8-2006

Flight Test Investigation of Propeller Effects on the Static Longitudinal Stability of the E-2C Airplane

Glenn Richard Jamison
University of Tennessee - Knoxville

Recommended Citation

Jamison, Glenn Richard, "Flight Test Investigation of Propeller Effects on the Static Longitudinal Stability of the E-2C Airplane. " Master's Thesis, University of Tennessee, 2006.
https://trace.tennessee.edu/utk_gradthes/1704

To the Graduate Council:

I am submitting herewith a thesis written by Glenn Richard Jamison entitled "Flight Test Investigation of Propeller Effects on the Static Longitudinal Stability of the E-2C Airplane." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

U. P. Solies, Major Professor

We have read this thesis and recommend its acceptance:

Stephen Corda, Rodney Allison

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Glenn Richard Jamison entitled “Flight Test Investigation of Propeller Effects on the Static Longitudinal Stability of the E-2C Airplane.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

U. P. Solies
Major Professor

We have read this thesis
and recommend its acceptance:

Stephen Corda

Rodney Allison

Accepted for the Council:

Anne Mayhew
Vice Chancellor and
Dean of Graduate Studies

(Original signatures are on file with official student records.)

FLIGHT TEST INVESTIGATION OF PROPELLER EFFECTS ON THE STATIC LONGITUDINAL STABILITY OF THE E-2C AIRPLANE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Glenn Richard Jamison
August 2006

ACKNOWLEDGMENTS

Since 1997, the men and women of the NP2000 Integrated Product Team have tirelessly labored to design, integrate, test, and field the replacement NP2000 propeller system for the Hawkeye Fleet. Without the efforts of this dedicated group of professionals, the Navy would not have received the quality product it now has operationally deployed. I would like to particularly thank Joe Spelz, whose leadership and commitment since program inception managed to keep the test program on course with only minimal rudder-steers. I also thank Ed Breau and Fred Schaefer for their sage knowledge and support while investigating the handling qualities and performance characteristics associated with the prototype propeller system. Lastly, I thank my wife Carolyn for her support and understanding during my tenure with the NP2000 Test Program and during the time later spent writing this thesis.

ABSTRACT

A flight test investigation of the E-2C airplane fitted with two different propeller designs – the Hamilton-Sundstrand model 54460-1 and model NP2000 – was conducted to study propeller effects on airplane static longitudinal stability. Test measurements were recorded at predetermined, mission-representative flight conditions for each propeller model while maintaining the remaining component contributions to longitudinal stability constant. Results were compared at similar test conditions to isolate changes in static stability resulting from a change in propeller contribution. Static elevator position neutral points were determined for those test conditions that indicated a definitive change in airplane static stability as a result of changing propeller design. The results of this work indicated that replacing the model 54460-1 with the model NP2000 propeller reduced the stick-fixed static longitudinal stability of the E-2C in the landing approach configuration, causing an approximate 3x change in the slope of elevator deflection versus airspeed and a 2% forward shift of the static neutral point at landing approach airspeeds.

PREFACE

Shortly before graduating from the U.S Naval Test Pilot School in June 1999, the author was visited by his soon-to-be Department Head and advised to garner as much knowledge as possible regarding propeller effects on airplane performance and flying qualities, as he was slated to be the Lead Test Pilot for a prototype, eight-bladed replacement propeller system for the E-2C Hawkeye. At that time however, propeller theory and test methods were not a part of the school's curriculum, and there was a dearth of propeller test programs in recent history from which to draw experience.

Upon reporting to the test program, the author learned that, among the myriad challenges in planning the flight test evaluation of the new propeller, the effects on airplane static longitudinal stability were of particular concern. Because program fiscal restraints prohibited wind-tunnel testing, and also due to a want for documented test results for similar airplane geometries and propeller designs, these concerns were to be answered only through flight test investigation.

The author successfully conducted the first flight of the E-2C equipped with the prototype propeller system – designated the model NP2000 – on April 19, 2001. Before his departure from the test program, he piloted an additional 17 test flights that expanded the airplane envelope and documented NP2000 propeller effects on airplane stability. The author currently looks forward to his return to the Hawkeye fleet in 2007 when he will lead an E-2C squadron during its transition to the new propeller system.

DISCLAIMER

The analyses, opinions, conclusions, and recommendations expressed herein are those of the author and do not represent the official position of the Naval Air Warfare Center, the Naval Air Systems Command, or the United States Navy. The author's conclusions and recommendations should not be considered attributable to any of the aforementioned authorities or for any purpose other than fulfillment of the thesis requirements.

TABLE OF CONTENTS

CHAPTER PAGE

TABLE OF CONTENTS (continued)

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

SYMBOLS

A	wing aspect ratio, b^2/S
B	propeller blade area
b	wingspan
b_t	tailplane span
C_L	lift coefficient, $L/(qS)$
C_m	pitching moment coefficient, $M/(qS\bar{c})$
$C_{m\delta e}$	derivative of C_m with respect to elevator deflection angle
C_{Np}	propeller normal force coefficient, $N_p/(qS_p)$
C_T	propeller thrust coefficient, $T_p/(\rho n^2 D^4)$
$\bar{c}$	mean aerodynamic chord
D	propeller diameter
F_s	control stick, or control yoke, force
H_p	pressure altitude
h_p	z-axis (vertical) distance from center of gravity to propeller
L	lift
l_p	x-axis (horizontal) distance from center of gravity to propeller
l_t	distance from center of gravity to tail aerodynamic center
M	pitching moment
N	number of propeller blades
N_p	propeller normal force
n	propeller rotational speed
P	power available
q	dynamic pressure
q_t	tail dynamic pressure
S	wing reference area
S_e	elevator area
S_f	flap area
S_p	propeller disc area
S_t	tailplane area
T_p	propeller thrust force
V_c	airspeed, calibrated
V_e	airspeed, equivalent
V_i	airspeed, indicated
V_T	airspeed, true
W	airplane gross weight
W_0	airplane zero-fuel gross weight
W_{TO}	airplane maximum takeoff gross weight
x_{AC}	location of aerodynamic center on longitudinal (x) axis

SYMBOLS (continued)

x_{CG}	location of center of gravity on longitudinal (x) axis
$x_{n.p.}$	location of stick-fixed neutral point on longitudinal (x) axis
Y_p	propeller side force
α	angle of attack
α_p	propeller angle of attack, or inflow angle
Δ	symbol denoting differences
δ_e	elevator deflection angle
$\delta_{eCL=0}$	elevator deflection angle required for zero airplane lift coefficient
ε	wing upwash
ε_t	downwash at the tailplane
ϕ	airplane roll angle
γ	flight path angle referenced to horizon
η_p	propeller efficiency, T_pV_T/P
θ	airplane pitch angle
ρ	air density
σ	propeller solidity, NB/S_p
ψ	airplane yaw angle

ACRONYMS

AOA	angle of attack
BIS	board of inspection and survey
CG	center of gravity
HMI	human-machine interface
ISHP	indicated shaft horsepower
ITT	integrated test team
MAC	mean aerodynamic chord
OFT	operational flight trainer
PCM	pulse code modulation
TED	trailing edge down
TEU	trailing edge up

REFERENCED TEST PROGRAMS

In chronological order:

E-2C Board of Inspection and Survey (BIS) Trials

Original flight trials of the E-2C airplane. Program documented the flying qualities and performance characteristics of the E-2C before it entered service with the U.S. Navy. Report of test results, NATC Technical Report FT-38R-74, published 13 May 1974.

Operational Flight Trainer (OFT) Test Program

Flight test program conducted to update flying qualities and performance database in order to support OFT development. Report of test results, NAWCAD Report No. NAWCADPAX-98-95-TEDR, published 14 September 1998.

Baseline Test Program

Flight test program conducted in support of the NP2000 Test Program (see next); established reference baseline for E-2C fitted with the Hamilton-Sundstrand model 54460-1 propeller against which changes attributed to the model NP2000 propeller were measured. Flight tests conducted between January and March 2000.

NP2000 Test Program

Evaluation of the E-2C fitted with the Hamilton-Sundstrand model NP2000 propeller. Program covered multiple disciplines, to include flying qualities and performance, propulsion system compatibility and loads, structural loads, human-machine interface (HMI), and carrier-suitability. Report of test results for handling qualities and performance characteristics, NAWCADPAX/RTR-2005-7, published 6 May 2005.

CHAPTER 1

INTRODUCTION

The effects of propeller and slipstream on airplane static longitudinal stability are generally significant, and while decades of experience with propeller-driven aircraft exist, accurate predictions of these effects remain difficult even today. Although some propeller effects have been successfully accounted for through theoretical analysis, many are still determined experimentally through wind-tunnel and flight testing. Estimating such effects during the design process frequently requires empirical knowledge of similar designs. Unfortunately, research availability for modern propeller-driven airplane designs is limited, particularly for the high power loadings being considered today.[1] Until a comprehensive analytical method is developed for the wide range of propeller designs and variations in airplane geometry, designers will continue to rely on an empirical knowledgebase for predicting propeller effects on static stability.

One of the challenges of flight test is definitively isolating the specific causal factors for an observed airplane characteristic. Because the net airplane response is observed, it is difficult to isolate the component contributions of the wing, fuselage, tail, and propeller to the measured static longitudinal stability of the airplane. This often forces designers to use wind-tunnel experimentation in order to isolate propeller effects.[2] A propeller refit program initiated in 1997 for the E-2C airplane provided an opportunity to directly measure the effects of a modern propeller design on static longitudinal stability. By comparing airplane stability with the original propellers to that measured with the replacement propellers installed, and maintaining all other component contributions constant, the resultant change in static stability could be attributed to a change in the propeller contribution. Documenting these findings adds to the empirical knowledgebase for high-powered, multi-engine aircraft configured with advanced propeller designs, and is of value to future designers seeking a reference for predicting propeller effects on the static stability of their designs.

NP2000 TEST PROGRAM

The propeller refit program materialized from a requirement to replace the Hamilton-Sundstrand model 54460-1 propeller on the E-2C airplane (figure 1). Installed on the E-2C since 1974, the model 54460-1 was removed from production in 1991, creating a need for a replacement propeller to meet fleet attrition and new airplane production requirements.

Figure 1. E-2C Airplane Fitted with the Model 54460-1 Propeller
Source: www.globalsecurity.org

In October 1997, the U.S. Navy contracted Hamilton-Sundstrand to design and produce the model NP2000, an eight-bladed, all-composite, digitally controlled propeller system featuring an aerodynamically advanced blade planform. An Integrated Test Team (ITT) was formed to plan and conduct the NP2000 Test Program, a comprehensive flight test evaluation of the new propeller fitted to the E-2C airplane. Planned to span two years and over 260 flight hours, the program integrated multiple disciplines, including classical flying qualities and performance, propulsion system compatibility, propulsion loads, and airframe structural loads and dynamics. To establish a current reference against which to quantify differences resulting from installation of the new propeller system, a Baseline Test Program was conducted to gather flight test data for the E-2C fitted with the original model 54460-1.[3]

The model NP2000, shown installed on the test airplane in figure 2, incorporated several design features that differed significantly from the model 54460-1. Blade planform and spinner design reflected considerable advances in propeller design, while propeller solidity (ratio of total blade area to disc area) was increased with the adoption of the eight-bladed design.

Of particular interest was the impact the NP2000 propeller would have on airplane static longitudinal stability. Although there were no comparable programs upon which predictions for the NP2000 propeller could be based, it had been established that increasing solidity is potentially destabilizing for a forward-mounted propeller configuration.[1] Since results from the original flight trials completed in 1974 indicated

Figure 2. Model NP2000 Propeller Installed on Test Airplane
Source: NP2000 ITT Archives, photo by Vernon Pugh.

the E-2C was characterized by weak to neutral static longitudinal stability through much of its operating envelope,[4] installing the NP2000 might result in an unacceptable reduction in stability. Due to time and cost considerations, wind-tunnel tests were not feasible. NP2000 propeller effects on static longitudinal stability therefore had to be determined through flight test investigation.

OBJECTIVES

The objective of this work was to measure, through flight test experimentation, the effects of the model NP2000 propeller on the static longitudinal stability of the E-2C airplane. A corollary of this work was the documentation of propeller influences on static stability for high-powered, multi-engine airplane geometries incorporating modern propeller designs. The results of this investigation will aid in future predictions for propeller effects on stability, and are of value to designers and testers involved with similar airplane configurations and propeller designs.

SIGN CONVENTIONS

A note on the sign conventions employed for this work – some of the conventions used herein differ from those frequently accepted in the study of airplane stability and control, and should be kept in mind for this work. While standard conventions were used for positive linear and angular directions in relation to the body-fixed reference frame of the airplane (figure 3), positive control deflections and positive control forces were defined as those generating *positive* moments about the axis system – i.e. trailing edge up (TEU) elevator deflection, generating a nose-up pitch, is positive, and thus the term $C_{m\delta e}$ has a positive value.

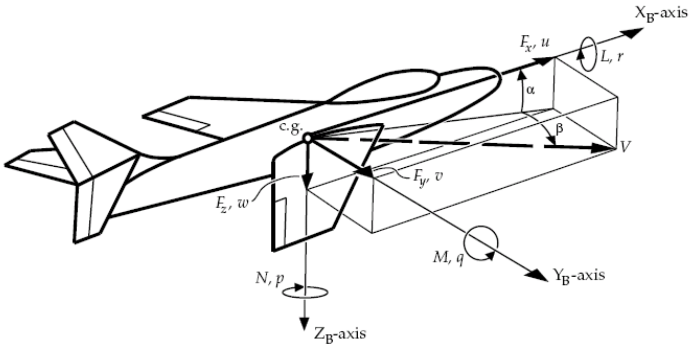

Figure 3. Orientation of Linear and Angular Directions
Source: www.xs4all.nl/~rauw/fdcreport/FDC14_preview_007.pdf, by Mark Rauw.

