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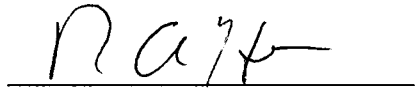
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AN INVESTIGATION OF THE STATIC LONGITUDINAL STABILITY CHARACTERISTICS OF A MD 500E HELICOPTER

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Roger A. Huneycutt

August 1995

DEDICATION

This thesis is dedicated to those members of my family, both here and gone, near and far, who have offered me nothing less than unselfish support, encouragement, and love throughout my academic career. May I be so honored to follow in their footsteps.

ABSTRACT

A MD 500E helicopter, registration number N5144Q, was flight tested to determine its compliance with the FAA's airworthiness criteria for helicopter single-pilot instrument flight. Upon completion of the flight test program, the FAA found questionable results with regard to the helicopter's static longitudinal stability. Specifically, the longitudinal cyclic stick force gradients for certain critical configurations were claimed to be "not perceivable". A review of the flight test results was made and the configurations critical to the helicopter's static longitudinal stability identified. Methods were then examined for improving or assisting the longitudinal cyclic stick force gradients. Modifications to the helicopter's operational envelope and "equivalent levels of safety" findings were considered. The only envelope modification found necessary was a density altitude limitation of 8,000 feet for IFR operations. With this limitation, the static longitudinal stability stick forces have been found to remain greater than the longitudinal cyclic stick friction forces for positive static longitudinal stability results. Furthermore, an equivalent level of safety is believed to be provided by the helicopter's oversized 5-inch ADI and 3-axis autopilot. In the author's opinion, the on–board systems and the recommended IFR operating limitations should alleviate any of the longitudinal cyclic stick force gradient concerns held by the FAA.

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LIST OF SYMBOLS

SYMBOL		DESCRIPTION	UNITS
R		Rotor radius	ft
A	= $\pi * R^2$	Main rotor disk area	ft^2
T		Main rotor thrust	lb
DL	= T/A	Main rotor disk loading	lb/ft^2
V		Forward velocity	ft/s
V_H/V_1		Induced Velocity Ratio	- - -
ρ	= .002378	Sea level density of air	sl/ft^3
q	= $(.5)*\rho*V^2$	Dynamic pressure	lb/ft^2
ε		Downwash angle	deg, rad
ΩR		Tip speed of rotor	ft/s
μ	= $V/\Omega R$	Tip speed ratio	- - -
α		Angle of attack	deg, rad
Θ		Fuselage attitude	deg, rad
i		Incidence	deg, rad
γ		Flight path angle of climb/descent	deg, rad

LIST OF ABBREVIATIONS

AC	Advisory Circular
ADF	Automatic Direction Finder
ADI	Attitude Director Indicator
CDI	Course Deviation Indicator
CFR	Code of Federal Regulations
CG	Center of Gravity
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GPS	Global Positioning System
HSI	Horizontal Situation Indicator
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
KCAS	Knots Calibrated Airspeed
LORAN	Long Range Navigation
MD	McDonnell Douglas
MDHC	McDonnell Douglas Helicopter Company
NOTAR	No Tail Rotor
RNAV	Area Navigation
SAS	Stability Augmentation System
SCAS	Stability and Control Augmentation System
SHP	Shaft Horsepower
STC	Supplemental Type Certificate
TIA	Type Inspection Authorization
VFR	Visual Flight Rules
VHF	Very High Frequency
VTOL	Vertical Takeoff and Landing

1. INTRODUCTION

Upon the completion of the first successful manned flights in powered aircraft by the Wright brothers in December of 1903, the famed inventor Thomas Edison (1847-1931) commented that "no aircraft [can] be considered truly practical until it [can] rise from the ground and settle back again, vertically" [2]. Although not meant to belittle the Wright's accomplishment, this statement probably typifies one aspect of flight man has always desired - the ability to leave and return to the earth using as little space as necessary. By the late 1930's, this capability had arrived in the form of the working helicopter [23].

Unfortunately, this arrival some 30 years after the appearance of the first practical airplane forced the helicopter to evolve in an airspace system and state of mentality geared for fixed-wing flight. Primarily, this has affected the helicopter in its efforts to operate under the instrument flight rules (IFR) of the national airspace system. As an illustration, consider that the Federal Aviation Administration (FAA) did not publish its airworthiness requirements for helicopter instrument flight until 1983 [29]. Although interim requirements existed before this time, the fact that it took until the 1980's to officially recognize the helicopter as a practical IFR aircraft demonstrates some of the bias that has worked against the helicopter since its inception. The helicopter IFR regulations themselves perpetuate this bias in that they share a number of fixed-wing IFR requirements even though the two types of aircraft are fundamentally different. The result has been the need to make the IFR helicopter fly like an airplane which, for most helicopters, has

required the use of expensive stability and control augmentation systems (SCAS) [27]. Combined with typical operating costs that far exceed those for comparable fixed-wing aircraft, a financial disincentive exists for the potential IFR helicopter that has ultimately kept the proliferation of helicopter IFR certifications to a minimum.

In one attempt to alter this course of events, UTSI Flight Research of Tullahoma, Tennessee, acquired a contract to flight test a MD 500E helicopter to determine its compliance with the FAA's airworthiness criteria for helicopter single-pilot instrument flight. The ultimate goal of the contract was to obtain a one-time supplemental type certificate (STC) that would approve the helicopter for single-pilot IFR operations. In the interest of reducing costs, the certification was to be pursued with the helicopter employing only limited stability augmentation about the directional axis (yaw SAS) from an on-board autopilot system. The unaugmented lateral and longitudinal axes thus became an area of primary focus because a failure of either one to meet the regulations would possibly result in the need to incorporate additional costly augmentation. In the sections that follow, an examination of the MD 500E's longitudinal flight characteristics is made with respect to the static longitudinal stability requirement of the federal aviation regulations (FAR) for helicopter instrument flight. A description of the helicopter and the flight tests performed by UTSI are given, followed by the static longitudinal stability flight test results. Determination of compliance with the regulations and the acceptability of the helicopter for IFR flight are then discussed with an emphasis towards minimizing the need for any additional augmentation.

As a technical note, it should be pointed out that the term "static longitudinal stability" as used throughout this thesis (and by the FAA) is actually a reference to longitudinal control force stability which is defined as the level of stick force present with an airspeed displacement from trim. This is quite different from the classical static longitudinal stability definition which concerns the initial (pitch moment) tendency of an aircraft to return to trim after a pitch or angle-of-attack disturbance. However, since pitching moments cannot be measured in free flight, a common method used for gaining an indication of an aircraft's static longitudinal stability is to examine longitudinal control force versus airspeed away from trim - two parameters that are easily measured in flight. This "speed stability" characteristic of an aircraft is a related but secondary effect of static longitudinal stability and is therefore not always an equivalent measure. In fact, there are cases where the "speed stability criterion" are quite misleading with respect to an aircraft's actual pitch stability as reported by Solies [21, 22]. Nevertheless, such an examination is beyond the scope of this thesis and hence only the above clarification is presented. A reminder regarding the usage of this term will be given in a following section.

2. THE MD 500E HELICOPTER

Background

Development History

The McDonnell Douglas MD 500E helicopter has a history that dates back to the early 1960's. Originally designed and built by the Aircraft Division of the Hughes Tool Company, the "Hughes 500" appeared as the result of a 1961 U.S. Army design competition for a light observation helicopter. Hughes' entry into this competition was a single-engine, turbine-powered helicopter called the OH-6A Cayuse. Specific design features of the Cayuse included a fully-articulated four-blade rotor system, two-blade tail rotor, 317 shp Allison 250-C18A turbine engine, and an empennage that utilized a vertical fin, short ventral fin, and upwardly canted horizontal stabilizer opposite the port-mounted tail rotor. The outstanding performance of the helicopter coupled with its ability to carry up to six crew members eventually led Hughes to a victory in the competition, and in 1965 the U.S. Army placed an initial order for 714 OH-6A's [24].

During the spring of 1966, military and civilian pilots publicly demonstrated the performance capabilities of the Cayuse by setting 23 international records over a two month period, including a non-stop straight-line flying distance of 2,213 miles and a maximum closed-course speed of 171.81 mph (149.3 knots). Not surprisingly, the military placed additional orders for the high performance helicopter, pushing the total up to 1,434 units (over twice the original amount) with deliveries to be completed by August

1970. Such strong demand for the OH–6A by the U.S. military inevitably drew interest from foreign governments and the private sector, and in 1968 production began on the Hughes 500 and 500M helicopters for civil and foreign military customers, respectively (Figure 2.1). Although it may seem rather remarkable, the civilian Hughes 500's were actually up-rated versions of the OH–6A. Increased engine power, a higher maximum takeoff weight, and greater fuel capacity were just a few of the improvements made for the Hughes 500 line [24].

Between 1968 and 1982, further improvements and modifications to the Hughes 500 helicopter led to the 500C and 500D versions. The first new version, the Hughes 500C, was produced through 1978 and came with an upgraded engine (the 400 shp Allison 250–C20) and improved hot-and-high performance. Its appearance, though, was virtually unchanged from the original Hughes 500. Remodeling of the helicopter did occur, however, in 1975 with the introduction of the Hughes 500D. Obvious changes included a T–tail empennage with endplate fins for improved forward flight stability and a five-blade main rotor (Figure 2.2). The 500D package also included a more powerful 420 shp Allison 250–C20B engine and numerous performance improvements. Accompanied by the aviation boom of the late 1970's, Hughes sold over 1,000 500D helicopters between 1976 and 1981. Shortly thereafter, in early 1982, the next version of the helicopter - the Hughes 500E - was introduced [25].

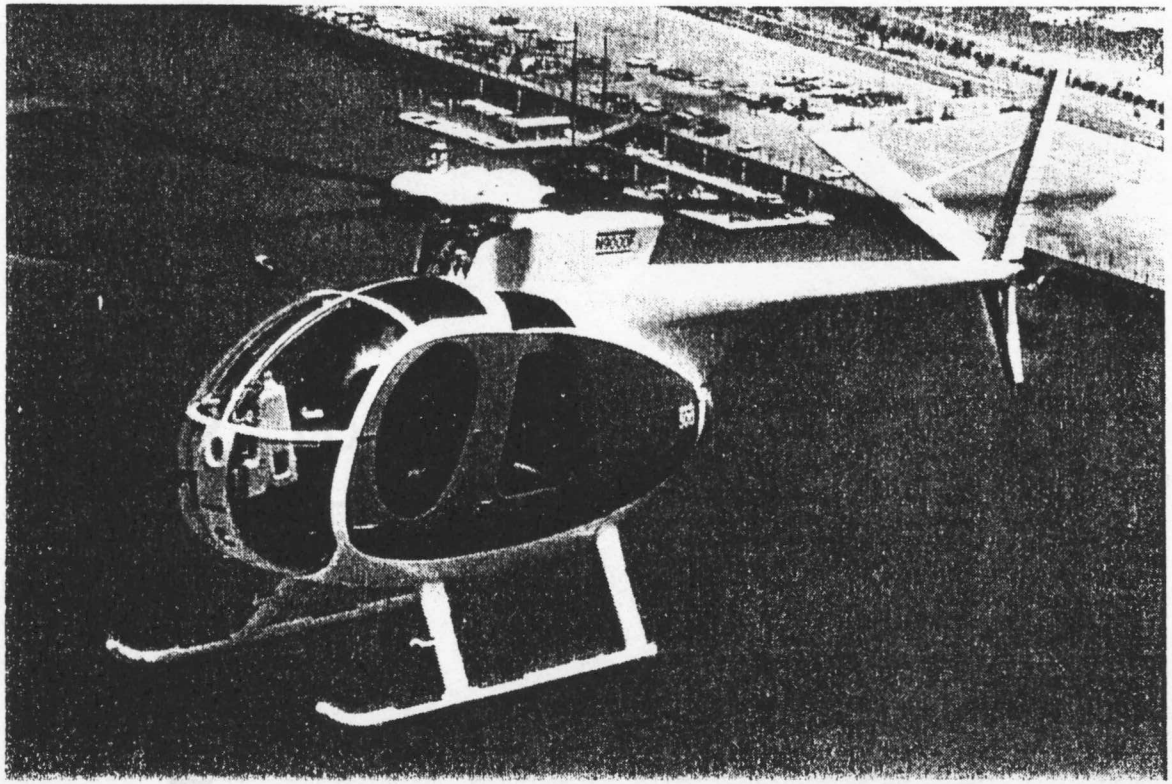


Figure 2.1. Hughes 500 (OH-6A) Helicopter.

Source: Taylor, John W. R., ed. Jane's All The World's Aircraft: 1970 - 1971. New York: McGraw-Hill, 1970.



Figure 2.2. Hughes 500D Helicopter.

Source: Taylor, John W. R., ed. Jane's All The World's Aircraft: 1977 - 1978. New York: Franklin Watts, 1977.

Production History

In late 1982, the Hughes 500D was replaced by the 500E (Model 369E) as the basic U.S. production version (Figure 2.3). Boasting a more streamlined nose, new endplate fins for the horizontal stabilizer, new "T" grouping of flight instruments, and a number of interior refinements including increased passenger leg and head room, the Hughes 500E represented a significant improvement over its predecessors. Production of the model continued for more than a decade with little change in design. In fact, the most notable change witnessed by this model occurred on paper when, in 1984, Hughes Helicopters Inc. became a subsidiary of the McDonnell Douglas Corporation. In 1985, Hughes Helicopters was renamed to McDonnell Douglas Helicopter Company (MDHC) and the Hughes 500E adopted its current "MD 500E" designation [26].

Possibly as a result of the depressed aviation market of the 1980's, sales of the MD 500E never matched those of its predecessor, the Hughes 500D. For instance, six years after its introduction, the MD 500E had managed only 275 sales. By the spring of 1992, only 500 MD 500E helicopters had been sold, marking a milestone that took some ten years to reach. Fortunately, military and specialized derivatives of the 500E were also being produced during this time. The MD 530F Lifter, first sold in 1984, is a specialized derivative of the MD 500E designed to operate at high altitudes and temperatures with the capability to carry external loads of up to 2000 pounds. On the military side, derivatives of both the MD 500E and 530F existed as the 500MG Defender and 530MG Defender, respectively. Altogether, four models shared the 500E airframe and allowed for the



Figure 2.3. Hughes/MD 500E Helicopter (Model 369E).

Source: Taylor, John W. R., ed. Jane's All The World's Aircraft: 1989 - 1990. Alexandria, VA: Jane's Information Group, 1989.

continued success of the MD 500E throughout a decade of moderate sales and stymied growth [13].

Present Status and Future Direction

As of early 1993, over 4,550 MD 500/530 series helicopters, including the OH–6A, had been sold worldwide. Currently, MD 500E helicopters are being produced at the company base in Mesa, Arizona, and in numerous foreign countries by companies such as Kawasaki (Japan), RACA (Argentina), and Agusta (Italy). Options for the 500E include a 450 shp Allison 250–C20R/2 engine, four-blade Quiet Knight tail rotor, and dedicated law enforcement variants. Unfortunately, the 500E was never IFR certified and hence remains a VFR machine to this day. McDonnell Douglas has no plans to pursue IFR certification for the model, either, because the successor to the MD 500E is already flying in a remarkable design that dates back to the days of Hughes Helicopters. Remarkable, because the new version has no tail rotor [13].

During the mid-1970's, Hughes Helicopters had been researching the possibilities of designing a helicopter with a no-tail-rotor (NOTAR) design. In 1980, they received funding from the U.S. Army to build a prototype NOTAR helicopter, and by the last quarter of 1981, a modified OH–6A NOTAR helicopter was in flight test [25]. In 1985, under the ownership of McDonnell Douglas, the OH–6A NOTAR was replaced with a MD 500E NOTAR and the new prototype renewed flight testing through mid-1986. Then, in 1989, McDonnell Douglas officially launched the MD 520N, the NOTAR version of the MD 500E (Figure 2.4). The first flight occurred in May 1990, and by

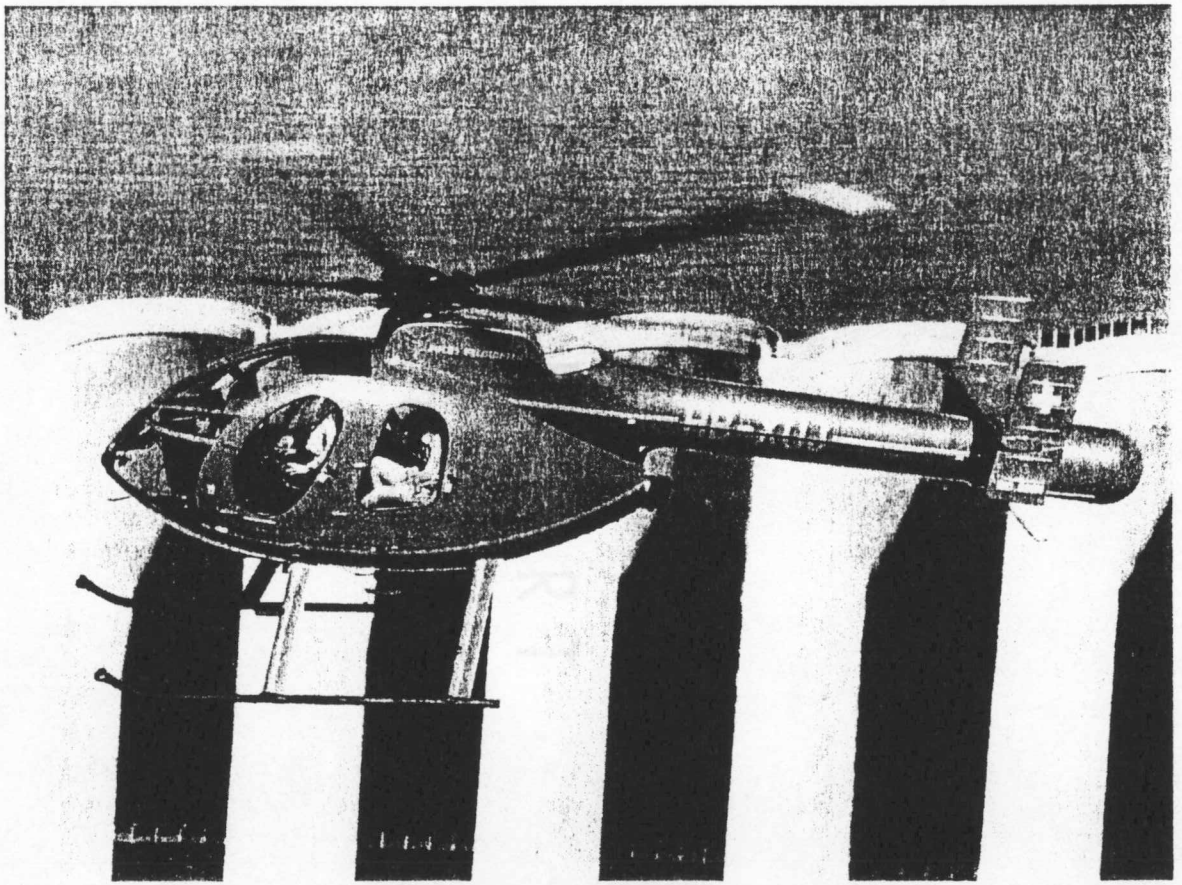


Figure 2.4. MD 520N NOTAR Helicopter.

Source: Lambert, Mark, ed. Jane's All The World's Aircraft: 1993 - 1994. London: Butler and Tanner, 1993.

September 1991 FAA certification had been granted [13].

Out of the 57 MD 500/520/530 series helicopters delivered in 1992, 38 were MD 520N's. This is not surprising considering that the 520N offers more power, quieter operation, a higher operating altitude, greater maximum takeoff weight, and increased safety over the 500E. Additionally, NOTAR system components provide twice the lifespan of conventional tail rotor assemblies, thus offering the owner and operator a significant savings in maintenance costs alone [13]. Facing these advantages, the MD 500E will most likely be replaced by its NOTAR successor on the production line. In fact, McDonnell Douglas may replace all of its helicopters with NOTAR configurations. Already, a six-seat stretched version of the MD 520N (known as the MD 630N) is in flight test, and deliveries of the IFR-certified MD Explorer - an eight-seat twin-engined NOTAR helicopter - are underway. Together, these helicopters cover a broad spectrum of the light helicopter market with NOTAR technology. Undoubtedly, McDonnell Douglas is poised to capitalize upon this investment, unhesitant to replace the MD 500E with the quieter, safer, more cost efficient NOTAR equivalent, the MD 520N [16].

