tests validated earlier requirements for effective dihedral. However, contrary to some earlier conclusions by Soule′ and Gilruth, it was found that small negative values of effective dihedral were tolerable[2], depending upon the configuration. For example, the minimum tolerable effective dihedral in the landing approach condition was -7 degrees, and in cruise condition was -5 degrees (the optimum, however, was 14.2 degrees for landing and approach and 6.2 degrees in cruise). This conclusion is consistent with Zimmerman's findings: "There is strong reason to believe that any tendency to diverge is undesirable but that, if such a tendency is of small magnitude, it will not seriously inconvenience the pilot." [8].

It is important to note that the variable stability tests conducted by NACA were carried out on naval carrier-based aircraft by naval pilots, although the landing tests were conducted on land. Traditionally, landing aboard ship was, and is, a very high gain maneuver requiring good handling qualities. Nevertheless, the pilots' opinions were that effective dihedral should be greater than -7 degrees

[2] The term tolerable describes a condition which would not be dangerous in normal fighter operation, but which is not necessarily "desirable" or "pleasant."[1]

for landing aboard a ship, but a negative value would still be tolerable. This is an important point: that negative effective dihedral was tolerable in this high gain application (though admittedly not desirable).

More recent studies of acceptable range of effective dihedral were carried out by Princeton University in 1967 [14, 15] and 1971 [16]. Using a variable stability Navion (low wing, single engine propeller airplane), flying qualities were evaluated during power-on approach and under simulated moderate turbulence conditions during instrument approaches. These conditions were considered critical in terms of the need for precise airplane control. The Princeton studies clearly present the connection between acceptable effective dihedral, roll time constant, and dutch roll damping, with excitation due to turbulence being a strong influence. This is consistent with earlier findings by NACA: "The tolerable amount of negative dihedral is apparently related to the growth of rolling motion following a yawing-moment disturbance." [11]

This relationship is shown in Figures A-4, A-5, and A-6 from the Princeton studies. Figure A-4 shows the relationship between roll time constant and the roll moment due to sideslip (L_β). From this it is seen that pilot ratings for a given value of L_β vary with roll time constant (τ_{rm}). Figures A-5 and A-6 show a similar relationship with L_β and dutch roll frequency (ω_d). Of primary interest in these figures is that the lines of constant Cooper-Harper (CH) rating can be extrapolated into the area of negative effective dihedral, especially in Figures A-5 and A-6. It can be hypothesized that in if the dutch roll frequency is appropriately optimized, then some amount of negative effective dihedral would be acceptable with CH ratings between 3 and 5. The boundaries for desirable and acceptable pilot ratings were found to be 3.5 and 5.0 respectively in the Princeton studies [16]. Typically the criteria for lateral and directional stability is developed separately and evidence that negative effective dihedral may be acceptable is seldom considered. However, the Princeton tests and those presented in Chapter 4 of this paper support the above hypothesis.

CHAPTER 2

EFFECTIVE DIHEDRAL

Most modern flying quality criteria, whether found in textbooks or military specifications, are based upon the early findings of NACA. However, little discussion is given to their origin or justification: "*It is known* that high directional stability is desirable and that dihedral effect should have the correct sign, but should not be too strong" (emphasis added) [17]. The criteria are simply assumed based upon earlier research. Furthermore, effective dihedral does not come without a cost. Although there are a number of excellent resources that describe how to estimate effective dihedral [2, 1, 18], accurate numbers typically require wind tunnel testing and even these are prone to error [8, 2]. This often leads to an airplane with insufficient effective dihedral to pass the desired criteria or to an aircraft with excessive effective dihedral. The common specifications effective dihedral and the consequences of complying, or failing to comply, are examined below.

2.1 Military Specifications

In 1954, the U.S. Military Services issued MIL-F-8785 (ASG), "Flying Qualities of Piloted Aircraft", a joint specification based partly on variable stability tests and partly on extensive flight experience on recent military aircraft. In the years following, methods books were written to aid the engineers and pilots engaged in aircraft design and flight testing in understanding the reasons for specific requirements, applying the correct test technique, and appropriately applying the specifications to a particular aircraft [19, 20, 21]. However, very little work was done in re-examining the necessity for positive effective dihedral. Later revisions of MIL-F-8785 (Rev. B in Aug. of 1969 and Rev. C in Nov. of 1980) and the modern replacement, MIL-STD-1797A, "Flying Qualities of Piloted Aircraft", all contain similar requirements for positive effective dihedral [22, 23].

However, exception is allowed in MIL-STD-1797A for the wave-off, or go-around condition provided the task performance is not impaired and certain other control criteria are met. MIL-STD-1797A also references Princeton University Report 727, "Lateral-Directional Flying Qualities for Power Approach" [14]. In this report it was stated that fighter pilots in particular wanted some positive effective dihedral, but pilots of a prototype assault transport airplane preferred zero effective dihedral and commented positively on the uncoupled yaw capability using rudder. Similar guidance is found in the commonly used reference book “Aerodynamics for Naval Aviators” [24]. Although not a true specification, this book is widely used as both textbook and reference book by flight schools and flight test departments. It states that certain exceptions can be considered when the airplane is in the takeoff and landing configuration since flaps and power are destabilizing. However, in most flight conditions, effective dihedral should be positive, but light. This is discussed further in Chapter 3 of this paper.

2.2 Civilian Specifications

The development of civilian requirements followed a similar path and also built upon the early work done by NACA. The Air Commerce Act of May 20, 1926 was the beginning of civil aircraft regulation in the United States. Among other things the act charged the Secretary of Commerce with certificating aircraft. The first requirements for certification of an airplane were in the form of Aeronautical Bulletins. In regards to stability, the 1934 Aeronautical Bulletin 7a, “Airworthiness Requirements for Aircraft,” simply stated that “Under all load and power conditions, all airplanes shall be longitudinally, laterally, and directionally stable” [25]. Obviously a great deal of discretion was left to the government inspector. In 1938, the responsibility for certificating aircraft was transferred to the newly formed Civil Aeronautics Authority (CAA). [26] After the formation of the CAA, the Aeronautical Bulletins were replaced by Civil Air Regulations (CARs). CAR 3 and CAR 4 governed certification of small and large airplanes respectively. Both of these regulations also required neutral or positive effective dihedral. These were eventually replaced by Federal Aviation Regulations Part 23 and Part 25, respectively, in 1964. Although each of these rules was revised over the years, little change was made to the requirement for positive effective dihedral [27]. The preamble for these rules, which is an explanation of the origin and purpose for the rule, states that the primary reason for requiring positive dihedral effect is for redundancy in the roll control capability of the airplane. Flying or handling qualities are not mentioned in the requirement.

There is a slight difference in today’s requirements in Part 23 versus Part 25. Aircraft certified under Part 23 must demonstrate that static lateral stability, “as shown by the tendency to raise the low wing in a sideslip,” is positive in all configurations throughout the normal flight envelope, with a few exceptions. Aircraft certified under Part 25 must also show positive effective dihedral throughout the normal flight envelope up to V_{mo}/M_{mo}. However, although the requirement was once worded similar to the Part 23 rule, it was reduced in the 1990 amendment 25-72 simply to the requirement that in straight, steady sideslips, the aileron and rudder movements and forces must be "substantially proportional" to the angle of sideslip in a stable sense. Prior to this amendment, the requirement was basically that static lateral stability not be negative. In other words, positive or neutral was allowed, but not negative. However, even after amendment 25-72, AC-25-7A retained the wording that when the ailerons are released with the rudder fixed, the low wing should "tend" to return to level, essentially requiring positive effective dihedral. Aircraft certified under Part 23 must meet this same requirement with the exception of low speed ($1.2Vs_1$) in the landing configuration and low speed ($1.3Vs_1$) in any other configuration. In these low speed conditions, effective dihedral may be zero, but not negative. In addition, positive stability in the landing configuration must be shown only with power required for a 3-degree descent angle. Appendix C contains pertinent text from current regulations, as well as exerts from historical regulations showing the evolution of the criteria.

An attempt was made to modify Part 23 lateral stability requirements in 1993 with the proposal to allow slightly negative effective dihedral in amendment 23-45. However, the proposal was rejected due to the difficulty in consistently measuring the degree of instability. Another proposal was made for this same amendment to relax the stability requirements to agree with those specified in MIL-STD-8785C. This proposal was rejected on the grounds that the military is more concerned with maneuverability than stability.

This last supposition is arguable since the military tests and operates aircraft across a broad range of applications, from fighter to transports. In much the same manner, the FAA certifies aircraft across a range of applications, from aerobatic airplanes, to light trainers, to heavy transports. Not all have the same level or need for stability. As for the first proposal, the difficulty with consistent measurement exists even in today's criteria. It is evident in the very wording of the rules. Both Part 23 and Part 25 require that the control forces and deflections be "substantially" proportional. How much is substantially? Both rules require that from a SHSS maneuver, when the ailerons are released the low wing should "tend" to return to level. What is "tend?" For how long must the wing tend to return? The very use of this wording implies that it is not necessary that the wing completely return to level. Otherwise, why not simply require the wing return to level instead of "tending" to return to level? AC25-7A specifically states the intent of the test is to evaluate short-term response of the airplane and that long-term effect's such as fuel migration need not be considered. However, recent interpretation of these rules have lead to the arbitrary assignment of a minimum time for apparent positive stability: 30 seconds after release of the ailerons. This criteria is found in neither rule nor guidance material and although it may be appropriate, it simply highlights the level of interpretation present in today's certification findings. If ambiguity is already present in today's rules, it is not a valid reason for avoiding a change to the rules.

Another significant change was made to the Part 23 requirement in 1996 with amendment 23-50. The first change to Section 23.177 was a minor formatting change to eliminate reference to two-control airplanes. The second change was to simply clarify that static lateral stability could be neutral at 1.3 Vs1 in all configurations except takeoff. The previous rule already allowed neutral stability at 1.2Vs1 in takeoff configuration and implied neutral for 1.3Vs1 in other configurations. The final change was to exempt aerobatic category airplanes from this requirement since positive static stability is not desirable in that application. Along with these minor changes to Section 23.177, a new rule, Section 23.147(c) was added which "compensates for the relieving nature of 23.177(b) [28]." The new rule stated that it must be possible to control the airplane in such a manner that a controlled landing could be made without the use of the primary roll control system. Furthermore, if the failure of any system component could result in the loss of additional control(s), then that control cannot be used for the test. So if an aileron rudder interconnect (discussed in Chapter 2) is used to show compliance with 23.177, but the design is such that a single failure would result in the loss of that interconnect, then compliance with 23.147(c) must be shown with the interconnect disabled.

The addition of this new rule is more sensible than the requirement for positive static lateral stability as it addresses the original concern for lateral stability, which is redundant roll control. However, the "relief" incorporated into 23.177 by amendment 50 can hardly be equated to the more stringent requirement of 23.147(c). Since this new rule addresses the safety concern for lateral stability, the requirement of 23.177 should have been completely deleted. Furthermore, the modern interpretation of the systems safety rules in both Part 23 and Part 25 addresses the redundancy issue and so it would be reasonable to delete the lateral stability requirements in both 23.177 and 23.147. This also is discussed further in Chapter 5.

2.3 Design for Dihedral

From a manufacturing standpoint, a wing with dihedral is only slightly more difficult to construct than one without dihedral. The basic wing structure would be identical, the only difference being the wing joint where the dihedral begins. This is usually at the wing root where it attaches to the fuselage, but could be outboard of the root, or the wings could mate together without a center carry-through section. Regardless, the weight and complexity of a typical wing with dihedral are usually not significantly different than a wing without dihedral.

From an engineering design standpoint, dihedral creates a mechanical stress riser at the point where the wing span gradient changes, typically at the wing root where stresses are the highest anyway due to wing bending moments and drag moments. However, this is not a significant concern and compensation is found with minor increase or modification in the structure. For airplanes with wing mounted landing gear, dihedral can increase the necessary length of the main gear struts, adding weight and cost. For aircraft with retractable landing gear, the angle the gear strut must swing to stow into the wheel well is increased with increased dihedral. This can result in larger actuator requirements and loss of mechanical advantage at the end of the stowing cycle.

In terms of aerodynamic losses, the more dihedral, the less efficient the wing. This is due to loss of the vertical component of lift of the wing as the dihedral is increased. However, this effect is typically very small, since it is directly proportional to cosine of the dihedral angle (Γ).

On the plus side, for aircraft with engines mounted beneath the wings, dihedral is beneficial in providing ground clearance for the engine nacelle without incurring the weight penalty of longer landing gear. For any airplane, dihedral provides additional wing tip clearance when maneuvering close to the ground such as when landing in a crosswind and using the wing-down landing method. Dihedral also allows wing fuel tanks to gravity feed toward the wing root where it is usually easier to feed to the engines, although many aircraft incorporate transfer pumps to assure proper fuel migration.

All of the above mentioned factors may be considered in dihedral design. However, the primary governing factor is usually dutch roll damping (dynamic lateral-directional stability), which is inversely proportional to effective dihedral on most aircraft [29].

As seen in Figures A-5 and A-6, Cooper-Harper handling quality ratings are strongly effected by dutch roll frequency. The smaller values of ω_d are unfavorable due to the difficulty in maintaining heading. The larger values are unfavorable because of the strong response to turbulence. Handling qualities criteria typically include a requirement for the dutch roll mode to be damped. CFR14 Part 23, for example, states that the dutch roll damping must be such that the amplitude decreases to $1/10^{th}$ its original value within 7 cycles. Part 25 simply states that the damping must be positive. However, the frequency ω_d is often not addressed. The impact on dihedral effect on handling qualities will be discussed further in Chapter 3.