CHAPTER 2

THEORY

STATIC LONGITUDINAL STABILITY DEFINED

Static longitudinal stability relates to the variation of pitching moment about the airplane's center of gravity with angle of attack. An airplane is said to exhibit positive static longitudinal stability if the initial tendency following a disturbance in pitch from equilibrium flight is a return to trim condition. Expressed mathematically in non-dimensional form, with nose-up pitch defined as positive, the variation of pitching moment coefficient (C_m) with angle of attack (α) for positive stability must be negative:

$$\frac{dC_m}{d\alpha} < 0 \tag{1}$$

Since angle of attack relates directly with lift coefficient for the unstalled flight regime, static longitudinal stability may also be expressed as the variation of pitching moment with lift coefficient (C_L).[5] For positive stability:

$$\frac{dC_m}{dC_L} < 0 \tag{2}$$

The *neutral point* is that center of gravity (CG) location for which the airplane demonstrates neutral static longitudinal stability, or, for which the expression dC_m/dC_L is equal to zero. Because CG locations forward or aft of the neutral point result in positive or negative stability, respectively, the neutral point is a primary determinant of the airplane's CG envelope. The neutral point is frequently presented in terms of percent mean aerodynamic chord (%MAC), a non-dimensional value determined by measuring the location from the leading edge of the wing mean aerodynamic chord and dividing by the mean aerodynamic chord length, $\bar{c}$.

PROPELLER INFLUENCE

Propeller contributions to static longitudinal stability are identified as either direct or indirect.[5] Direct effects are those contributions to airplane pitching moment resulting from forces generated by the propeller and acting at the plane of rotation. Indirect effects result from propeller slipstream interaction with the wing and tailplane. The propeller direct effects will be discussed first.

The force generated by a rotating propeller can be resolved into components acting along the axis of rotation and parallel to the plane of rotation (figure 4). Of primary interest to this investigation was the propeller normal force component (N_P) acting in the plane of rotation and upward with respect to the airplane body.

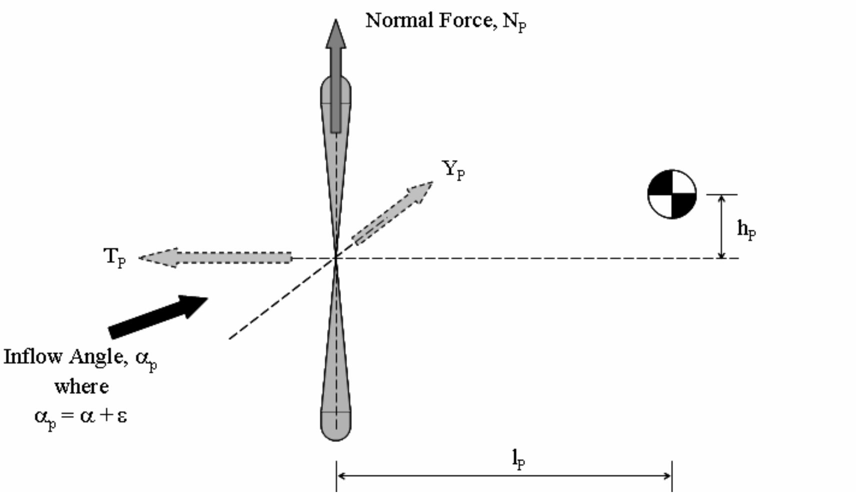

Figure 4. Propeller Direct Effects

The normal force contribution to airplane pitching moment is a function of the distance, l_p, from the CG to the propeller plane of rotation. In non-dimensional form, where N_p is the propeller normal force and S_p is the propeller disc area:

$$C_m\Big|_{prop} = C_{Np}\frac{l_p}{\bar{c}}\frac{S_p}{S}\text{, where } C_{Np} = \frac{N_p}{qS_p} \qquad (3)$$

To determine the normal force contribution to stability, the influence of wing upwash (ε) on the propeller inflow angle (α_p) must be included. Differentiating equation 3 with respect to α and adding wing upwash results in the following:

$$\frac{dC_m}{d\alpha}\Bigg|_{prop} = \frac{dC_{Np}}{d\alpha}\frac{l_p}{\bar{c}}\frac{S_p}{S}\frac{d\alpha_p}{d\alpha}\text{, where } \frac{d\alpha_p}{d\alpha} = 1+\frac{d\varepsilon}{d\alpha} \qquad (4)$$

Since $d\alpha_p/d\alpha$ is a function of wing aspect ratio and propeller location with respect to the wing quarter chord,[6] all the right-side terms in equation 4 remained constant for this investigation (values for S_p and l_p were the same for both propeller installations) except for the variation of normal force with angle of attack, $dC_{Np}/d\alpha$.

It is known that C_{Np} increases nearly linearly with α through much of the angle of attack range; at higher values of α, the gradient remains positive but begins to decrease.[1] It is therefore observed that for a propeller mounted forward of the airplane CG (positive value of l_p), all the terms in equation 4 are positive and thus the propeller contribution is destabilizing. It has also been demonstrated that the increase in C_{Np} with α is greater and that the linear range is slightly larger for propellers of higher solidity (σ),[1] as represented in figure 5. Increasing propeller solidity is therefore destabilizing for a forward-mounted propeller configuration.

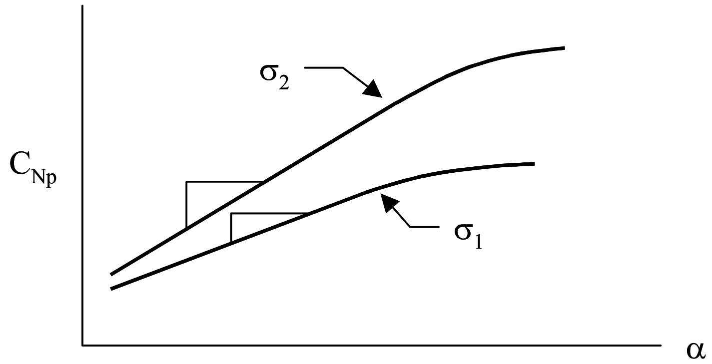

Figure 5. Influence of Solidity on C_{Np} Variation with α

Now consider the propeller indirect effects resulting from the aerodynamic interactions between the slipstream and the airplane. The main indirect contributions to static pitching moment are slipstream effects on the lift coefficients and lift-curve slopes of the wing and tailplane, slipstream-induced downwash at the tailplane, and the effect of slipstream on fuselage moments.[5] Indirect propeller effects are complex and difficult to predict, and are usually determined empirically through wind tunnel experimentation and flight test. Successful methods have been developed for estimating slipstream effects on wing and fuselage moments. Methods for estimating propeller effects at the tail have been less successful, and generally require experimental data gathered from similarly configured airplanes to provide reasonably accurate predictions.[7]

It is known, however, that airfoil sections immersed in a slipstream are subjected to an increase in lift-curve slope.[2] By applying this knowledge to the component contributions to airplane stability:

$$\left.\frac{dC_m}{d\alpha}\right|_{\text{airplane}} = \left.\frac{dC_m}{d\alpha}\right|_{\text{wing}} + \left.\frac{dC_m}{d\alpha}\right|_{\text{fuselage}} - \left.\frac{dC_m}{d\alpha}\right|_{\text{tail}} + \left.\frac{dC_m}{d\alpha}\right|_{\text{prop}} \quad (5)$$

where: $$\left.\frac{dC_m}{d\alpha}\right|_{wing} = \frac{dC_L}{d\alpha}\left(\frac{x_{CG} - x_{AC}}{\bar{c}}\right) \tag{6}$$

and: $$\left.\frac{dC_m}{d\alpha}\right|_{tail} = \left(\frac{dC_L}{d\alpha}\right)_{tail} \frac{l_t}{\bar{c}} \frac{S_t}{S} \frac{q_t}{q}\left(1 - \frac{d\varepsilon_t}{d\alpha}\right) \tag{7}$$

it can be shown that for the wing contribution, with the CG aft of the aerodynamic center (AC), a slipstream-induced increase to $dC_L/d\alpha$ is destabilizing, and for the tail contribution, slipstream immersion is stabilizing.[5]

FLIGHT TEST

The direct, in-flight measurement of pitching moments about the airplane center of gravity is not feasible. Instead, pitching moments may be obtained indirectly through the measurement of the elevator deflection required to achieve equilibrium conditions – zero pitching moment about the airplane center of gravity. The following expression establishes a relationship between elevator deflection (δ_e) and airplane lift coefficient as a function of pitching moment variation with lift and elevator control power ($C_{m\delta_e}$):

$$\delta_e = \delta_{e_{C_L=0}} - \frac{\left(\frac{dC_m}{dC_L}\right)}{C_{m_{\delta e}}} C_L \text{ [5]} \tag{8}$$

where $\delta_{eC_L=0}$ is the elevator position for zero lift coefficient, and is a constant. Every point described by the curve of the above expression represents equilibrium conditions, that is, the elevator deflection required for each corresponding C_L value to achieve zero pitching moment about the airplane center of gravity. Differentiating equation 8 with respect to C_L yields the following expression for the slope of the elevator deflection versus lift coefficient curve:

$$\frac{d\delta_e}{dC_L} = \frac{-\left(\frac{dC_m}{dC_L}\right)}{C_{m_{\delta e}}} \tag{9}$$

From equation 9, it is seen that the elevator deflection required to vary lift coefficient varies directly with static longitudinal stability and inversely with elevator control power. With trailing edge up elevator deflection defined as positive, the variation of elevator deflection with lift coefficient for positive stability must be greater than zero:

$$\frac{d\delta_e}{dC_L} > 0 \tag{10}$$

This relationship is the basis for the flight test techniques applied in this investigation, since elevator deflection values can be determined directly from in-flight measurements.

STICK-FIXED VERSUS STICK-FREE STABILITY

The relationship of $d\delta_e/dC_L$ with static stability expressed in equation 9 applies to the airplane with the longitudinal control system fixed – the elevator is restrained from responding to flight variables or control system variables. The determination of elevator deflection variation with lift coefficient is therefore, more correctly, an indication of the *stick-fixed* static longitudinal stability of the airplane. It is also of interest to investigate the *stick-free* static longitudinal stability of the airplane since it is the stick-free response that is apparent to the pilot.

Stick-free, or apparent, static longitudinal stability relates to the airplane's stability characteristics when the longitudinal control is free to respond to some in-flight variable. For the irreversible flight control system – one in which the system provides no direct control surface response to aerodynamic forces – the free control response is predominantly a function of programming within the longitudinal control system itself. In figure 6, stick-fixed stability is indicated by the variation of elevator deflection required for equilibrium with lift coefficient; the stick-free response is the programmed elevator deflection versus lift coefficient. For the airplane system illustrated, the pilot is required to move the elevator trailing edge down at lift coefficients below trim condition and trailing edge up at C_L values greater than trim in order to achieve equilibrium.

For *positive* stick-free stability, the pilot must overcome *restoring* pitching moments away from trim by applying longitudinal control force to move the elevator from the programmed deflection to the equilibrium position. Although the in-flight

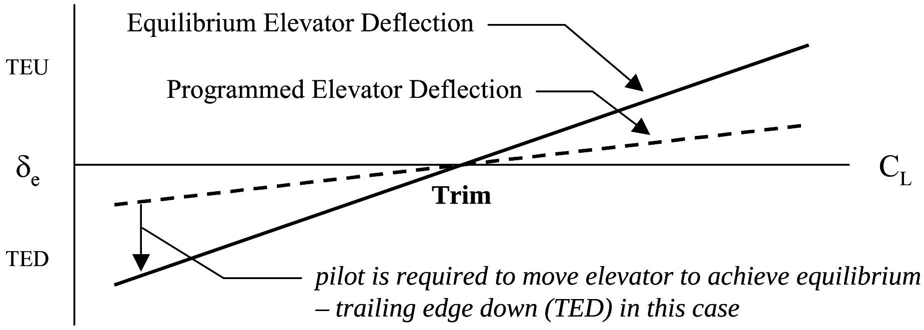

Figure 6. Stick-Fixed vs. Stick-Free Stability

measurement of programmed elevator deflection with lift coefficient is impractical, since the stick-free response away from trim results in non-zero pitching moments and corresponding non-stable conditions, the longitudinal control force required to deflect the elevator from the programmed position to the required equilibrium condition can be readily determined. With longitudinal control pull force – that required to overcome a nose-down pitching moment – defined as positive, the variation of control force (F_s) with lift coefficient for positive stick-free stability must be greater than zero:

$$\frac{dF_s}{dC_L} > 0 \tag{11}$$

NEUTRAL POINT DETERMINATION

Recalling equation 9, it can be seen that when $dC_m/dC_L = 0$, or when the CG is at the stick-fixed neutral point, the slope of the elevator deflection versus lift coefficient curve will also be zero. By applying this relation to δ_e and C_L measurements collected at more than one test CG, a simple method for deriving the neutral point is suggested. For a plot of $d\delta_e/dC_L$ versus center of gravity location, the x-intercept, or the CG at which $d\delta_e/dC_L$ equals zero, is the stick-fixed neutral point (refer to figure 7). Since airplane pitching moments are not being directly measured, the neutral point determined from δ_e versus C_L measurements is more correctly referred to as the stick-fixed *elevator position neutral point.*[5]

Also, because the variation of elevator deflection with lift coefficient is frequently determined to be nonlinear for the real airplane, neutral points are calculated for several

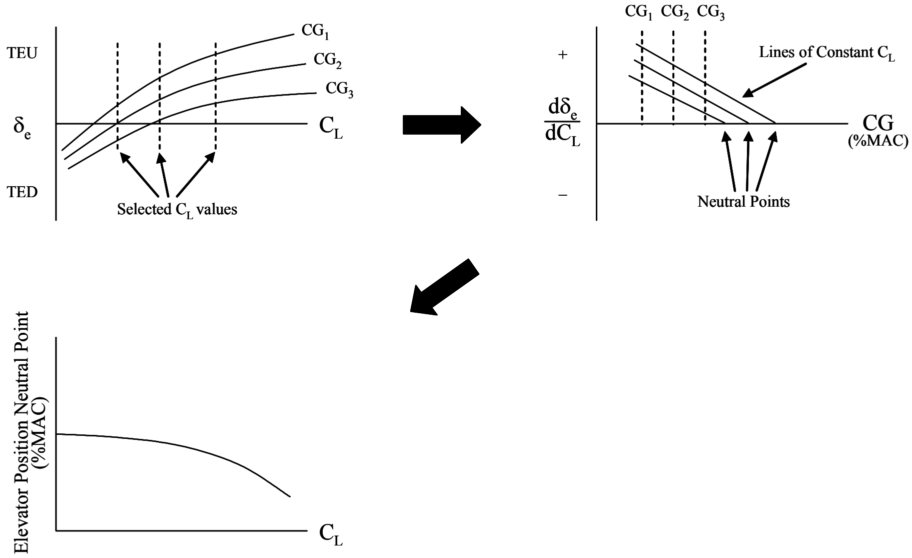

Figure 7. Static Neutral Point Determination

constant values of lift coefficient to describe any movement of the neutral point with varying C_L. By plotting derived neutral points versus lift coefficient, the elevator position neutral point for any value of C_L may be determined from the resultant curve.