Description

Basic Model

Overview. The MD 500E is a multipurpose, turbine-powered light helicopter with a maximum cruise speed of 135 knots and a service ceiling of 15,000 feet MSL. Capable of transporting up to seven persons, the 500E is more commonly configured for a crew of four with two front seats and two forward facing rear seats. In civilian versions of the 500E, the left front seat is the pilot's seat. Baggage space is available in the cabin behind the rear seats. If desired, the rear seats can be removed and the back of the cabin used as a cargo area. Four doors (two on each side of the fuselage) allow for entry and egress of crew and cargo and can be removed if desired. Transparent tinted acrylic panels make up the cockpit windscreen and windows for the doors, allowing for a generous outside view. Forward of the seats and on the centerline of the aircraft is a T–shaped instrument panel. The horizontal portion of the panel houses various flight instruments, engine instruments, and warning indicators while the vertical portion of the panel is available for radios and circuit breakers. Additional equipment can also be installed in the compartment space located beneath the floorboard of the pilot and front passenger positions [8]. A three-view drawing of the MD 500E, including its external dimensions, is provided in Appendix A as Figure A.1.

Airframe and Powertrain. The MD 500E fuselage is a semi-monocoque structure constructed primarily of aluminum alloy. It has a central framework consisting of a center beam, two bulkheads (one between the front and rear seats, and one between the rear seats and the engine),

and a mast support structure. The mast supports the rotor hub and absorbs the associated lifting loads. Similar to the fuselage, the tailboom is a monocoque structure of aluminum alloy frames and skin. It supports the stabilizers, tail rotor assembly, and tail rotor transmission. As a whole, the fuselage plus tailboom airframe rests on a non-retractable skid-type landing gear that is attached to the fuselage at twelve points (three attachments at each of four strut locations). Nitrogen charged dampers between the struts and the structure provide for cushioned landings and increased ground stability [8].

Housed at the juncture of the fuselage and tailboom is a 420 shp Allison 250–C20B turbine engine or optional 450 shp Allison 250–C20R/2. Clamshell doors forming the lower aft end of the fuselage allow access to the engine and its compartment. Fuel for the power system is drawn from two fuel cells - one on either side of the aircraft centerline beneath the rear-seat floorboards - with a total capacity of 64 gallons. The engine transmits power to the rotors through an overrunning clutch (to allow for autorotation), drive shafts and two transmissions. The main transmission, located above the rear seats, distributes engine power to both of the rotors. The main rotor receives power directly from the main transmission via the main rotor drive shaft. The tail rotor, however, receives power from the main transmission through a tail rotor drive shaft and separate tail rotor transmission. Located at the aft end of the tailboom, it is the tail rotor transmission that directly feeds the tail rotor assembly [8]. Figure A.2 details the helicopter's major components.

Control Surfaces and Systems. The two primary lifting and control mechanisms of the MD 500E helicopter are the main rotor and tail rotor

assemblies. The main rotor group consists of five main rotor blades attached to a fully articulated rotor hub with offset flapping hinges. A scissors assembly, swashplate and associated mixer control mechanisms completes the arrangement. Rotation of the main rotor is counterclockwise as seen from above per standard "American" rotation. The pilot's cyclic and collective controls yield authority over main rotor tilt and pitch, respectively, allowing for pitch, roll, horizontal and vertical velocity control over the aircraft. Somewhat more straightforward is the tail rotor group which consists of two variable-pitch blades attached semi-rigidly (i.e. in a teetering configuration) to a short output shaft belonging to the tail rotor transmission. Rotation of the tail rotor is counterclockwise as seen from the pilot's side, or "bottom aft" in reference to the direction of motion of the lower rotor. The pilot's tail rotor control pedals, or antitorque pedals, provide authority over tail rotor pitch which allows for yaw (or directional) control over the aircraft. Together, the main rotor and tail rotor assemblies provide the helicopter with six-degree-of-freedom motion capabilities and allow the pilot full control over the aircraft in all axes [8]. The principal parameters for both rotor groups are outlined in Table A.1 of Appendix A.

As briefly noted above, the pilots's controls consist of a cyclic control stick, antitorque pedals, and collective control stick. The cyclic stick and antitorque pedals are located directly in front of the pilot's seat, while the collective control is located to the left of the pilot's seat. The entire control system, from pilot to both rotors, is a solid mechanically-linked type that utilizes tubular push-pull rods throughout. Hence, the control system is reversible since rotor hinge moments are fed back to the pilot's controls.

Hydraulic boost is not incorporated by any of the systems. However, the cyclic control stick, which provides lateral and longitudinal control over the main rotor, does employ a hydraulic one-way lock device on its longitudinal component. The lock device resists uncommanded aft movement of the cyclic stick (i.e. feedback from the main rotor) for positions aft of trim. The antitorque and collective systems receive some control assistance through the use of bungee springs. In the antitorque system, a bungee spring resists right pedal movement (i.e. encourages left pedal movement) to assist in antitorque control and is set to provide zero pedal force in balanced flight at 130 KCAS. In the collective system, the bungee spring is set to assist in movement of the collective away from the center or mid-pitch position.

As an aid to the pilot in forward flight, electric force trim has been incorporated into the cyclic control system. Two trim actuators are utilized for this purpose: one for the lateral cyclic control linkage and one for the longitudinal cyclic control linkage. The actuators employ pre–loaded springs to provide direct force feedback to the stick. As a result, the cyclic stick moves in response to trim input. Control of either trim actuator is accomplished through a five-position thumb switch located atop the pilot's cyclic control grip. Spring loaded to the center position (OFF), the switch allows movement fore and aft for pitch trim, and left and right for roll trim. With this system, lateral and longitudinal control forces can be trimmed to zero throughout the speed range of the aircraft [8].

Stabilizing Surfaces. An important part of the MD 500E design is the horizontal and vertical stabilizing surfaces of the T-tail empennage section (Figure 2.5). Although immovable and hence uncontrollable by the pilot, the

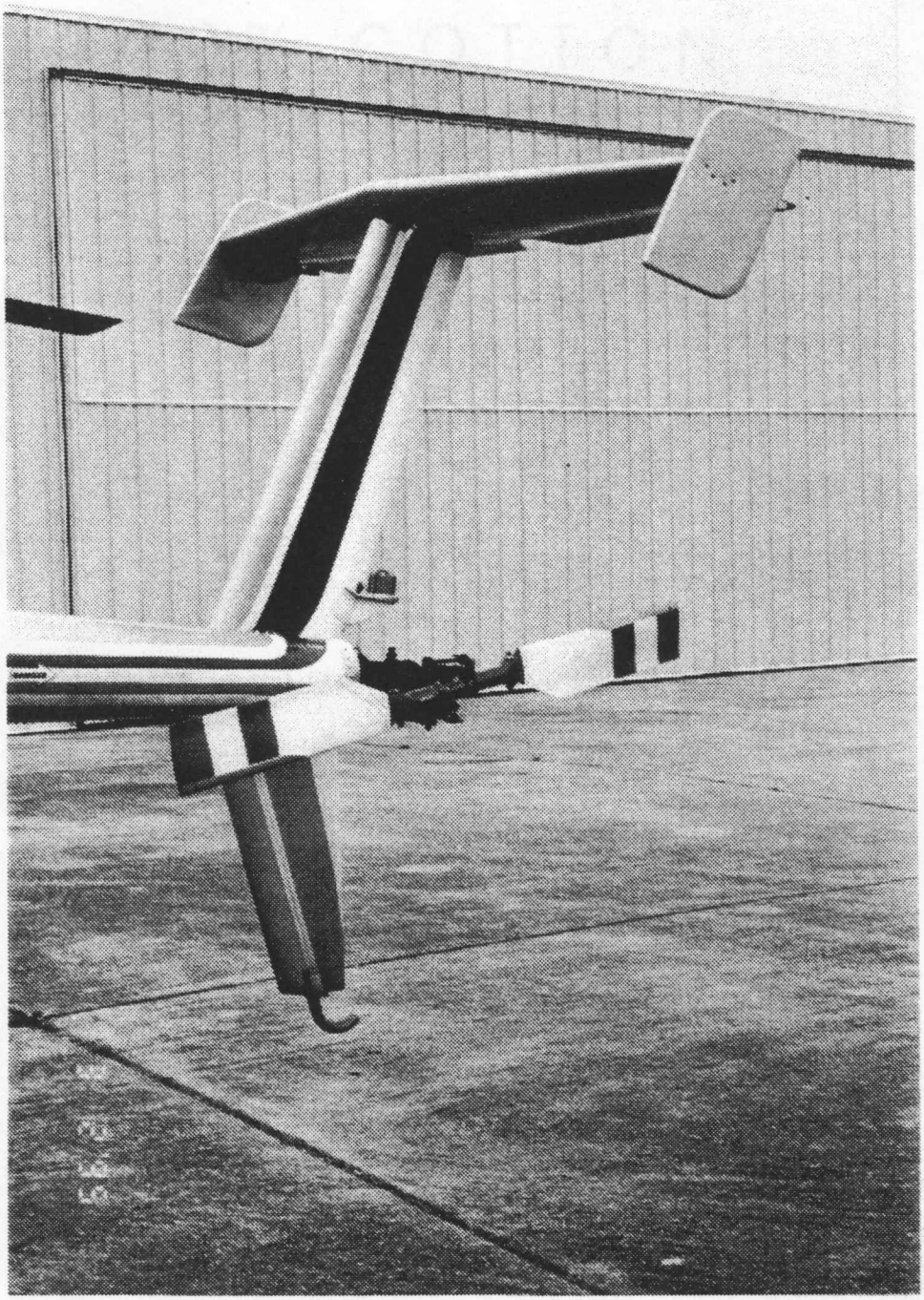


Figure 2.5. Empennage of MD 500E Helicopter.

surfaces do provide for increased stability in forward flight. Directional stability is enhanced by the flat sided, constant thickness airfoil of the vertical stabilizer section which extends above and below the tailboom. The lower half of the vertical stabilizer serves to lower the center of pressure of the section for lateral-directional concerns and serves as a mount for the tail skid. Both the upper and lower portions of the stabilizer form an oblique angle with the tailboom which provides for increased effectiveness in climbing and descending flight. Attached to the top of the vertical stabilizer is the horizontal stabilizer section. Comprised of an inverted NACA 6518 airfoil, the horizontal stabilizer is designed to enhance the helicopter's longitudinal stability characteristics. End plates on the horizontal stabilizer serve to increase the effective aspect ratio of the surface, in this case by a factor of approximately 1.4. Also, as shown by Figure 2.6, the center of the horizontal stabilizer is offset to the right of the aircraft centerline due to the mounting of the vertical stabilizer on the starboard side of the tailboom. This, too, serves an advantage since it places more of the horizontal stabilizer in the higher dynamic pressure flow field of the advancing rotor [18]. Table A.1 of Appendix A outlines the major parameters for both the vertical and horizontal stabilizing surfaces of the helicopter's T-tail empennage.



Figure 2.6. Location of MD 500E Empennage with respect to Fuselage Centerline.

N5144Q

N5144Q is the registration number of the MD 500E tested in this report (Figure 2.7). Its serial number, 0007E, signifies that this helicopter was the seventh helicopter to come off the 500E production line. Manufactured in 1982 by Hughes Helicopters, the aircraft is technically a Hughes 500E helicopter. However, since McDonnell Douglas made no changes to the model when they acquired the Hughes line in 1984, and since McDonnell Douglas is now responsible for all 500E helicopters, N5144Q will be referred to in this report as a MD 500E. In any case, it should be pointed out that all Hughes and McDonnell Douglas 500E helicopters are Model 369E helicopters. The title "500E" is only a marketing designation.



Figure 2.7. The Tested MD 500E Helicopter, N5144Q.

N5144Q derives its unique character from a number of internal and external additions and modifications. For instance, a number of avionic systems - many of which are nonstandard - have been added to the instrument panel. These include:

- An attitude director indicator (ADI) [oversized 5-inch diameter] with accompanying flight director system (FDS);
- Horizontal situation indicator (HSI);
- Standby attitude indicator with slip/skid indication;
- 3-Axis Autopilot;
- Yaw stability augmentation system (Yaw SAS);
- Combined GPS/LORAN receiver;
- Two VHF navigation radios, NAV 1 and NAV 2, with area navigation (RNAV) capability on NAV 1;
- Course deviation indicator (CDI);
- Two VHF communication radios (COMM 1 and 2);
- Argus 5000 moving map with ADF display;
- 3M Stormscope lightning strike detector, and
- An altitude encoding transponder.

In addition to providing standard course information, all three of the primary navigation displays listed above - the ADI, HSI, and CDI - have localizer and glideslope presentations for usage with a standard instrument landing system (ILS). With this equipment and the remaining flight instruments, N5144Q is fully equipped for IFR flight.

Another distinctive feature of N5144Q is its modified instrument panel. Based on a suggestion by UTSI Flight Research, the vertical portion (or pedestal) of the instrument panel now rests inclined from the front seats up to the horizontal portion of the panel. With this new configuration, all radios and circuit breakers look upwards and aft. This improves both the viewing angle and the pilot's ability to reach the radios and circuit breakers during flight.

The horizontal portion of the panel has also been modified and expanded to accommodate the installed avionics. Figure 2.8 presents a picture of N5144Q's cockpit from the pilot's point of view showing both the modified instrument panel and its assorted avionics.

Other important modifications to N5144Q include changes to the pilot's cyclic and collective control grips that allow for a limited amount of command over the aircraft's avionics. For instance, in addition to the trim and transmit switches, the cyclic control grip has an autopilot disengage/reengage button (in place of the cargo hook button) and an autopilot heading "bug" set button. Hence, limited control over the autopilot is possible from the cyclic control grip alone. Collective control grip modifications include a frequency flip-flop button for the COMM 1 communications radio, a toggle switch for moving between the various screens of the Argus 5000 moving map display, and another autopilot disengage/reengage button. Since the cyclic and collective controls of a helicopter are almost always held during flight, these modifications serve to reduce the number of times a control must be released in order to manipulate equipment on the instrument panel. In effect, safety of flight is increased through a simultaneous reduction in pilot workload and hands-off flying time.

Remaining additions and modifications particular to N5144Q include:

- A Fargo 21-gallon auxiliary fuel tank;
- Dual, independent pitot-static systems with pitot heat;
- Secondary, auxiliary battery;
- Independent emergency avionics bus, and
- A secondary, independent inverter.

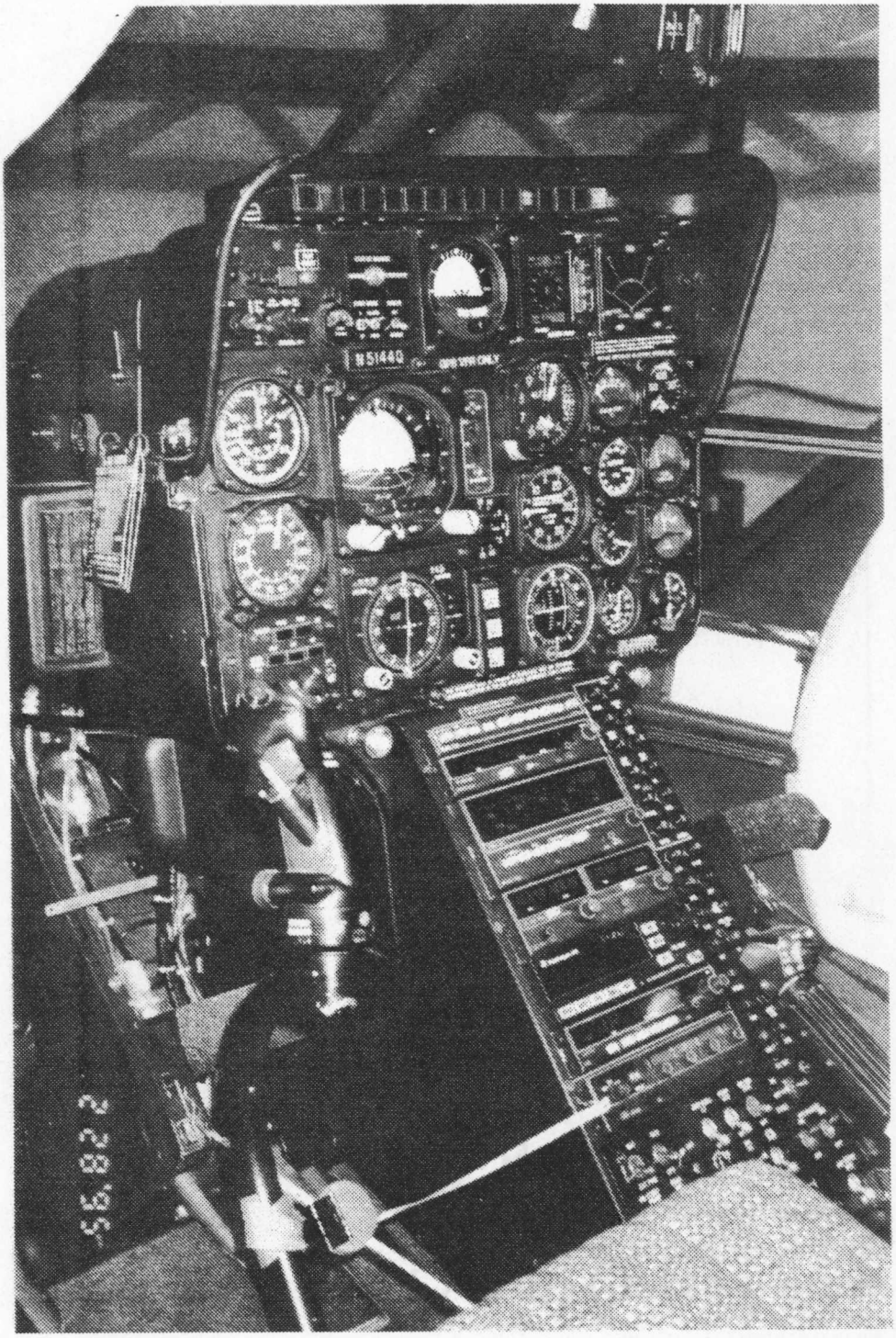


Figure 2.8. Modified Instrument Panel and Avionics of N5144Q.

The auxiliary fuel tank brings the total fuel capacity of N5144Q to 85 gallons or 552.5 pounds [8]. Burning approximately 150 lbs/hour at a low-altitude cruise speed of 120 knots yields an endurance of over 3.5 hours and a no-wind range of over 420 nautical miles. Even in the event of a generator failure, the main and auxiliary battery can supply power to minimum equipment for up to 1.2 hours which yields a 144 nautical mile no-wind range cushion till complete power loss [20]. The remaining redundant systems simply further enhance the safety potential of this particular aircraft.

Summary

As described previously, the MD 500E is a very capable single engine helicopter that combines speed and utility into a single VTOL package. Though soon to be replaced by the MD 520N, there are hundreds of MD 500E's already on the market that can be bought for a fraction of the price of a comparable new helicopter. Combined with its extraordinary capabilities, the MD 500E will unquestionably survive for years to come as a helicopter of choice for private and public interests alike. Furthermore, highly modified MD 500E's such as N5144Q will find special favor with secondary market consumers. Its array of avionics, workload-relieving modifications, and additional redundant systems serve to make it a very unique single-engine helicopter. And if work done by UTSI Flight Research proves to be successful, N5144Q will obtain a supplemental type certificate (STC) for IFR flight. Such an accomplishment would not only place this particular MD 500E in a class by itself, but would hopefully pave the way for other helicopters seeking increased access to the IFR system.

3. MD 500E FLIGHT TEST FOR IFR APPROVAL

Background

In the fall of 1993, UTSI Flight Research of Tullahoma, TN, received a contract to flight test a MD 500E helicopter (registration number N5144Q) for IFR certification purposes. The ultimate goal of the contract was to obtain a one-time STC that would approve the helicopter for single-pilot IFR operations. If granted, N5144Q would become the first civil MD 500E approved for IFR operations in the United States. The project was coordinated with the FAA and placed under the jurisdiction of the FAA's southwest regional office where a FAA project number was promptly assigned (SW-170-869). In late November of the same year, N5144Q was flown to the UTSI Flight Research facilities at the Tullahoma Regional Airport where flight testing and systems testing could begin. Flight testing was estimated to take about two weeks, while systems testing and modifications would occur as necessary over the ensuing months. The following section describes the requirements that applied to the flight test portion of the program.

Flight Test Requirements

The FAA's airworthiness requirements for helicopter instrument flight, normal category rotorcraft, are contained in Title 14 of the Code of Federal Regulations, Part 27, Appendix B (14 CFR 27, App. B). Often referred to as "Federal Aviation Regulation (FAR) Part 27, Appendix B", these regulations outline the flight characteristics and systems requirements necessary for a

helicopter to receive FAA type certification for single-pilot or multiple-pilot IFR operations. The regulations are judicially noted and hence must be complied with by law. Specifically, Appendix B of FAR Part 27 is made up of nine paragraphs, the titles of which are listed below [29].

I. General
II. Definitions
III. Trim
IV. Static longitudinal stability
V. Static lateral-directional stability
VI. Dynamic stability
VII. Stability augmentation system (SAS)
VIII. Equipment, systems, and installation
IX. Rotorcraft Flight Manual

Generally, paragraphs II through VI address requirements related to helicopter flight characteristics, while paragraphs VII through IX address helicopter systems requirements. The first six paragraphs are reproduced in Appendix B of this paper.