2.4 Mechanics of Effective Dihedral

Effective dihedral is the ability to raise a wing by using rudder alone. The primary factor in this capability is dihedral effect, or the rolling moment due to sideslip (Cl_β). The difference between Cl_β and effective dihedral is the other factors that impact the ability to roll using rudder.

The total airplane rolling moment for a steady flight condition such as a SHSS that does not involve angular rates is:

$$L_A = (Cl_\beta \beta + Cl_{\delta a} \delta a + Cl_{\delta r} \delta r) q S b \tag{4.1}$$

The act of raising a wing with rudder, or simply maneuvering with rudder only, is a dynamic maneuver that includes a yaw rate around the vertical (z) axis, as well as the static effects of the previous equation. The SHSS test does not account for the dynamic motion exhibited by the aircraft when the rudder is used to control bank angle. By eliminating the effect of rotation about the airplane's z-axis, the dynamic terms are ignored which could make the difference between successfully demonstrating positive effective stability or not. When the moments due to angular rates are included, the total airplane rolling moment equation becomes:

$$L_A = [(Cl_\beta \beta + Cl_{\delta a} \delta a + Cl_{\delta r} \delta r) q S b] + \{[Cl_r (rb/2U_1) + Cl_p (pb/2U_1)] q S b \tag{4.2}$$

Cl_β is the rolling moment due to sideslip derivative and is negative for stability. During a sideslip, the upwind wing experiences an increase in AOA and thus an increase in lift while the downwind wing experiences the opposite. The net effect is a rolling moment toward the downwind wing. Cl_β is the strongest contributor to effective dihedral. It is usually divided into three components, wing-body, vertical tail, and horizontal tail:

$$Cl_{\beta} = Cl_{\beta wb} + Cl_{\beta v} + Cl_{\beta h} \quad (4.3)$$

The three contributors to the wing-body component are wing geometric dihedral, wing position on the fuselage, and wing sweep angle. Obviously, an increase in geometric dihedral results in an increase in effective dihedral. Wings mounted high on the fuselage typically increase dihedral effect while low mounted wings decrease dihedral effect. Finally, sweep angle has a large positive contribution to dihedral effect, especially at high angles of attack.

$Cl_{\delta a}$ is the rolling moment due to aileron deflection derivative and is greater than zero for normal control. This is the primary roll control derivative and is caused by the unsymmetric deflection of the ailerons on each wing, which produces asymmetric lift on the wings, resulting in a rolling moment. During the SHSS maneuver, the ailerons are used to hold the desired bank angle. Once the ailerons are released, the ailerons return to some "float" position for the remainder of the maneuver. The variation of aileron hinge moment with sideslip can have a significant impact on dihedral effect. Ideally, a nose right yaw (left sideslip) would produce a negative pressure gradient on the underside of the right-hand (RH) aileron, causing it to deflect downward, simultaneously deflecting the left-hand (LH) aileron upward. This aileron deflection would cause a LH rolling moment in the same direction as the yaw and thus be stabilizing. Should a sideslip cause the opposite aileron motion (right yaw causing left roll aileron motion), the aileron motion would be destabilizing. Typically, $Cl_{\delta a}$ is significantly higher than other roll derivatives and therefore this aileron motion can have a strong influence on effective dihedral.

$Cl_{\delta r}$ is the rolling moment due to rudder deflection derivative and is greater than zero for normal control. A rudder deflection will create a "lift" force acting in the horizontal direction above the x-axis, thus creating a rolling moment about the x-axis. A right rudder depression would cause a left rolling moment. Therefore, $Cl_{\delta r}$ normally contributes to negative effective dihedral.

Cl_r is the rolling moment due to yaw rate derivative and is greater than zero for stability. When the rudder is deflected, for example if the right rudder is depressed, the airplane yaws about it's center of gravity. The left-hand wing advances compared to the right-hand wing. This causes an increase in local flow velocity over the left-hand wing resulting in an increase in lift. Correspondingly, the right-hand wing experiences a decrease in lift, causing a net rolling moment to the right, in the same direction as the rudder pedal depression. Therefore, a stable Cl_r would contribute to positive effective dihedral.

Cl_p is the rolling moment due to roll rate, the so-called roll-damping derivative, and is less than zero for stability. When an airplane is rolled about it's x-axis, the down-going wing experiences an increase in local angle of attack resulting in an increase in lift while the up-going wing experiences a correspondingly decrease in angle of attack and decrease in lift. These asymmetric changes in lift tend to oppose the rolling motion of the airplane and therefore do not contribute to positive effective dihedral. However, this only acts as a damping force and not a driving force and therefore does usually impact effective dihedral.

2.5 "Band-Aids™" for Effective Dihedral

Since adding geometric dihedral to an aircraft after it has been constructed is a lengthy and costly undertaking, various artificial methods or "Band-Aids™" have been developed to create or simulate positive dihedral effect. On of the most common of these is the aileron-rudder interconnect (ARI). ARI's can take a variety of forms depending upon the complexity of the flight control system. For simple mechanical control aircraft, the ARI is usually a simple spring interconnect between the rudder and the aileron control cables such that when the rudder pedals are deflected, the ailerons are also deflected, to some degree, in the same direction. This is clearly seen on many aircraft while on the ground. For example, pushing the LH rudder pedal of a Beech Bonanza (one of the first, if not the first, aircraft to incorporate an ARI), causes the cockpit control yoke to deflect to the left, and vice versa. During pre-flight walk-around of the Cessna Citation V, movement of either aileron results in some complimentary movement of the rudder, and vice versa. In aircraft with more complex flight control systems, the ARI may be variable with configuration and/or airspeed so that it's effects are only felt in the areas of the flight envelope where effective dihedral is unstable. With fly-by-wire aircraft, the ARI function can be incorporated into the control laws of the flight control system.

From a piloting standpoint, ARI's certainly achieve the desired result – positive effective dihedral. However, from a regulatory standpoint, considering that the purpose of requiring positive lateral stability is to ensure the ability to control the airplane in roll following loss of the primary roll control system, an ARI often does not meet the intent of the rule in many installations. An exception would be a fly-by-wire system in which the required redundancy of the system ensures continued safe operation in the event of the roll control malfunction. On the other hand, aircraft with mechanical flight control systems incorporating an ARI can rarely, if ever, show continued safe operation following a major malfunction of the primary roll control system. For example, an aileron jam would render the ARI completely ineffective. Also, an aileron cable failure outboard of the ARI, depending upon the design, would likely render it ineffective.

In addition to the dubious ability of the ARI to meet the intent of the FAR's, the characteristic uncommanded movement of aileron with rudder deflection, and vice versa, is not an enhancement to the handling qualities of the airplane, especially when landing in a crosswind. The typical ARI adds to the control forces necessary to maintain the forward slip (wing down, opposite rudder). Even when taxiing, ARI's are unwelcome since flight crews do not appreciate the roll control (yoke or stick) banging back and forth during turns. Typically the crewmember that is not in control during taxi will hold the yoke somewhat rigid to prevent this, similar to taxi operations in high winds. ARI's can also add undesirable friction to the primary roll control system. The latest military specification MIL-STD-1797 states that it is not desirable to use an ARI to meet the lateral stability requirements since it augments $L_{\delta r}$ and not L_{β} as desired [23]. Regardless of these obvious shortcomings, the FAA has allowed ARI's to be incorporated in many different aircraft in order to show compliance with static lateral stability requirements. However, Amendment 23-50 added paragraph 23.147(c), which more adequately addresses interconnect system failures, as previously stated.

Other, less common "band-aides" are aerodynamic in nature. Early studies have shown that wing-tip shape can strongly influence effective dihedral [30]. The Cessna Model 210 Centurion is a example of wingtips being scarfed upward so that in a sideslip, air tends to be deflected beneath the wing thus creating a stabilizing rolling moment. Winglets can have a similar effect. Fences installed on the ailerons have been used to enhance effective dihedral. Although their effect is typically weak, they have been used successfully on aircraft that are marginal stable or very weakly unstable laterally in a limited area of the flight envelope. Fences are typically installed on the upper surface of each aileron as an extension to the inboard edge so that the fence has little effect in straight flight. In the presence of a sideslip from the wingtip direction of a given aileron, the fence creates a local high-pressure area on the upper surface of the aileron causing it to deflect downward and lifting the opposite aileron. This causes a stabilizing rolling moment away from the sideslip. Fences can also be installed on the lower surface at the outboard edge of the aileron and function in much the same way to create a low-pressure area to "suck" the aileron down. Although aesthetically preferable, these are usually less successful. Some examples of aileron fences used for static lateral stability can be found on a wide range of aircraft: Cessna 206 (single engine piston), Cessna 208 (single engine turboprop), and Cessna Citation CJ3 (twin engine turbojet, Figure A-7).

Depending upon the flow field over the wing and surrounding surfaces, vortex generators (vg's), boundary layer energizers (BLE's), and any number of fences and LMT's (little metal things) have been used to improve stability. These are typically successful when there exists an usually strong area flow separation in the presence of a sideslip.

Another recent aerodynamic device being studied for improvement of static lateral stability is "canted tabs." These are small tabs or flat rectangular plates installed along the trailing edge of the each aileron, with the edge of each tab facing forward offering the least amount of drag in straight flight. The tabs are mounted at an angle or "canted", usually at about a 45 degree angle away from the nearest wing tip so that in a sideslip, air strikes the exposed flat faces of the tabs pushing the aileron up and the opposing aileron down, creating a stabilizing rolling moment. These devices were demonstrated successfully on the Bosbak aircraft at the National Test Pilot School (Figure A-8). Unfortunately, the installation is cosmetically unappealing and likely unacceptable except in the most utilitarian applications.

2.6 Steady Heading Sideslip vs. Rudder Turns

As described previously, the steady heading sideslip has been the standard test for effective dihedral. However, by definition, effective dihedral is the ability to control the bank angle of the airplane with the use of rudder alone. Therefore, an adequate test for effective dihedral is simply to demonstrate that the bank angle of the airplane can be reasonably controlled with the rudders, beginning from a wings-level condition. After all, the intent is to fly with the rudders, not to enter or exit a sideslip condition. Using rudder turns allows full use of the rudder up to the specified force or deflection limits. The SHSS method only allows enough rudder to maintain a constant heading - once the ailerons are released for the test, the rudder deflection must be held constant. Typically, a large amount of rudder deflection is still available at this point, but the test method does not allow for its use.

Furthermore, fuel migration issues are avoided with the rudder turn method. Fuel migration occurs when the airplane is held in the SHSS condition. This uncoordinated sideslip causes fuel to be forced toward the tip of the down wing. This increased fuel imbalance can make the difference between passing and failing the test. In the event of an actual roll-control failure, a small sideslip would only be experienced for that amount of time when the airplane is being maneuvered. Once a bank angle or wings-level condition is established, the sideslip angle would approach zero since there would be no aileron control available to hold the airplane in an uncoordinated state.

CHAPTER 3

OPERATIONAL PHILOSOPHY OF EFFECTIVE DIHEDRAL

It has been shown that positive effective dihedral is a required by many agencies and that the two dominant concerns behind this requirement are safety and handling qualities. These two issues will be addressed independently.

3.1 Safety

The desire is that a backup be provided in the event of a failure of the primary roll control system. Take, for example, a conventional small aircraft with mechanical flight controls consisting of simple aileron, rudder, and elevator. Should the control cable to the ailerons break (for whatever reason), the pilot should still be provided with adequate roll control through the rudders, using dihedral effect, and thus be able to maneuver to an airport for a safe landing. This scenario presumes many things. First of all, that no other backup for roll control exists - no roll spoilers, no push-rods allowing control of a single aileron should the other fail, etc. Second, the dihedral effect is sufficient to counter any adverse weather conditions that may be present. Wind gusts that upset the airplane laterally can not exceed the capability of the rudder to restore a level attitude. Last of all, that the pilot will have the skills, using rudder only, to adequately maneuver and navigate the aircraft to a desired location (presumably an airport), align the aircraft for landing, and maintain this alignment all the way to touch down and full stop.

The first assumption may or may not be correct and simply depends upon the aircraft design. Many modern aircraft, especially jet aircraft, incorporate both aileron and roll spoilers for roll control. Some aircraft incorporate push-rods versus simple cable/bellcrank systems for roll control. Many aircraft designs incorporate separate aileron trim tabs which can also be used to control aileron deflection in the event of aileron cable failure. Should the requirement for positive (or not negative) dihedral effect be restated such that redundant roll control is available to the pilot, many roll control designs currently in use could be shown to meet this requirement. This issue is examined in more detail in Section 5.2 in terms of system safety analysis.

The second assumption is questionable at best. Since the typical requirement for dihedral effect is only that it be positive or zero, very small values of effective dihedral could potentially be overpowered by wind gusts. This author has experienced gusts in normal flight, especially at low speeds during landing approach, which required significant aileron deflection to counteract rolling moments caused by atmospheric turbulence. It is not unusual to use ¼ to ½ available aileron travel during landing approach in gusty conditions. Obviously, if the requirement is simply for zero dihedral effect, any lateral upset at all could not be countered and the probability to safely reaching the ground, much less an airport, is nearly zero.

The third assumption involves crew training. During basic training it is not unusual to demonstrate and practice, to a small degree, turns using rudder only (as a matter of fact, the Cessna 152 can be turned using only the cabin doors, as is sometimes demonstrated to students in that aircraft). The handling qualities of typical aircraft are certainly explored during training and in most training aircraft that means some amount of dihedral effect is experienced during maneuvers such as turn coordination exercises, side slips, and forward slips in a cross-wind. However, the use of rudder as a replacement for the primary roll control is rarely found in any training syllabus, much less the actual practice of using rudder as the primary roll control while maneuvering all the way throughout descent to landing [31]. In addition, no degree of proficiency is obtained, nor practiced in the years following basic training [32]. Therefore, it is unreasonable to expect that an average pilot would be able to successfully accomplish such as feat in a true emergency situation.