CHAPTER 3

TEST AIRPLANE DESCRIPTION

BASIC AIRPLANE

The E-2C Hawkeye was a high-wing, twin-engine turboprop powered airplane manufactured by Northrop Grumman. Designed for carrier and land based airborne early warning and tactical command and control, the airplane is readily identified by its 24 ft diameter horizontal rotodome and four vertical stabilizers on the tailplane (figure 8). The airplane first entered U.S. naval service in September 1972, and, with the exception of an upgraded engine core introduced in 1991, has undergone no significant changes to the basic airframe.[8] The airplane was 57.6 ft in horizontal length and 80.6 ft in wingspan. The airplane's zero-fuel basic weight was approximately 41,000 lb and it could takeoff at gross weights up to 55,000 lb.[9] Tabulated airplane parameters relevant to this investigation are presented below in table 1.

Table 1. Tabulated Parameters, Model E-2C Airplane
Sources: Jane's All The World's Aircraft[8] and E-2C NATOPS Flight Manual[9]

		Wing				Tailplane		Elevator		Flap
W_0 (lb)	W_{TO} (lb)	b (ft)	S (ft^2)	A --	MAC (in)	b_t (ft)	S_t (ft^2)	S_e (ft^2)	δ_e range (deg TEU)	S_f (ft^2)
41,000	55,000	80.6	700	9.3	112.64	28.1	125	40	+25 to -15	119

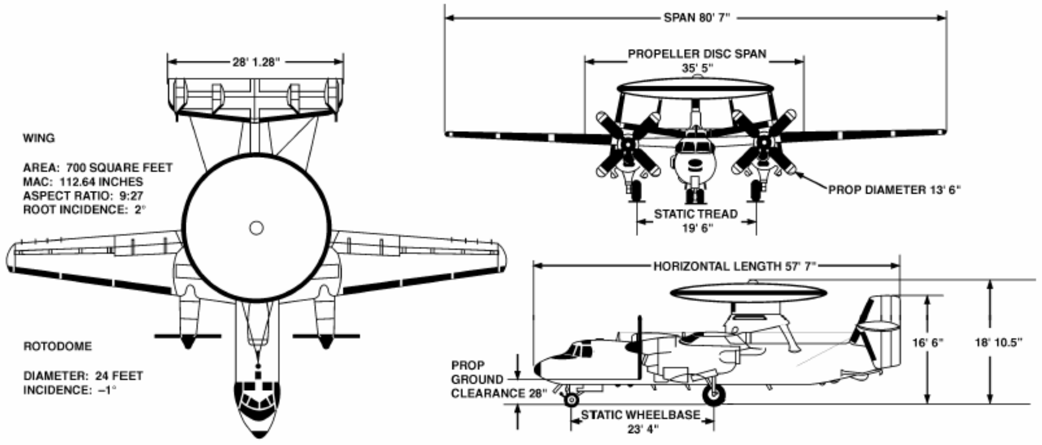

Figure 8. E-2C Three-View
Source: E-2C NATOPS Flight Manual[9]

CONTROL SYSTEM

The primary flight control surfaces – ailerons, elevators, and rudders – were conventionally operated through mechanically interconnected control yokes, columns, and rudder pedals from either the pilot or copilot position. All flight control surfaces were hydraulically actuated and irreversible. To simulate aerodynamic forces, feel springs were incorporated in all three control axes. Control force feedback was further augmented in the longitudinal axis by a pitch-feel system. In the normal mode of operation, dynamic pressure, supplied from the pitot-static system, was converted to an electric signal and sent to a q-feel actuator that scheduled longitudinal feel spring position as a function of airspeed. In the event the automatic mode of pitch-feel system operation failed, a backup mode was available that enabled the pilot to manually control the q-feel actuator via a two-position toggle switch. The longitudinal control system also incorporated bobweights to augment control forces during maneuvering flight.[9]

Longitudinal trim was provided by an electromechanical pitch trim actuator that repositioned the zero force control column position in response to manual actuation of momentary-type switches on the outboard grips of each control yoke. The airplane was fitted with hydraulically operated fowler flaps selectable for 10, 20 and 30 deg of deflection and incorporating automatic long-span aileron droop.[9]

PROPULSION SYSTEM

The E-2C was powered by two Allison T56-A-427 engines, each with a maximum rating of 5,100 Indicated Shaft Horsepower (ISHP). The engines were fitted with four-bladed Hamilton-Sundstrand model 54460-1 constant-speed, reversible propellers.[9] Upon completion of the Baseline Test Program, the engines were refitted with replacement Hamilton-Sundstrand model NP2000 propellers.

The constant-speed, reversible NP2000 propeller system operated at the same rotational speed and retained mass and dimensional properties similar to those of the four-bladed 54460-1, but incorporated eight blades of advanced planform design and a different spinner assembly (figure 9). The NP2000 propellers also featured upgraded digital electronic propeller controls and electronic valve-housing assemblies. Although the NP2000 retained the same diameter and disc area as those of the 54460-1, 13.5 ft and 143.1 ft^2, respectively, solidity was increased approximately 30%, from $\sigma = 0.19$ for the 54460-1 to $\sigma = 0.25$[*] for the NP2000.[3]

---

[*] Values for σ estimated by graphical analysis.

Figure 9. Model 54460-1 vs. Model NP2000
Source: www.globalsecurity.org

TEST AIRPLANE MODIFICATIONS

The test aircraft was equipped with a flight test instrumentation measuring, recording, and telemetry package. Other modifications to the airplane included a right wingtip mounted boom with angle of attack (AOA) and sideslip vanes and a remote pitot-static source, externally mounted telemetry antennas, and cockpit mounted sensitive airspeed, altitude, and load factor indicators that replaced the production indicators. Instrumented parameters applicable to this investigation are listed in table A-1. The test aircraft was not equipped with a functional weapons system, but, for the purposes of these tests, was considered representative of the production aircraft in terms of gross weight and center of gravity.

CHAPTER 4

TEST METHODOLOGY

GENERAL

The approach undertaken for this investigation was to document airplane static longitudinal stability characteristics with first the 54460-1 propeller, and then with the NP2000 propeller installed under similar test conditions, and measure observed changes. By maintaining all other variables constant, measured changes in airplane stability characteristics could be attributed directly to a change in the propeller contribution to static stability.

Theory predicted that the increased solidity of the model NP2000 design would be destabilizing – a result of an increase in the term $dC_{Np}/d\alpha$ in the propeller normal force contribution to static stability. Similar increases in propeller solidity have demonstrated corresponding increases in $dC_{Np}/d\alpha$ of up to 20 to 30 percent.[10] Because the linear range of $dC_{Np}/d\alpha$ is also extended with increased solidity, the destabilizing influence of the normal force contribution was expected to be slightly greater at higher inflow angles (recall figure 5). Differences in slipstream characteristics with the NP2000 were not quantified and therefore propeller indirect effects could not be predicted, however, it was expected the advanced blade design would result in changes to slipstream velocity gradients and therefore possibly alter interactions with the wing and tailplane.

Since it was anticipated that installing the NP2000 propeller would reduce airplane static longitudinal stability, and because fiscal restraints prohibited the use of wind tunnel experimentation for quantifying NP2000 effects on stability prior to flight, particular steps with regard to CG were taken to ensure the safety of the test aircrew and airplane. Initial flight tests with the NP2000 propeller installed were conducted at a CG position forward of the production CG in order to establish a reference for the magnitude of change under a more stable test loading. After comparing the results to those for the 54460-1 propeller at a similar test CG, a decision was made to load the aircraft for a production-representative CG. Additional test loadings necessary for accurately deriving static neutral points were deferred until the end of the NP2000 Test Program at which time the entire structural and performance envelopes of the airplane had been expanded and the static longitudinal stability characteristics for a production-representative CG had been adequately documented.

TEST TECHNIQUE

A stabilized point technique was used during test flights for gathering static longitudinal stability data. Maintaining constant power and trim setting, longitudinal control force and elevator position measurements were taken at airspeed increments above and below a selected trim airspeed. Prior to commencing initial quantitative tests on the NP2000 installation, the pilot performed a qualitative investigation of stick-free stability to ensure proper airplane characteristics – i.e. aft force required with decreasing airspeed – had been maintained with the replacement propeller.

For each set of test conditions, the airplane was stabilized and carefully trimmed at a pre-selected trim airspeed with power set to that necessary for level flight. Without adjusting power or trim setting, airspeed was varied in approximate 5 kt increments above and below the trim airspeed. At each airspeed increment, the aircraft was stabilized and measurements were recorded. Per established convention,[5] off-trim speeds covered a range of at least ± 15% of the trim airspeed in order to sufficiently document stability characteristics about the trim condition. Altitude was maintained within 1,000 ft of the base test altitude by alternating the fast then slow test airspeeds as necessary. Additional airspeed increments were added for redundancy should subsequent data analysis indicate stabilized flight had not been reasonably achieved at each test point.

TEST CONDITIONS

Due to the performance characteristics of the E-2C, test methods that specify collecting data over the entire airspeed envelope at a single trim and power condition, such as those established for certification under Federal Aviation Regulations,[11] could not be employed. Instead, the airspeed envelope was parsed into specific trim/power conditions about which data were collected as previously described. Ideally, the entire envelope would be covered; however, time and cost considerations limited selected test conditions to those mission-representative portions of the operating envelope of greatest interest. Specifically, measurements for the landing approach condition were given priority as this condition resulted in higher propeller inflow angles and greater flap-

Table 2. Selected Test Conditions for Comparison

Configuration[1]	Gear	Flaps	Airspeed	Mission Relation
PA(30)	down	30	20u[2]	Normal landing approach
PA(30)	down	30	130 kt	Landing pattern configuration[3]
CR(0)	up	0	250 kt	Cruise/ferry
CR(0)	up	0	180 kt	Loiter
CR(0)	up	0	145 kt	Approach to stall warning[4]
PA(20)	down	20	20u[2]	Alternate landing approach[5]

Notes: 1. PA=Power Approach; CR=Cruise. Number in parenthesis indicates flap setting. Power set to power required for level flight at the test airspeed.
2. 20u refers to production AOA gauge indication for normal landing approach; equivalent to 6.3 deg and 6.9 deg AOA for PA(30) and PA(20), respectively.[9]
3. 130 kt is the normal crosswind and downwind pattern airspeed for the E-2C.[9]
4. Functional Check Flight requirement.[9] Provided an additional point of comparison at high propeller inflow angles.
5. Alternate landing configuration; also, used for many types of degraded / emergency landings.[9]

induced downwash at the tailplane. Additional test conditions, listed in table 2, were selected to adequately characterize the airplane's stability characteristics for cruise, mission loiter, and an alternate landing configuration.

TEST MEASUREMENTS

Measurements for the parameters listed in table A-1 were collected by an instrumentation package installed in the test airplane. Electrical signals supplied by transducers installed for each parameter of interest were routed through a low-pass signal conditioner to a 4,000,000 bps pulse code modulation (PCM) encoder mounted in the airplane aft-equipment compartment. After a time index was inserted, the PCM stream was recorded to high-density 8mm magnetic tape cartridge by means of an onboard DRS-4 Digital Data Recorder. Telemetry of the PCM stream to a ground-control station allowed engineers to monitor test maneuvers in real-time and provide feedback to the pilot as to maneuver quality. Test conditions and qualitative observations were manually recorded by the pilot on kneeboard cards.

A test airplane weight and balance was performed prior to both Baseline and NP2000 flight tests using under-gear scales and ramps to determine longitudinal, lateral, and vertical CG locations and to establish references for the zero- and maximum-fuel gross weights. The desired test CG loading was achieved by adding up to 412 lb of ballast plates to the cockpit floor or aft-equipment compartment, as necessary. Test weight was determined by subtracting total fuel used – determined primarily by integrating the instrumented fuel flow parameters, and backed up with the production fuel gauges – from the reference maximum-fuel gross weight; test CG was determined by entering figure 10 below with the calculated test weight.