Another publication, Advisory Circular (AC) 27–1: Certification of Normal Category Rotorcraft, contains regulatory guidance and methods of compliance in the basic design, ground test, and flight test procedures of FAR Part 27. However, advisory circulars, unlike the Code of Federal Regulations, do not have any legal status and "must be treated accordingly" [28, p. II]. For this reason, AC–27–1 was referenced only as a guide to achieving the requirements set forth by the regulations.

Additional testing requests were made by the FAA regional office assigned to the project. As shown by Appendix C, the requested flight test items included applicable FAR Part 27 regulations plus other items of

concern to the office. Though the regulations of FAR Part 27 are still the only requirements that must be satisfied by law, accommodating additional requests made by the FAA generally accelerates the certification process. For this reason, attempts were made to examine all of the FAA's requested flight test items. This took a considerable amount of time, however, since the request was not received until four months after initial testing had begun [4].

Definitions (FAR Part 27, App. B.II)

The primary focus of paragraph II is airspeed nomenclature. With this in mind, each of the defined airspeeds was assigned a value appropriate to the capabilities of N5144Q as spelled out by the pilot's flight manual. The three airspeeds assigned to the helicopter and their definitions are as follows:

V_{YI} (IFR Climb Speed) ..... 90 KCAS

V_{NEI} (IFR Never Exceed Speed) ..... 125 KCAS

V_{MINI} (IFR Min. Flight Speed) ..... 60 KCAS

Eventually, these speeds were used to define the trim airspeeds at which the helicopter was tested.

Trim (FAR Part 27, App. B.III)

Paragraph III states that it must be possible to trim all the helicopter's control forces to zero for "all approved IFR airspeeds, power settings, and configurations appropriate to the type." The approved IFR airspeeds, power

settings, and configurations chosen for N5144Q were based in large part on the five trim conditions and associated critical combinations of weight and center of gravity required by paragraph IV for static longitudinal stability testing. Defined in section (b) of paragraph IV, the five trim conditions - Climb, Cruise, Slow Cruise, Descent and Approach - resulted in the following numbers for N5144Q:

Climb:	
Airspeed (V_{YI}):	90 KCAS
Power:	Max. Continuous or as needed for 1000'/min., whichever is less.
Cruise:	
Airspeed (.9*V_{NEI}):	113 KCAS
Power:	As Needed
Slow Cruise:	
Airspeed (1.1*V_{MINI}):	66 KCAS
Power:	As Needed
Descent:	
Airspeed (.8*V_{NEI}):	100 KCAS
Power:	As Needed for -1000'/min.
Approach:	
Airspeed:	80 KCAS
Power:	As Needed for -425'/min. (3° glideslope at 80 KCAS)

The approach airspeed, left undefined by the regulations, was arbitrarily chosen based on the capabilities of the helicopter. Also left undefined by paragraph IV were the critical combinations of weight and center of gravity, or "critical loadings", that must be utilized during testing. For N5144Q, the critical loadings were thus determined by utilizing the

manufacturer's published center of gravity envelope and the test team's ability to load the helicopter to the extremes of that envelope. Figure 3.1 depicts the manufacturer's weight and balance envelope and the loadings obtained by the test team. Due to the configuration of the helicopter at the time, aft CG locations beyond 103 inches and takeoff weights below 2,300 pounds could not be readily obtained. Two weights and two CG locations, listed below, provided for a total of four "test" loadings for the helicopter.

Heavy Weight	=	2750 lbs. to 3000 lbs.
Light Weight	=	2300 lbs. to 2465 lbs.
Forward CG	=	99.0 in. aft of datum
Aft CG	=	103.0 in. aft of datum

Together with the five trim conditions, the four test loadings resulted in exactly twenty (20) trim configurations for the helicopter. (Note: A trim *configuration* is a trim *condition* in conjunction with a test loading.) Examination of N5144Q's trim characteristics was accomplished in all 20 trim configurations while examining the requirements of paragraphs IV, V and VI.

Static Longitudinal Stability (FAR Part 27, App. B.IV)

Paragraph IV requires that the helicopter possess a tendency to return to trim speed after experiencing a longitudinal displacement from that speed. This tendency should be transferred through the aircraft controls so that "any substantial speed change results in a stick force clearly perceptible to the pilot." For single-pilot approval, the requirement is defined even further, stating that airspeed must return to within ±10 percent of the trim speed after the control has been gradually released during a "free return". The helicopter

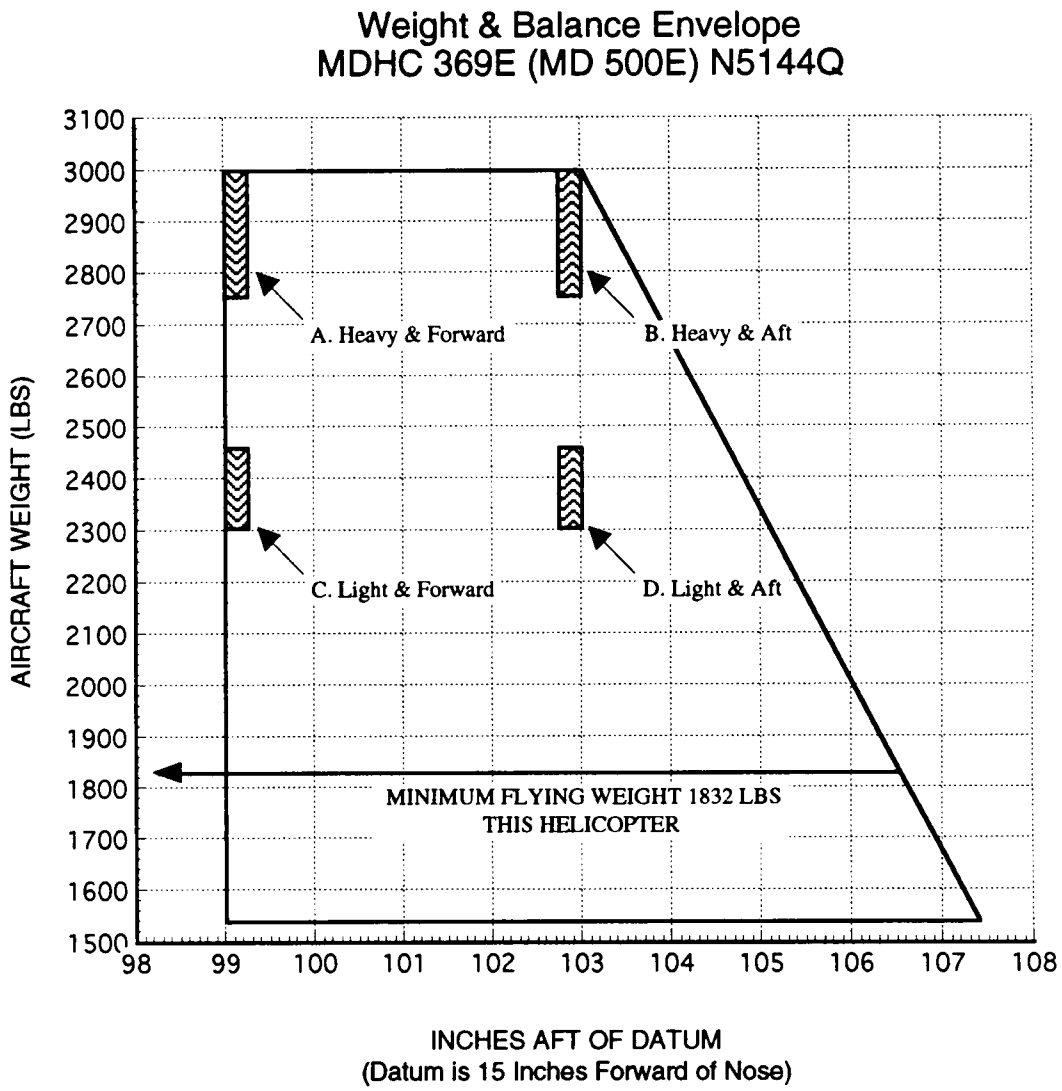


Figure 3.1. Weight and Balance Test Loadings for N5144Q.

must meet these requirements at the five trim conditions specified by section (b) of the paragraph while at "critical combinations of weight and center of gravity". Hence, the testing of N5144Q was performed at each of the 20 trim configurations determined for the helicopter. The required airspeed displacements for the testing of each trim condition are also specified by section (b) of this paragraph. These airspeed "test ranges" and the free return ranges required for the static longitudinal stability testing of N5144Q are outlined below in Table 3.1.

Table 3.1

Trim Conditions and Target Airspeeds for N5144Q Static Longitudinal Stability

Trim Condition	Target Airspeeds (KCAS) Low		High
Climb @ 90 KCAS:			
Required Displacement Range	70	to	110
Required Free Return Range	81	to	99
Cruise @ 113 KCAS:			
Required Displacement Range	93	to	133
Required Free Return Range	102	to	124
Slow Cruise @ 66 KCAS:			
Required Displacement Range	54	to	86
Required Free Return Range	59	to	73
Descent @ 100 KCAS:			
Required Displacement Range	80	to	120
Required Free Return Range	90	to	110
Approach @ 80 KCAS:			
Required Displacement Range	56	to	100
Required Free Return Range	72	to	88

Static Lateral-Directional Stability (FAR Part 27, App. B.V)

Paragraph five of Appendix B requires that in straight, steady sideslips up to ±10° from trim, the position of the directional controls (antitorque pedals) must increase "in approximately constant proportion to angle of sideslip". Furthermore, during the sideslip, "there must be no negative dihedral stability perceptible to the pilot through lateral control motion or force", and longitudinal movement of the cyclic with sideslip "must not be excessive". These tests, too, had to be performed for all 20 trim configurations determined for the helicopter.

Dynamic Stability (FAR Part 27, App. B.VI)

Although the distinction is not made, the dynamic stability requirement of Appendix B covers periodic and aperiodic dynamics for both the longitudinal and lateral-directional axes. Generally, four types of dynamic motion are tested. These include the short period, long period (phugoid), dutch roll and spiral motions. The four motions, their primary axis, and the typical response are presented below.

Motion Name	Primary Axis	Response
Short Period	Longitudinal	Generally Periodic
Long Period	Longitudinal	Generally Periodic
Dutch Roll	Lateral-Directional	Generally Periodic
Spiral	Lateral-Directional	Generally Aperiodic

As always, every motion had to be examined at each trim configuration. The requirements for dynamic motion, spelled out by sections 1 through 5 of paragraph VI, deal mainly with oscillatory periods and damping limits. For

N5144Q, sections 1 and 2 covered the short period and dutch roll motions, while sections 3 and 4 covered the long period motions. The aperiodic requirement of section 5 applied to the spiral motion. This paragraph concludes the flight characteristics testing required by the FAA for determination of helicopter IFR airworthiness.

Methodology

During the flight test, various methods were employed for configuring the helicopter, measuring its physical characteristics, and recording data. For instance, as a general rule, the helicopter was always configured with the yaw SAS and autopilot controls turned off for the stability and control flight tests. This was done to show that the basic aircraft could meet the regulations without any stability or control augmentation. However, since both of these systems are believed to strengthen the helicopter's ability to meet the regulations, use of the yaw SAS was made a required part of the IFR package and approval is being sought to employ the autopilot as an IFR workload reliever.

Another important configuration task performed during the flight test was the loading of the helicopter to the extremes of the center of gravity envelope. This was accomplished by defining various ballast locations along the vehicle's longitudinal axis and by loading people, fuel, and ballast as necessary to achieve the desired results. Ballast arms were determined with the aid of a station diagram and by direct measurement. The ballast locations used most often during the flight test and their respective moment arms are listed below.

Ballast Location	Arm (Inches Aft of Datum)
Auxiliary Battery	49.1"
Aft Front Floor	56.5"
Forward Seats	76.0"
Arm Rest Storage	76.0"
Forward Rear Floor	80.0"
Aft Seats	110.0"
Aft Rear Floor	113.0"
Engine Compartment	134.0"

Final calculation of the helicopter's weight and CG location was determined by utilizing the weight and balance sheet depicted in Figure 3.2. Presented in the figure is a sample weight and balance calculation with the helicopter configured for an aft CG at maximum weight. Hence, this would represent the "Heavy and Aft" test loading illustrated earlier by Figure 3.1. As shown, the weight and balance sheet contains room for full flight identification information, including crew names and weights, date of flight, time of flight, and additional comments. Ultimately, these sheets were used to compile a flight test log for the FAA.

The physical flight characteristics of the helicopter were measured during the flight test using a variety of instrumentation techniques. For instance, cyclic control positions were measured by mounting tape measures longitudinally and laterally from the airframe to the cyclic stick, and directional control positions were measured by extending a pointer downwards from one of the pedals to a scaled grid located on the floor. In a similar fashion, sideslip angle was measured using a windscreen-mounted yaw string superimposed on a calibrated scale. The only control force measured during the flight test was the cyclic stick force. This was

WEIGHT AND BALANCE

DATE MM/DD/YY **Flight ID** Example

Aircraft Type	MD 500E Helicopter	**Pilot**	Standard 1	**Weight**	170 **lbs**
Model Number	369E	**R.F.**	Standard 2	**Weight**	170 **lbs**
Serial Number	0007E	**L.R.**	Standard 3	**Weight**	170 **lbs**
Registration Number	N5144Q	**R.R.**		**Weight**	**lbs**

Comments: Sample weight and balance calculation for heavy weight, aft CG configuration.

Time Aloft 1.11 **hrs** (Hobbs Meter)

TAKEOFF CONDITION	**Weight (lbs)**		**Arm (in)**		**Moment (in*lbs)**	
Basic Empty Weight	1832.99	x	105.40	=	193197.15	Hour: 11:30a
Pilot & Front Passenger	340.00	x	73.50	=	24990.00	Hobbs: 123.45
Rear Seat Passengers (2 max.)	170.00	x	105.00	=	17850.00	
Fuel Main (64 gal. max.)	400.00	x	97.57	=	39028.68	61.54 Gallons Main
Fuel Aux. (21 gal. max.)	136.50	x	119.00	=	16243.50	21.00 Gallons Aux.
Remove Auxiliary Battery	-25.00	x	49.10	=	-1227.50	
Ballast Aft Rear Floor	50.00	x	113.00	=	5650.00	
Ballast in Engine Compartment	100.00	x	134.00	=	13400.00	
Ballast	0.00	x	0.00	=	0.00	
Pre-Taxi Fuel Burn (2 gal.)	-13.00	x	Variable	=	-1325.85	**CG Position**
TAKEOFF TOTALS	**2991.49 lbs**				307805.98	= **102.89 in**
					+ 2991.49	**aft of datum**

LANDING CONDITION	**Weight (lbs)**		**Arm (in)**		**Moment (in*lbs)**	
Basic Empty Weight	1832.99	x	105.40	=	193197.15	Hour: 12:36p
Pilot & Front Passenger	340.00	x	73.50	=	24990.00	Hobbs: 124.56
Rear Seat Passengers (2 max.)	170.00	x	105.00	=	17850.00	
Fuel Main (64 gal. max.)	200.00	x	95.59	=	19117.86	30.77 Gallons Main
Fuel Aux. (21 gal. max.)	136.50	x	119.00	=	16243.50	21.00 Gallons Aux.
Remove Auxiliary Battery	-25.00	x	49.10	=	-1227.50	
Ballast Aft Rear Floor	50.00	x	113.00	=	5650.00	
Ballast in Engine Compartment	100.00	x	134.00	=	13400.00	
Ballast	0.00	x	0.00	=	0.00	**CG Position**
LANDING TOTALS	**2804.49 lbs**				289221.01	= **103.13 in**
					+ 2804.49	**aft of datum**

Figure 3.2. Flight Test Weight and Balance Calculation for N5144Q.

accomplished using a hand-held force gauge calibrated in 1 pound increments. Since it was not required, neither the force nor the position of the collective control was measured during the flight test. Instead, power settings were measured using the installed engine instruments. Other installed instruments such as the airspeed indicator, altimeter, and attitude indicator were also utilized. As required, the airspeed indicator and altimeter were calibrated prior to the flight test. Finally, aircraft attitudes and rates were measured using an instrumentation platform that consisted of a pitch and roll attitude gyro, 3-axis rate gyro, and dedicated power supply. Time was measured with a quartz-controlled stopwatch.

Data recording performed during the flight test was accomplished by hand and by electronic means. Time, sideslip angle, installed instrument readings, and control position and force data were all recorded by hand. Attitude and rate data, however, was broadcast by a telemetry system in real time to a computer controlled ground station where the information was automatically stored on a hard drive. A sampling frequency of 2 Hertz for each attitude and rate channel provided for a minimum number of data points with which to analyze the dynamic responses of the helicopter.

Summary

The initial flight test project ended on December 13, 1993, with a majority of the flight tests and systems investigations completed. System additions and modifications were installed over the following three months and the remaining flight tests were performed sporadically over the following six months. Based on the results of the flight test program, three major restrictions were placed on the helicopter for IFR operation. First, an IFR weight and balance envelope was developed for the helicopter as shown by Figure 3.3. The forward and aft CG limits of the IFR envelope represent the CG limits utilized during the flight test, and the maximum weight limitation of 2,750 pounds represents the result of a dynamic stability concern encountered at high altitude. As a consequence of this concern, the second restriction imposed on the helicopter was a maximum IFR operating altitude of 8,000 feet density altitude. Finally, planned IFR flight was limited to 2 hours and 20 minutes based on the endurance capabilities of the systems on the emergency bus [30]. Given these limitations, the test team concluded that N5144Q met the design and installation requirements set forth by FAR Part 27, Appendix B, and should be considered as an aircraft capable of safely operating in the IFR environment [9].

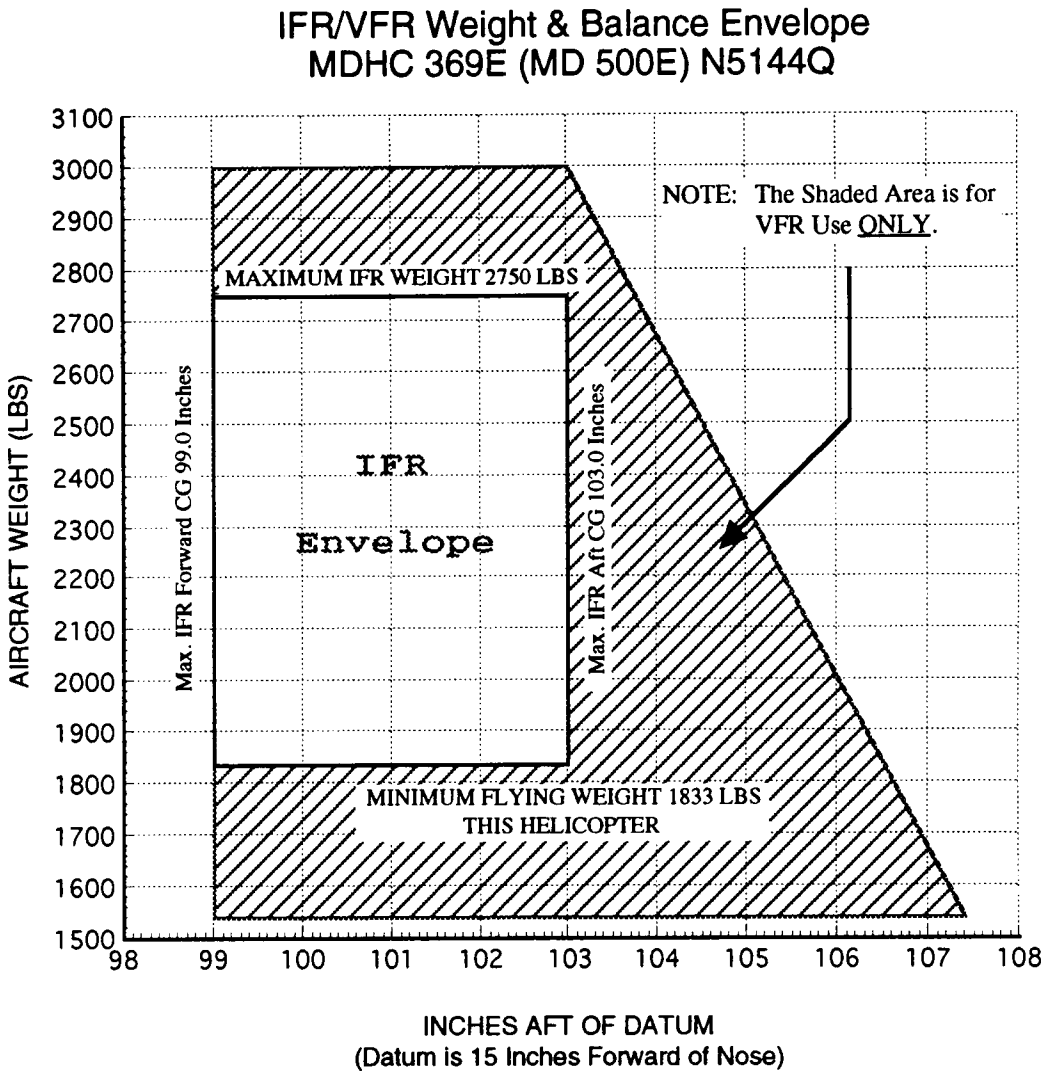


Figure 3.3. IFR Weight and Balance Envelope for N5144Q.