Despite this proficiency deficit, it should be stated that a positive dihedral effect of sufficient magnitude or some other secondary means to control roll angle will at least offer the pilot (and passengers) some chance of reaching the ground in some controlled attitude following loss of a primary roll control system whereas with no roll control redundancy, the likelihood of survival is almost nil. However, as stated above, the current certification rules allow for minimal or zero dihedral effect, essentially negating this possibility.

3.2 System Safety Analysis

In addition to the stability requirements of Part 23.177, 23.145, and 25.177, paragraph 231309 and 25.1309 requires that a rigorous safety analysis of each aircraft system be conducted and an appropriate level of redundancy be present in the basic design. This process begins with an Aircraft Functional Hazard Assessment (AFHA) which examines each possible functional failure condition and assigns a probability requirement for that failure based upon the consequence. For example, the consequence of loss of all roll control is catastrophic. Therefore, based upon Part 25 requirements, the probability of occurrence of loss of all roll control must be 1 in $1x10^{-9}$. In other words, the chances for loss of all roll control must be one in a billion flight hours.

This analysis is, to a large extent, independent of airplane design. For a conventionally configured airplane, loss of all roll control means precisely what it says. Regardless of amount of redundant systems, spoilers, dihedral effect, etc. - the question is "what is the effect if ALL roll control is lost?" The airplane will obviously be uncontrollable and loss is inevitable. The means to mitigate this risk to an acceptable level is addressed in the specific airplane design analysis.

The second part of the safety analysis is the System Functional Hazard Assessment (SFHA). This is an in-depth look at the specific airplane design, system by system. It's probability of failure and the effect of each failure. Following this is the Preliminary System Safety Assessment (PSSA), which contains the plan for addressing the design requirements set in the AFHA and SFHA. Finally, the System Safety Assessment (SSA) shows how the final design met the requirements.

The purpose of this look at the FAR's is to point out that a requirement and rigorous method already exists for determining the safety of the airplane and it's systems. As stated previously in this paper, the primary reason for requiring positive dihedral effect is for roll control redundancy. But this presupposes the solution to the system safety assessment of the roll control system, required by 23.1309 and 25.1309. The option should be left to the airplane designer. Dihedral effect is just one of many options the designer could utilize to meet the necessary roll control redundancy requirement. If the requirement for positive dihedral effect is indeed safety, that is, redundancy in roll control, then a more appropriate approach would be to simply require redundancy in roll control and allow the aircraft designer to comply with that requirement with whatever method best fits that particular aircraft design.

3.3 Handling Qualities - Cooper Harper and the FAA

As pointed out before, flying and handling qualities are subjective at best. Although excellent tools have been developed over the years to help narrow the subjectivity, to a large extent good or bad is still a matter of opinion. The best method available is to evaluate a given condition with multiple flight crews and try to draw a conclusion from the culmination of their feedback. The Cooper-Harper scale has become the standard for quantifying these opinions. Nevertheless, this scale is subject to interpretation and largely depends upon the adjectives used by the evaluating pilots. A detailed explanation of the Cooper-Harper method is contained in references 22 and 45 so only the highlights will be mentioned here.

The Cooper-Harper scale is task dependent - it is used for evaluating handling qualities. Therefore is can only be discussed in relation to a specific flying task such as landing in a cross-wind or performing a 180 degree turn at constant bank and airspeed, etc. The Cooper-Harper system aides the evaluating pilot in determining the adequacy of the airplane for these specific tasks by asking differentiating questions: "is it controllable?" and "is adequate performance attainable with a tolerable pilot workload?" etc. Based upon the pilots' answers to these questions, the pilot assigns a rating of 1 through 10 for that airplane's performance of that specific task.

The differentiating question between ratings of 1,2,3 and 4,5,6 is this: "is it satisfactory without improvement?" The question arises: "what is satisfactory?" Cooper [33] proposes the opinion rating system shown in Figure A-9 as a tool to further assist the pilot in differentiating between "satisfactory" and "unsatisfactory." This is somewhat consistent with the Princeton study [16] in which a static lateral stability HQR (handling quality rating) of 3.5 was considered the lower boundary for "desirable" and 5.0 the lower boundary for "acceptable" although Mr. Cooper would probably propose 4.5 for the latter. As previously established, a number of studies have shown that some amount of lateral instability is "tolerable" or even "acceptable" for even high-gain tasks.

In the United States Legal Code, Title 49, the primary role of the Federal Aviation Administration is to "encourage the development of civil aeronautics and safety of air commerce in and outside of the United States." Throughout the code it is clear that the primary concern is safety in aviation. The Code is not written to ensure "good" flying airplanes, only "safe" airplanes. Anyone experienced in civilian aircraft certification has seen the approval of airplanes and products that have poor operating or handling characteristics, but are nevertheless certificable. The regulations allow a great deal of latitude in the design of the airplane and only provide for "minimum safe" standards. This is obvious from the wide variety of handling characteristics found among certified airplanes.

It can be difficult to draw a line between "good" handling qualities and "safe" handling qualities. It could be argued that safety is related to how "good" are the handling qualities. For example, heavy pitch forces may not detract from safety directly, but should the pilot become fatigued during high gain tasks and the response of the pilot to correct for gust upsets be compromised, it is easy to see how this could affect safety. In addition, the capabilities and strengths of pilots vary significantly. The FAA has established numerical limits to the allowable control forces in order to account for pilot strength. The same cannot be said, unfortunately, for pilot capability. The guidance given is typically that the task must be within the capabilities of the "average" pilot, although some tasks such as stall characteristics may not require "exceptional" piloting skill, but may be beyond the skill of the "average" pilot [27, 28].

And so when possible the FAA has established numerical limits and where this is not possible, the FAA has deemed the airplane acceptable provided the "average" pilot is able to accomplish the task. The question is not whether the average pilot would find the airplane pleasant to fly, but simply whether the average pilot can accomplish the task. Utilizing the Cooper-Harper scale shown in Figure A-10, it is clear that any rating from 1 though 6 indicates successful completion of the task, although with varying degrees of compensation on the part of the pilot. Few would argue that an HQR of 6 should be allowed by regulation, based upon the earlier discussion on pilot workload and safety. However, experience shows that an HQR of 4 or 5 has been shown to be compliant with FAA regulations.

Therefore we can conclude that the FAA regulations are concerned primarily with safety, and only with handling qualities to the degree to which safety is affected. But "good" handling qualities are not a requisite. As stated many times by various FAA certification pilots to this author: the FAA does not dictate design, it only provides oversight to ensure the design is safe.

3.4 The Handling Qualities related to Effective Dihedral

What impact does positive effective dihedral have on handling qualities? The primary effect, by its very definition, is the ability of the pilot to raise a wing with the use of rudder alone. Its role in redundancy of roll control has already been examined. In addition, some pilots use rudder input to make small bank angle and heading corrections. This is more common in large aircraft with significant wing sweep (KC135, Boeing 747, etc). However, some pilots have developed this habit, usually while flying aircraft with a roll response that is heavy, slow, or imprecise and in which the addition of rudder control for turning provides superior performance over the primary roll control system. This is not a practice common to all pilots and varies as much as the variation of airplane handling qualities. Should a rudder input provide not additional rolling moment, or even a slightly opposite rolling moment, the pilot would quickly cease using the rudder to assist in roll control or simply fail to notice the effect of the rudder. This was evident in the evaluations described in Chapter 4.

Another effect of dihedral is the control inputs required while landing in a crosswind. Two types of landing techniques are commonly used: the wing-down method and the crab method. The crab method requires the airplane to remain in a "crab" or offset heading into the wind until immediately prior to touchdown, at which point the airplane is aligned with the runway using rudder. Since this occurs just seconds before touchdown, the airplane drift due to crosswind is very small. The more common method, especially in smaller airplanes, is the wing-down or sideslip method. In this method, the airplane is placed in a slip by banking into the wind just enough to counter the crosswind, and utilizing opposite rudder control to keep the airplane aligned with the runway center line. In doing this, a constant sideslip angle is maintained to touchdown.

In the first method, when the rudder is used to align the airplane with the runway, a rolling moment is created due to effective dihedral. In this position very close to touchdown, any rolling moment is undesirable. It could be argued that neutral effective dihedral would best suit this task. However, whether the effective dihedral is negative or positive, some small aileron input is necessary to counter the roll. Typically the roll moment is small so that most pilots will input the correct control on instinct. In fact, it is not unusual to have active roll control inputs throughout the landing sequence, especially in a gusty crosswind. It is unlikely the pilot would even notice the additional roll moment created by this last second rudder input.

In the second method, typically aileron control is held into the crosswind while opposite rudder is needed to maintain runway alignment. Aircraft with negative effective dihedral, once the bank angle is established, would require aileron input away from the crosswind but in the same direction as the rudder input. This could be disconcerting to most pilots since they are not accustomed to this control movement. However, a pilot's attention is typically more focused on maintaining proper airspeed and glidepath than whether the roll control is left of center or right of center. In other words, a small amount of negative dihedral would likely go unnoticed. However, for the sake of training and consistency with other aircraft, it can be argued any amount of negative effective dihedral in the landing configuration should be of such small magnitude as to not detract from the pilots performance.

As stated in Chapter 2, effective dihedral has a strong relationship with dutch roll and roll time constant. As seen in Figures A-4, A-5 and A-6, an airplane with adequate effective dihedral can still have poor handling qualities due to inadequate roll or dutch roll characteristics. These latter two traits typically drive HQR's more than effective dihedral alone. Airplanes with strong effective dihedral may exhibit good spiral mode stability, but poor roll authority and dutch roll damping. Conversely, airplanes with good roll authority and dutch roll characteristics may exhibit weak effective dihedral. The primary consequences of negative effective dihedral are described above in the crosswind landing and rudder-turn conditions. The consequences of poor roll authority are felt throughout the flight envelope, regardless of the task. The consequences of poor dutch roll characteristics may also be seen throughout the flight envelope, especially in gusty or turbulent conditions. The side to side motion of the airplane can be very disconcerting to the passengers and make accurate flight path control difficult, especially during landings.

The effect of dihedral on stall and spin characteristics is unknown at this time. It is likely that dihedral has some influence, but quantifying this would be very difficult since these flight conditions are very dynamic and unpredictable. During stall entry and recovery, some aircraft exhibit a nose "slice" characterized by a yaw with little or no roll. This slice is usually inconsistent from one stall to the next. The author has experienced this on aircraft that normally exhibit good effective dihedral. Since it occurs at a high angle of attack, the effective dihedral characteristics of the airplane in the normal flight envelope are probably not applicable to this regime. Experience has shown that stall and spin characteristics cannot be extrapolated from other operating characteristics and must be determined independently.

CHAPTER 4

IRON BIRD AND AIRPLANE EVALUATION

Previous studies have shown that some amount of negative effective dihedral is acceptable, however it was desired in the first phase of this experiment to validate this hypothesis on a modern high performance business jet. The goal of the second phase is to find a more effective and realistic method of testing for effective dihedral than the current steady heading sideslip method.

4.1 Phase 1 - Iron Bird Evaluation

The aircraft chosen for phase 1 was a mid-size business jet recently certified to FAA Part 25 and European Aviation Safety Agency (EASA) rules. Due to the cost of operation and the fact that the airplane available did not have variable stability capability, the necessary evaluations were conduced on a high fidelity fixed base simulator specifically designed to model the flight controls and handling characteristics of the airplane. The simulator consisted of a mockup of the basic aircraft cockpit controls with force measurement of the roll, pitch, and yaw inputs. The Electronic Flight Instrument System (EFIS) display consisted of a primary flight display (PFD) and multifunction display (MFD). The PFD contained standard attitude, heading, altitude, airspeed, and vertical speed information, as well as a horizontal situational display (HSI) with navigational guidance (not used for test). The MFD contained engine parameters and well as a moving map with a depiction of relative aircraft and airport positions. The flight control system including control cable size and length, pulleys, etc. were identical to those installed on the airplane. Load cells were utilized to simulate control surface forces into the flight control system. Three large 3ft x 3ft flat panel displays placed side by side were used to simulate outside reference.

4.1.1 Iron Bird Set-up

Since stability derivatives of an airplane vary with aircraft configuration and flight conditions, the simulator derivatives were in the form of look-up tables. Therefore it was not possible to change the derivatives directly without a great deal of effort. However, a simple multiplier was input into the simulation program that allowed modification of the desired stability derivatives. By changing this multiplier, the specific stability derivative could be altered by any desired factor, including zero.

Earlier studies have shown the strong effect of dutch roll damping on the pilot's perception of effective dihedral effect. However, conducting an experiment over a broad range of dutch roll damping and effective dihedral would require a significant test matrix and a large investment of time and effort. The primary area of interest is effective dihedral, not dutch roll damping. The desire is to confirm that a negative effective dihedral of small magnitude is acceptable or even unnoticeable to the pilot. The accomplish this, all that is necessary is to show a consistent CH ratings for effective dihedrals ranging from positive to negative, or at least a small change in CH ratings through this range.

In order to accomplish this, the dutch roll damping was held relatively constant while varying dihedral effect, or Cl_{β}. This was done using trail and error. Initial tests showed that the dutch roll damping of the basic airplane, although certified, was undesirable. It was felt that the poor damping would negatively affect the pilot ratings. Therefore the damping derivative (Cn_r) of the baseline airplane was doubled.