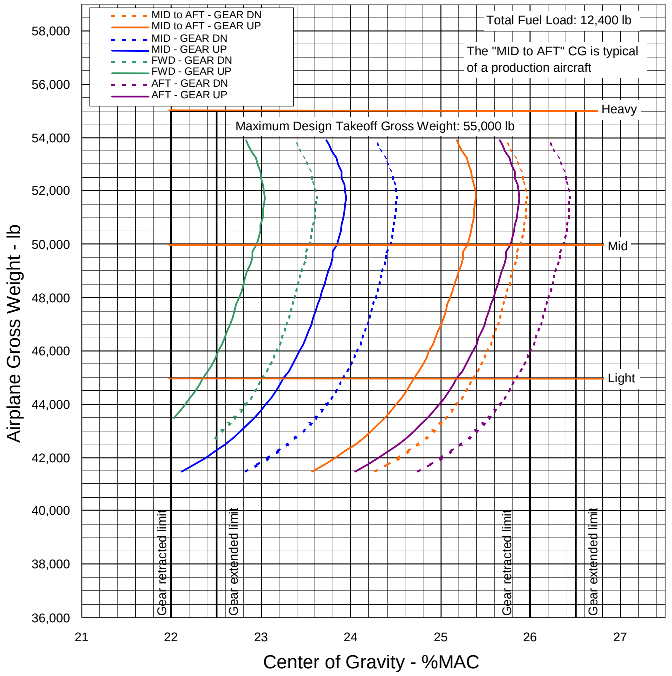

Figure 10. Test Weight and Balance Envelope

Source: NP2000 Flight Test Program Test Plan[3]

Elevator deflection and longitudinal control force were measured by transducers installed at the tailplane and in the control column, respectively, and recorded to 8mm magnetic tape. All data were referenced to a common time index and backed-up by manual activation of an event marker that stamped the PCM stream when the pilot had achieved stable test conditions. Prior to commencing each test flight, an on-deck control sweep was performed to establish parameter tares and ensure no drift in the instrumentation package or associated sensors.

Airspeed and altitude measurements for data processing were collected from the wingboom pitot-static source. The wingboom pitot-static systems were calibrated for position error using the space-positioning calibration method detailed in reference 12 in order to determine air data corrections for deriving pressure altitude and calibrated, equivalent, and true airspeeds for each test point. Where test conditions called for a trim angle of attack rather than a trim airspeed, the production AOA gauge was used for both pilot reference and data measurement.

Left and right engine power settings were measured by transducers installed on each engine torque shaft. For each test condition, power was set to that required for level flight at the pre-selected trim airspeed, ensuring a maximum 100 ISHP split between left and right power settings was not exceeded.

The additional parameters listed in table A-1 were recorded for test point validation and redundancy. All the parameters listed in table A-1 were recalibrated between the Baseline and NP2000 Test Programs to preclude errors in test results due to instrumentation drift.

DATA REDUCTION

After completing each test flight, PCM data recorded to the DRS-4 tape were converted to engineering units files, segmented by time, and copied to hard disc. Once on disc, data were reviewed on screen using a time slice program to further refine the time segment desired for processing. Data were initially processed using proprietary software that applied air data corrections to the engineering units data to produce corrected pressure altitudes and calibrated, equivalent, and true airspeeds; corrected values were used to produce time histories of the desired parameters for each flight test maneuver.[3] Stabilized points were selected after reviewing the time histories to ensure maneuver quality. Accelerometers in the six degrees of freedom (x, y, z, θ, ϕ, ψ) were used to aid in determining the quality of each test point. Verified were: proper configuration, stabilized engine power, stabilized flight conditions as indicated by stable airspeed, angle of attack, and pitch attitude, and steady bank angle and sideslip less than 5 degrees. Test points where conditions were judged not to be reasonably stabilized were discarded. Data for the selected test points were converted to ASCII, comma delimited format for final processing using the Microsoft Excel® program.

CHAPTER 5

RESULTS AND DISCUSSION

GENERAL

The data presented in this work were collected over the course of ten test flights conducted during daylight, visual meteorological conditions within the Patuxent River, Maryland local operating airspace. To reduce program costs, data collected during the 1998 Operational Flight Trainer (OFT) Test Program[13] were used to augment data collected for the model 54460-1 installation during the Baseline Test Program. A tabulated list of the test flights and test conditions from which quantitative data were collected is presented in table A-2 for Baseline tests and table A-3 for NP2000 tests. In most figures, longitudinal control force and elevator deflection values are plotted versus calibrated airspeed (V_c) rather than lift coefficient for easier association to mission representative flight conditions. In this case, positive stick-fixed and stick-free static stability are indicated by negative variation of elevator deflection and control force with calibrated airspeed, respectively:

$$\frac{d\delta_e}{dV_c} < 0 \tag{12}$$

and,

$$\frac{dF_s}{dV_c} < 0 \tag{13}$$

BASELINE TEST RESULTS

Test results from the flights conducted with the 54460-1 propellers installed correlated closely with those results documented in references 4 and 13, and provided an updated reference against which to measure longitudinal stability characteristics of the test airplane with the NP2000 replacement propellers installed. The variation of δ_e and F_s with airspeed is discussed in detail in the NP2000 Test Results section; flight test measurements are cross-plotted against NP2000 data for comparison and to determine areas and magnitude of change in airplane static stability.

Overall, the airplane exhibited weakly stable to slightly unstable stick-fixed static longitudinal stability characteristics at all test conditions, as indicated by the variation of δ_e with airspeed. For configuration CR(0) test conditions, the gradients of δ_e versus V_c were shallow and essentially linear. At landing approach airspeeds with landing gear and flaps extended, the airplane exhibited non-linear elevator deflection versus airspeed gradients and unstable stick-fixed stability characteristics at airspeeds less than trim. At all test conditions, the airplane demonstrated positive stick-free static longitudinal stability above trim airspeed and positive to neutral stick-free stability at airspeeds below trim, as indicated by the variation of F_s with V_c.

Static elevator position neutral points were calculated for configuration PA(30) as a reference for determining the NP2000 propeller’s influence on neutral point location. Because test flights for configuration PA(30) were limited to two test centers of gravity, data from the 1998 OFT Test Program[13] were used to provide an additional test CG and a reasonable range for calculating neutral points.* The variation of δ_e with computed effective lift coefficient, together with calculated stick-fixed stability, $d\delta_e/dC_L$, as a function of CG and C_L are presented in figure B-1. The resultant variation of static neutral point location with C_L is presented in figure B-2. The data indicate the elevator position neutral point for an effective lift coefficient of 1.75 – corresponding to the landing approach condition of 6.3 deg (20 units) angle of attack – is approximately 26.2 %MAC.

The method used here for calculating neutral points is less reliable when the x-intercept is extrapolated rather than interpolated and when the gradient of $d\delta_e/dC_L$ versus CG approaches zero. Reviewing figure B-1, confidence in the results for lift coefficients less than 1.7 was judged to be low, as the resulting calculated neutral point moved aft at an increasing rate. The neutral point corresponding to a C_L of 1.5 was therefore not weighted in the results shown in figure B-2. The lift coefficient corresponding to the point at which variation of $d\delta_e/dC_L$ with CG equals zero was determined to be approximately 1.3.

PRELIMINARY INVESTIGATION, NP2000 PROPELLERS INSTALLED

Initial tests for the NP2000 propeller installation were conducted at a mid-CG loading between 24.0 and 24.4% MAC. δ_e and F_s versus airspeed data were measured at two test conditions and are plotted against baseline measurements taken under similar conditions in figures B-3 and B-4.

---

* The OFT Test Program was conducted using the same test aircraft, BuNo 163535, and a similar instrumentation measuring and recording package.

Configuration CR(0) measurements were recorded for stable airspeeds approaching 14.6 deg angle of attack – artificial stall warning – to investigate longitudinal stability characteristics at higher inflow angles for the NP2000 propeller. The gradient of δ_e versus airspeed calculated from two test flights was similar to that calculated for the 54460-1 installation. Data from the first flight indicated that although the NP2000 and 54460-1 installations resulted in similar stick-fixed stability gradients, the NP2000 installation required an approximate 1 deg of additional trailing edge down elevator deflection to stabilize at each of the test points. The test maneuver was repeated on a subsequent flight and yielded values of δ_e similar to those for the 54460-1. The additional elevator trailing edge down required for the first data set is attributed to the higher power setting (1,510 ISHP average engine power versus 1,080 ISHP for the 54460-1) and a resultant increase in N_p forward of the CG during the test maneuver. The observed variance in trimmed power settings for these test conditions was a result of the difficulty experienced in achieving a stable trim condition below the minimum power required airspeed, or on the "back-side" of the power required curve.

The stick-fixed longitudinal stability characteristics for configuration PA(30) showed significant divergence from the baseline installation at airspeeds below trim condition. Whereas the E-2C fitted with the model 54460-1 demonstrated positive stick-fixed stability (negative slope of $d\delta_e/dV_c$) at the test CG for the entire test airspeed band, the NP2000 installation indicated negative stick-fixed stability at airspeeds below approximately 110 kt. At airspeeds above trim, $d\delta_e/dV_c$ gradients did not diverge significantly from that of the 54460-1 installation.

Using the data collected for configuration PA(30), the effective lift coefficients for which the gradient of $d\delta_e/dC_L$ equaled zero were calculated to estimate the NP2000 propeller's influence on the static elevator position neutral point. The results are plotted in figure B-5 against neutral point calculations for the 54460-1 installation. Preliminary investigations for the NP2000 propeller's influence on static neutral point location indicated a 1½ to 2% forward shift in the neutral point at a lift coefficient slightly below 1.8 – an approximation only as results were derived for a single test CG and rely on curve fit accuracy.

TEST RESULTS, NP2000 PROPELLERS INSTALLED

After completing the preliminary investigation at a mid-range CG, the test airplane was re-ballasted for a production-representative CG – nominally 25.6% MAC, landing gear extended, at maximum fuel load. Data were gathered at five trim airspeeds to characterize longitudinal stability characteristics for loiter, cruise, landing pattern, and landing approach flight conditions.

Configuration CR(0) data were collected at trim airspeeds of 180 kt and 250 kt, representing loiter and cruise airspeeds, and are presented in figures B-6 and B-7, respectively. For 180 kt, both the 54460-1 and NP2000 installations exhibited similar stick-fixed static longitudinal stability, indicated by similar, stable gradients of δ_e versus V_c above and below trim airspeed. NP2000 data indicated an approximate ½ deg additional trailing edge down elevator deflection was required for stable conditions within the range of test airspeeds. Data collected for a trim airspeed of 250 kt indicated essentially identical static stability characteristics for both propeller configurations: mild stick-fixed instability and weakly stable stick-free stability above and below trim condition.

The most significant changes were observed in the power approach configurations at a trim condition of 20 units[*] AOA, corresponding to the normal landing approach airspeed of the E-2C. Measurements taken for configurations PA(20) and PA(30) indicated a marked reduction in stick-fixed stability below trim airspeed with the NP2000 propellers installed. For configuration PA(20), the gradient of δ_e versus V_c below trim increased from an average 0.17 deg/5 kt for the 54460-1 to approximately 0.50 deg/5 kt for the NP2000, as shown in figure B-8. A similar increase in the average below-trim gradient, from approximately 0.14 deg/5 kt to 0.48 deg/5 kt, was observed for configuration PA(30), presented in figure B-9. Above trim airspeed in both approach configurations, the NP2000 installation demonstrated weakly stable stick-fixed stability gradients similar to those for the 54460-1 propeller.

Measurements taken at a 130 kt trim airspeed in configuration PA(30) indicated no changes to static stability; stick-fixed and stick-free stability gradients were essentially identical for both the 54460-1 and NP2000 propellers (figure B-10). The slight reduction in required elevator deflection for the NP2000 installation – approximately ¼ deg additional trailing edge down across the test airspeed band – is most likely a result of the slightly higher (2,260 ISHP versus 2,120 ISHP for the 54460-1 reference data) trim power setting. Of note were the slightly unstable (positive) gradients of δ_e versus V_c for

---

[*] 6.3 deg AOA for PA(30); 6.9 deg for PA(20). Refer to table 2, note 2.

both propellers. Recall from figure B-9 that both propellers demonstrated positive stick-fixed stability gradients above approximately 105 kt in configuration PA(30), suggesting an inflection point exists as airspeed is increased towards 130 kt.

NEUTRAL POINT COMPARISON

Static elevator position neutral points were calculated for configuration PA(30) and compared to those derived for the 54460-1 propeller installation. Data were collected at four test CG loadings ranging from 22.8 to 26.3% MAC. Calculations are shown in figure B-11 and the resulting variation of the static neutral point with CG is compared against that for the 54460-1 propeller in figure B-12. Flight test results yielded an effective lift coefficient of 1.78 at the landing approach condition of 20 units AOA. The elevator position neutral point at this value was calculated to be 24.4% MAC, an approximate 2% forward shift compared to results derived for the 54460-1 propeller. This forward shift with the NP2000 propellers installed indicates negative stability at landing approach speed for approximately half of the current CG envelope of the airplane. As expected, due to the similar stability characteristics above trim condition, figure B-12 shows the neutral point locations for the two propeller installations converging with decreasing C_L.