4. MD 500E STATIC LONGITUDINAL STABILITY

Flight Test Results

The static longitudinal stability of N5144Q was assessed by longitudinally displacing airspeed from the trim speed in even increments up to the minimum and maximum airspeeds required (without changing trim) while recording longitudinal cyclic stick force versus airspeed. (Note: Although this is technically a speed stability examination, it is referred to in this paper and by the FAA as "static longitudinal stability". See the introduction for more information regarding this usage of terminology.) Free returns were measured from the airspeed end points by allowing the cyclic stick to gradually return to a trim position and recording the airspeed at which zero cyclic stick force was obtained. This was done at four test loadings for all five trim conditions specified in paragraph IV (b) of FAR Part 27, Appendix B (see section 2 - Flight Test). The results are presented in Appendix D as Figures D.1A through D.5D and are grouped by trim condition (i.e. Climb - all four test loadings; Cruise - all four test loadings; etc.). The trim point, required test range and free return range limits are appropriately depicted in each figure.

A general analysis of all plots reveals positive static longitudinal stability in that longitudinal cyclic stick force increases with displacement of airspeed from trim [11]. The stability is positive in that a pull force is required to obtain airspeeds below trim while a push force is required to obtain airspeeds above trim. In either case, a slow release of cyclic stick force resulted in the aircraft returning to ±10 percent of the trim airspeed. As

evidenced by the shallow force versus airspeed gradients, the static longitudinal stability of N5144Q could easily be characterized as "light" since longitudinal cyclic stick forces never exceed a maximum of 5 pounds for any of the tested configurations in the required range of airspeeds. This should not be surprising, however, since light control forces are generally a common denominator of helicopter design due to the hover control task and low speed "collective to pitch" cross-coupling concerns [27]. Nonetheless, the longitudinal cyclic forces away from trim must still be "clearly perceptible to the pilot" in order to meet the IFR certification requirements. Due to the lack of a better definition for "clearly perceptible", this determination is often made on qualitative grounds by an FAA test pilot. In this case, average static longitudinal stick force gradients (airspeed versus cyclic force) were in the range of 10 knots per pound and allowed, according to the UTSI test pilot, clearly perceptible force characteristics. (Since the force gradients obtained were less than 1 pound per knot, the inverse "knots per pound" was used to express the force gradients with numbers greater than 1.) The force gradients did vary, however, anywhere from 6 kts/lb to 16 kts/lb depending on aircraft configuration and trim condition. For a quantitative look at the results, Table 4.1 outlines the static longitudinal force gradients encountered for all twenty test points and averages the gradients across the four weight and CG configurations and five trim conditions.

Table 4.1

Gradients of Longitudinal Cyclic Force versus Airspeed for Various Trim Conditions and Configurations of N5144Q.

	Heavy/Fwd CG	Heavy/Aft CG	Light/Fwd CG	Light/Aft CG	**Average**
Climb	6	10	6	8	**7.5**
Cruise	7	12	16	16	**12.8**
Slow Cruise	6	8	8	8	**7.5**
Descent	8	12	12	14	**11.5**
Approach	6	12	14	16	**12.0**
Average	**6.6**	**10.8**	**11.2**	**12.4**	(kts / lb)

Observations

Examination of the average force gradients supplied by Table 4.1 reveals a number of points about the static longitudinal stability of N5144Q with respect to CG position, weight, and trim condition. For a better perspective on these relationships, the gradients have been plotted versus the helicopter's CG position and weight as shown by Figure 4.1.

Effect of CG Position

In viewing both Table 4.1 and Figure 4.1, a definite trend towards decreased static longitudinal stability with aft movement of the CG position is clearly shown for the two heavy weight (3000 lbs, maximum gross weight) configurations, moving from an average of 6.6 kts/lb for the forward CG position to 10.8 kts/lb for the aft CG position. In reviewing the actual data it

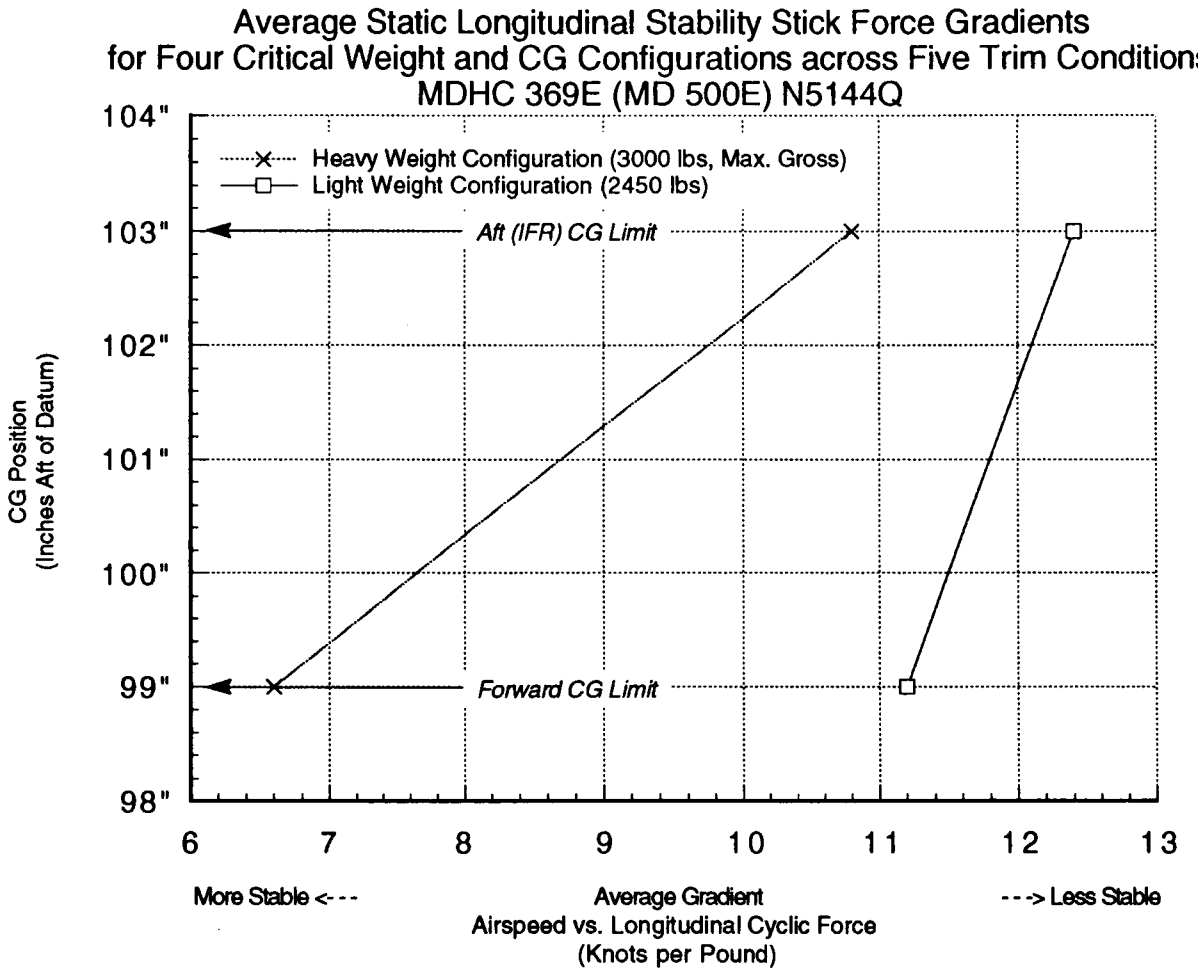
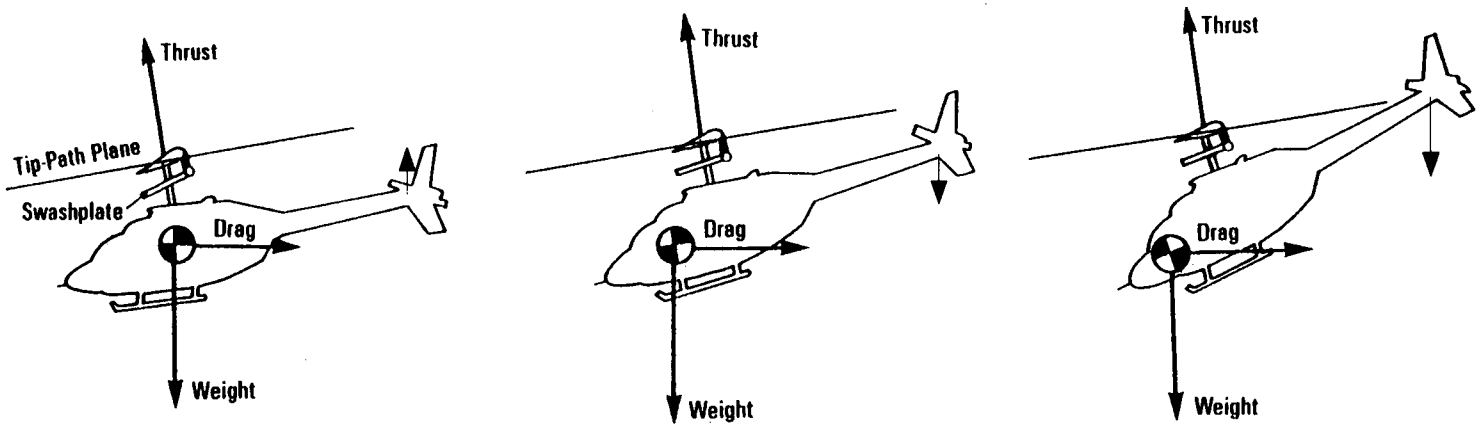


Figure 4.1. Variation of N5144Q's Average Static Longitudinal Stability Stick Force Gradient with Weight and CG Configuration.

can be seen that this trend is true regardless of trim condition. Unfortunately, the light weight (2450 lbs) configurations cannot be examined with the same confidence since some of the data in the "Light/Aft CG" category had to be estimated (underlined figures) due to purely qualitative results supplied by the test pilot. However, conservatively assuming the existence of a similar tendency for the light weight configurations results in a shift from 11.2 kts/lb (actual data) for the forward CG position to 12.4 kts/lb (estimated data) for the aft CG position.

The reason for this apparent shift in stability with longitudinal CG location can probably be traced to the flow conditions at the horizontal stabilizer and the angle-of-attack stability of the helicopter. First, consider that a shift in a helicopter's CG results in a different fuselage attitude for a given trim condition which in turn affects the angle of attack of the horizontal stabilizer. Figure 4.2 displays this effect rather dramatically for a helicopter at a given weight and trim speed where three different trim attitudes are required for three longitudinal placements of the CG. Note that, in each case, the tip-path plane attitude remains the same since its position is fixed entirely on the requirement to overcome parasite drag and rotor H-force (which are essentially constant for small fuselage attitude changes) [17]. For the fixed horizontal stabilizer at the empennage, the resulting change in angle of attack associated with these various attitudes can obviously make a difference in the size of the upload or download produced by the stabilizer. In general, tail downloads at the horizontal stabilizer are considered stabilizing for helicopters since, theoretically, an increase in speed will increase the tail download and produce a stabilizing nose-up moment [18].



Note: Force vectors are for illustration only and are not to scale.

Figure 4.2. Change in Helicopter Fuselage Attitude with Longitudinal CG Position.

Source: Prouty, Raymond W. Helicopter Aerodynamics. 2nd ed. Potomac: Phillips, 1985.

(This is strictly a speed stability effect. For a pitch or angle-of-attack disturbance at constant speed, a tail download is not stabilizing.) In this case, the flight attitude (and corresponding CG location) that is most likely to generate a tail download would follow as being the most stable configuration for the helicopter. A quick review of Figure 4.2 coupled with the knowledge that downloads are produced through negative angles of attack (i.e. wind from above the chord line) arrives at the conclusion that the "nose down" attitude associated with a forward CG position places the horizontal stabilizer into the most favorable position for incurring downloads. Hence, with respect to the effects of the horizontal stabilizer, this observation supports the data of Table 4.1 in that an increase in static longitudinal stability will occur with forward movement of the CG position.

The other factor that is "CG dependent" and affects the static longitudinal stability of a helicopter is angle-of-attack stability. As its name implies, angle-of-attack stability has to do with the stability of the helicopter with respect to changes in the angle of attack of the main rotor. (This is static longitudinal stability in the classical sense where speed stability appears as a secondary effect.) In general, angle-of-attack stability is negative for helicopters in that any increase (or *decrease*) in angle of attack seen by the main rotor causes nose-up (*nose-down*) flapping which thus exacerbates the situation by further increasing (*decreasing*) the rotor's angle of attack. In addition, any change in the angle of attack will also change the thrust of the rotor. If the CG is ahead of the thrust line, then a change in thrust will result in a stabilizing nose-down moment. On the other hand, if the CG is behind the thrust line, then a change in thrust will result in a destabilizing nose-up

moment. This can have an apparent effect on the static longitudinal stability of a helicopter whenever turbulence is encountered due to frequent changes in the angle of attack of the main rotor. However, even in the absence of turbulence, angle-of-attack stability should be taken into consideration during the static longitudinal stability flight tests, especially at higher speeds. Quoting from Prouty's Helicopter Aerodynamics,

> Had the aircraft been an airplane, the angle of attack would have decreased as the speed went up [for 1G flight] - but a helicopter may not follow this pattern. At low speeds, [the helicopter] has the same trend as an airplane but at high speeds, the growth of the reverse-flow region [on the main rotor] with its download requires that the rotor angle of attack be slightly increased to maintain 1G flight (p. 34).

Overall, a forward CG position should yield a more stable condition for static longitudinal stability flight tests. This, too, helps to explain the destabilizing trend found in N5144Q's static longitudinal stability with respect to aft movement of the CG [17].

Effect of Weight

Another trend that becomes readily apparent upon viewing Figure 4.1 is that the heavy loadings are in general more stable than the light loadings. Most likely, this is the result of the amount of rotor flapping that occurs with respect to the weight of the aircraft. Although not discussed to this point, a very important characteristic of the main rotor that is generally stabilizing in nature is its tendency to flap up (longitudinally) with an increase in forward speed and down with a decrease in forward speed. For an increase in

forward speed, the nose up flapping is stabilizing since the helicopter will pitch up due to the resultant nose up moment and slow down to its original speed. Likewise, the nose down flapping associated with a decrease in forward speed is also stabilizing following the same logic. The magnitude of this stabilizing flapping, however, is a function of the lift of the rotor which itself is a function of the weight of the helicopter in level, 1G flight. The more lift produced by the rotor, the greater the flapping. (If the rotor has no lift to begin with, then there there will be no flapping with a change in forward speed). Hence, it follows that heavier weights will produce greater stabilizing flapping moments with respect to changes in forward speed [18]. This supports the results of Figure 4.1 that show an increase in static longitudinal stability with an increase in weight.

Effect of Trim Condition

It can be concluded from the discussion so far that N5144Q's static longitudinal stability is most stable at a heavy loading with a forward CG and most unstable at a light loading with an aft CG, irrespective of trim condition. Turning the analysis around for a moment and looking solely at the average force gradients for the five trim conditions supplied by Table 4.1, another trend becomes obvious in that two of the trim conditions are substantially more stable than the other three, irrespective of weight and CG location. Specifically, the most stable trim points were the climb and slow cruise conditions (averaging 7.5 knots per pound) while the least stable trim points were the cruise, descent and approach trim points (averaging 11.5 to 12.8 knots per pound).

This observation is somewhat in contradiction to the first impressions of the UTSI test team who believed that the most stable gradients were realized with a combination of low speed and low power, while the least stable gradients were realized with a combination of high speed and high power [12]. Clearly, the more stable climb trim point obtained at 90 knots with power for 1000 ft/min is no more a low speed, low power condition than the less stable approach trim point obtained at 80 knots with power for –425 ft/min is a high speed, high power condition. Although power and speed most certainly play a role, the trim condition itself and its effect on the flow conditions at the horizontal tail should also be examined.

In order to do this, a first estimate of the downwash angle at the horizontal stabilizer due to the main rotor has been made utilizing the following formula and associated data from Prouty's Helicopter Aerodynamics, Stability and Control (p. 493):

$$\varepsilon_{MH} = \frac{V_H}{V_1} \cdot \frac{DL}{4q}$$ downwash angle (radians) at horizontal stabilizer; (1)

where

$V_H/V_1 \approx 2.25$ induced velocity ratio for location of MD 500E horizontal stabilizer.

The data from which the induced velocity ratio was derived was obtained at a tip speed ratio (μ) of 0.23. The MD 500E maintains a rotor tip speed (ΩR) of 680 ft/s which, at a tip speed ratio of 0.23, corresponds to a forward velocity of 156.4 ft/s or 92.6 kts. Hence, given the following conditions,

$V = 156.4$ ft/s forward velocity;

$T = 3000$ lb main rotor thrust;

the remaining terms of equation **(1)** can be solved. This results in a downwash angle at the horizontal stabilizer of

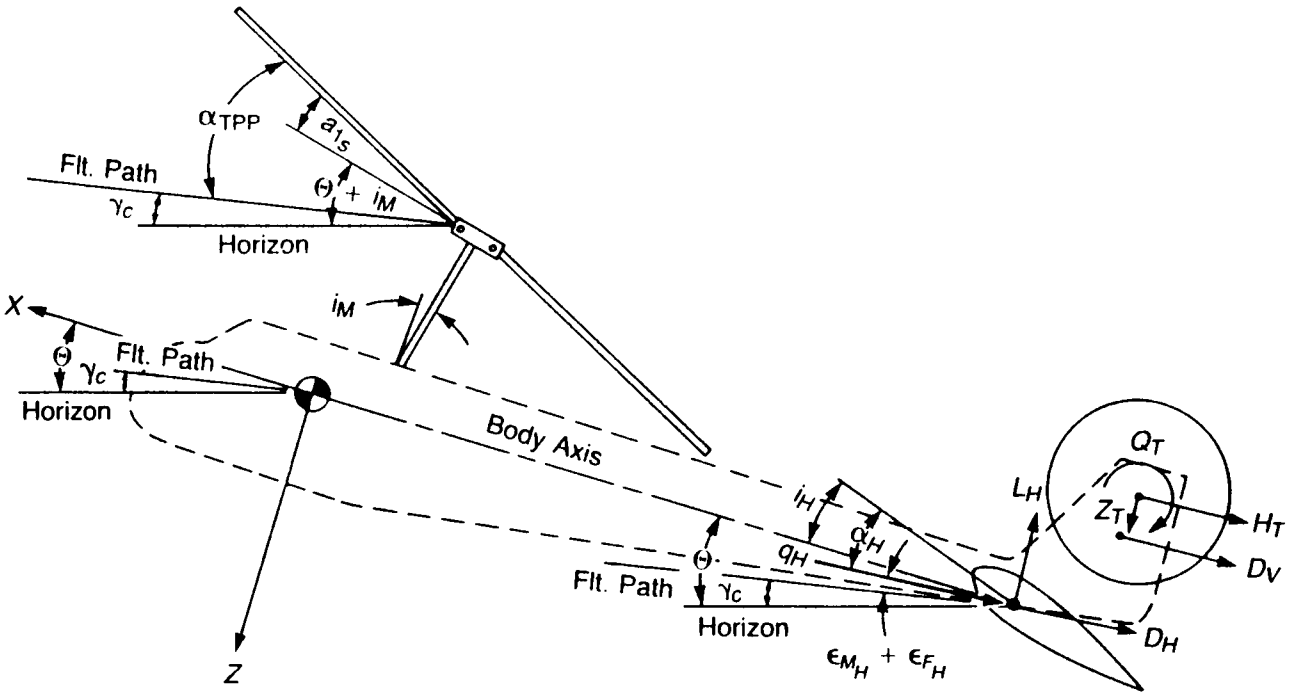
$$\varepsilon_{MH} = 0.1060 \text{ radians or } 6.07 \text{ degrees.}$$

Figure 4.3 reveals the relationships that define the geometric angle of attack of the horizontal stabilizer. This yields the following relationship:

$$\alpha_H = \Theta + i_H - (\varepsilon_{MH} + \varepsilon_{FH}) - \gamma_c. \qquad \textbf{(2)}$$

Since the incidence of the MD 500E's horizontal stabilizer is 9° with respect to the main rotor hub plane, and the main rotor hub plane is tilted 3° forward (nose down) with respect to the fuselage waterline, then the horizontal stabilizer's incidence with the fuselage waterline (i_H) is 6° [8]. The term ε_{FH} is the downwash angle due to the fuselage and can be considered negligible for helicopters without a wing or widely spaced engine nacelles with a combined span greater than the span of the horizontal stabilizer. Therefore, in level flight ($\gamma_c = 0$) at 93 kts with a fuselage attitude level to the horizon ($\Theta = 0$), the 6° downwash angle due to the main rotor results in almost no geometric angle of attack at the horizontal stabilizer.

$$\alpha_H = 0 + 6 - (6.07) - 0 = -0.07 \text{ degrees.}$$



Note on subscripts: The first subscript refers to the element generating the effect. The second subscript refers to the element receiving the effect.