By experimentation in the simulator, it was found that setting Cl_{β} to zero resulted in a strongly negative effective dihedral. This was likely due to other factors that contribute to effective dihedral as discussed in Chapter 2, such as $Cl_{\delta r}$. The desire was to evaluate three aircraft configurations: (1) baseline (with improved dutch roll damping), (2) neutral effective dihedral, and (3) slight to moderately negative effective dihedral. The multipliers for Cn_r and Cl_{β} for these conditions are shown in table 1. Since a decrease in dihedral effect increases dutch roll damping, the damping was restored to original for conditions 2 and 3. The dutch roll damping was found to be identical in the 3 conditions by measuring the time and cycles to decay following a rudder doublet input.

TABLE 1

SIMULATOR STABILITY DERIVATIVE MULTIPLIERS

Configuration	Cn_r multiplier	Cl_{β} multiplier
1	2.0	1.0
2	1.0	0.3
3	1.0	0.0

4.1.2 Test Profile

Five experienced pilots were chosen to participate in the evaluation. Four of these were experienced engineering test pilots each with 10 to 25 years of experience testing military aircraft or certifying Part 23 and Part 25 aircraft. The fifth pilot was an experienced business jet pilot. Four of the five pilots had over 2000 hours flying Part 25 business jets. Each of these pilots had experience in the particular type of airplane being simulated. This was important in order to minimize the effect of unfamiliarity with the airplane on the pilot ratings. The airplane being simulated has unusually high roll control forces that could cause bias in the ratings of a pilot who is new to the airplane.

Test pilots were chosen for their familiarity with the Cooper-Harper rating system and their ability to describe what they are experiencing in the cockpit. However, the danger in using test pilots is that, unless strongly instructed otherwise, they tend to conduct their own impromptu evaluations to determine the airplanes handling qualities. This was the case with pilot 1 and his comments reflect this. A non-test pilot was used as a "truth check" comparison with the test pilot's results to determine if any significant differences exist between the two.

Two simple closed loop tasks were chosen for the evaluation (see Appendix C) and were similar to tasks used in the Princeton studies [16, 14]. The first was a normal takeoff followed by a typical landing pattern to a full stop on the departure runway. Approximately 75 feet above the ground, a side-step[3] maneuver was accomplished to the parallel runway (actually a taxiway) for touchdown. The simulation ended upon touchdown due to limitations of the simulator ground model. A constant fifteen knot direct (90°) left-hand crosswind was simulated for all runs.

Turbulence was not simulated. Due to difficulties with the simulation ground model, the evaluation for pilot's 3, 4, and 5 began already airborne off the departure end of the runway. This was considered acceptable since each of the five pilots was instructed to ignore the ground handling characteristics of the simulation, including takeoff and landing.

The second task was similar to the first with the exception of being flown with one engine inoperative and the side-step maneuver was omitted. The two tasks were completed sequentially

[3] A side-step is a moderately aggressive maneuver during which the pilot re-aligns the airplane on a course parallel with the initial course, or in this case, alignment with a different parallel runway.

for a particular stability condition. The stability derivative multiplier was changed, then the task repeated. This was accomplished for all three stability conditions. Each evaluation was video taped for later review and pilot comments were hand recorded. Pilot comments are found in Appendix C. Pilot rating using the Cooper-Harper scale for each task was plotted against the condition being flown (Figures A-11 and A-12).

4.1.3 Test Results

Although the average pilot rating for each task varies among pilots, the point of interest is the variation for each pilot for the range of conditions (or effective dihedral). Task 1 results in Figure A-11 indicate that 4 out of 5 pilots gave the negative effective dihedral configuration a more favorable rating than the baseline airplane. Even the pilot who rated this configuration lower only gave it a slightly lower rating than the baseline. The argument could be made that the baseline airplane has poor handling qualities and this accounts for the lower ratings. However, the point is that the baseline airplane is certificable, the airplane in condition 3 is not, due to the negative effective dihedral. Also as mentioned earlier, the only difference between conditions 1 and 3 is the amount of effective dihedral.

Results from Task 2 were slightly different than those from Task 1. However, the evidence is still clear that negative effective dihedral has little effect on pilot rating, within reasonable limits. Figure A-12 shows that the majority of pilots actually rated neutral effective dihedral more favorably than the baseline or negative effective dihedral for this task. One pilot rated negative effective dihedral the most favorable of the conditions, only one rated it as the least favorable. The remaining two pilots rated it equal to the baseline.

It's important to recognize that CH ratings vary even for the same pilot for different tasks. Therefore a rating difference of plus or minus half a point is not significant. What is significant is that large variations in effective dihedral do not have a significant effect on pilot handling qualities ratings. This is consistent with findings from earlier studies previously mentioned.

4.2 Phase 2 - Flight Evaluation

Interviews with test pilots who participated in the initial development and certification of the aircraft simulated in phase 1 indicated that the airplane initially did not pass the steady heading sideslip stability requirement of FAR Part 25. However, even in this initial condition it was possible to control the aircraft with the use of rudder alone in the same configurations that failed the SHSS test. This was likely due to the issues specified previously with the SHSS test. This evidence, however, is anecdotal. Actual flight test data would be more useful and was thus obtained.

It appears that a more appropriate test for effective dihedral is to simply use the rudder to bank the airplane left and right in the configuration in question. This eliminates any detrimental effects of fuel migration and takes advantage of such aerodynamic effects such as Cl_r. In order to validate this conclusion, another small business jet currently in development was used. This jet, although small, exhibits similar stability characteristics as the larger jet. The basic aircraft has negative effective stability in most configurations, an example of which is shown by the steady heading sideslip test in Figure A-13. The test aircraft was trimmed for level flight at approximately 114 KCAS and 7344 ft. MSL with gear and flaps retracted. A positive angle of roll (AOR1) is established at 9.53°. The rudder (RUDPS) is held constant at 15° for an angle of sideslip (AOSS) of approximately 8°. At this point, the aileron force (ALFOR1) is released, yet the angle of roll continues to increase over 12° within 5 seconds, exhibiting negative effective dihedral.

Immediately after performing this SHSS test, the test pilot then established a wings level attitude at the same speed and configuration. Using rudder only, the pilot was able to control the bank angle of the aircraft both left and right and return to a wings-level attitude as shown in the second half of Figure A-13. Notice at time 08:19:22, a positive (left) rudder deflection (RUDPS - trace 3) of approximately 10° is input. The angle of roll (AOR1) reverses from positive (right wing down) 12.39° to negative (left wing down) 21.08°. At approximately 08:19:30, a negative (right) rudder deflection of approximately 12° is made, causing the airplane to roll back in the positive direction. Therefore, adequate control is shown using rudder alone, even though the traditional steady heading sideslip test is failed.

This same aircraft has been flown for over two hundred hours and landed in crosswinds up to 15 knots with no negative comments from the flight crews in terms of handling qualities. Quite the contrary, each of the ten to twelve pilots who have flown the airplane have commented positively on the airplane's pleasant handling qualities in all configurations throughout the entire flight envelope, from stalling speed up to the maximum dive speeds (V_D/M_D) required for certification. Figures A-14 and A-15 show the landing characteristics during in a crosswind. Figure A-14 shows a landing in gusty conditions with 7 to

13 knots of crosswind from the left. Notice aileron force (ALFOR1) is predominately negative (left) during the landing while rudder force (RUDFOR1) and position (RUDPOS) are nearly centered. The black squat switch bars at the bottom of the plot indicate touchdown. Figure A-15 shows another crosswind landing in approximately 16 knots of wind, again from the left. Immediately prior to touchdown, the left wing is lowered approximately 6° and the rudder is deflected to the right approximately 7° in the traditional low-wing style of crosswind landings. The squat switch bars indicate the left main making contact prior to the right main, as expected. Both of these landings exhibit satisfactory handling characteristics, as further attested by pilot comments. Nevertheless, the airplane also fails the SHSS test in the landing configuration.

CHAPTER 5

DISCUSSION

5.1 Conclusion

The predominant opinion accepted over the years concerning effective dihedral is that it should be positive, but light. There is little argument that this would be optimal, provided other handling qualities are equally acceptable. However, aircraft design is far from an exact science and handling qualities throughout the entire flight envelope are seldom optimal, especially with mechanical flight controls. It has been shown that negative effective dihedral is acceptable and at times even preferred over neutral or positive effective dihedral. The difficulty is "how much is good enough?"

Even the earliest handling qualities studies by Zimmerman [8], Liddell [10], and Kauffman [11] indicate that negative effective dihedral is acceptable, but with few exceptions this view has not been incorporated into handling qualities criteria. This was likely due to the difficulty in specifying an acceptable level of negative dihedral. It is simple to say effective dihedral must be positive and leave it to the design engineers to comply. But as shown previously, this can place an unnecessary burden on the airplane design and cost the manufacturer significant time and money should the design engineer miss the mark.

Nevertheless, a criterion is necessary, as well as an appropriate method to test the airplane for compliance to that criterion. As previously shown, the currently accepted method of the steady heading sideslip, though used for many years, is not the optimal method and incurs such secondary effects as fuel migration. A more appropriate method is to simply trim the airplane in the desired configuration and show, with ailerons free, that the airplane can be banked left and right using rudder alone. The bank angle necessary should depend upon the safety analysis of the airplane. If the effective dihedral is to provide redundancy for the primary roll control, then a bank angle of at least 10 degrees should be possible in each direction without re-trimming the aircraft. If redundancy is provided by another means, then effective dihedral should not be required provided normal piloting tasks (such as crosswind landings) are not compromised. The desire is simply to demonstrate that with rudder input, the aircraft tends to roll in the direction of the input. It need not be sustained and the amount of rudder required should simply remain within the already established force limits for rudder control (FAR 23.143 or 25.143) or the rudder travel limits, whichever is reached first.

The acceptance criteria should be limited to specific areas of the flight envelope. The commonly used "*Aerodynamics for Naval Aviators*" states that "…the effective dihedral should not be negative during the predominating conditions of flight, e.g., cruise, high speed, etc." But exceptions can be made in the takeoff and landing phase of flight due the destabilizing effects of gear, flaps and power [23]. However, this position is likely due to the fact that most Naval aircraft are operated on and off aircraft carriers where cross winds are practically non-existent. Furthermore, for combat aircraft, the use of rudder to aid in turn rate or even as a primary roll control has been common in the past (F-4 Phantom, F-100 Super Sabre, etc). For civilian applications, the primary concern is that the airplane handles the way pilots are accustomed. Per the discussion on crosswind landings, when using the wing down method pilots should not expect to use a great deal of aileron away from the bank angle to maintain the desired flight path. Therefore, effective dihedral should not be negative in the landing configuration, although neutral stability is acceptable. However, it is acceptable if the effective dihedral degrades somewhat during the approach due to fuel migration since the effect will likely be very small and the pilot is not likely to notice the change.

On the other hand, if the civilian aircraft exhibits slightly negative stability in any other configuration other than the landing configuration, there is no impact to safety or handling qualities. Landing is typically the only portion of a normal civilian flight profile where the aircraft is likely to experience a prolonged sideslip. Any other encounter should be due to turbulence, which is short in endurance and is usually most unpleasant due to the dutch roll it excites. And as previously shown, decreasing effective dihedral typically results in increased dutch roll damping. Therefore the ride quality in turbulence should be improved. It may be appropriate to adopt the military criteria of MIL-STD-1797A for the wave-off or go-around conditions which allows negative effective dihedral provided the task performance is not impaired and no than 50% of control power is used and no more than 10lbs for control force is required in the direction opposite for positive stability during a 10 bank. This should be allowed throughout the flight envelope, provided adverse characteristics that degrade task performance are not exhibited. It may be more appropriate to simply require effective dihedral be easily controllable and not detract from the task being accomplished.

5.2 Recommendations

The current FAR's, both Part 23 and Part 25 should be revised to state that effective dihedral may not be negative (neutral is acceptable) in the landing configuration (normal or abnormal). All reference to steady heading sideslip should be deleted. AC25-7B and AC23-8A should be revised to add the rudder turn method for effective dihedral, when required. The steady heading sideslip method should remain as an optional method. The turn method is that which was described earlier in which the rudders are used to bank the aircraft left and right then back to wings level in succession. The AC's should also specify the 10° minimum bank angle when used for redundant roll control. And if not required for redundant roll control, the induced bank angle (if any) may not be in the opposite direction of rudder application. For all other configurations, any dihedral (positive or negative) should be easily controllable. All other handling qualities tasks which could be influenced by effective dihedral, such as directional stability, have their own requirements which will ensure extreme amounts of effective dihedral are avoided and not detrimental to aircraft safety.

Further research could be conducted with variable stability aircraft such as the Navion currently operated by the University of Tennessee and the Learjet operated by Calspan out of Niagara, NY. Tests should be conducted to further validate the hypothesis that slight negative dihedral effect is acceptable throughout the aircraft flight envelope, especially when landing in crosswind conditions. Utilizing both the Navion and Learjet would provide justification for Part 23 and small Part 25 aircraft. Testing should include missions representative of the typical use of small personal and corporate aircraft including extended cross-country flying and operations at heavily trafficked airports. With adequate justification, it may be possible to reduce the FAA certification requirements for static lateral stability to simply state that for all configurations, dihedral effect should be easily controllable. Other requirements for control redundancy are addressed in the application of paragraphs 23.1309 and 25.1309. Other necessary stability and control requirements, including landing in crosswinds, are addressed in existing regulations contained in Part 23 and Part 25.