Recall that the neutral point calculations for the 54460-1 installation indicated a reversal in the variation of $d\delta_e/dC_L$ with CG at a C_L of approximately 1.3. The estimated variation of neutral point location with decreasing C_L below a value of 1.7 for the model 54460-1 and 1.5 for the NP2000 is shown in figure B-12. This estimated movement of the neutral point is based on the gradient reversals observed for both propeller installations between 105 kt and 130 kt, indicated in figures B-9 and B-10, and the observed convergence in static stability with decreasing C_L. Although confidence in the illustrated trends with decreasing C_L is relatively high, further tests are necessary to quantitatively define static neutral point values at lower values of C_L.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

NET PROPELLER EFFECTS

A comparison of flight test data collected from the E-2C airplane fitted with the original 54460-1 propellers to data collected with the replacement NP2000 propellers installed indicates a definitive change in airplane static longitudinal stability. By maintaining all other component contributions to static stability constant, the observed change to airplane stability can be attributed with a high level of confidence to a change in the propeller contribution resulting from propeller replacement.

Installing the model NP2000 propeller on the E-2C airplane resulted in reduced stick-fixed static longitudinal stability below trim airspeed in the landing approach configurations, indicated by an approximate 3x increase in below-trim variation of required elevator deflection with airspeed. Stick-fixed static stability above trim and for all the cruise conditions tested was not significantly affected by propeller replacement. The below-trim change in stick-fixed stability resulted in forward movement of the airplane neutral point – an approximate 2% forward shift of the static elevator position neutral point at approach airspeed in the landing configuration. Changes to stick-free static stability following propeller replacement were observed as negligible. Since the elevator deflection schedule programmed by the airplane pitch-feel system was not modified, changes in stick-free stability expected as a result of the reduced stick-fixed stability observed below trim airspeed are believed to be small, and therefore masked by control system friction and shallow control-force gradients about trim conditions.

Although the flight test results demonstrate a clear change to airplane static longitudinal stability resulting from propeller replacement, the nature of the observed change did not match pre-test expectations. Rather than a destabilizing contribution at all flight conditions tested, changes in the propeller contribution to static stability were observed to be limited to airspeeds below a 20 units AOA trimmed flight condition with the flaps extended. For all other flight conditions and configurations tested, there were no significant changes observed as a result of replacing the propeller. This departure from predicted results does, however, offer insight into the relative influence the propeller direct and indirect contributions had on the measured change to airplane stability.

PROPELLER DIRECT EFFECTS

Recall from figure 5 that the positive variation of C_{Np} with α is greater for increased propeller solidity. From equation 4, an increase in $dC_{Np}/d\alpha$ for a forward-mounted propeller configuration is destabilizing. Also, the normal force contribution to static stability should be nearly constant through the linear range of C_{Np} variation with α. This was not supported by the test results, as a destabilizing contribution was only observed at α values below 20 units AOA with the flaps extended. At higher values of α, the increase in $dC_{Np}/d\alpha$ due to increased solidity is expected to be greater due to a slightly larger range of linear variation for the propeller of higher solidity. However, for this to be the cause for the reduced stick-fixed stability observed below 20 units AOA, the 54460-1 propeller would have had to diverge from $dC_{Np}/d\alpha$ linearity at a value well below that observed for other propellers during wind tunnel experiments – an estimated 10 deg* compared to 30 deg nominally.[1] Moreover, test results for configuration CR(0) at high AOA conditions demonstrated essentially identical stick-fixed stability characteristics for the 54460-1 and NP2000 propellers.

Although increased propeller solidity is expected to result in an increase to $dC_{Np}/d\alpha$, it has been shown that $dC_{Np}/d\alpha$ is also a function of blade planform, which was significantly modified for the NP2000 design.[10] Because the data failed to support any substantial change to static stability that could be linked to a change in the term $dC_{Np}/d\alpha$, it is believed that the normal force variation with α for the NP2000 propeller is similar to that for the 54460-1, and that consequently, propeller direct effects were not a significant contributor to the observed changes to airplane static stability.

It is acknowledged that thrust has not been included in considering propeller direct effect contributions. The effects of the thrust coefficient (C_T) on static stability were assumed to be negligible since it has been demonstrated that C_T remains nearly constant within a range of ± 10 deg α_p, and that for values greater than 10 deg, the variation with α is less pronounced than that of C_{Np}.[1] Also, for the E-2C airplane, the distance at which C_T acts with respect to airplane CG – the vertical offset, h_p, of the thrust axis from the CG – is small compared to the distance, l_p, at which C_{Np} acts.[9]

---

* 20 units AOA corrected to 8.3 deg true AOA referenced to the thrust axis (from reference 9) and adding estimated wing upwash from reference 6.

Similarly, performance tests conducted on the model NP2000, reported in reference 14, and the methodology adopted for this investigation suggest thrust line offset effects did not significantly influence the observed change to airplane static stability. Conventional flight test methods result in an apparent thrust line offset contribution to static stability and resultant shift in derived neutral points:

$$\Delta\frac{dC_m}{d\alpha} = \frac{3}{2}\eta_p P\left(\frac{\left(\frac{dC_L}{d\alpha}\right)}{W\cos\gamma}\right)^{3/2}\sqrt{\frac{\rho}{2}S}\,\frac{h_p}{\bar{c}}\,\alpha^{1/2} \quad [15] \tag{14}$$

and,

$$\Delta\frac{x_{n.p.}}{\bar{c}} = -\frac{3}{2}\eta_p P\left(\frac{1}{W\cos\gamma}\right)^{3/2}\sqrt{\frac{\rho}{2}S\left(\frac{dC_L}{d\alpha}\right)\alpha}\,\frac{h_p}{\bar{c}} \quad [15] \tag{15}$$

Any influence on the change in airplane static stability attributable to thrust line offset effects was limited to a change in the term $\eta_p P$ since all other terms were held constant for comparing test results for the two propeller configurations. Substituting $T_p V_T$ for $\eta_p P$* and combining all constants (V_T is also held constant here), the changes in thrust line offset effects due to changing the propeller are:

$$\Delta\left(\Delta\frac{dC_m}{d\alpha}\right) = [\text{constant}]\,\Delta T_p \tag{16}$$

and,

$$\Delta\left(\Delta\frac{x_{n.p.}}{\bar{c}}\right) = [\text{constant}]\,\Delta T_p \tag{17}$$

---

[*] Thrust for a propeller aircraft is given by: $T_p = (\eta_p P)/V_T$

Although a slight increase in η_p was observed for the model NP2000, the airplane drag polar remained unchanged.[14] Because test measurements were taken at stabilized airspeed increments for which thrust equals drag, it follows that T_p required for each test airspeed was unchanged with the model NP2000, and therefore ΔT_p for equations 16 and 17 equals zero.

PROPELLER INDIRECT EFFECTS

Because changes in propeller direct effect contributions were considered negligible, it is believed the change to airplane static stability is a result of differences in the propeller indirect effects with the NP2000 propeller installed. More precisely, the measured change in static stability is most likely a result of different slipstream interaction with the tailplane. Considering the propeller location on the E-2C, slipstream induced changes in fuselage and wing contributions to static pitching moment are unlikely causal factors. The nacelles are configured far enough out from the airplane centerline so that slipstream interactions with the fuselage can be considered small. Changes in the wing contribution due to slipstream immersion are generally significant for a forward mounted propeller configuration due to the close proximity of the wing and the propeller plane of rotation.[7] However, since airplane static stability was only affected at airspeeds less than 20 units AOA, it is highly improbable that a change in slipstream interaction with the wing is responsible.

The change in slope below trim speed observed for both propeller configuration in figures B-8 and B-9 is most likely a result of a change in wing downwash characteristics at the tailplane as AOA is increased with the flaps extended. Similar gradient changes at high angles of attack have been observed for other high-wing, multi-engine propeller airplanes when the flaps are extended – also attributed to downwash at the tail.[16] Since the measured change to E-2C static stability is observed to occur at this point, it is suggested the change in airplane stability is a result of a change in slipstream-induced downwash at the tailplane with the NP2000 propeller installed.

RECOMMENDATIONS

With the advanced propeller-driven airplane designs being considered today, integrating such features as Super-short Take-off and Landing, deflected slipstreams, partially tilting wings, and large-diameter propellers, it is desirable to continue to advance the understanding of propeller effects on airplane stability. Experimental results from the flight tests of these designs should be documented so as to add to the collective knowledgebase and provide designers a reference for predicting propeller effects for future airplane geometries and propeller configurations under consideration. Such a reference source will help reduce the time and costs needed for testing future designs. With a large enough base of experimental data, it should eventually be possible to develop a comprehensive predictive theory for propeller effects on static stability.

SUMMARY OF RESULTS

A flight test investigation of propeller effects on static longitudinal stability has been conducted by comparing the static stability of the E-2C fitted with the 54460-1 propeller to that measured with the model NP2000 propeller installed. The results may be summarized as follows:

1. Replacing the model 54460-1 with the NP2000 propeller resulted in a definitive change in the static longitudinal stability characteristics of the E-2C airplane. Specifically, installing the new propeller resulted in reduced stick-fixed static stability below trim airspeed in the landing configuration as indicated by a 3x increase in the variation of required elevator deflection with airspeed, and an approximate 2% MAC forward shift of the stick-fixed neutral point at landing approach airspeed.

2. Test results indicated that propeller direct effect contributions to airplane static longitudinal stability were not significantly different following propeller replacement, and that the observed change in airplane static stability is a result of a change in slipstream-induced downwash at the tailplane with the NP2000 propeller installed.

REFERENCES

REFERENCES

1. Gentry, G. L. et al., “Effect of Solidity and Inclination on Propeller-Nacelle Force Coefficients,” NASA Report TM-4316, Dec. 1991.

2. Etkin, B. and Reid, L. D., *Dynamics of Flight: Stability and Control*, 3rd ed., John Wiley & Sons Inc., New York, NY, 1996.

3. Jamison, G. and Spelz, J., “Evaluation of the NP-2000 Propeller System on the E-2C PLUS Airplane,” Naval Air Warfare Center Aircraft Division, Test Plan 00-044, Patuxent River, MD, Jun. 2000.

4. Anon., “Flying Qualities and Performance Trials of the Model E-2C Airplane,” NATC Technical Report FT-38R-74, May 1974.

5. Anon., *U.S. Navy Test Pilot School Flight Test Manual – Fixed Wing Stability and Control, Theory and Flight Test Techniques*, Naval Air Warfare Center Aircraft Division, USNTPS-FTM-103, Patuxent River, MD, revised Jan. 1997.

6. Ribner, H. S., “Notes on the Propeller Slipstream in Relation to Stability,” NACA Report No. L-25, Oct. 1944.

7. Wolowicz, C. H. and Yancey, R. B., “Longitudinal aerodynamic characteristics of light, twin-engine, propeller driven airplanes,” NASA Report TN D-6800, Jun. 1972.

8. *Jane’s all the world’s aircraft, 1998-1999 edition*, edited by Mark Lambert, Kenneth Munson, and Michael J H Taylor, Jane’s Information Group, Alexandria, VA, 1998.

9. Anon., “NATOPS Flight Manual, Navy Model E-2C PLUS Aircraft,” NAVAIR 01-E2AAB-1, revised Jun. 2004.

10. Ribner, H. S., “Formulas for Propellers in Yaw and Charts of the Side-Force Derivative,” NASA Report No. 819, Apr. 1943.

11. Anon., “Flight Test Guide for Certification of Part 23 Airplanes,” FAA Advisory Circular No. 23-8A, Feb. 1989.

12. Anon., *U.S. Navy Test Pilot School Flight Test Manual – Fixed Wing Performance, Theory and Flight Test Techniques*, Naval Air Warfare Center Aircraft Division, USNTPS-FTM-108, Patuxent River, MD, revised Sep. 1992.

13. Anon., “Flying Qualities and Performance Flight Test Data Baseline for the E-2C Operational Flight Trainer,” Naval Air Warfare Center Aircraft Division, NAWCADPAX-98-95-TEDR, Patuxent River, MD, Sep. 1998.

14. Keller, S. and Breau, E., “Handling Qualities and Performance Evaluation of the E-2C PLUS Aircraft Equipped with the NP2000 8-Bladed Propeller,” Naval Air Warfare Center Aircraft Division, NAWCADPAX/RTR-2005/7, Patuxent River, MD, May 2005.

15. Solies, U. P., “Effects of Thrust Line Offset on Neutral Point Determination in Flight Testing,” *Journal of Aircraft*, Vol. 31, No. 2, 1994, pp. 362-366.

16. Quigley, H. C. et al., “A Flight Investigation of the Performance, Handling Qualities, and Operational Characteristics of a Deflected Slipstream STOL Transport Airplane Having Four Interconnected Propellers,” NASA TN D-2231, 1964.