Figure 4.3. Longitudinal Component Forces and Moments at Empennage.

Source: Prouty, Raymond W. Helicopter Performance, Stability, and Control. Malabar, FL: Krieger, 1990.

An aerodynamic angle of attack still exists, however, that would result in the production of a stabilizing tail download at this trim condition.

Remaining in the level flight situation, then, equation **(1)** shows that as speed is decreased (q variable), the downwash angle at the horizontal stabilizer will increase. In this instance, an increased downwash angle would place the horizontal stabilizer into more favorable download producing conditions. This would imply increased stability for a slower speed and hence supports the flight test data that shows increased stability for the slow cruise (66 kts) trim condition. Conversely, an increase in speed will result in a decrease in the downwash angle at the tail. This would tend to decrease the stability of the helicopter for a higher speed and again supports the flight test data that shows decreased stability for the faster cruise (113 kts) trim condition.

Now, in considering flight with a vertical speed component, equation **(2)** shows that the introduction of a climb angle ($+\gamma_c$) will increase the negative angle of attack of the horizontal stabilizer, thus increasing its download. This would represent a more stable configuration and supports the flight test data that shows increased stability for the climb (90 kts) trim condition. Conversely, the introduction of a descent angle ($-\gamma_c$) would decrease the negative angle of attack of the horizontal stabilizer and hence decrease its download. This would represent a less stable configuration which again supports the flight test data that shows decreased stability for the descent (100 kts) and approach (80 kts) trim conditions.

From this analysis, it appears that the most stable trim conditions were

those that provided the horizontal stabilizer with a tail download. Equations **(1)** and **(2)** can also be used to show that an increase in weight and a nose down fuselage tilt will promote increased negative angles of attack at the horizontal stabilizer. This helps to support the previous conclusions regarding the increase in stability that occurs with an increase in weight and movement of the CG position forward.

FAA Results

The first FAA evaluation of the helicopter occurred in April 1994 after the issuance of a Type Inspection Authorization (TIA) and included systems checks and flight tests. Unfortunately, the evaluation of the helicopter's flight characteristics was cut short after two flights and resulted in a postponement of the evaluation. In August 1994, the FAA returned to UTSI to continue its evaluation of the helicopter's flight characteristics. As before, testing ended prematurely due to outside circumstances after only three additional flights. However, at the end of this limited evaluation, the FAA pilot expressed some concern over the static longitudinal stability of the helicopter in addition to a number of other parameters. In a fax from the FAA's southwest regional office dated September 27, 1994, six certification issues were identified as needing resolve prior to completion of the TIA. As shown by a limited reproduction in Appendix E, the FAA's discrepancies concerning N5144Q's flight characteristics included its static longitudinal stability and "significant" cross-coupling between the axes. With regards to the static longitudinal stability, they wrote:

> The static longitudinal stability does not comply with the requirements of FAR 27, Appendix b, IV(b) in that a substantial speed change does not result in a stick force that is clearly perceptible to the pilot.
>
> The first FAA evaluation was conducted during mild turbulence and the static longitudinal stability and the return to trim was not apparent. The second evaluation was conducted during stable atmospheric conditions and the aircraft exhibited weak positive stability and return to trim for a heavy-forward c.g. configuration; but neutral stability at a density altitude near 10,000 feet with the aircraft at light weight, mid c.g. configuration.

Convinced of their position, the FAA concluded the fax with the following paragraph:

> You must determine what modifications to the aircraft or the proposed operational envelope are necessary to demonstrate compliance with the applicable portions of FAR 27. If you have justification why these issues should not prevent approval, "equivalent levels of safety" findings or "petition for exemptions" must be considered by the FAA [5].

In defense of the helicopter, a response was quickly drafted by the project team and returned to the southwest regional office (Appendix F) [31]. Though this quickly cleared up many of the certification issues raised in the fax, the static longitudinal stability of the helicopter remained questionable in the eyes of the FAA. The result was yet a third evaluation of the helicopter's flight characteristics in February 1995, this time by another FAA test pilot. Three flights were completed (including a static stability check) before the weather put a halt to the investigation. Unfavorable testing conditions, however, resulted in unreliable static stability data. With this parameter still unresolved, the TIA evaluation of N5144Q remains incomplete.

5. DISCUSSION

Given the current situation, the FAA must either be convinced that the longitudinal force gradient characteristics of N5144Q do not pose a safety risk to IFR flight due to "equivalent levels of safety" findings, or the force gradient characteristics must be increased to perceivable levels through modifications to the helicopter and/or its operational envelope. In the interest of minimizing costs, increasing the force gradients through modifications to the helicopter have been avoided to this point. This leaves modifications to the operational envelope or equivalent levels of safety findings open for consideration.

Operational Envelope Considerations

Since N5144Q did reveal solid and perceivable longitudinal force gradients under certain testing conditions, then it follows that restricting the IFR operation of the helicopter to those favorable conditions should facilitate its approval. For instance, the poor static stability characteristics encountered during the second FAA evaluation was for a takeoff loading of 2,480 pounds with a CG location 102.25 inches aft of datum. Although this CG location is roughly in the middle of the helicopter's VFR CG envelope, it corresponds more directly to the "Light and Aft" test loading utilized by UTSI to define the aft portion of the IFR weight and balance envelope. As previously pointed out, the light weight, aft CG configuration represents the most critical loading for the static longitudinal stability of the helicopter. However, the fact that "neutral" stability was found at this loading probably

has more to do with the tested altitude than the tested configuration. In general, UTSI's testing was conducted below a density altitude of 8,000 feet, with a majority of the results obtained below a density altitude of 6,000 feet. The 10,000 foot density altitude tested by the FAA is not only above the highest altitude tested by UTSI, but also above the IFR density altitude limitation of 8,000 feet requested for certification. Undoubtedly, the lighter control responses encountered at the higher density altitude were completely masked by the longitudinal cyclic stick friction forces, thus yielding what was perceived as a "neutral" static stability characteristic. In addition, turbulent conditions on the day of the test (which prompted such a high test altitude in the first place) are felt to have further contaminated this data. If testing is performed in stable atmospheric conditions below the maximum IFR density altitude limitation of 8,000 feet, then the static longitudinal stability forces have been found to remain greater than the longitudinal cyclic stick friction forces for positive static longitudinal stability results.

This does not solve the problem, however, of determining whether or not the cyclic stick forces are clearly perceptible to the pilot for a substantial change in speed. Of course, the undefined qualifiers "clearly" and "substantial" tend to make this type of evaluation difficult. It can be said, though, that a force gradient of 6 kts/lb is "clearly" more perceptible than a force gradient of 16 kts/lb. Since it has been shown that moving the CG forward tends to improve the force gradient, the suggestion had been made to further restrict the aft CG limit of the helicopter for IFR flight. Although this could be accomplished, the amount of improvement that would be obtained for the single-pilot configuration is questionable, especially in the presence of

the results presented earlier by Figure 4.1.

As an illustration, take a 170 pound pilot with 30 pounds of baggage who has planned an IFR flight of 2.33 hours duration (including a trip to the alternate airport, if required). This would adequately represent the single-pilot situation for a planned IFR flight of the maximum allowable time in the helicopter. Given an average fuel burn of 150 lb/hr, such a trip would necessitate a minimum of 350 pounds of fuel which, in turn, would encourage filling the main fuel tank to its 416 pound capacity. This results in a takeoff weight of 2,450 pounds and, with the baggage in the front passenger's seat, a CG position of 101.5 inches aft of datum. According to Figure 4.1, this configuration should result in an overall average force gradient of approximately 12 kts/lb. Now, restricting the aft CG limit to, say, 101.0 inches would require an additional 80 pounds of ballast in the front passenger seat and would raise the takeoff weight to 2,530 pounds. Returning to Figure 4.1 with this new configuration and extrapolating reveals that the overall average force gradient improves only slightly to 11 kts/lb. Obviously, this is not a very significant improvement. For this reason, it does not appear that a reduction in the aft CG limit would provide any substantial benefit toward increasing the perceptibility of the longitudinal cyclic stick force gradients for lightly loaded configurations.

Another possibility for increasing the longitudinal force gradients, then, would be to increase the weight of the helicopter in addition to restricting the aft limit of the CG. The only problem is that 400 to 500 pounds of ballast would be required to raise the helicopter's takeoff weight to the 3000 pound maximum limit where the most favorable and perceptible force gradients

were obtained. In addition, in order to keep the CG position forward of 101.0 inches, 150 to 200 pounds of the ballast would need to go in the front passengers seat. Although this solution is not entirely unrealistic, it is certainly impractical and should be considered only as a last resort.

Equivalent Levels of Safety Considerations

Placing modifications to the aircraft and operational envelope aside, justification as to why the helicopter's "imperceivable" force gradients should not prevent approval must be given. This can be accomplished by showing that the helicopter has a level of functional equivalence that makes it as safe without a perceivable force gradient as it would be with a perceivable force gradient. However, demonstrating functional equivalence in this case is not entirely obvious since the intent of the force gradient requirement is not clearly defined (i.e. not quantified). As stated by paragraph 775 of Advisory Circular 27–1, "Positive static longitudinal stability is a key IFR requirement which assures a self-correcting airspeed response and allows a pilot to recognize any substantial change in speed" (p. 1348). Since the pilot already has the airspeed, attitude and vertical speed indicators to detect substantial changes in speed from a trimmed condition, the rationale behind the need for a perceivable, positive force gradient for helicopter IFR flight must be determined before any arguments for an equivalent level of safety can be made.

Fortunately, during the time that the FAA was finalizing the airworthiness criteria for helicopter instrument flight, a number of studies were published regarding helicopter IFR flying qualities and the issue of

longitudinal cyclic stick force and position gradients. As put by one author, "Since very low or even zero forces are frequently considered desirable for low-airspeed and hover flight in visual conditions, it is of interest to ascertain whether stable [cyclic stick] force gradients are necessary in addition to position gradients for helicopter IMC operations" [15, p. 7]. The studies utilized either ground based or airborne simulators to examine these issues, and the results were commonly based on the pilot's qualitative assessment of the experience.

A substantial review of these studies leads to the conclusion that some amount of positive cyclic stick force gradient is considered desirable for helicopter single-pilot IFR flight. In general, a positive cyclic stick force gradient facilitates a pilot's ability to acquire and maintain a trim airspeed and guards against inadvertently large cyclic stick inputs [15]. However, the amount of positive force gradient needed to achieve this result is unclear. For instance, it has been shown that variations in positive force gradients have little effect on the ease of flying a helicopter [19], and numerous helicopter handling qualities studies have shown that helicopter pilots are willing to accept much less in terms of stability than their fixed wing counterparts [7]. The pilot of one handling qualities study even believed that a force gradient of 20 kts/lb was too heavy for one of the IFR tasks [6]! Hence, it appears that a relatively weak longitudinal force gradient could be considered satisfactory for IFR flight if the helicopter's trim effort and susceptibility to inadvertent cyclic stick inputs were found to be acceptable.

For this reason, it is proposed that these parameters (i.e. trim effort and susceptibility to inadvertent cyclic stick inputs) could be determined for a

given helicopter by measuring the following items during a flight test:

1. The time required to trim the helicopter between flight conditions, and;

2. The response of the trimmed helicopter to a large and abrupt longitudinal cyclic stick input without correction.

Given a set of minimum criteria supported by the FAA, the results of these tests could then be used to show whether or not the helicopter had acceptable longitudinal characteristics for IFR flight in light of its existing longitudinal force gradient. For instance, an average time of 10 seconds for trimming the helicopter might be considered a satisfactory requirement, with trim defined as hands-off stable flight plus or minus certain allowable deviations in speed, altitude, vertical speed and heading over a fixed period of time. The flight transitions for determining trim effort would include all 20 possible combinations of the five trim conditions at the helicopter's most critical loading. If the helicopter was able to meet the minimum criteria, then the trim effort of the helicopter would be considered satisfactory for IFR flight regardless of the perceivability of the longitudinal force gradient. Similarly, a "large", inadvertent cyclic stick input could be defined as a 3 to 5 pound input that occurs over a time period of no more than 1 second. The hands-off response of the aircraft to the input would be examined for each trim configuration and applied against the minimum criteria. (The approach trim condition would be exempt from this latter requirement, however, since it is a hands-on, control intensive task. Instead, the test method would simply involve measuring the time necessary to retrim the helicopter immediately

following the input.) Since this test closely parallels that of the dynamic stability test for the phugoid, then it might suffice to simply use the existing phugoid criteria and test technique as a substitute for this particular examination. In either case, if the requirement was met then the helicopter's susceptibility to an inadvertent input would be considered nonrestrictive to IFR flight regardless of the perceivability of the longitudinal force gradient. As can be seen, such a test and evaluation system would greatly improve the ability to determine whether or not a weak longitudinal force gradient was actually detrimental to the control of an aircraft. Certainly, the determination of appropriate criteria for this proposed system is an area that should be considered for future study.

Barring the current existence of such a system, however, dictates the pursuit of functional equivalence evaluations based on the amount of aid supplied by on-board systems to the pilot's longitudinal control task. If the aid supplied by these systems is considered substantial enough by the FAA (on subjective grounds), then the helicopter will be said to possess an "equivalent level of safety" that will allow its existing longitudinal force gradients to be approved for IFR flight. For N5144Q, two existing on-board systems - the attitude director indicator (ADI) and the 3-axis autopilot - are believed to significantly aid the pilot with respect to this concern.

The benefit supplied by the ADI stems from the fact that helicopter pilots utilize both longitudinal motion/force cues and pitch attitude to obtain and maintain trimmed airspeed [27]. Obviously, without an outside visual reference, the pilot must depend on the attitude indicator (ADI) for the presentation of the helicopter's pitch attitude response characteristics [14].

Quoting from Traybar,

> Classic flying qualities research says nothing about pitch attitude but any helicopter pilot will tell you that pitch attitude is what he flies by, IFR. It would appear that a strong attitude gradient in conjunction with a good attitude indicator should have some offset or trade-off value when considering the need for stable statics (p. 4-18).

In considering what constitutes a "good" attitude indicator, a report by Lebacqz suggests that a 5-inch ADI provides an adequate attitude gradient for the IFR task [14]. This is exactly the size of the ADI installed in N5144Q. Of course, the location of the ADI with respect to the pilot is also an important factor that ultimately determines the usability of the instrument. In N5144Q, the ADI is located some 17 degrees to the right of the pilot's design eye point. This allows the instrument to remain within the pilot's optimum viewing zone of ±20 degrees while simultaneously restricting the extent to which the instrument panel obstructs the pilot's forward view [20]. Although forward view is usually not considered a factor for IFR flight, it becomes highly significant to the pilot during the IFR/VFR transition phase of an instrument approach or, more importantly, emergency autorotation procedure. Furthermore, the ADI's placement and domineering appearance on the instrument panel allow it to remain an obvious and distinguishable feature in the pilot's peripheral vision for a majority of flight control and auxiliary tasks. This being the case, deviations from trim attitude remain recognizable to the pilot throughout all phases of flight. Hence, for these reasons, it is believed that the 5-inch ADI as installed in N5144Q clearly provides an increased level of safety with regards to the pilot's longitudinal control task under IFR

conditions.

The second system - the 3-axis autopilot - benefits the pilot's longitudinal control task by reducing both the trim effort and the helicopter's susceptibility to outside disturbances. With attitude hold capabilities in both pitch and roll, the ability to maintain a trim condition once obtained is vastly enhanced by this system. Furthermore, the attitude hold function does not need to be disengaged in order to trim the helicopter between flight conditions. Instead, trimming can be accomplished as usual with the cyclic stick beep trim button and results in the autopilot immediately acquiring and maintaining the new trim attitude. Not only does this aid in the ability to trim the aircraft, but it also reduces the amount of time that the pilot must interface with the basic, unaugmented helicopter [1]. Along these lines, it should be pointed out that almost every helicopter approved for single-pilot IFR operations has required the use of the attitude hold mode of a basic autopilot. If for nothing else, attitude hold capabilities provide workload relief to the pilot by allowing for substantial amounts of stable hands-off flying time [27]. This particular autopilot, however, displays a number of additional features beyond the basic attitude hold function. Included among these additional features are yaw rate damping (through the yaw SAS), heading hold, turn coordination, altitude hold, vertical speed and airspeed hold, and navigational tracking capabilities [1]. Hence, not only does N5144Q's autopilot provide an increased level of safety with regards to the pilot's longitudinal control task, but the safety of the IFR flight task in general is improved as well.

Collectively, then, the presence and use of N5144Q's installed 5-inch ADI and 3-axis autopilot should ease the FAA's concerns over the

helicopter's longitudinal force gradients and hopefully pave the way for an "equivalent level of safety" finding. Undoubtedly, these two systems provide a level of safety far better than that which could be obtained by increasing the force gradients alone. The extent to which the FAA agrees with this opinion, however, will not be known until the evaluation of the helicopter is completed sometime this summer.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of a flight test of a MD 500E helicopter, registration number N5144Q, reveal positive static longitudinal stability in that longitudinal cyclic stick force increases with displacement of airspeed from trim. The most stable results were obtained with the helicopter at its maximum weight and most forward CG position while the least stable results were obtained with the helicopter in a minimum weight, aft CG configuration. Furthermore, the climb and slow cruise trim conditions were generally more stable than the cruise, descent and approach trim conditions. These effects have been traced to combinations of rotor flapping characteristics, angle-of-attack stability characteristics, and flow conditions presented to the horizontal stabilizer. Overall, longitudinal cyclic stick force gradients were light, averaging 10 kts/lb, but were strong enough to allow the helicopter to return to within ±10 percent of trim during free returns. At density altitudes above 8,000 feet, the force gradients were sometimes excessively contaminated by the longitudinal cyclic stick friction forces. This resulted in the FAA designating some of the force gradients as imperceivable for certain critical configurations and has thus hindered the approval of the helicopter's STC for single-pilot IFR operations.

Regarding this specific problem, the following recommendations are made based on the flight test results and a review of the currently installed systems:

1. Limiting IFR operations to a maximum density altitude of 8,000 feet allows the static longitudinal stability forces to remain greater than the longitudinal cyclic stick friction forces for positive static longitudinal stability results.

2. The maximum IFR weight limitation of 2,750 pounds should be reconsidered since the helicopter displayed the most stable longitudinal force gradients at its maximum loading of 3000 pounds.

3. A further reduction in the aft CG limit should be avoided since only a minimal gain in longitudinal cyclic stick force gradients would be realized for single-pilot IFR configurations (i.e. lightly loaded configurations).

4. The oversized 5-inch ADI should be considered a significant aid to the pilot's trim effort task and used to support "equivalent level of safety" findings in regards to the longitudinal force gradient concerns.

5. The 3-axis autopilot with attitude hold should also be considered a significant aid to the pilot's trim effort task and used to support "equivalent level of safety" findings in regards to the longitudinal force gradient concerns.

6. The FAA should consider developing and quantifying minimum criteria regarding the static longitudinal stability requirement so that objective functional equivalence evaluations can be made for helicopters seeking IFR certification.