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APPENDICES

APPENDIX A

FIGURES

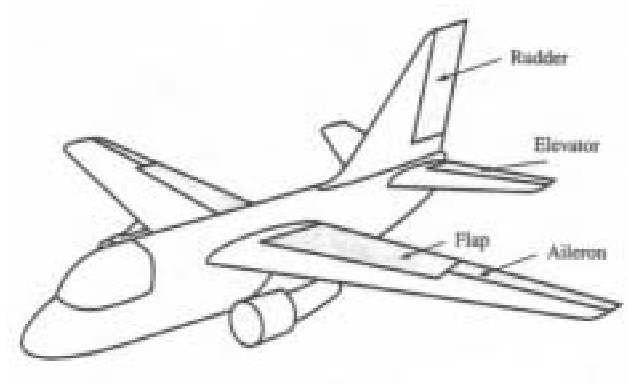

Figure A-1. Normal airplane configuration.

Figure A-2. The Stinson SR-8E.

Figure A-3. Variable Stability F6F-3 [8].

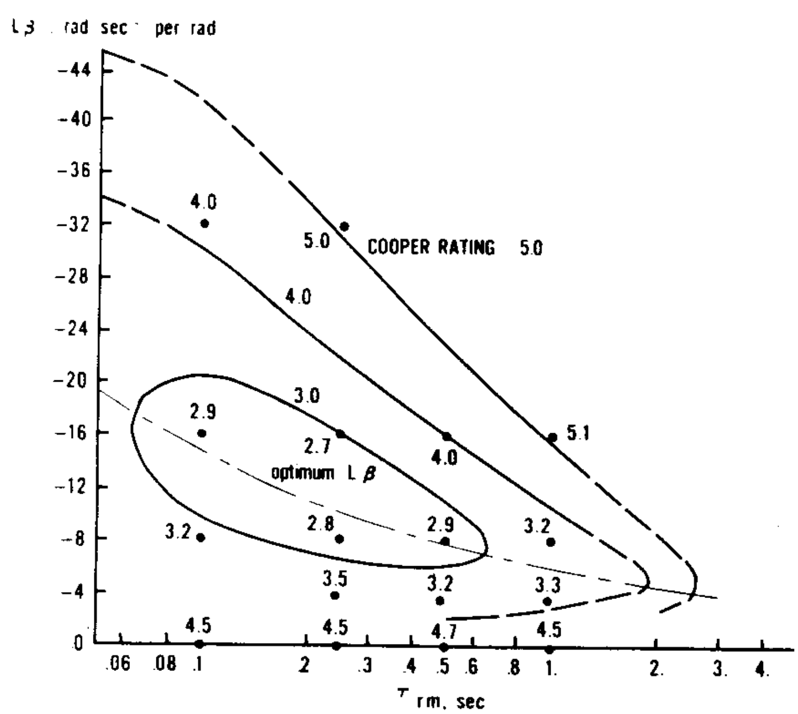

Figure A-4. Pilot Rating Contours for dihedral vs. roll time constant [14].

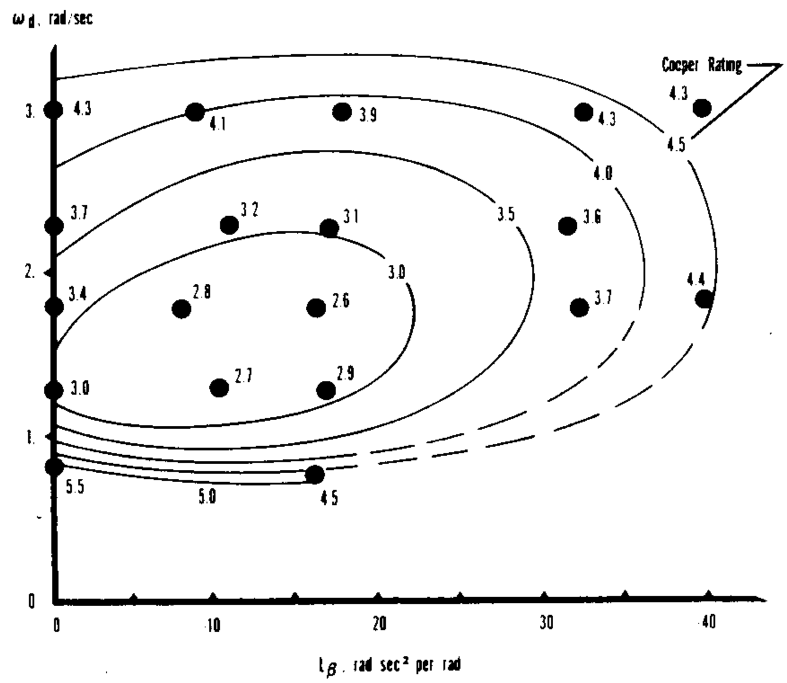

Figure A-5. Pilot Rating Contours for dihedral vs. dutch roll frequency [15].

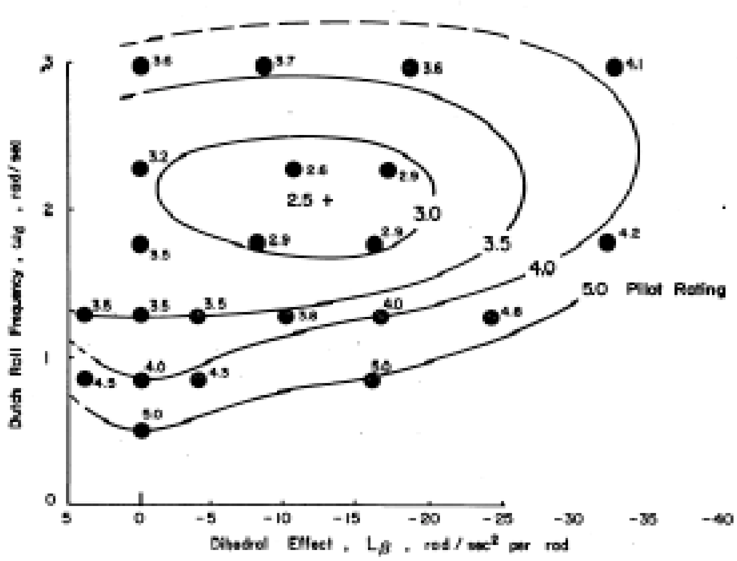

Figure A-6. Pilot Rating Contours for dihedral vs. dutch roll frequency with $\zeta_d = 0.1$ [16].

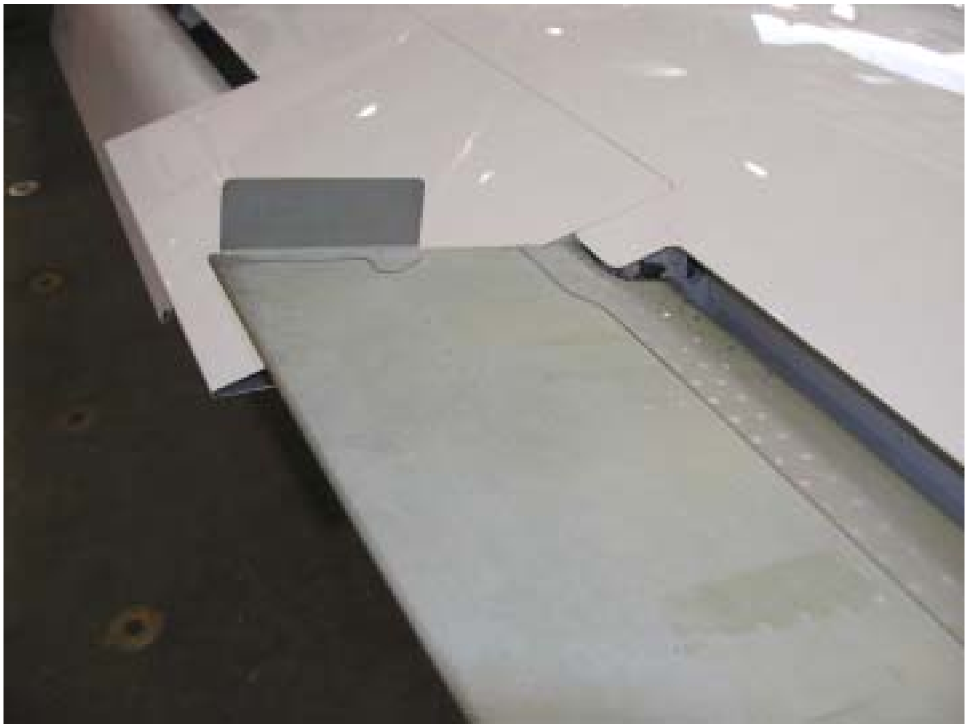

Figure A-7. Citation CJ3 Aileron Fence

Figure A-8. Aileron Tabs installed on Bosbok
(photo courtesy of Mr. Joachim Grenestedt, Lehigh University)

ADJECTIVE RATING	NUMERICAL RATING	DESCRIPTION	PRIMARY MISSION ACCOMPLISHED?	CAN BE LANDED
NORMAL OPERATION — Satisfactory	1	Excellent, includes optimum	Yes	Yes
	2	Good, pleasant to fly	Yes	Yes
	3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
EMERGENCY OPERATION — Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
	5	Unacceptable for normal operation	Doubtful	Yes
	6	Acceptable for emergency condition only*	Doubtful	Yes
NO OPERATION — Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
	8	Unacceptable - dangerous	No	No
	9	Unacceptable - uncontrollable	No	No
Unprintable	10	X!@#*!! Did not get back to report	What mission?	

*(Failure of a stability augmenter)

Figure A-9. Cooper Opinion Scale [33].

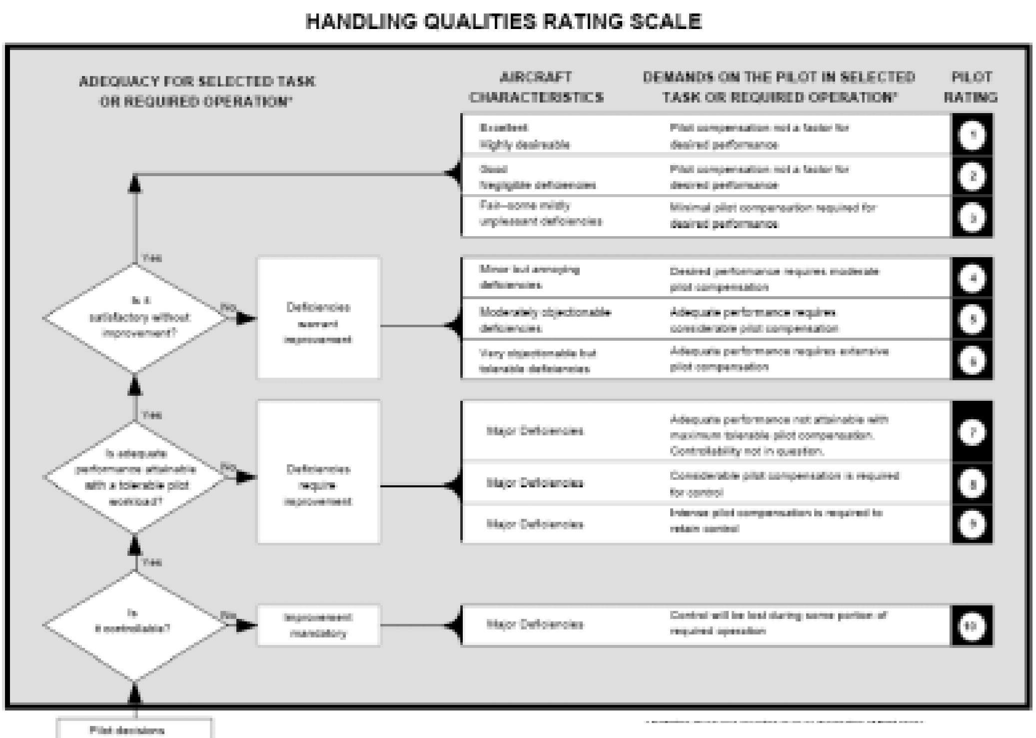

Figure A-10. Cooper-Harper rating scale [5].

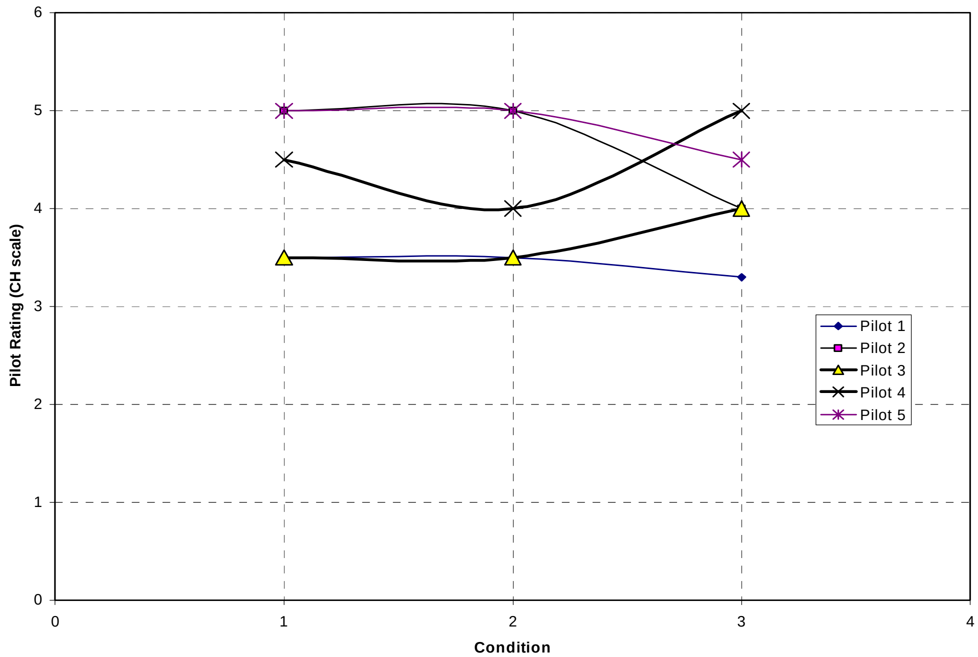

Figure A-11. Pilot rating (Cooper-Harper scale) for Task 1.