APPENDICES

APPENDIX A (TABLES)

Table A-1. Instrumented Airplane Parameters

Measurement	Symbol	Range	Freq (Hz)	Accuracy	Resolution	Remarks
Pilot Sensitive Altitude	H_p	-1,000 to 40K ft	41	±10 ft	2 ft	Production gauges replaced by sensitive gauges
Pilot Sensitive Airspeed	V_i	50 to 400 KIAS	41	±0.23 kt	0.0875 kt	
Wingboom Altitude	H_p	-1,000 to 40K ft	41	±4.5 ft	2 ft	--
Wingboom Airspeed	V_c	50 to 400 KIAS	41	±0.23 kt	0.0875 kt	--
Production AOA	--	0 to 30 units	41	±0.10 unit	0.007 units	+ CCW rotation of probe
Wingboom AOA	α	±45 deg	41	±0.20°	0.045°	+ vane nose down
Wingboom Sideslip	β	±45 deg	41	±0.20°	0.045°	+ vane nose right
HARS Pitch Attitude	θ	±90 deg	41	±0.12°	0.045°	+ nose up
Pitch Rate	$d\theta/dt$	±45 deg/sec	41	±0.1°/sec	0.023°/sec	+ nose up change
HARS Roll Attitude	ϕ	±180 deg	41	±0.1°	0.09°	+ right wing down
Roll Rate	$d\phi/dt$	±90 deg/sec	41	±0.1°/sec	0.045°/sec	+ right wing down change
HARS Magnetic Heading	ψ	0 to 360 deg	41	±0.2°	0.09°	+ nose right
Yaw Rate	$d\psi/dt$	± 45 deg/sec	41	±0.2°/sec	0.023°/sec	+ nose right change
Elevator Position	δ_e	25°TEU to 15°TED	41	± 0.1°	0.01°	+ TEU
Longitudinal Yoke Force	F_s	±100 lb	41	± 0.5 lb	0.05 lb	+ pull
Longitudinal Yoke Position	d_s	9 in aft to 5 in fwd	41	± 0.1 in	0.004 in	+ aft
Rt. Flap Position	--	0 to 30°	41	± 0.5°	0.008°	+ TED
Elevator Trim Command	--	<discrete>	41	--	--	0 no trim, 1 ND, 2 NU
Elevator Trim Position	--	units	41	0.25 units	--	+ nose up
Landing Gear Position	--	<discrete>	41	--	--	0 is gear extended
CG Vertical Acceleration	n_z	±5 g	578	±0.003 g	0.002 g	+ up
CG Long. Acceleration	n_x	±5 g	578	±0.003 g	0.002 g	+ forward
CG Lateral Acceleration	n_y	±2 g	578	±0.003 g	0.002 g	+ right

Table A-1 (Continued).

Measurement	Symbol	Range	Freq (Hz)	Accuracy	Resolution	Remarks
Lt. Engine Horsepower	--	-2,000 – 6,000 ISHP	41	+/- 0.29 %	5 HP	--
Lt. Engine Fuel Flow	dw/dt	0 – 3,200 lb/hr	41	+/-1.2%	0.8 lb/hr	--
Rt. Engine Horsepower	--	-2,000 – 6,000 ISHP	41	±0.29%	5 HP	--
Rt. Engine Fuel Flow	dw/dt	0-3,200 lb/hr	41	+/- 1.2%	0.8 lb/hr	--
Total Fuel Used	--	0 – 12,000 lb	83	+/- 3.2%	4 lb	--
IRIG Time	t	--	1157	--	--	--
Event Marker	--	--	41	--	--	+ is on
Total Air Temperature	TAT	-60° C to +50° C	41	±0.173°	0.027°	--

Table A-2. Tests and Test Conditions, E-2C with 54460-1 Propellers

Date	Config	Gear	Flaps	W (lb)	CG (%MAC)	H_p (ft)	V_c (kts)	Avg Pwr (ISHP)	File	Notes
--	CR(0)	up	0	47,600	25.1	25,100	177	2,060	SLS_03	Data collected during OFT Test Program. Refer to reference 13.
	CR(0)	up	0	45,500	24.9	25,850	246	3,510	SLS_04	
	PA(20)	down	20	48,200	25.7	4,850	111	1,580	SLS_07	
	PA(30)	down	30	47,800	25.7	4,750	104	1,640	SLS_09	
23mar00	CR(0)	up	0	49,510	23.9	14,980	147	1,080	F0003231	--
24mar00	PA(20)	down	20	49,640	24.4	16,020	105	1,960	F0003241	--
23mar00	PA(30)	down	30	50,520	24.5	5,100	131	2,120	F0003231	--
23mar00	PA(30)	down	30	50,970	24.5	4,960	106	1,890	F0003231	--
23mar00	PA(30)	down	30	44,860	23.3	5,020	101	1,550	F0003231	--

Table A-3. Tests and Test Conditions, E-2C with NP2000 Propellers

Date	Config	Gear	Flaps	W (lb)	CG (%MAC)	H_p (ft)	V_c (kts)	Avg Pwr (ISHP)	File	Notes
24may01	CR(0)	up	0	51,180	24.0	14,810	139	1,510	F0105242	--
04jun01	CR(0)	up	0	51,350	24.0	15,020	142	1,180	F0106041	--
02oct01	CR(0)	up	0	48,120	25.3	25,020	178	2,010	F0110021	--
04nov03	CR(0)	up	0	45,590	25.0	23,950	251	3,230	F0311041	From reference 14[1]
04jun01	PA(20)	down	20	51,160	24.5	15,100	117	1,715	F0106041	--
01nov01	PA(20)	down	20	48,570	25.9	5,090	113	1,390	F0111011	--
24may01	PA(30)	down	30	50,410	24.5	5,060	138	2,260	F0105242	--
24may01	PA(30)	down	30	50,880	24.5	5,125	109	1,735	F0105242	--
31may01	PA(30)	down	30	50,760	24.5	5,040	108	1,810	F0105311	--
01nov01	PA(30)	down	30	48,090	25.8	5,170	108	1,590	F0111011	--
03dec03	PA(30)	down	30	48,190	26.3	4,940	105	1,590	F0312031	From reference 14[1]
08dec03	PA(30)	down	30	48,140	22.8	5,170	106	1,540	F0312081	From reference 14[1]

Notes: 1. Author did not conduct these test flights; data reflects that documented in reference 14.

APPENDIX B (FIGURES)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
△	54460-1	44,860	23.3	5,020	AUTO	101	1,550
○	54460-1	50,970	24.5	4,960	AUTO	106	1,890
□	54460-1	47,800	25.7	4,750	AUTO	104	1,640

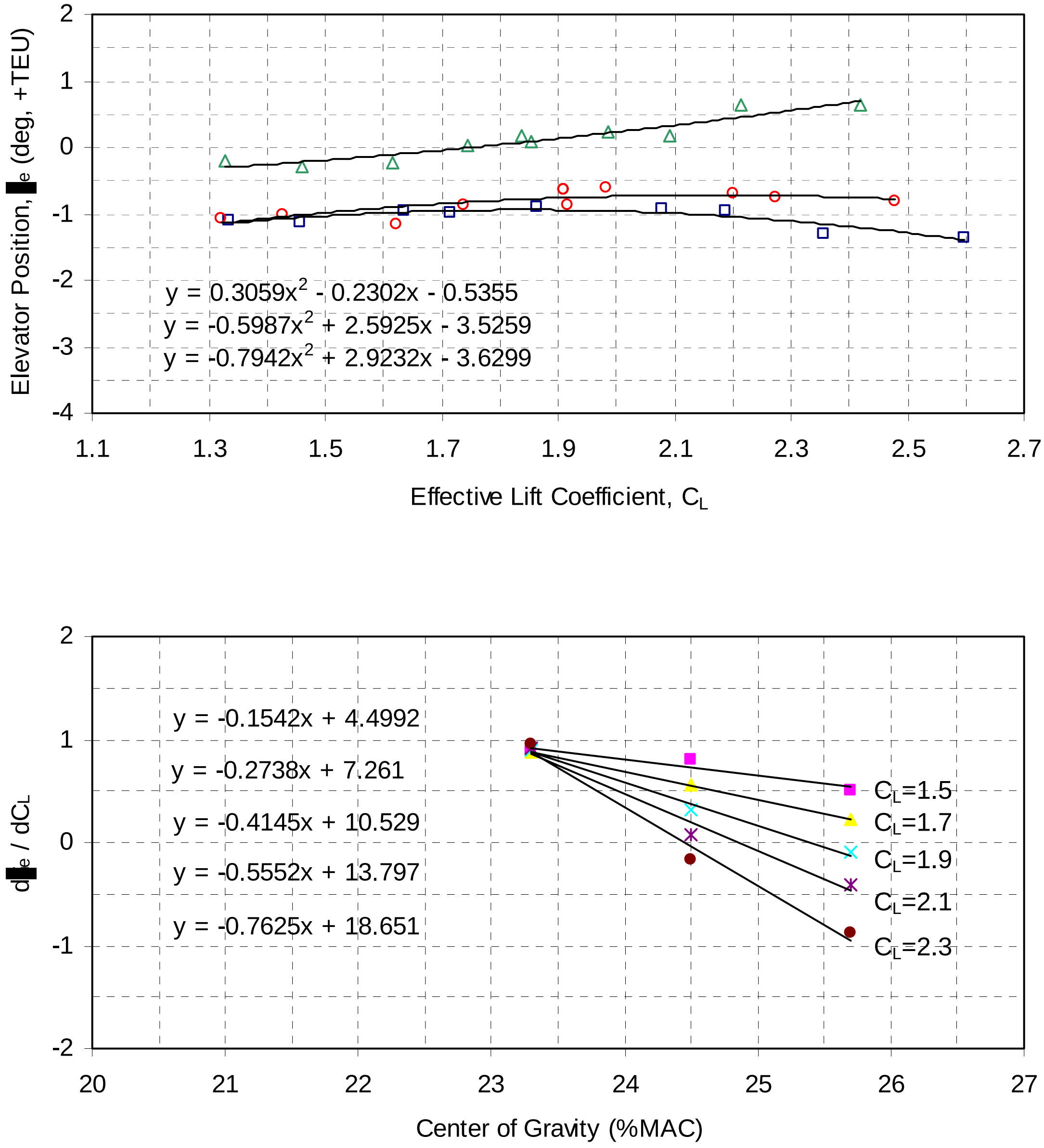

Figure B-1. Static Elevator Position Neutral Points, E-2C with 54460-1 Propellers, Configuration PA(30)

Model E-2C Aircraft, BuNo 163535

Symbol	Propeller	Description
○	54460-1	Points derived from calculations in figure B-1[1]
— —	--	Airplane fwd and aft CG limits
▮	--	Effective C_L corresponding to 20u AOA

1. Data presented are derived values where $d\delta_e/dC_L$ was calculated to equal zero for each CG and C_L combination.

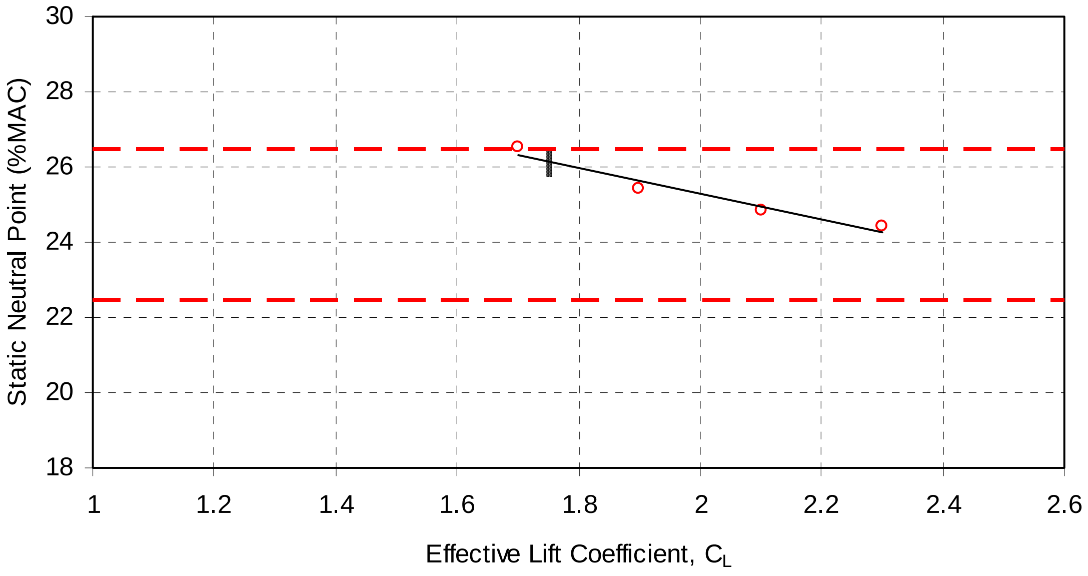

Figure B-2. Static Neutral Point Summary, E-2C with 54460-1 Propellers, Configuration PA(30)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	49,510	23.9	14,980	AUTO	147	1,080
Δ	NP2000	51,180	24.0	14,810	AUTO	139	1,510
□	NP2000	51,350	24.0	15,020	AUTO	142	1,180