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APPENDICES

Appendix A: MD 500E (Model 369E) Physical Data
Appendix B: 14 CFR 27, Appendix B Excerpts
Appendix C: FAA Requests for N5144Q Flight Test
Appendix D: N5144Q Static Longitudinal Stability Results
Appendix E: FAA Response to Limited TIA Evaluation of N5144Q
Appendix F: UTSI Response to FAA Certification Issues

APPENDIX A

MD 500E (Model 369E) Physical Data

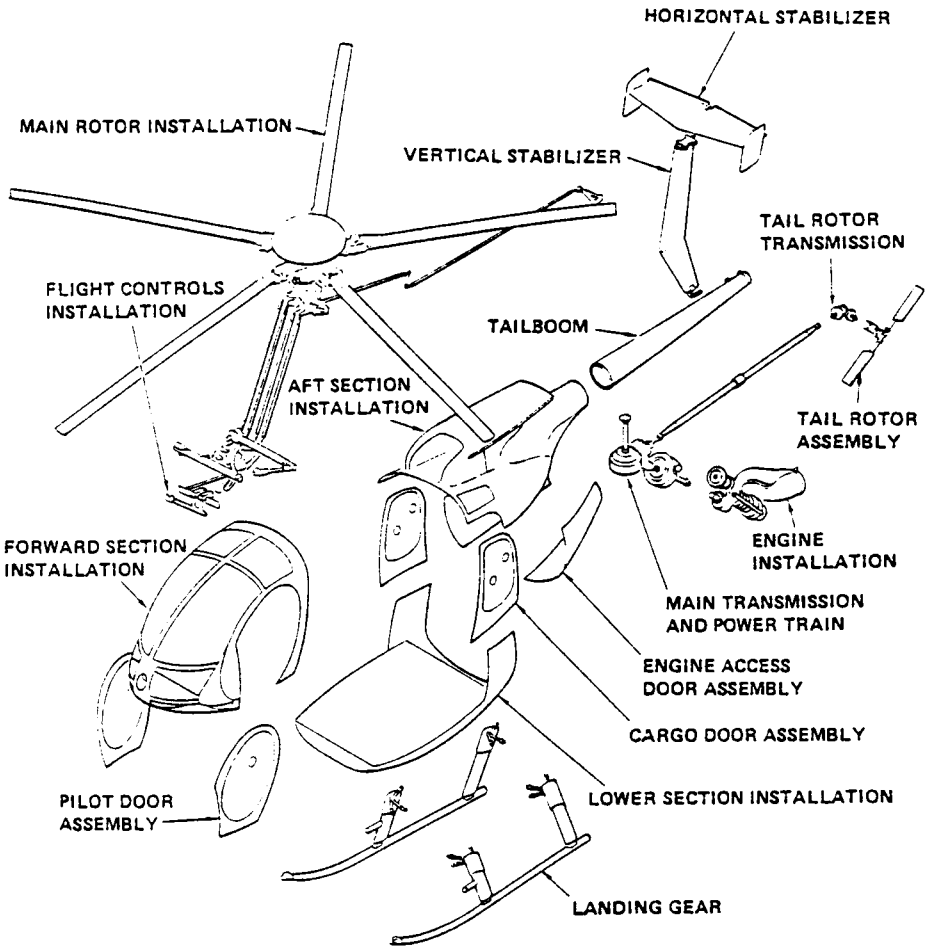


Figure A.2. MD 500E Major Components.

Source: Hughes Helicopters, Inc. Pilot's Flight Manual Containing The FAA Approved Rotorcraft Flight Manual for Hughes 500E Helicopter, Model 369E. Culver City, CA: 1982.

Table A.1. MD 500E Principal Data.

Weights (lb)		Engines	
Empty	1,455	Type	Allison 250-C20B
Maximum takeoff	3,000	Number	1
Fuel capacity	416	Max. T.O. rating	420 shp
		Max. usable power	375 shp

Rotor Parameters		Main Rotor	Tail Rotor
Radius (ft)	R	13.2	2.3
Chord (ft)	c	.56	0.44
Solidity	σ	.068	.119
No. of blades	b	5	2
Tip speed (ft/sec)	ΩR	680	704
Twist (deg)	θ_1	-9	-8.6
Hinge offset ratio	e/R	.032	- - -
Airfoil		NACA 0015	NACA 63-415
Collective range (deg)		0 to 14.3	-13 to 27
Longitudinal cyclic range (deg)		-7 to 17	- - -
Lateral cyclic range (deg)		-8.5 to 5.5	- - -
Polar Moment of Inertia (slug ft^2)	J	263	.23

Stabilizer Parameters	Horizontal	Upper Vertical	Lower Vertical
Span (ft)	5.33	3.54	2.29
Tip Chord (ft)	1.22	0.94	0.59
Root Chord (ft)	1.90	1.27	1.27
Area (ft^2)	8.18	3.91	2.14
Airfoil Root	NACA 6518 Inverted	13.4% thick*	13.4% thick*
Airfoil Tip	NACA 6515 Inverted	18.3% thick*	28.0% thick*
Incidence	9° relative to hub plane	- - -	- - -
End Plates	(2) four-sided polygons	- - -	- - -
End Plate Total Area (ft^2)	2.38	- - -	- - -

*Vertical stabilizer is flat sided, constant thickness (2.06 inch) section.

Adopted from: Prouty, Raymond W. Helicopter Performance, Stability, and Control. Malabar, FL: Krieger, 1990; and
Hughes Helicopters, Inc. Pilot's Flight Manual Containing The FAA Approved Rotorcraft Flight Manual for Hughes 500E Helicopter, Model 369E. Culver City, CA: 1982.

APPENDIX B

14 CFR 27, Appendix B Excerpts

I. *General.* A normal category helicopter may not be type certificated for operation under the instrument flight rules (IFR) of this chapter unless it meets the design and installation requirements contained in this appendix.

II. *Definitions.* (a) V_{YI} means instrument climb speed, utilized instead of V_Y for compliance with maximum limit speed requirements for instrument flight.

(b) V_{NEI} means instrument flight never exceed speed, utilized instead of V_{NE} for compliance with maximum limit speed requirements for instrument flight.

(c) V_{MINI} means instrument flight minimum speed, utilized in complying with minimum limit speed requirements for instrument flight.

III. *Trim.* It must be possible to trim the cyclic, collective, and directional control forces to zero at all approved IFR airspeeds, power settings, and configurations appropriate to the type.

IV. *Static longitudinal stability.* (a) *General.* The helicopter must possess positive static longitudinal control force stability at critical combinations of weight and center of gravity at the conditions specified in paragraph IV (b) or (c) of this appendix, as appropriate. The stick force must vary with speed so that any substantial speed change results in a stick force clearly perceptible to the pilot. For single-pilot approval, the airspeed must return to within 10 percent of the trim speed when the control force is slowly released for each trim condition specified in paragraph IV(b) of this appendix.

(b) *For single-pilot approval*:

(1) *Climb.* Stability must be shown in climb throughout the speed range 20 knots either side of trim with -

(i) The helicopter trimmed at V_{YI};

(ii) Landing gear retracted (if retractable); and

(iii) Power required for limit climb rate (at least 1,000 fpm) at V_{YI} or maximum continuous power, whichever is less.

(2) *Cruise.* Stability must be shown throughout the speed range from 0.7 to 1.1 V_H or V_{NEI}, whichever is lower, not to exceed ±20 knots from trim

with -

(i) The helicopter trimmed and power adjusted for level flight at 0.9 V_H or 0.9 V_{NEI}, whichever is lower; and

(ii) Landing gear retracted (if retractable).

(3) *Slow Cruise.* Stability must be shown throughout the speed range from 0.9 V_{MINI} to 1.3 V_{MINI} or 20 knots above trim speed, whichever is greater, with -

(i) The helicopter trimmed and power adjusted for level flight at 1.1 V_{MINI}; and

(ii) Landing gear retracted (if retractable).

(4) *Descent.* Stability must be shown throughout the speed range 20 knots either side of trim with -

(i) The helicopter trimmed at 0.8 V_H or 0.8 V_{NEI} (or 0.8 V_{LE} for the landing gear extended case), whichever is lower;

(ii) Power required for 1,000 fpm descent at trim speed; and

(iii) Landing gear extended and retracted, if applicable.

(5) *Approach.* Stability must be shown throughout the speed range from 0.7 times the minimum recommended approach speed to 20 knots above the maximum recommended approach speed with -

(i) The helicopter trimmed at the recommended approach speed or speeds;

(ii) The landing gear extended and retracted, if applicable; and

(iii) Power required to maintain a 3° glide path and power required to maintain the steepest approach gradient for which approval is requested.

(c) Helicopters approved for a minimum crew of two pilots must comply with the provisions of paragraphs IV(b)(2) and IV(b)(5) of this appendix.

V. *Static lateral-directional stability.* (a) Static directional stability must be positive throughout the approved ranges of airspeed, power, and vertical speed. In straight, steady sideslips up to ±10° from trim, directional control position must increase in approximately constant proportion to angle of sideslip. At greater angles up to the maximum sideslip angle appropriate to the type, increased directional control position must produce increased angle of sideslip.

(b) During sideslips up to ±10° from trim throughout the approved ranges of airspeed, power, and vertical speed, there must be no negative dihedral

stability perceptible to the pilot through lateral control motion or force. Longitudinal cyclic movement with sideslip must not be excessive.

VI. *Dynamic stability.* (a) For single-pilot approval -

(1) Any oscillation having a period of less than 5 seconds must damp to 1/2 amplitude in not more than one cycle.

(2) Any oscillation having a period of 5 seconds or more but less than 10 seconds must damp to 1/2 amplitude in not more than two cycles.

(3) Any oscillation having a period of 10 seconds or more but less than 20 seconds must be damped.

(4) Any oscillation having a period of 20 seconds or more may not achieve double amplitude in less than 20 seconds.

(5) Any aperiodic response may not achieve double amplitude in less than 6 seconds.

(b) For helicopters approved with a minimum crew of two pilots - [...].

VII. *Stability augmentation system (SAS).* [...].

VIII. *Equipment, systems, and installation.* [...].

IX. *Rotorcraft Flight Manual.* [...].

Source: United States. Federal Aviation Administration. Code of Federal Regulations Title 14 - Aeronautics and Space: Parts 1 to 59. Washington, D.C.: U.S. Government Printing Office, 1992.

APPENDIX C

FAA Requests for N5144Q Flight Test

Item 18, Part II, Flight Test

The Flight Test Representative is requested to accomplish the following:

1. Evaluate the cockpit instrument and avionic control panels for single pilot IFR operations during day and night, non-icing conditions. Determine if the angle of the primary flight instruments away from the forward head/eye position causes pilot fatigue or disorientation.

2. Evaluate the mechanical characteristics of the control system, including breakout forces, force gradient and control system friction. This information is needed to determine the control "force" stability required for IFR approval.

3. Evaluate the aircraft trim system in flight to assure that the control forces can be trimmed to zero and that the cyclic exhibits self-centering characteristics.

4. Evaluate trim system failures to determine the effects on pilot workload and continued safe flight under IMC.

5. Evaluate the static longitudinal stability tests required for single pilot IFR approval at the most critical center-of-gravity at low and high altitudes. Flight conditions to be tested include:

a. Climb at V_{YI} at maximum continuous power or maximum approved climb rate.

b. Cruise at 0.9 V_H or V_{NEI}, whichever is less.

c. Slow cruise at 1.1 V_{MINI}.

d. Descent at 0.8 V_H or V_{NEI}, whichever is less, and at 1000 feet per minute rate of descent.

e. Approach at the recommended approach speed.

6. Evaluate the static lateral-directional stability tests required for single pilot IFR approval at the same configuration and altitudes as #5.

7. Evaluate the dynamic stability tests required for single pilot IFR approval at the same configuration and altitudes as #5.

8. Evaluate the electrical system for adequate redundancy and isolation of systems to allow continued safe flight under IFR conditions following probable failures. The duration of the flight following failure should be at least one-half of the normal fuel endurance.

9. Evaluate vibration and buffeting characteristics at 1.1 V_{NEI} to assure acceptable under IMC.

10. Evaluate the autopilot functions for acceptable performance as a workload reliever during IFR flight. Assure that the autopilot approval is not limited for VFR operations only.

11. Evaluate autopilot failures to determine if hazardous conditions can be created following such failures during IFR conditions.

12. Evaluate the pilot workload following probable malfunctions or failures such as:

a. Individual COMM, NAV, or intercom failure;
b. Engine failure (simultaneous generator failure);
c. Trim failure;
d. Failure of each vertical and directional gyro;
e. Autopilot;
f. Each component of the electrical system;

13. Evaluate if the pilot normal response time for an engine failure, while the aircraft is coupled to the autopilot, is acceptable to prevent excessive rotor RPM decay.

14. Evaluate pilot workload for single pilot IFR operations, during both day and night conditions, including operations within "high" density air traffic areas.

15. Evaluate the pilot visibility during low approach conditions in precipitation.

16. Evaluate the effects of glare and reflection at night in clouds.

17. Evaluate the position error of the alternate static source and insure that the corrections are included in the Rotorcraft Flight Manual Supplement.

18. Evaluate the protection of the electrical and avionic systems from precipitation.

19. Evaluate the control system coupling to insure no unacceptable handling qualities that would prevent the smooth transition between flight conditions under IMC, including autorotational entries.

20. Evaluate the design of the electrical and avionic systems to assure that failure modes are not introduced that will result in excessive or total loss of all required systems.

21. Review the proposed Rotorcraft Flight Manual Supplement for limitations, normal procedures, emergency procedures, etc. Verify that this information is appropriate for single pilot operations.

22. Conduct any other tests deemed necessary.

Source: Federal Aviation Administration. Southwest Region. Aircraft Certification Service: Rotorcraft Directorate, ASW-100. Fax to UTSI Flight Research from Jim Arnold on April 4, 1994.

APPENDIX D

N5144Q Static Longitudinal Stability Results

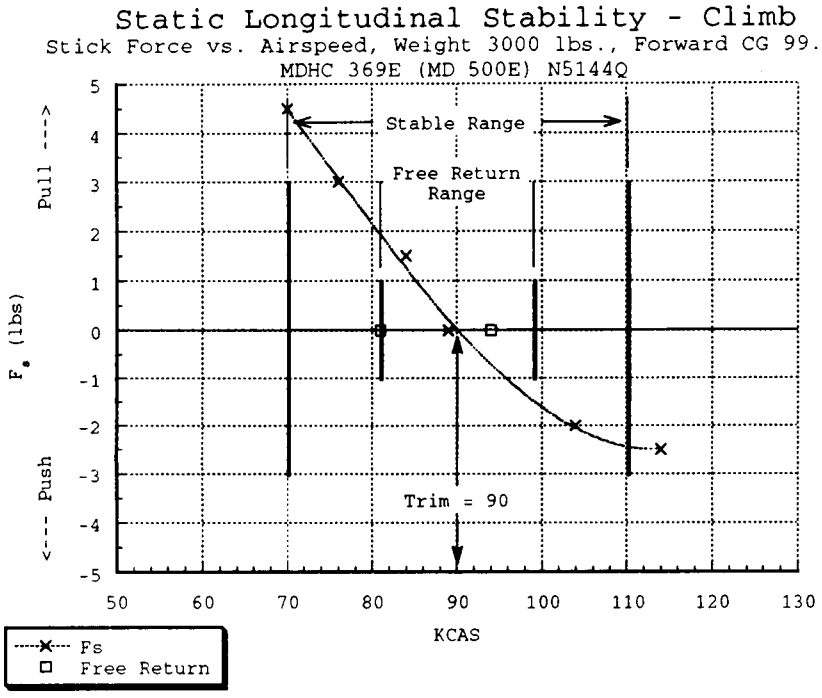


Figure D.1A. Climb at Heavy Weight, Forward CG.

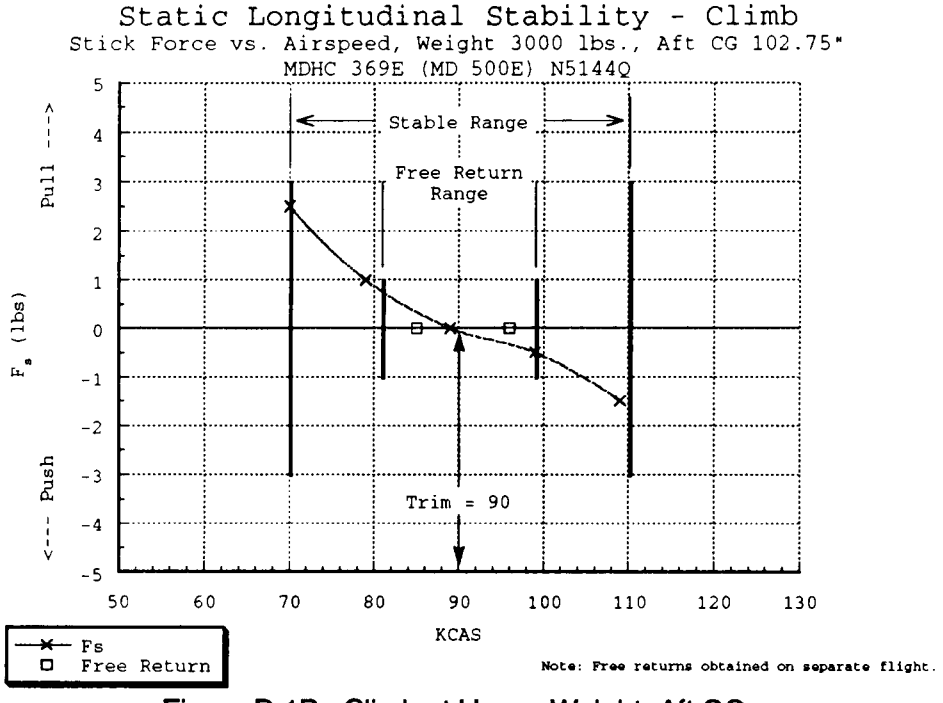


Figure D.1B. Climb at Heavy Weight, Aft CG.

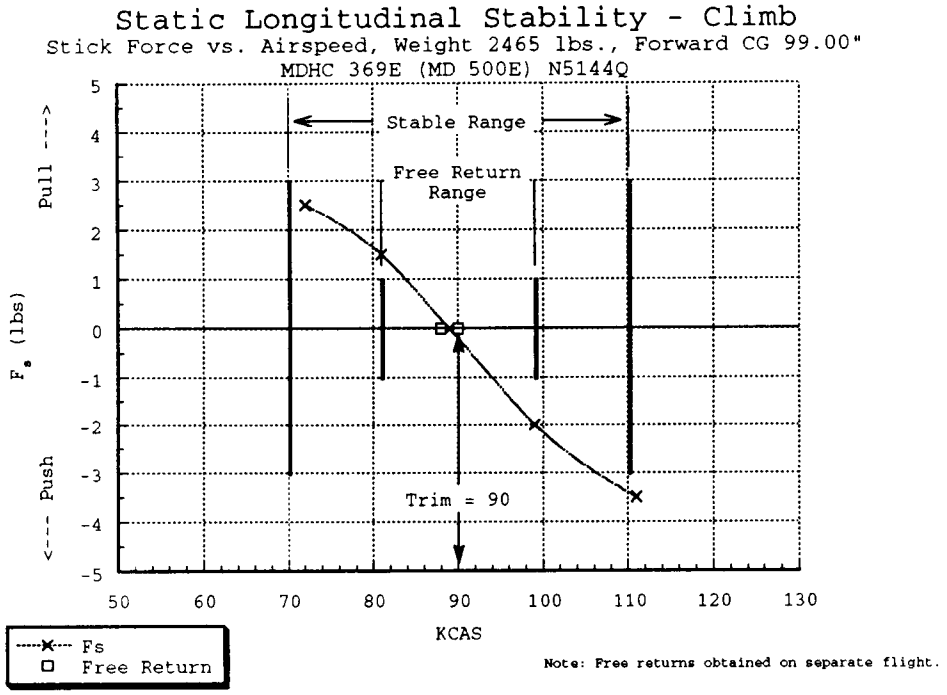


Figure D.1C. Climb at Light Weight, Forward CG.

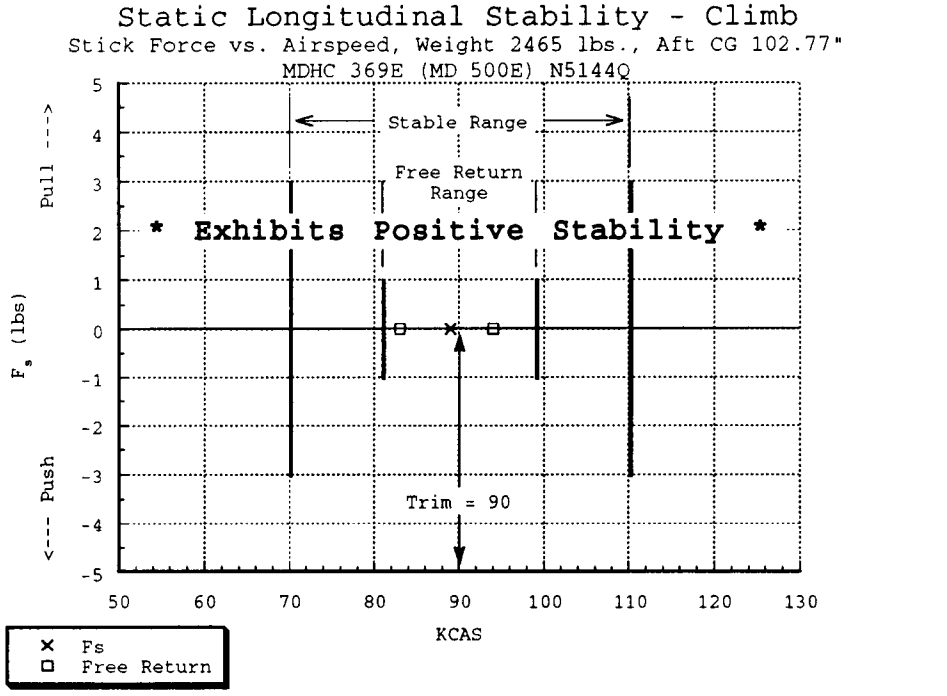


Figure D.1D. Climb at Light Weight, Aft CG.