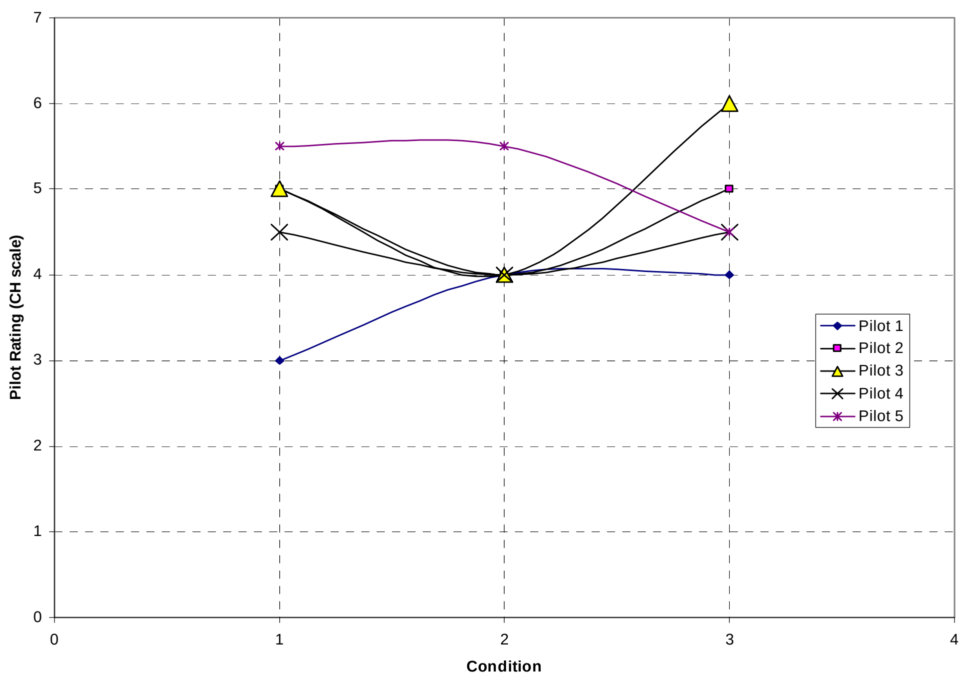

Figure A-12. Pilot rating (Cooper-Harper scale) for Task 2.

APPENDIX A (continued)

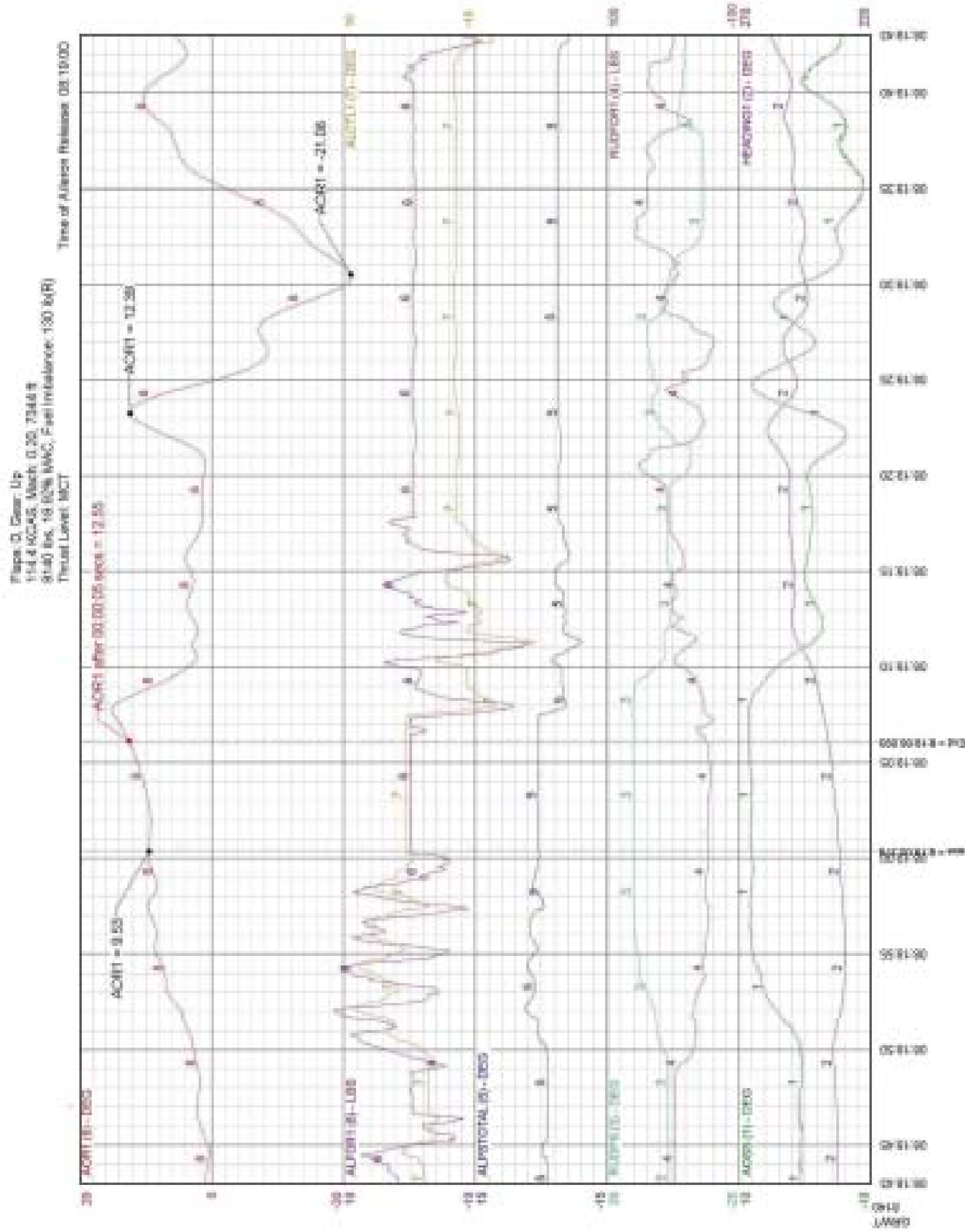

Figure A-13. Steady heading sideslip and rudder turn comparison data plot.

APPENDIX A (continued)

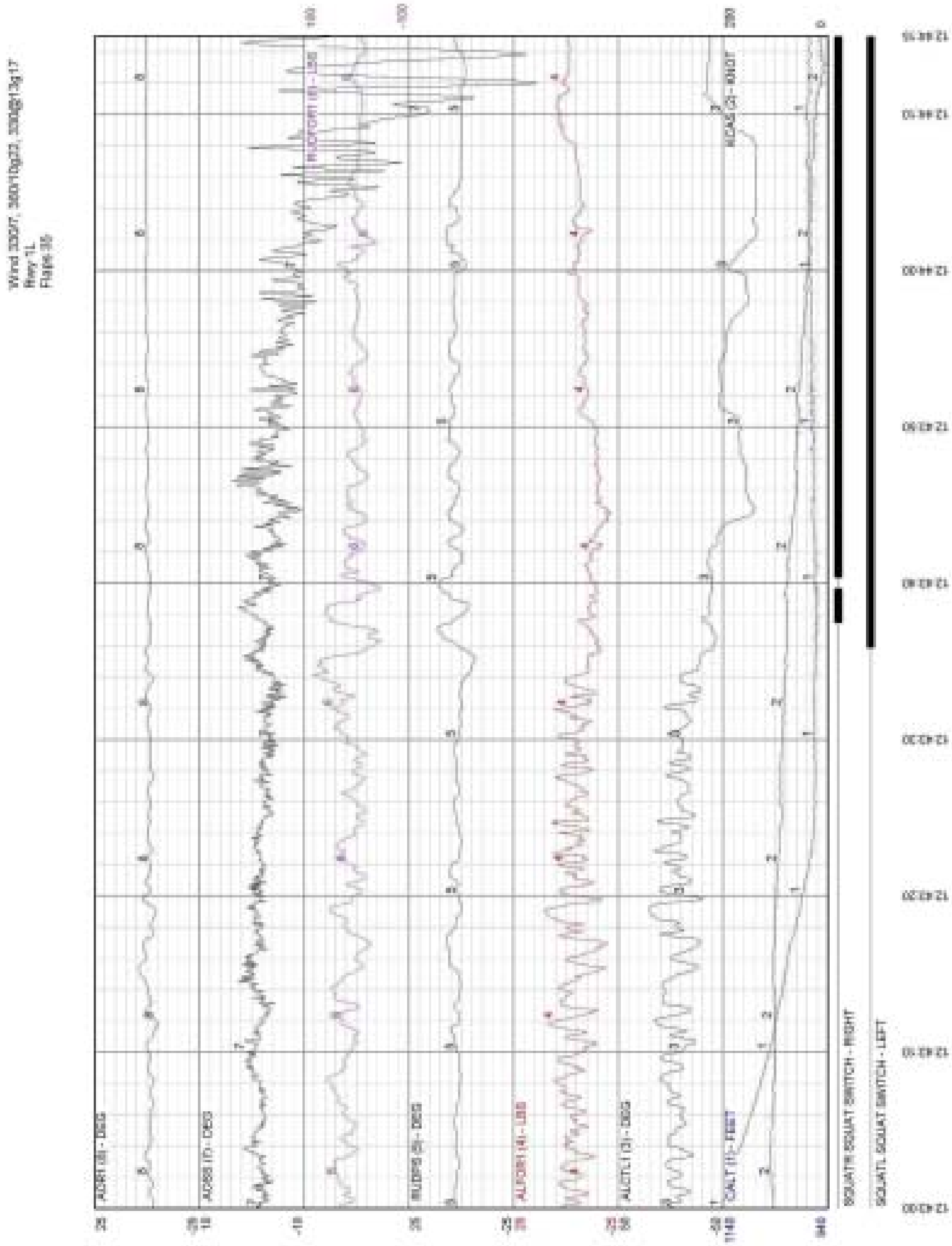

Figure A-14. Crosswind landing data trace.

APPENDIX A (continued)

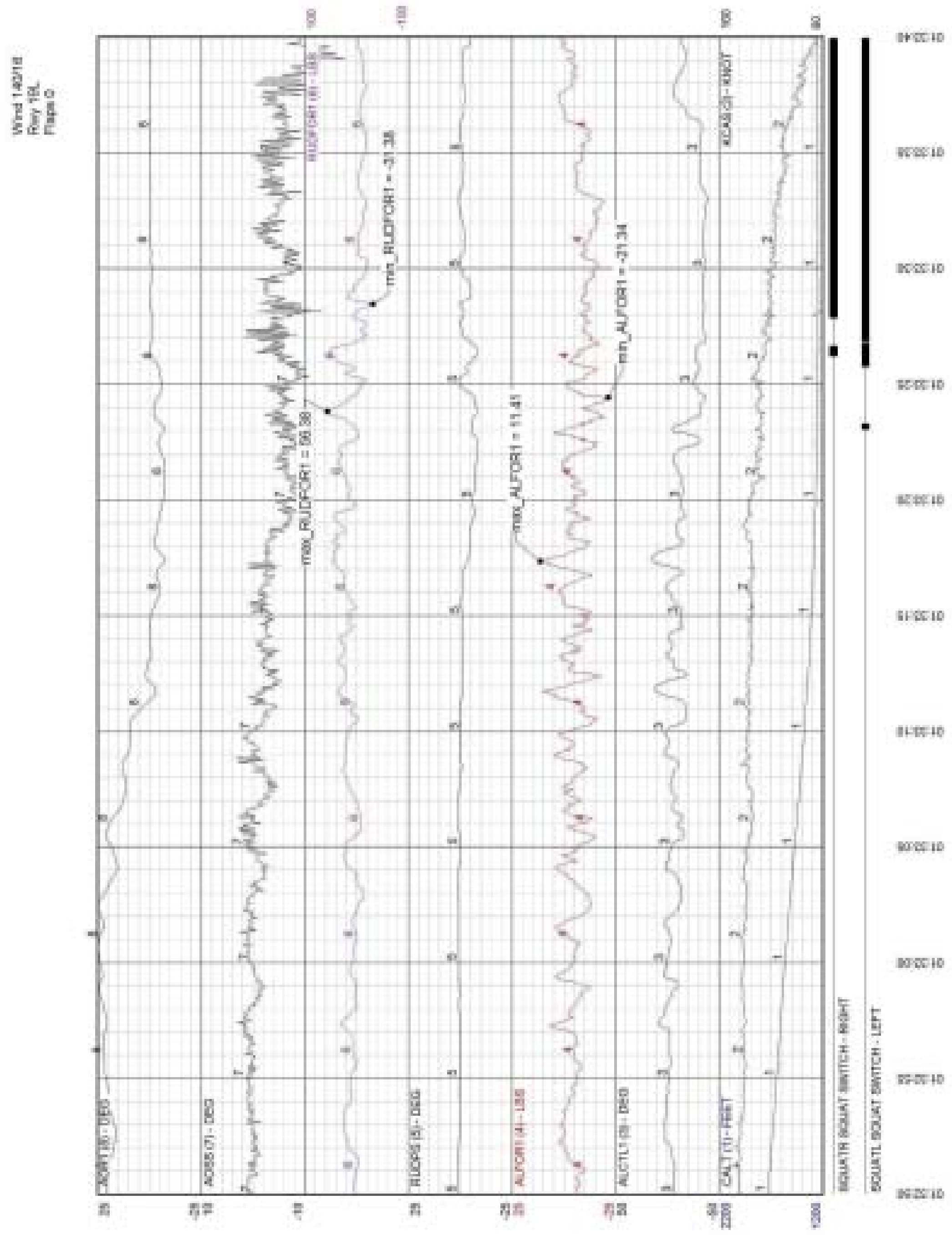

Figure A-15. Crosswind landing data trace.