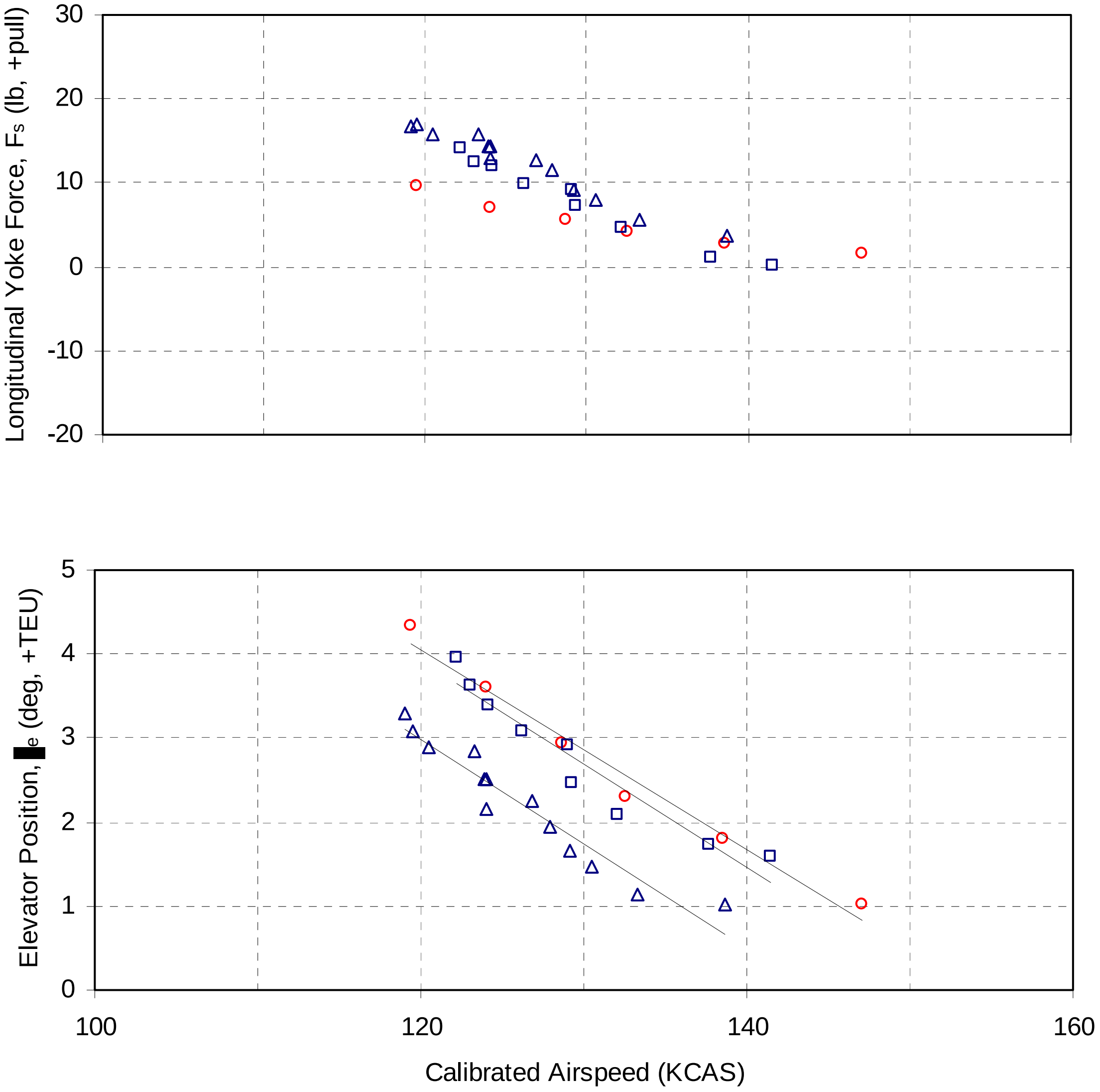

Figure B-3. Static Longitudinal Stability, Approach to Stall Warning,
Mid CG, Configuration CR(0)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	50,970	24.5	4,960	AUTO	106	1,890
Δ	NP2000	50,760	24.5	5,040	AUTO	108	1,810
□	NP2000	50,880	24.5	5,125	AUTO	109	1,735

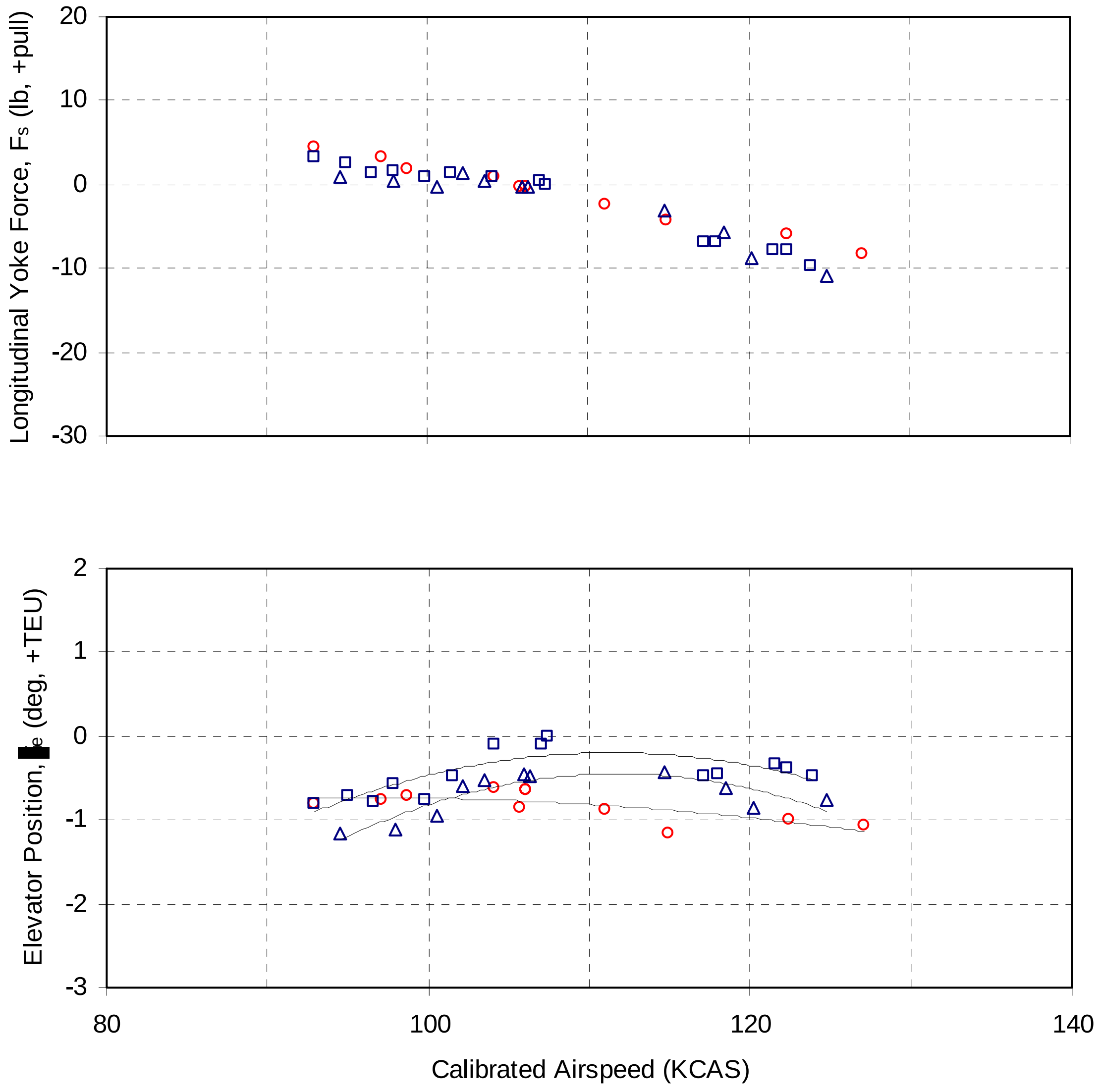

Figure B-4. Static Longitudinal Stability, 20 units AOA,
Mid CG, Configuration PA(30)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	50,970	24.5	4,960	AUTO	106	1,890
Δ	NP2000	50,760	24.5	5,040	AUTO	108	1,810
□	NP2000	50,880	24.5	5,125	AUTO	109	1,735

Symbol	Description
— —	Airplane fwd and aft CG limits
▮	Effective C_L corresponding to 20u AOA

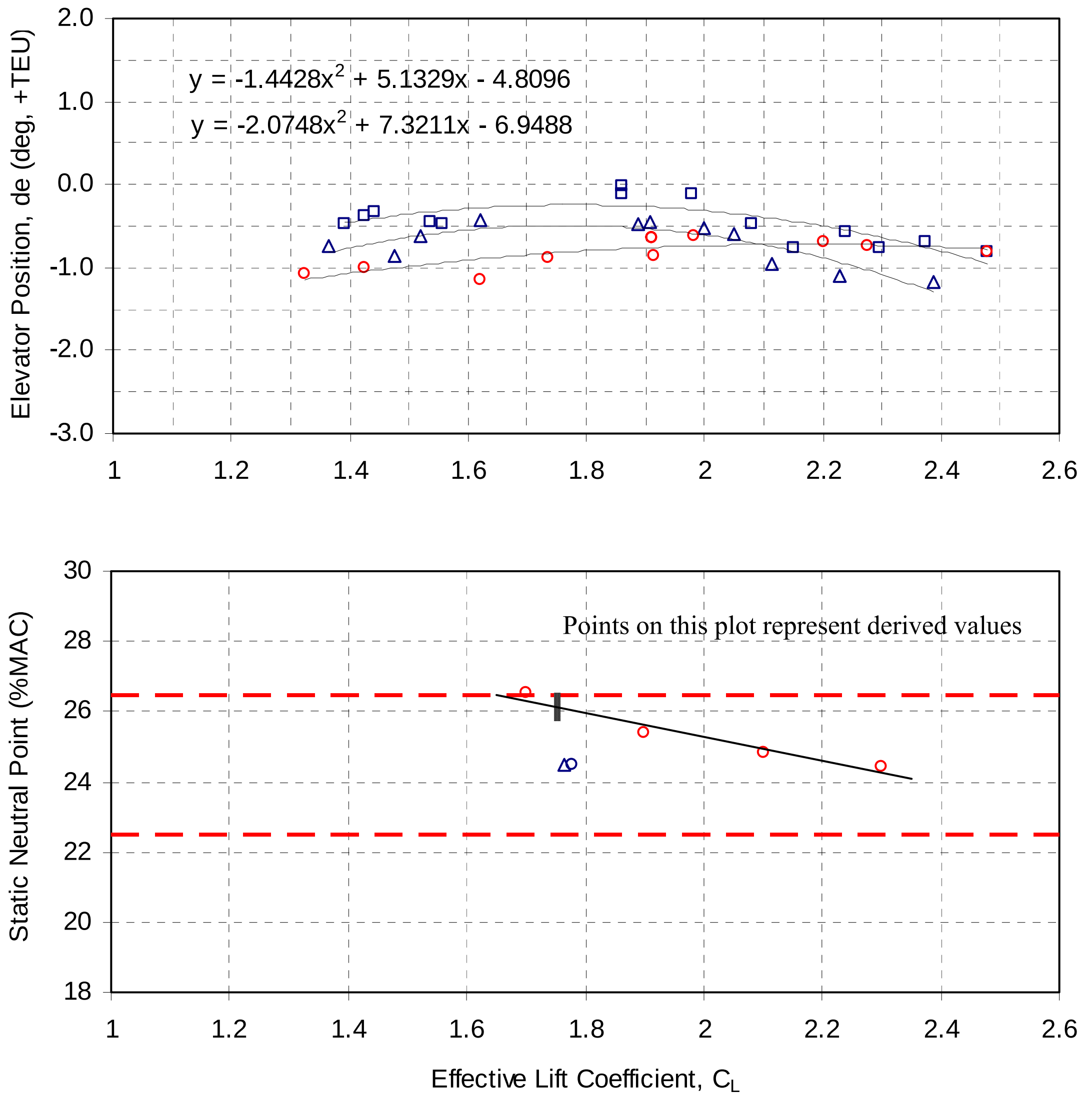

Figure B-5. Preliminary Neutral Point Indications, E-2C with NP2000 Propellers, Configuration PA(30)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	47,600	25.1	25,100	AUTO	177	2,060
Δ	NP2000	48,120	25.3	25,020	AUTO	178	2,010

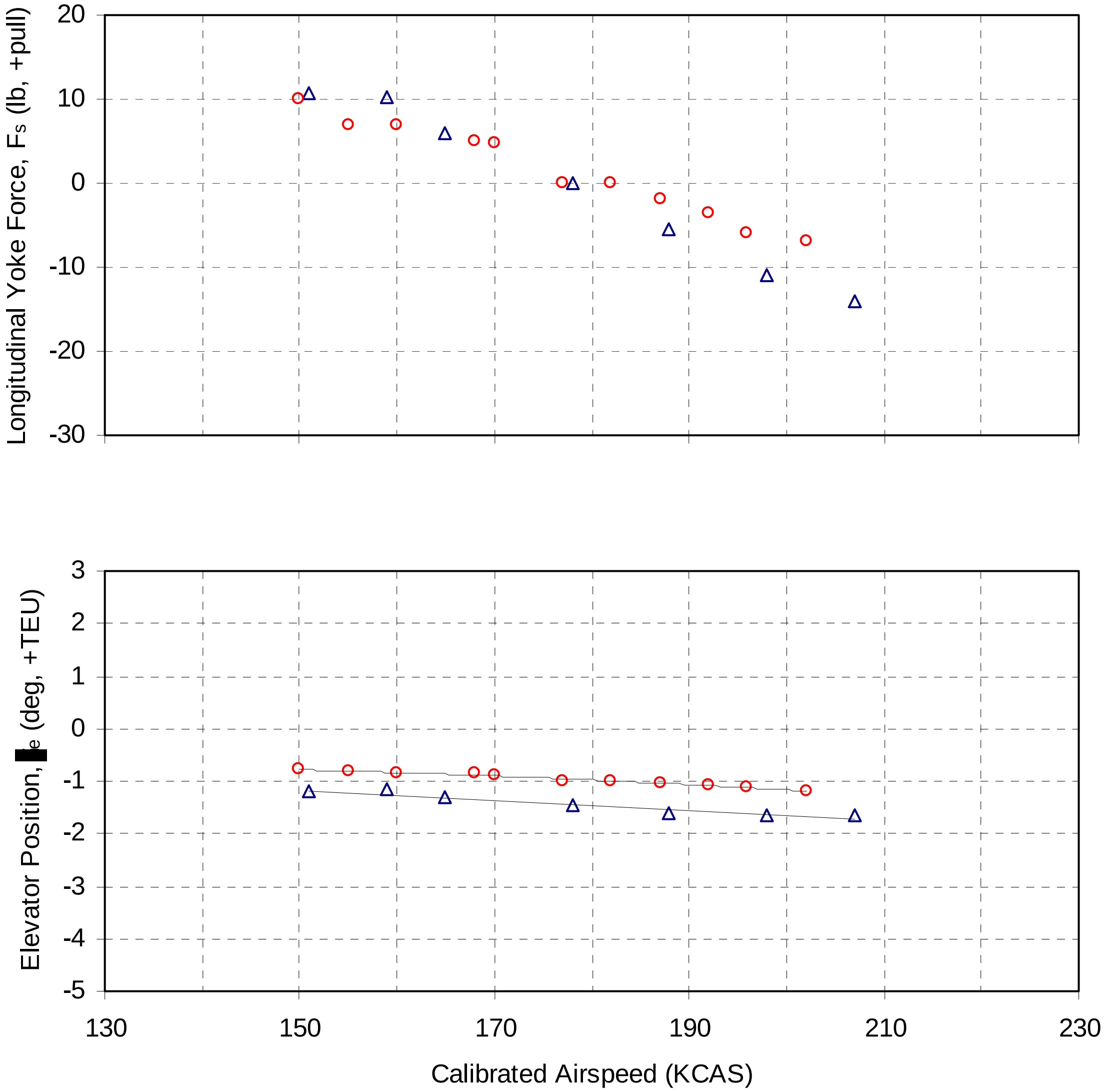

Figure B-6. Static Longitudinal Stability, 180 KCAS, Configuration CR(0)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	45,500	24.9	25,850	AUTO	246	3,510
Δ	NP2000	45,590	25.0	23,950	AUTO	251	3,230