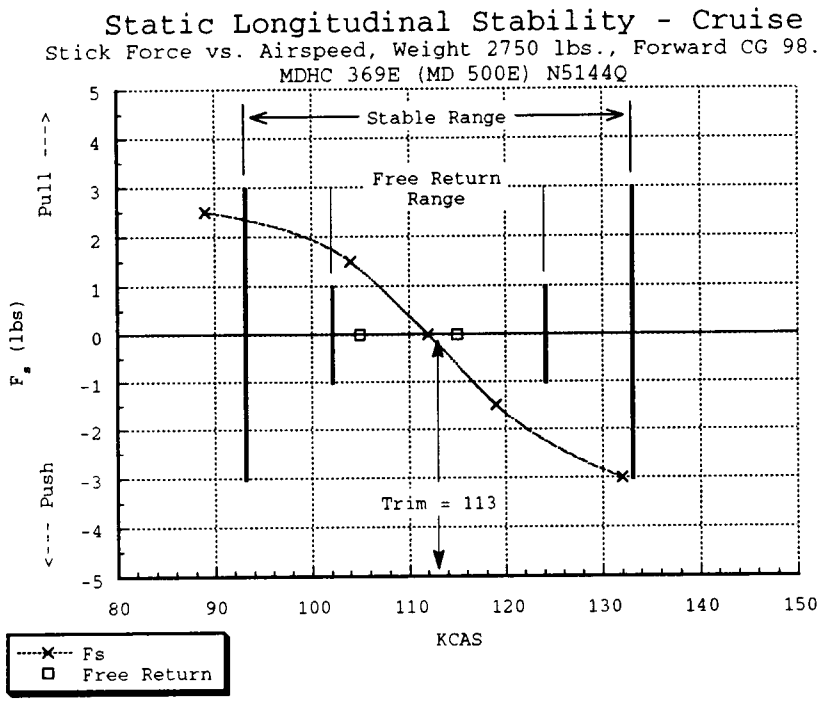


Figure D.2A. Cruise at Heavy Weight, Forward CG.

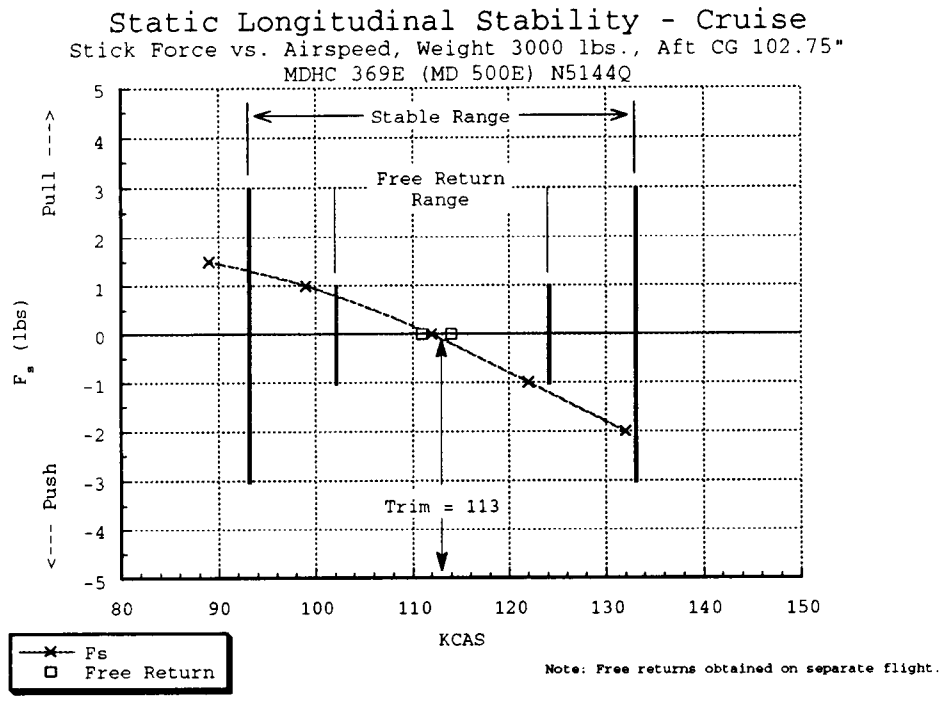


Figure D.2B. Cruise at Heavy Weight, Aft CG.

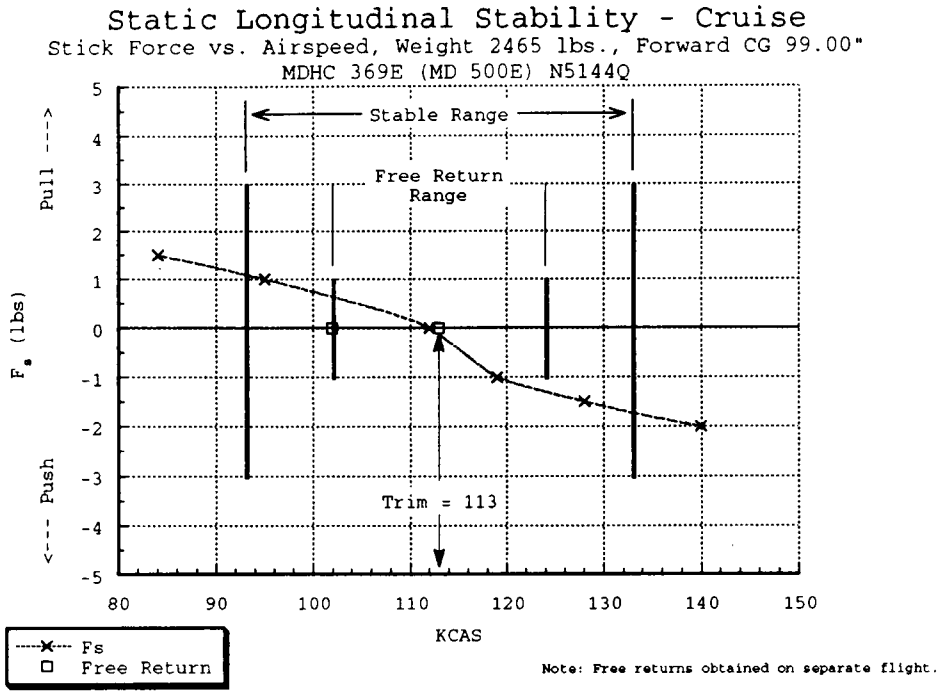


Figure D.2C. Cruise at Light Weight, Forward CG.

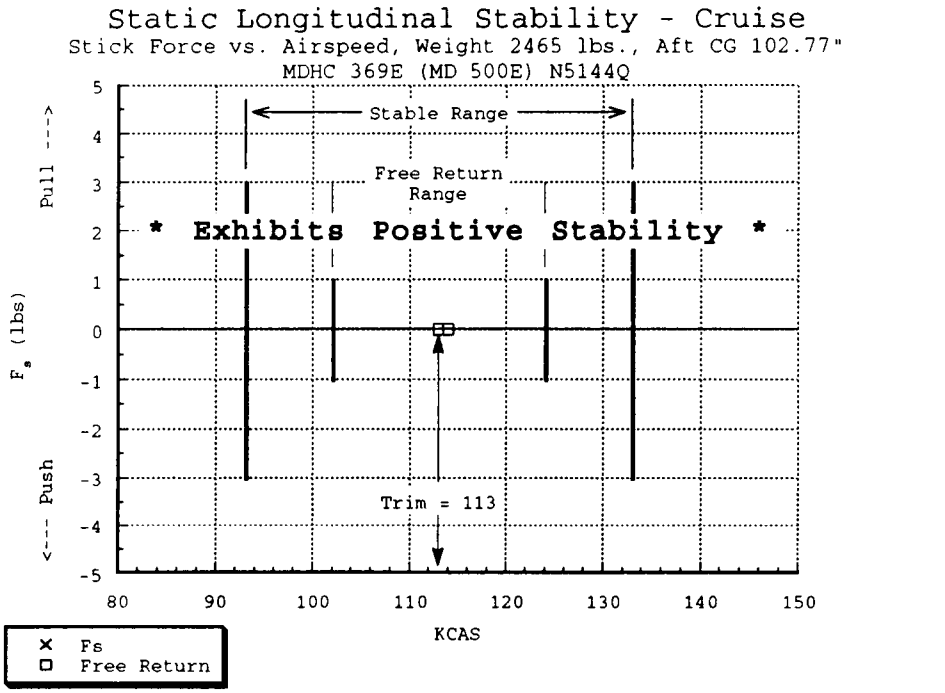


Figure D.2D. Cruise at Light Weight, Aft CG.

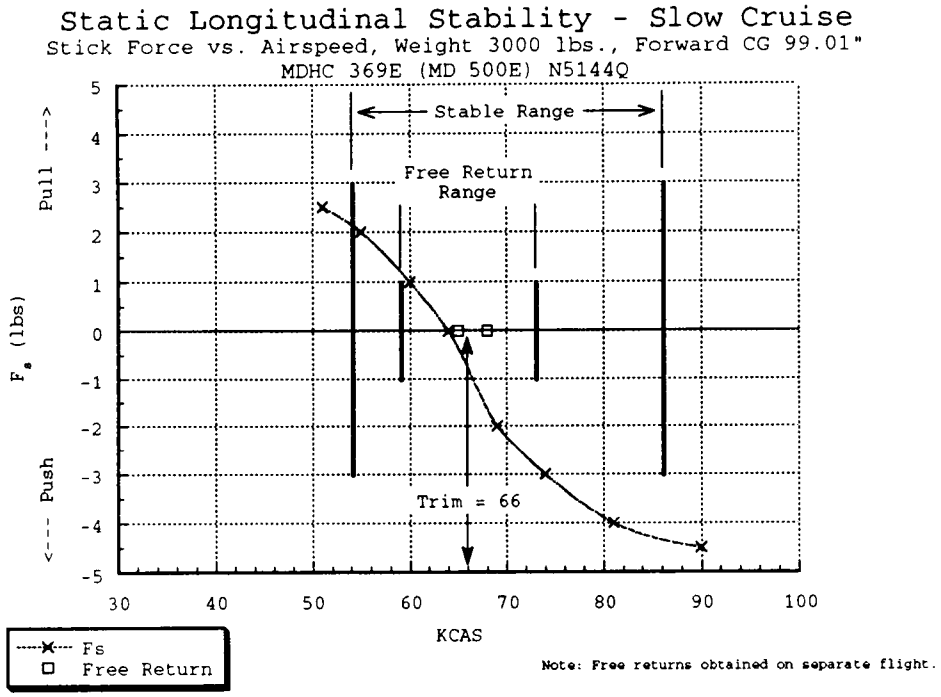


Figure D.3A. Slow Cruise at Heavy Weight, Forward CG.

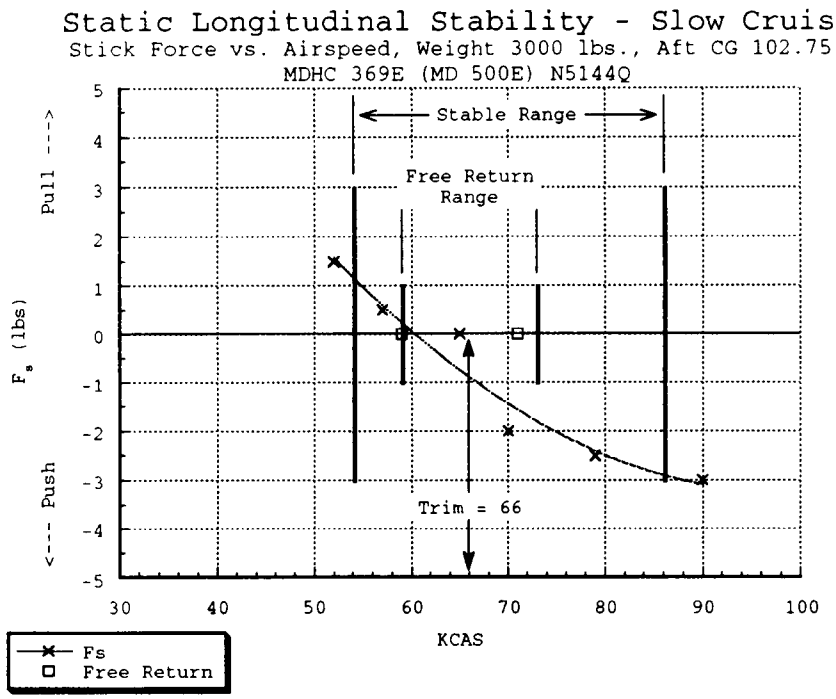


Figure D.3B. Slow Cruise at Heavy Weight, Aft CG.

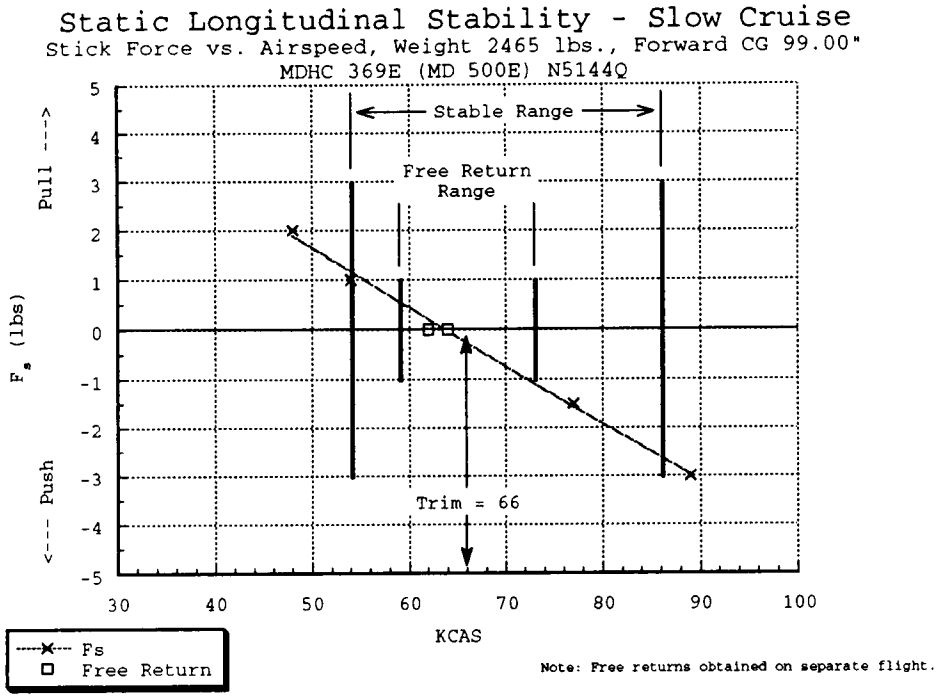


Figure D.3C. Slow Cruise at Light Weight, Forward CG.

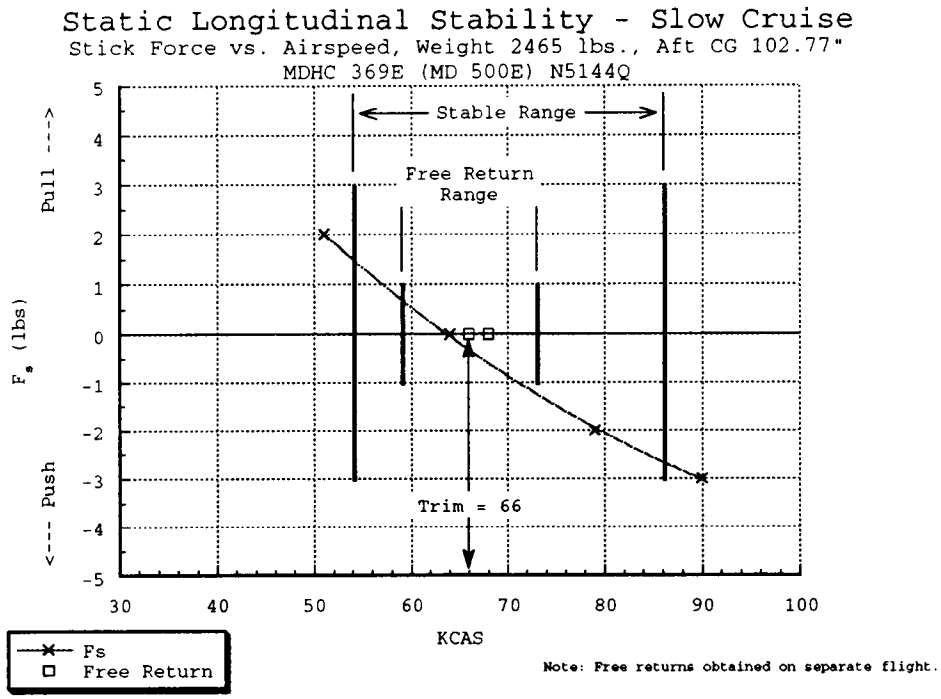


Figure D.3D. Slow Cruise at Light Weight, Aft CG.

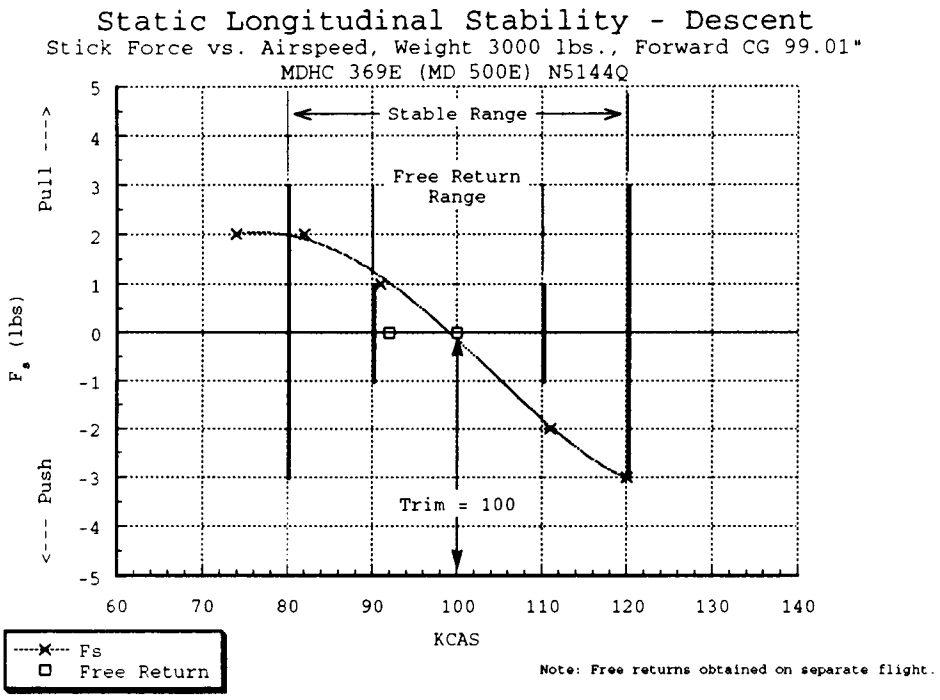


Figure D.4A. Descent at Heavy Weight, Forward CG.

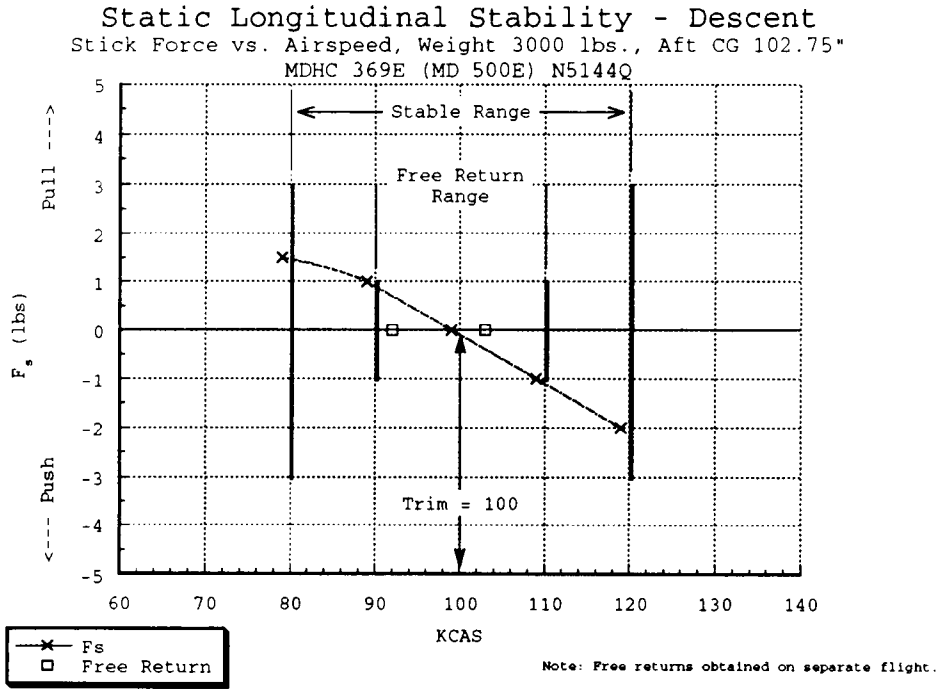


Figure D.4B. Descent at Heavy Weight, Aft CG.