APPENDIX B

COOPER-HARPER RATING SCALE

The modern Cooper-Harper scale is a rating method for pilots to quantify their opinions concerning the flying qualities of a particular aircraft. The rating system was initially created by George Cooper following extensive research at NACA's Ames Aeronautical Laboratory at Moffett Field, California. Initially published in 1957, the Cooper Pilot Opinion Rating Scale was created to give engineers and designers a method to quantify the pilot's judgment of an aircraft's handling qualities in a fashion that could be used in the stability and control design process. The system was eventually modified in collaboration with Robert Harper of the Cornell Aeronautical Laboratory to become the Cooper Harper Handling Qualities Rating Scale., published in 1969 [40].

This scale has seen widespread use throughout the aviation community worldwide. It is taught in test pilot schools and often found in civilian flight test organizations as well. Although originally designed as a tool for rating aircraft, it was evolved into a subjective method to evaluate the human interaction with a given system. As such it can be used in any application where the human interface is a concern.

The first step of this process of rating the handling qualities of an aircraft begins with the identification of the specific factor which is to be evaluated and the task or maneuver on which this task can best be evaluated. For example, the factor evaluated in this paper was effective dihedral. The tasks used to evaluate this factor were the landing pattern maneuvers identified in Appendix D. Ideally, the pilot works with the engineer to identify these factors and design the appropriate tasks for the evaluations.

The next step in the process is the collection of the pilot's feedback during and after the task execution. In order to do this, the pilot is guided through a series of simple questions (Figure 10), beginning with the most basic: "Is it controllable?" Assuming an affirmative answer, the next question asks if adequate performance is attainable. If so, then is the factor satisfactory without improvement? Depending upon the answers to these question, pilots are asked to rate the degree of deficiency, if any, and provide any additional feedback pertinent to the evaluation.

APPENDIX B (continued)

The final step of analyzing of the data, including the pilot's actual performance. It is important to consider the pilot's background in interpreting the result [25]. A pilot accustomed to very heavy control forces will tend to rate an aircraft with heavy control forces more favorably than a pilot experienced in aircraft with lighter control forces. Initial impressions can be most accurate due to the tendency of pilots to compensate for inadequacies over a period of time. A pilot's experience level is often reflected in the ratings. An inexperienced or less capable pilot may rate a task less favorable do this his own lack of skill in performing that task. On the other hand, he may assign a higher rating because he doesn't realize that aircraft can be better than those he has flown, which can lead to a higher quality rating. Some pilots believe they can fly anything, which also leads to higher quality ratings. Other experienced pilots may believe themselves to be more skilled than most, and therefore assign lower ratings since if they had difficulty in a task, then the "normal" pilot would certainly find it insurmountable. It is also important to note that the rating only applies to a particular factor in a particular task or mission. Furthermore, pilot ratings of 1 (excellent, highly desirable) are rare and a great number of aircraft have enjoyed long careers with some aircraft characteristics which would certainly be rated by most pilots as falling between 4 and 6, or worse.

APPENDIX C

UNITED STATES CIVIL AVIATION REGULATION HISTORY

TABLE 2

FAA HISTORY
(Aircraft Certification Perspective)

YEAR	RULES	REGULATING AGENCY
1926	Aeronautical Bulletin No. 7, basic rule.	Depart of Commerce (Aeronautics Department)
1928	Aeronautical Bulletin No. 14, Airplane Structures, Engines and Propellers; Aeronautical Bulletin No. 7A, Airframe.	
1931	Aeronautical Bulletin No. 7G, Engines and Propellers.	
1933	Aeronautical Bulletin No. 7F, Airworthiness Requirements for Aircraft Components and Accessories.	
1934	Civil Aviation Regulation.	Bureau of Air Commerce
1937	Airplane Airworthiness CAR 04.	
1938		Civil Aeronautics Administration
1944	CAM 04.	
1945	CAR 03, Small Airplanes.	
1946	CAR 6, Rotorcraft.	
1947	CAR 04a-1, TSO's Adopted.	
1949	CAM 3	
1952	CAR 5, Gliders.	
1955	CAR 10, Export; CAR 7, Transport Rotorcraft.	
1958		Federal Aviation Agency
1965	FAR 21, Certification Procedures; FAR 23, Small Airplane; FAR 25, Transport Airplane; FAR's 27 and 29, Normal and Transport Rotorcraft; FAR's 33 and 35, Engines and Propellers.	
1966		Federal Aviation Administration
Present		

APPENDIX C (continued)

Following are the pertinent sections of U.S. Government regulations concerning static lateral stability beginning with the 1934 Aeronautics Bulletin 7a and ending with the current CFR 14 Part 23.177, amendment 23-50, effective 3/11/96 and CFR 14 Part 25.177, amendment 25-108, effective 12/26/2002.

1.0 Small Aircraft

1.1 Aeronautics Bulletin Amendment 7a, effective October 1, 1934.

"Airworthiness Requirements for Aircraft," Section 74, Flight Tests:

(C) Under all load and power conditions, all airplanes shall be longitudinally, laterally, and directionally stable.

1.2 Civil Air Regulations, Part 3, as amended to November 1, 1949.

§ 3.118 Directional and lateral stability.

(a) Three-control airplanes.

(2) The static lateral stability as shown by the tendency to raise the low wing in a sideslip, for all flap positions and symmetrical power conditions, shall:

(i) Be positive at the maximum permissible speed.

(ii) Not be negative at a speed equal to 1.2 Vs1.

(3) In straight steady sideslips (unaccelerated forward slips), the aileron and rudder control movements and forces shall increase steadily, but not necessarily in constant proportion, as the angle of sideslip is increased; the rate of increase of the movements and forces shall lie between satisfactory limits up to sideslip angles considered appropriate to the operation of the type. At greater angles, up to that at which the full rudder control is employed or a rudder pedal force of 150 pounds is obtained, the rudder pedal forces shall not reverse and increased rudder deflection shall produce increased angles of sideslip. Sufficient bank shall accompany sideslipping to indicate adequately any departure from steady unyawed flight.

1.3 Federal Aviation Regulation, Part 23, effective February 1, 1965.

Sec. 23.177 Static directional and lateral stability.

(a) Three-control airplanes. The stability requirements for three-control airplanes are as follows:

(2) The static lateral stability, as shown by the tendency to raise the low wing in a slip, must be positive for any landing gear and flap positions. This must be shown with symmetrical power up to 75 percent of maximum continuous power at speeds above 1.2Vs1, up to the maximum allowable speed for the configuration being investigated. The static lateral stability may not be negative at 1.2Vs1 . The angle of slip for these tests must be appropriate to the type of airplane, but in no case may the slip angle be less than that obtainable with 10 degrees of bank.

1.4 Federal Aviation Regulation, Part 23, Amendment 23-21, effective March 1, 1978.

Sec. 23.177 Static directional and lateral stability.

(a) Three-control airplanes. The stability requirements for three-control airplanes are as follows:

(2) The static lateral stability, as shown by the tendency to raise the low wing in a slip, must be positive for any landing gear and flap positions. This must be shown with symmetrical power up to 75 percent of maximum continuous power at speeds above 1.2Vs1, up to the maximum allowable speed for the configuration being investigated. The static lateral stability may not be negative at 1.2Vs1 . The angle of slip for these tests must be appropriate to the type of airplane, but in no case may the slip angle be less than that obtainable with 10° of bank.

1.5 Federal Aviation Regulation, Part 23, Amendment 23-45, effective September 7, 1993.

Sec. 23.177 Static directional and lateral stability.

(a) Three-control airplanes. The stability requirements for three-control airplanes are as follows:

(2) The static lateral stability, as shown by the tendency to raise the low wing in a sideslip, must be positive for any landing gear and flap position. This must be shown with symmetrical power, up to 75 percent of maximum continuous power, at speeds above 1.2Vs1in the takeoff configuration and 1.3Vs1 in other configurations, up to the maximum allowable speed for the configuration being investigated in the takeoff, climb, approach, and cruise configurations. For the landing configuration, the power must be up to that necessary to maintain a three degree angle of descent in coordinated flight. The angle of bank for these tests must be appropriate to the type of airplane, but in no case may the constant heading sideslip angle be less than that obtainable with 10° bank, or, if less, the maximum bank angle obtainable with full rudder deflection or 150 pounds rudder force. The static lateral stability may not be negative at 1.2Vs1 .

1.6 Federal Aviation Regulation, Part 23, Amendment 23-50, effective March 11, 1996.

Sec. 23.177 Static directional and lateral stability.

(b) The static lateral stability, as shown by the tendency to raise the low wing in a sideslip, must be positive for all landing gear and flap positions. This must be shown with symmetrical power up to 75 percent of maximum continuous power at speeds above 1.2Vs1 in the takeoff configuration(s) and at speeds above 1.3Vs in other configurations, up to the maximum allowable speed for the configuration being investigated, in the takeoff, climb, cruise, and approach configurations. For the landing configuration, the power must be that necessary to maintain a 3 degree angle of descent in coordinated flight. The static lateral stability must not be negative at 1.2 in the takeoff configuration, or at 1.3 in other configurations. The angle of sideslip for these tests must be appropriate to the type of airplane, but in no case may the constant heading sideslip angle be less than that obtainable with a 10 degree bank, or if less, the maximum bank angle obtainable with full rudder deflection or 150 pound rudder force.

(c) Paragraph (b) of this section does not apply to acrobatic category airplanes certificated for inverted flight.

Sec. 23.147 Directional and lateral control

c) For all airplanes, it must be shown that the airplane is safely controllable without the use of the primary lateral control system in any all-engine configuration(s) and at any speed or altitude within the approved operating envelope. It must also be shown that the airplane's flight characteristics are not impaired below a level needed to permit continued safe flight and the ability to maintain attitudes suitable for a controlled landing without exceeding the operational and structural limitations of the airplane. If a single failure of any one connecting or transmitting link in the lateral control system would also cause the loss of additional control system(s), compliance with the above requirement must be shown with those additional systems also assumed to be inoperative.

APPENDIX C (continued)

2.0 Transport Category Aircraft

2.1 Aeronautics Bulletin Amendment 7a, effective October 1, 1934.
"Airworthiness Requirements for Aircraft," Section 74, Flight Tests:

> (C) Under all load and power conditions, all airplanes shall be longitudinally, laterally, and directionally stable.

2.2 Civil Air Regulations, Part4, effective November 1, 1937
§4.705 Stability.
Under all power conditions all airplanes shall be longitudinally, laterally, and directionally stable. An airplane will be considered to be longitudinally stable if, in stability tests, the amplitude of the oscillations decreases.

2.3 Civil Air Regulations, Part 4b, effective December 31, 1953.
§4b.150 General.
The airplane shall be longitudinally, directionally, and laterally stable in accordance with §§ 4b.151 through 4b.157. Suitable stability and control "feel" (static stability) shall be required in other conditions normally encountered in service if flight tests show such stability to be necessary for safe operation.

§4b.157 Static Directional and Lateral Stability.

> (b) The static lateral stability, as shown by the tendency to raise the low wing in a sideslip with the aileron controls free and with all landing gear and flap positions and symmetrical power conditions, shall:
>
> > (1) Be positive at the operating limit speed,
> > (2) Not be negative at a speed equal to 1.2 V_{S1}.
>
> (c) In straight steady sideslips (unaccelerated forward slips) the aileron and rudder control movements and forces shall be substantially proportional to the angle of sideslip, and the factor of proportionality shall lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles up to that at which the full rudder control is employed or a rudder pedal force of 180 pounds is obtained, the rudder pedal forces shall not reverse, and increased rudder deflection shall produce increased angles of sideslip. Sufficient bank shall accompany sideslipping to indicate clearly any departure from steady unyawed flight, unless a yaw indicator is provided.

2.4 Federal Aviation Regulation, Part 25, effective February 1, 1965.
Sec. 25.177 Static lateral-directional stability.

> (b) The static lateral stability (as shown by the tendency to raise the low wing in a sideslip with the aileron controls free and for any landing gear and flap position and symmetrical power condition) must be positive at V_{FE}, V_{LE}, or V_{FC}/M_{FC} (as appropriate) and may not be negative at $1.2V_{S1}$.
>
> (c) In straight, steady, sideslips (unaccelerated forward slips) the aileron and rudder control movements and forces must be substantially proportional to the angle of sideslip, and the factor of proportionality must lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles, up to the angle at which full rudder control is used or a rudder pedal force of 180 pounds is obtained, the rudder pedal forces may not reverse and increased rudder deflection must produce increased angles of sideslip. Unless the airplane has a yaw indicator, there must be enough bank accompanying sideslipping to clearly indicate any departure from steady unyawed flight.

2.5 Federal Aviation Regulation, Part 25 , Amendment 25-42, effective March 1, 1978.

Sec. 25.177 Static lateral-directional stability

(b) The static lateral stability (as shown by the tendency to raise the low wing in a sideslip with the aileron controls free and for any landing gear and flap position and symmetrical power condition) may not be negative at any airspeed (except speeds higher than V_{FE} or V_{LE}, when appropriate) in the following airspeed ranges:

(1) From 1.2 V_S to V_{MO} / M_{MO}.

(2) From V_{MO} / M_{MO} to V_{FC} / M_{FC} unless the Administrator finds that the divergence is--

(i) Gradual;

(ii) Easily recognizable by the pilot; and

(iii) Easily controllable by the pilot.]

(c) In straight, steady, sideslips (unaccelerated forward slips) the aileron and rudder control movements and forces must be substantially proportional to the angle of sideslip, and the factor of proportionality must lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles, up to the angle at which full rudder control is used or a rudder pedal force of 180 pounds is obtained, the rudder pedal forces may not reverse and increased rudder deflection must produce increased angles of sideslip. Unless the airplane has a yaw indicator, there must be enough bank accompanying sideslipping to clearly indicate any departure from steady unyawed flight.

2.6 Federal Aviation Regulation, Part 25, Amendment 25-72, effective August 20, 1990.

Sec. 25.177 Static lateral-directional stability.

(c) In straight, steady sideslips, the aileron and rudder control movements and forces must be substantially proportional to the angle of sideslip in a stable sense; and the factor of proportionality must lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles, up to the angle at which full rudder is used or a rudder force of 180 pounds is obtained, the rudder pedal forces may not reverse; and increased rudder deflection must be needed for increased angles of sideslip. Compliance with this paragraph must be demonstrated for all landing gear and flap positions and symmetrical power conditions at speeds from 1.2 V_{S1} to V_{FE}, V_{LE}, or V_{FC}/M_{FC} , as appropriate.

(d) The rudder gradients must meet the requirements of paragraph (c) at speeds between V_{MO}/M_{MO} and V_{FC}/M_{FC} except that the dihedral effect (aileron deflection opposite the corresponding rudder input) may be negative provided the divergence is gradual, easily recognized, and easily controlled by the pilot.

2.7 Federal Aviation Regulation, Part 25, Amendment 25-108, effective December 26, 2002.

Sec. 25.177 Static lateral-directional stability.

(c) In straight, steady sideslips, the aileron and rudder control movements and forces must be substantially proportional to the angle of sideslip in a stable sense; and the factor of proportionality must lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles, up to the angle at which full rudder is used or a rudder force of 180 pounds is obtained, the rudder pedal forces may not reverse; and increased rudder deflection must be needed for increased angles of sideslip. Compliance with this paragraph must be demonstrated for all landing gear and flap positions and symmetrical power conditions at speeds from 1.13 V_{SR1} to V_{FE}, V_{LE}, or V_{FC}/M_{FC} , as appropriate.

(d) The rudder gradients must meet the requirements of paragraph (c) at speeds between V_{MO}/M_{MO} and V_{FC}/M_{FC} except that the dihedral effect (aileron deflection opposite the corresponding rudder input) may be negative provided the divergence is gradual, easily recognized, and easily controlled by the pilot.

APPENDIX D

TEST PROFILE AND DATA

Iron Bird Stability Evaluation Test Conditions

Task 1

1. Initial Point: 130 KIAS, 2300 ft MSL, hdg 013°, 2nm N. of Rwy 1L.
2. Climbing LH turn to heading 280°.
3. Level at 3000 ft MSL, 200 KIAS
4. LH turn to hdg 190°, approximately 2nm downwind leg.
5. LH turn to hdg 100°, slow to 150 KIAS, extend flaps to approach, base leg.
6. LH turn to final, course 013°
7. Extend gear, extend flaps to landing, slow to 120 KIAS
8. Approximately 1/8 nm from Rwy, sidestep to taxiway and land.

Task 2

1. Initial Point: 130 KIAS, 2300 ft MSL, hdg 013°, 2nm N. of Rwy 1L
2. Climbing LH turn to heading 280° - RH engine to cutoff.
3. Level at 3000 ft MSL, 200 KIAS
4. LH turn to hdg 190°, approximately 2nm downwind leg.
5. LH turn to hdg 100°, slow to 150 KIAS, extend flaps to approach, base let.
6. LH turn to final, course 013°.
7. Extend gear, extend flaps to landing, slow to 120 KIAS.
8. SE landing on Rwy 1L.

Notes:

1. 3 levels of static lateral stability (tested in order 1,2,3):
   - 1 - baseline airplane (positive)
   - 2 - neutral
   - 3 - slight negative
2. 15 kt.s crosswind (left) for both tasks
3. All turns target 30° bank
4. ATP performance standards.

APPENDIX D (continued)

Iron Bird Stability Evaluation Data Sheets (blank)

Mustang Iron Bird Evaluation

Pilot: ____________________
Time: ____________
Date: ____________

	Task 1	comments
1	130 kias, 2300 ft	
2	LH turn 280	
3	3000 ft, 200 kias	
4	LH downwind hdg 190	
5	LH base, 150 kias, flaps appr.	
6	LH final	
7	gear down, flaps down, 120 kias	
8	sidestep and land	

Mustang Iron Bird Evaluation

Pilot: ____________________
Time: ____________
Date: ____________

	Task 2	comments
1	130 kias, 2300 ft	
2	LH turn 280, RH engine off	
3	3000 ft, 200 kias	
4	LH downwind hdg 190	
5	LH base, 150 kias, flaps appr.	
6	LH final	
7	gear down, flaps down, 120 kias	
8	SE landing	

APPENDIX D (continued)

Results of Iron Bird Evaluation

Pilot 1. Ralph Rissmiller, August 3, 2005.

Configuration 1 - *baseline airplane (positive).*

Task 1 (CH rating 3.5)

"Heavy in roll. Lots of yaw roll coupling. Heavy in control forces. Smooth around center, less adverse yaw. Annoying deficiency is heavy forces, but harmonized in pitch and roll. CH rating 3.5 mostly due to forces. Very little PIO tendency.

Task 2 (CH rating 3.0)

"No new comments. More roll with engine cut than I remember."

Configuration 2 - *neutral.*

Task 1 (CH rating 3.5)

"No tendency to overshoot or lateral PIO. Quicker response. Lighter rudder gradient, smaller inputs needed. Some adverse yaw, maybe. Tendency to overshoot on sidestep - maybe due to visual cues. Lighter forces, higher rates."

Task 2 (CH rating 4.0)

"Roll tendency to over control greater. Lots of right hand aileron input for left hand turn angle hold. Roll tendency higher single engine than typical aircraft [of this model]. Slower response to roll, maybe. Opposite aileron to stop roll. Tendency to overcontrol. Small corrections are visibly easier [to make]."

Configuration 3 - *slight negative.*

Task 1 (CH rating 3.3)

"Slower responding. Release yoke tends toward level versus other [configuration 2] tends to roll into turn. Rolls opposite yaw input. Largest input to start and stop a roll. Larger than before. Counter intuitive roll and yaw inputs."

Task 2 (CH rating 4.0)

"Hard to hit a roll target. Small lateral PIO tendency. Seems more active directionally. Flat phi/beta ration. Get some oscillation with aggressive roll. Large forces, high rates. CH rating 4 due to opposite roll with rudder input."

Observers Comments:

"Ralph stated that it was noticeable when the aircraft rolled in opposite direction of rudder input in configuration 3. However, he conducted periodic impromptu stability evaluations and therefore "knew the answer" before the test was complete. Subsequent pilot evaluators were coached not to attempt to determine the differences made for each configuration but to just fly normally. My observations from flying with many different pilots in this class of aircraft is that the rudder is seldom used except in crosswind landings and during takeoff. Other times the yaw damped is engaged and the pilots feet are on the floor or lightly resting on the rudder pedals. Ralph also raised concern about nose slice during stalls and what affect negative effective dihedral could have. Stalls are so dynamic and unpredictable and the nose slice is experienced even on airplanes with positive effective dihedral. This is likely not an issue."

APPENDIX D (continued)

Pilot 2. Bob Rice, August 4, 2005.

Configuration 1 - *baseline airplane (positive).*
Task 1 (CH rating 5.0)
"Feels heavy in roll, unresponsive. Tendency to overshoot due to forces and lack of response."
Task 2 (CH rating 5.0)
"Same comments as before."
Configuration 2 - *neutral.*
Task 1 (CH rating 5.0)
"No difference [from previous configuration]."
Task 2 (CH rating 4.0)
"Same as before. Slightly better response to small inputs."
Configuration 3 - *slight negative.*
Task 1 (CH rating 4.0)
"Seems better with small corrections, better response. Easier to correct for crosswind, quicker response."
Task 2 (CH rating 5.0)
"More responsive in roll. Not desired performance despite considerable workload. Subjectively better than condition 1."

Observers Comments:
"Obviously fewer comments from pilot. Smooth on controls, good performance."

Pilot 3. Maurice (Moe) Girard, August 5, 2005.

Configuration 1 - *baseline airplane (positive).*
Task 1 (CH rating 3.5)
"Roll forces moderately high. Too much roll, not enough roll damping. Overly sensitive."
Task 2 (CH rating 5.0)
"Easy to maintain bank at 200 knots, feels solid. Slow speed, very light dutch roll damping. CH rating 5 due to alignment and landing, due to effort to get close to center line. Ended up right of center line."
Configuration 2 - *neutral.*
Task 1 (CH rating 3.5)
"Roll forces lighter, maybe due to low speed. No, roll forces still heavy. No problem hitting bank. Roll forces seem higher. Still dutch roll. Adverse yaw. Easier to control roll and yaw."
Task 2 (CH rating 4.0)
"Still lots of dutch roll. Lightly damped directionally."
Configuration 3 - *slight negative.*
Task 1 (CH rating 4.0)
"Forces appear a little lighter, at speed. Damping seems better but still light [with flaps 15]. Lightly damped, fighting dutch roll a bit. Too aggressive on sideslip. Aircraft responded quicker than expected, moderate to aggressive."
Task 2 (CH rating 6.0)
"Same comments as before at 200 knots. Difficult to maintain centerline on final."

Observers Comments:

"General comment from pilot is that he spends most of his time fighting dutch roll. It was obvious in Configuration 3 (negative effective dihedral) that the pilot fights the tendency of the airplane to roll into the down wing. Pilot repeated configuration 3 sidestep maneuver due to his aggressiveness on first attempt. He used more rudder but had better performance, more in line with configuration 1 and 2 performance. In all configurations, this pilot always needed to apply additional correction - never rolled out exactly on target, but usually overshot target."

Pilot 4. Brad Oblak, August 5, 2005.

Configuration 1 - *baseline airplane (positive).*

Task 1 (CH rating 4.5)

"Adequate, controllable, but needs improvement. Requires considerable compensation. Heavy in Roll. Deadband in Center. Lot of effort for sideslip. Roll damping OK. Slight overshoot tendency. Dutch roll damping adequate. Forces high."

Task 2 (CH rating 4.5)

"Lack of rudder trim aggravates feel. Rudder very effective, helps for roll corrections. Lateral effective but heavy. Some dutch roll but not objectionable. Not significant except aligning with centerline.

Configuration 2 - *neutral.*

Task 1 (CH rating 4.0)

"Seems to be more yaw-roll coupling. Workload tolerable. A little more responsive laterally. Forces still high. Dutch roll a little more noticeable."

Task 2 (CH rating 4.0)

More responsive laterally. Dutch roll a little annoying - residual motion, hunting."

Configuration 3 - *slight negative.*

Task 1 (CH rating 5.0)

"Seems less responsive at high speed, but pretty hot at low speed [in roll]. Got into some roll PIO. I was more aggressive than previous sidesteps. A little too sensitive in pattern. Didn't have much rudder use."

Task 2 (CH rating 4.5)

"Fair amount of compensation laterally. Heavy forces."

Observers Comments:

"Brad leads roll-out much better. Moe tends to start rolling out at the target heading. Brad also concentrates more on performance. In configuration 3, Brad appears to be struggling on short final with roll/yaw control - trying to put wing down into the crosswind."

Pilot 5. David Bodlak, August 11, 2005.

Configuration 1 - *baseline airplane (positive).*

Task 1 (CH rating 5.0)

"Slow to respond in roll. Roll at lower speed felt better."

Task 2 (CH rating 5.5)

"Nothing new. Noticeable challenge with roll. No overshooting. Some bracketing of bank angle, oscillating left and right."

Configuration 2 - *neutral.*

Task 1 (CH rating 5.0)

"Easier to roll around and bank. Feels a little better in roll, especially small angles. Feels better harmonized, a little rudder to start turns seems to work well."

Task 2 (CH rating 5.5)

"Less force needed to roll. Roll rate seems faster. Easy to roll into [failed] engine, hard to roll out."

Configuration 3 - *slight negative.*

Task 1 (CH rating 4.5)

"Tend to overbank, more than other configurations. More challenge holding wings level. Roll rate better. CH rating 4.5 due to better roll rate."

Task 2 (CH rating 4.5)

"Seems like more rudder aileron coupling. Better roll rate."

Observers Comments:

"David is smooth on the controls and attempts to be precise as well. Overshoots headings in configuration 1. Overshoots some in configuration 2 as well, but not as much. Configuration 3 he was more reserved and careful on side step maneuver. Did better hitting heading targets. Dave appeared to struggle trying to use rudder during turns at slow speed in configuration 3, likely because they rudder input was not giving the expected results, but he failed to recognize this."

General Observer Comments:

"The visual display, consisting of 4 side by side flat panel screens, seems to have caused some confusion and may have negatively affected the ratings. The center line of the airplane was not clearly evident when observing the runway on the screens. However, since the visual depiction was the same for all configurations, any affect is inconsequential since the primary concern is the relative ratings between the configurations. Furthermore, the pilots all tended to fly using the EFIS displays until aligning with the runway on final approach.

It is also apparent that the heavy forces, especially in pitch, have some affect on the CH ratings. Another feature of the simulator is the tendency to "balloon" with flap extension. Again, these affects are consistent in all configurations and therefore tend to be inconsequential."