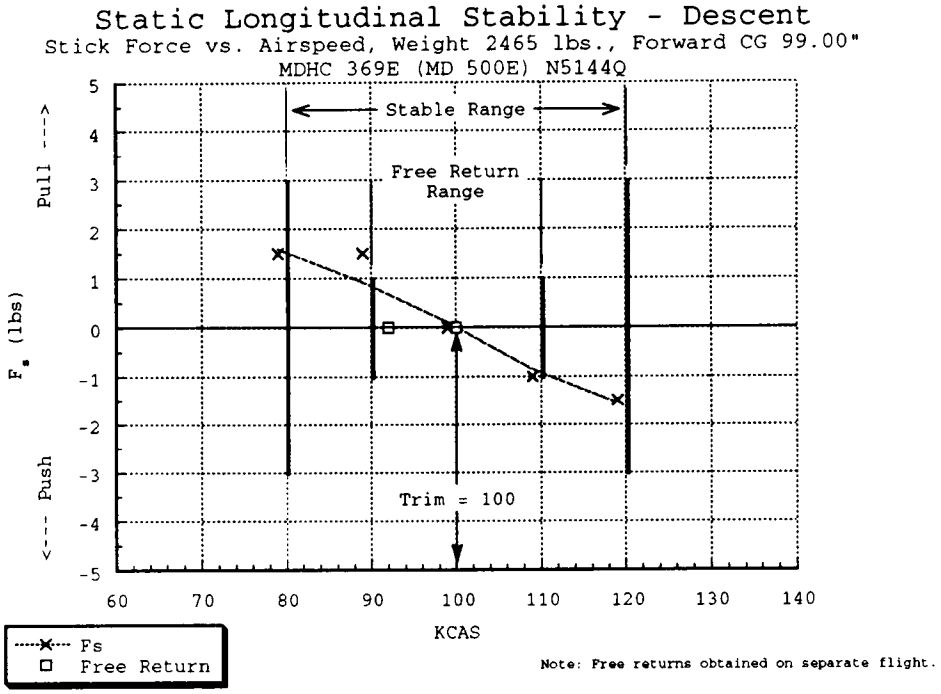


Figure D.4C. Descent at Light Weight, Forward CG.

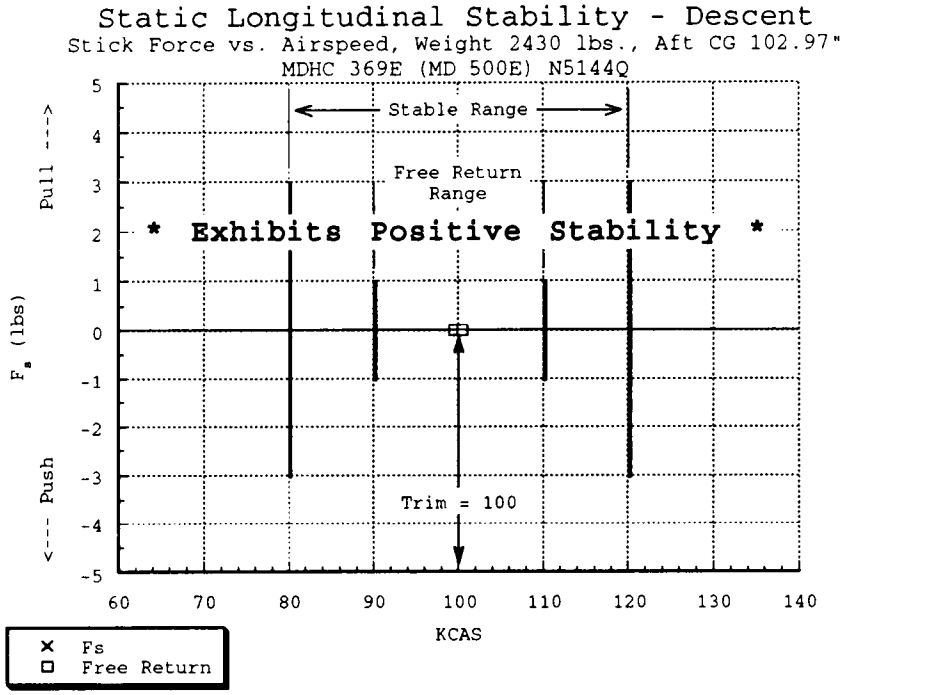


Figure D.4D. Descent at Light Weight, Aft CG.

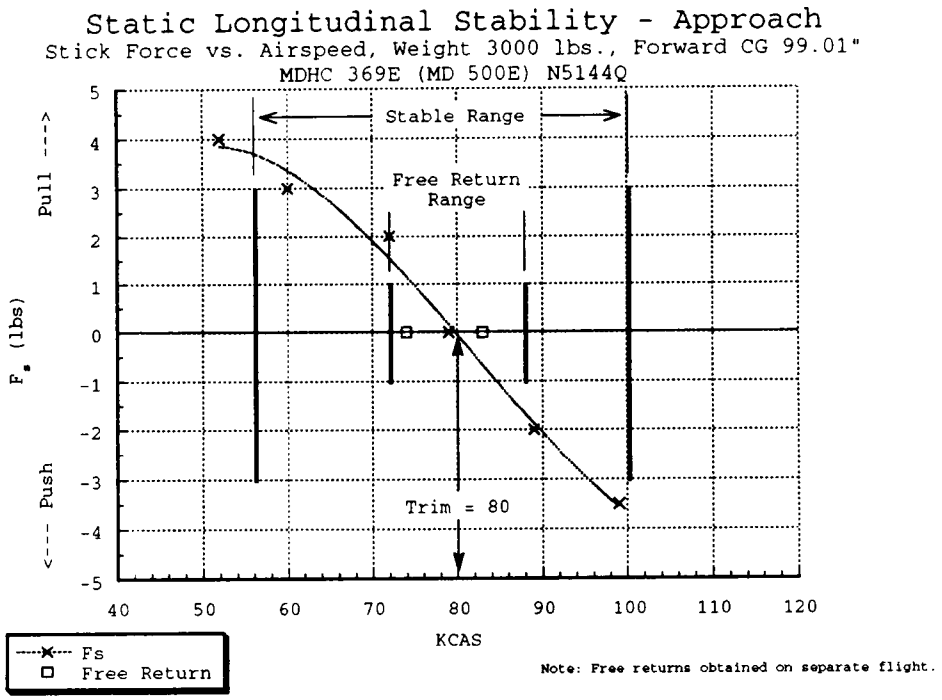


Figure D.5A. Approach at Heavy Weight, Forward CG.

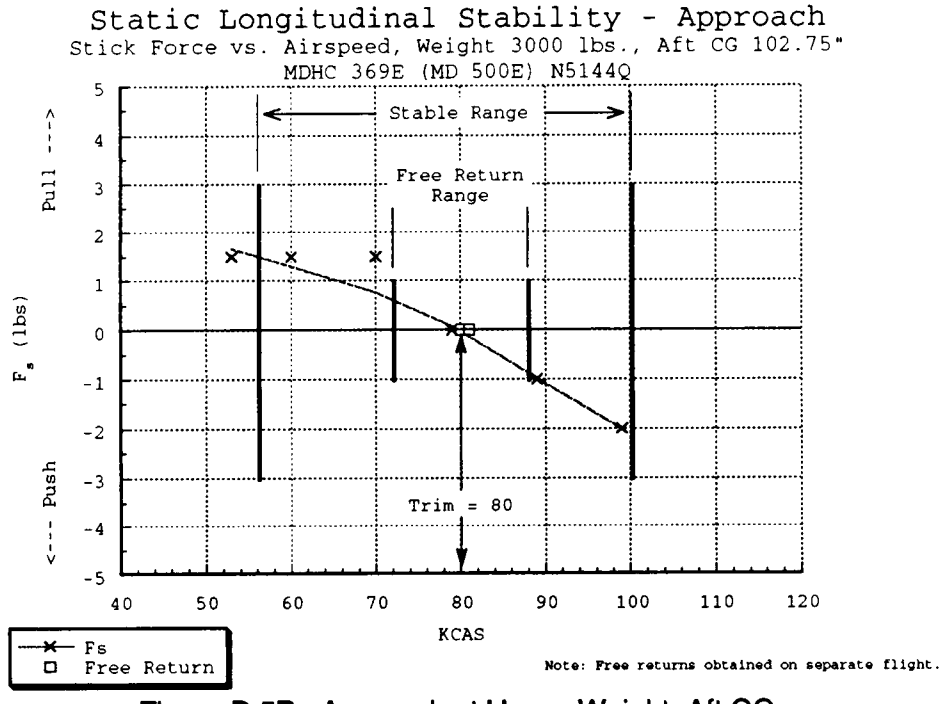


Figure D.5B. Approach at Heavy Weight, Aft CG.

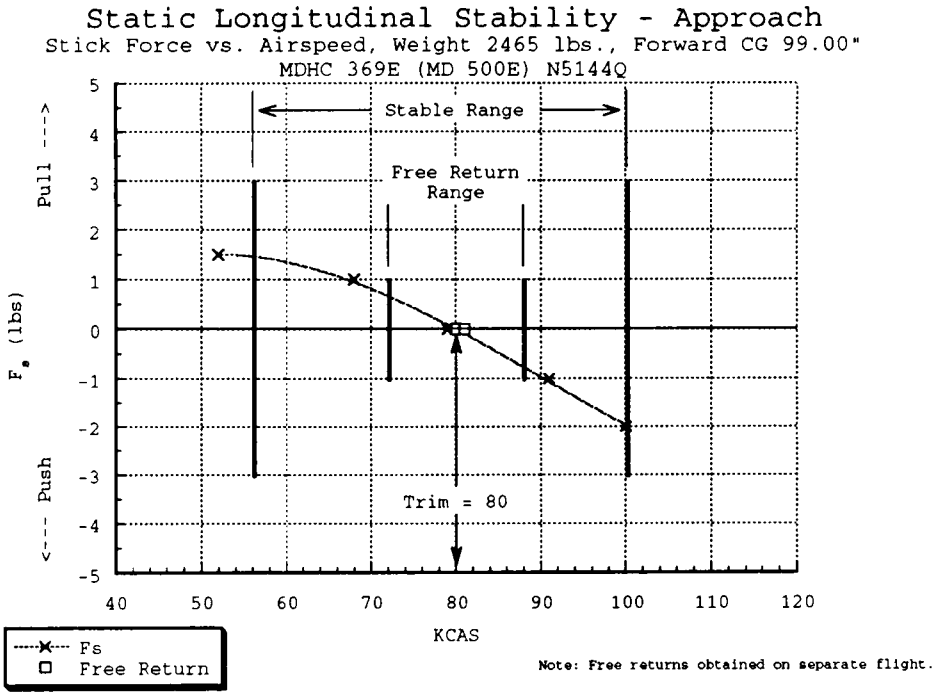


Figure D.5C. Approach at Light Weight, Forward CG.

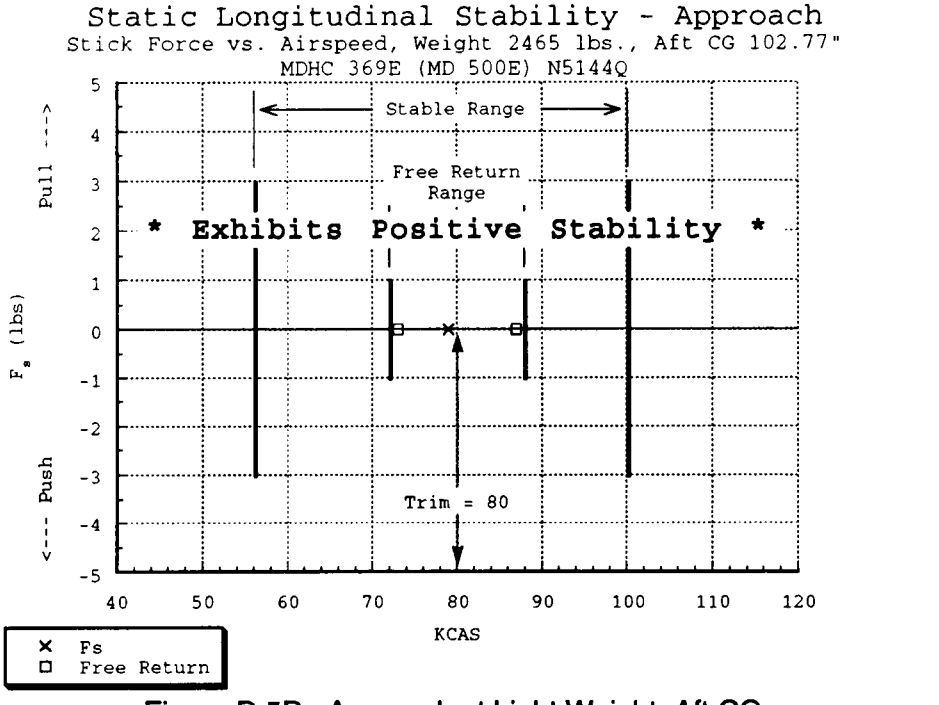


Figure D.5D. Approach at Light Weight, Aft CG.

APPENDIX E

FAA Response to Limited TIA Evaluation of N5144Q

Reference: FAA Project No. 170-869

FAA evaluation of the McDonnell-Douglas Model 369E, S/N 0007E, was being conducted to determine compliance with FAR 27 single pilot IFR requirements in accordance with Type Inspection Authorization SW-170-869, dated April 11, 1994. Testing was discontinued on August 30, 1994, [...].

[...] The following certification issues have been identified during these limited evaluations and should be resolved prior to completion of the TIA.

1. Static Longitudinal Stability. The static longitudinal stability does not comply with the requirements of FAR 27, Appendix b, IV(b) in that a substantial speed change does not result in a stick force that is clearly perceptible to the pilot.

UTSI flight test report indicates the static longitudinal stability was weakly positive for those configurations and conditions tested. The data was based on measurement of the cyclic control forces required to "fly" the aircraft away from the trim conditions, and were obtained during very stable atmospheric conditions. When the control forces were released under these conditions the aircraft returned toward the trim condition.

The first FAA evaluation was conducted during mild turbulence and the static longitudinal stability and the return to trim was not apparent. The second evaluation was conducted during stable atmospheric conditions and the aircraft exhibited weak positive stability and return to trim for a heavy-forward c.g. configuration; but neutral stability at a density altitude near 10,000 feet with the aircraft at light weight, mid c.g. configuration.

2. Cockpit Design. [...].

3. The lack of turn-and-bank failure annunciation. [...].

4. Cross Coupling. The IFR handling qualities are degraded by significant coupling between the axes. The aircraft does not comply with the requirements of FAR 27.171 in that undue pilot fatigue will result from IFR operations for the expected duration of flight time.

The limited evaluation indicates the most objectionable couplings are between the yaw and roll axes and between the heave (collective) and pitch axes. The aircraft stability seems to be adversely affected by an "out-of-trim" condition and this is further complicated by the displacement of the primary flight instruments to the right of the forward eye position. Additionally, the

collective position is sensitive to aircraft "g" loading, and small positive pitch rates result in downward force on the collective. Adjustment of collective friction to prevent this nuisance coupling will hinder pilot response to an engine failure and potentially result in excessively low rotor RPM.

5. Autopilot. [...].

6. Failure Modes. [...].

End of issues.

You must determine what modifications to the aircraft or the proposed operational envelope are necessary to demonstrate compliance with the applicable portions of FAR 27. If you have justification why these issues should not prevent approval, "equivalent levels of safety" findings or "petition for exemptions" must be considered by the FAA. Please advise this office when you have modified the helicopter or the proposed operational envelope to insure compliance with the regulations.

Source: Federal Aviation Administration. Southwest Region. Aircraft Certification Service: Rotorcraft Directorate, ASW-100. Fax to Joel Schneider from Larry Kelly on September 27, 1994.

APPENDIX F

UTSI Response to FAA Certification Issues

November 1, 1994

Mr. Larry M. Kelly
Manager, Rotorcraft Certification Office
ASW-170
2601 Meacham Blvd.
Fort Worth, TX 76137-4248

Dear Mr. Kelly:

Reference: FAA Project No. 170-869 and Mr. Kelly's letter dated Sep. 23, 1993.

We have carefully reviewed and considered all of the certification issues addressed in your letter of Sep. 23, 1994 and wish to submit the following responses which we believe adequately answers your concerns regarding the "one time" STC for single pilot IFR for N5144Q:

1. Static Longitudinal Stability. We disagree that the static longitudinal stability does not comply with the requirements of FAR 27, Appendix B, IV(b). In fact, a stick force does exist that is not only clearly perceptible to the pilot with airspeed change but also measurable with stable slopes for the loadings and altitudes for which we are requesting certification. This is shown in our Flight Test Report previously submitted.

The case where your pilot said he experienced neutral stability is inapplicable, because at the time he was 2000 feet above our requested maximum altitude of 8,000 feet density altitude. He also misstated that he was in the middle of the C.G. envelope. In fact, he was at the requested aft C.G. for IFR flight at light weight.

This helicopter exhibits stick force characteristics that are equal to or greater than many light aircraft that have been certified for instrument flight. We see no reason why this helicopter, as equipped, should be held to a higher standard than these aircraft which have a history of being operated safely during single pilot IFR.

It should be noted, however, if the autopilot is engaged during speed changes, the aircraft will be trimmed to the new speed, so that when the autopilot is disengaged there will be no control force remaining and the aircraft will be "in trim" at the new speed.

It should be further noted that this aircraft has a five inch attitude director

indicator and flight director. This system operates independent of the autopilot and under IFR conditions will significantly reduce pilot workload.

2. Cockpit Design. [...].

3. The lack of a Turn-and-Bank Failure Annunciator. [...].

4. Cross Coupling. We disagree that "The IFR handling qualities are degraded by significant coupling between the axes. The aircraft does not comply with the requirements of FAR 27.171 in that undue pilot fatigue will result from IFR operations for the expected duration of flight time." This conclusion appears unfounded and not warranted by the available data.

First, in the IFR Flight Manual Supplement that we submitted, we are requiring that the Yaw SAS be operative and ON for IFR flight. This Yaw SAS eliminates coupling between the yaw and roll axis. In as much as all helicopters suffer from coupling between the heave and pitch axes, we do not feel that this helicopter is significantly different than helicopters that are already certified for IFR flight.

The problem regarding the collective and "g" loading existed during original VFR certification of the helicopter and we wonder why it is any more of a problem now than it was then. Engine failures and autorotations can occur at any time and are more likely to occur VFR than IFR just due to the amount of time spent in each mode of flight. We believe that this aspect of the helicopter is more related to pilot training than to any relation between VFR vs. IFR flight. A pilot who has had a proper transition into this helicopter will not be affected by this predictable and manageable feature.

5. Autopilot. [...].

6. Failure Modes. [...].

End of Issues.

We have completed all modifications to the helicopter that will bring it into compliance with the regulations as we understand them. There are, however, some outstanding issues that we believe are a matter of pilot opinion. The applicant, who will be the sole operator of this helicopter with this "one time" STC feels that this helicopter is a superior IFR machine to one he previously owned and operated that did have multiple, single pilot IFR approval obtained by its manufacturer. He is a well qualified pilot who operates single pilot IFR jet aircraft on a regular basis. We feel that it will be

infinitely safer for him to operate this helicopter single pilot IFR than to "scud run" as he must now do.

We are ready to resume testing at your earliest convenience. If you have questions please contact Dr. Ralph Kimberlin at [...].

Sincerely,

Ralph D. Kimberlin, PhD.
Program Chairman, Aviation Systems
FAA Flight Test DER SO-264

Attachment

xc: Dr. Joel Schneider

Source: UTSI. Letter to Larry Kelly (FAA) from UTSI Flight Research on November 1, 1994. Tullahoma, TN: UTSI Flight Research, 1994.

VITA

Roger A. Huneycutt was born to Marolyn Lou and Don Lee Huneycutt on March 22, 1968, in the town of Jackson, Tennessee. Raised in Jackson, he graduated from Jackson Central Merry High School in 1986 where he had been an all state trumpet player. An extreme interest in aviation led him to pursue civilian flight training in 1984, and in 1986 he received his private pilot's license. Remaining in Jackson, he attended Lambuth College where he majored in mathematics with an emphasis in computer science and physics. Graduating with top honors, he received his Bachelor of Science degree from Lambuth in 1990. In 1991, he received a one-year fellowship from the University of Tennessee for graduate study in Aviation Systems at the University of Tennessee Space Institute (UTSI) in Tullahoma, TN. From 1992 to 1994, he served as a graduate research assistant for UTSI Flight Research where he worked on a number of projects including the MD 500E flight test upon which this thesis is based. After graduation, he intends to marry his fiancée, Frédérique S. Auzeill.