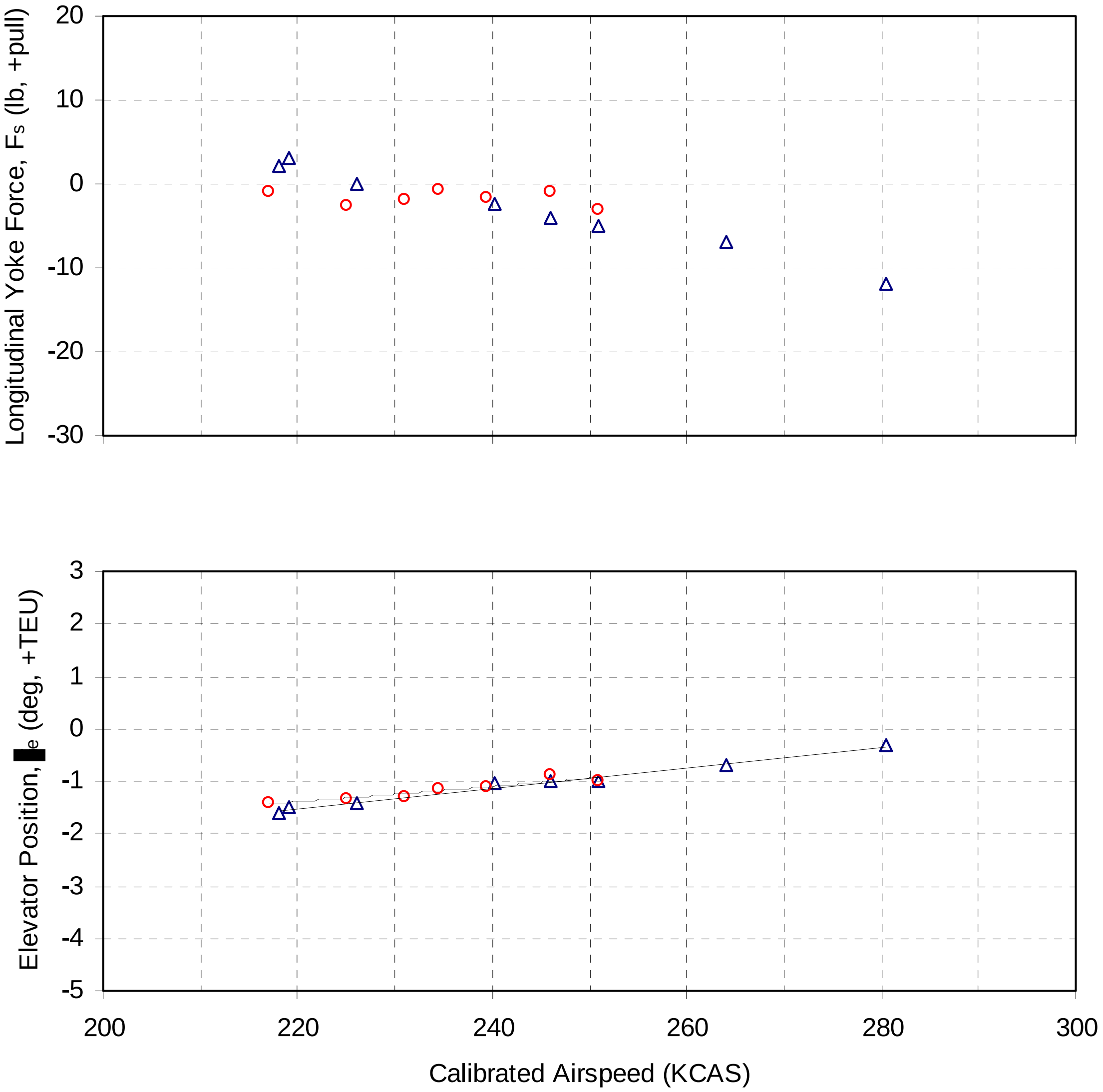

Figure B-7. Static Longitudinal Stability, 250 KCAS, Configuration CR(0)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	48,200	25.7	4,850	AUTO	111	1,580
Δ	NP2000	48,570	25.9	5,090	AUTO	113	1,390

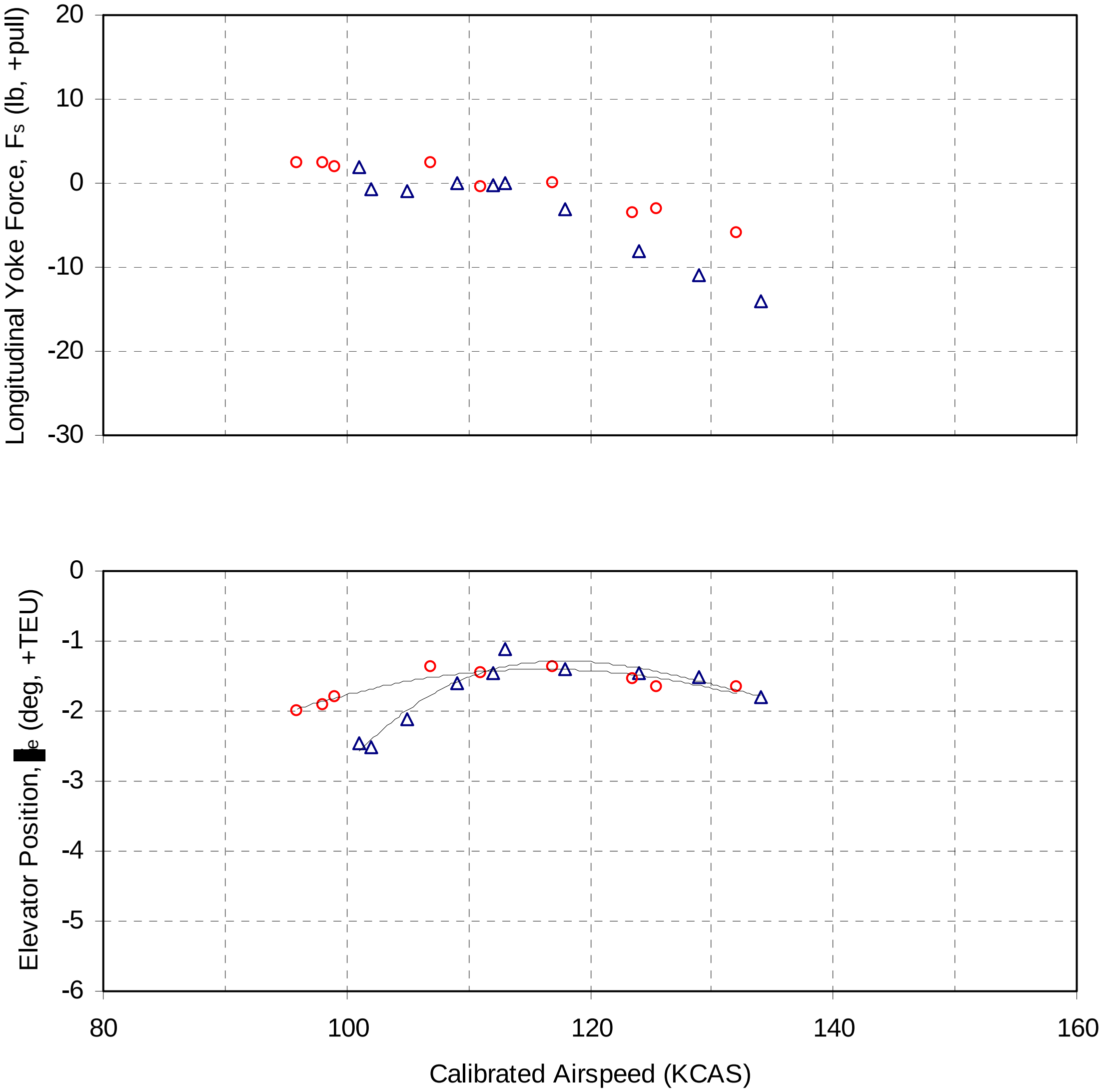

Figure B-8. Static Longitudinal Stability, 20 units AOA, Configuration PA(20)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	47,800	25.7	4,750	AUTO	104	1,640
Δ	NP2000	48,090	25.8	5,170	AUTO	108	1,590

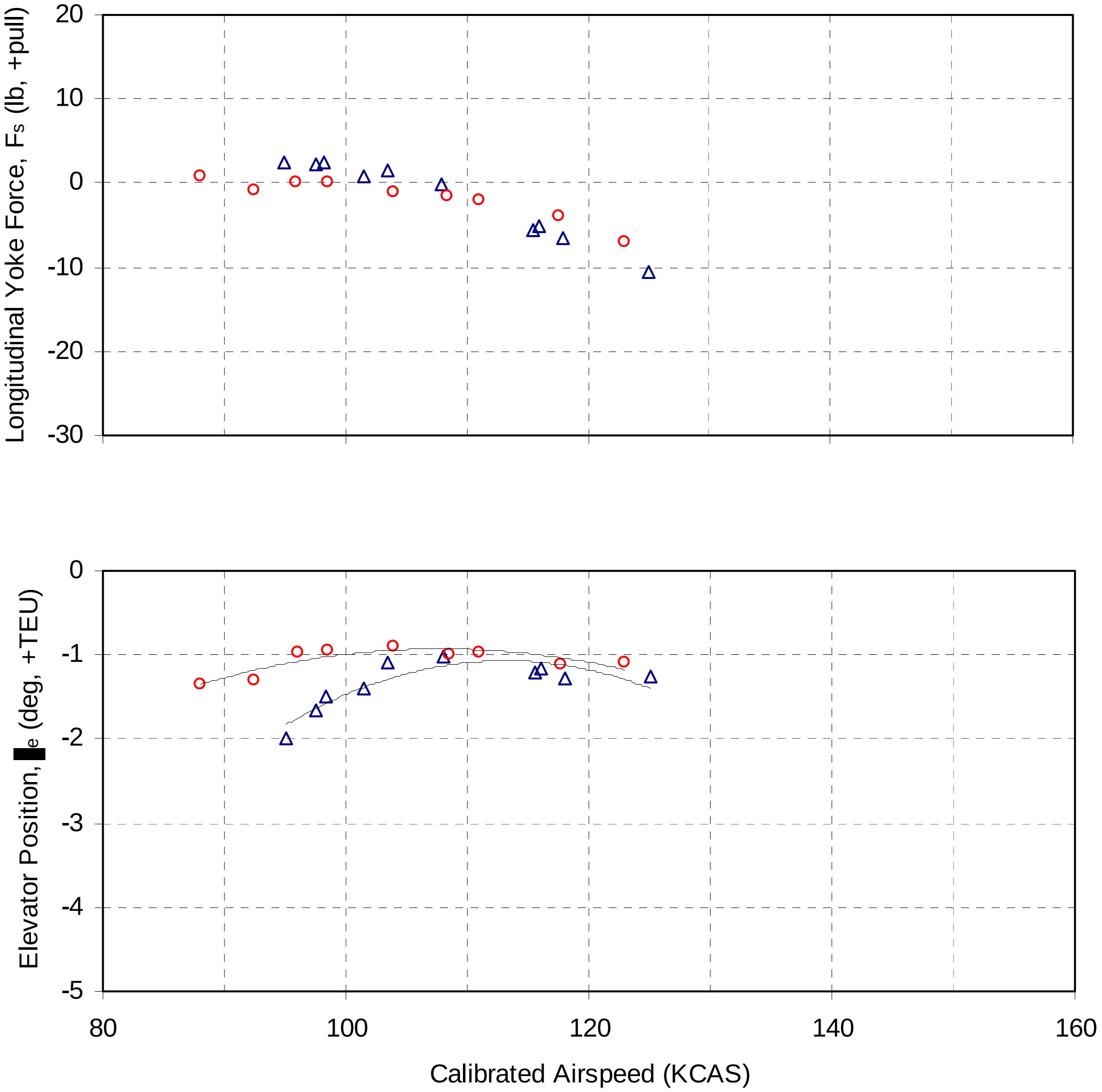

Figure B-9. Static Longitudinal Stability, 20 units AOA, Configuration PA(30)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
○	54460-1	50,520	24.5	5,100	AUTO	131	2,120
Δ	NP2000	50,410	24.5	5,060	AUTO	138	2,260

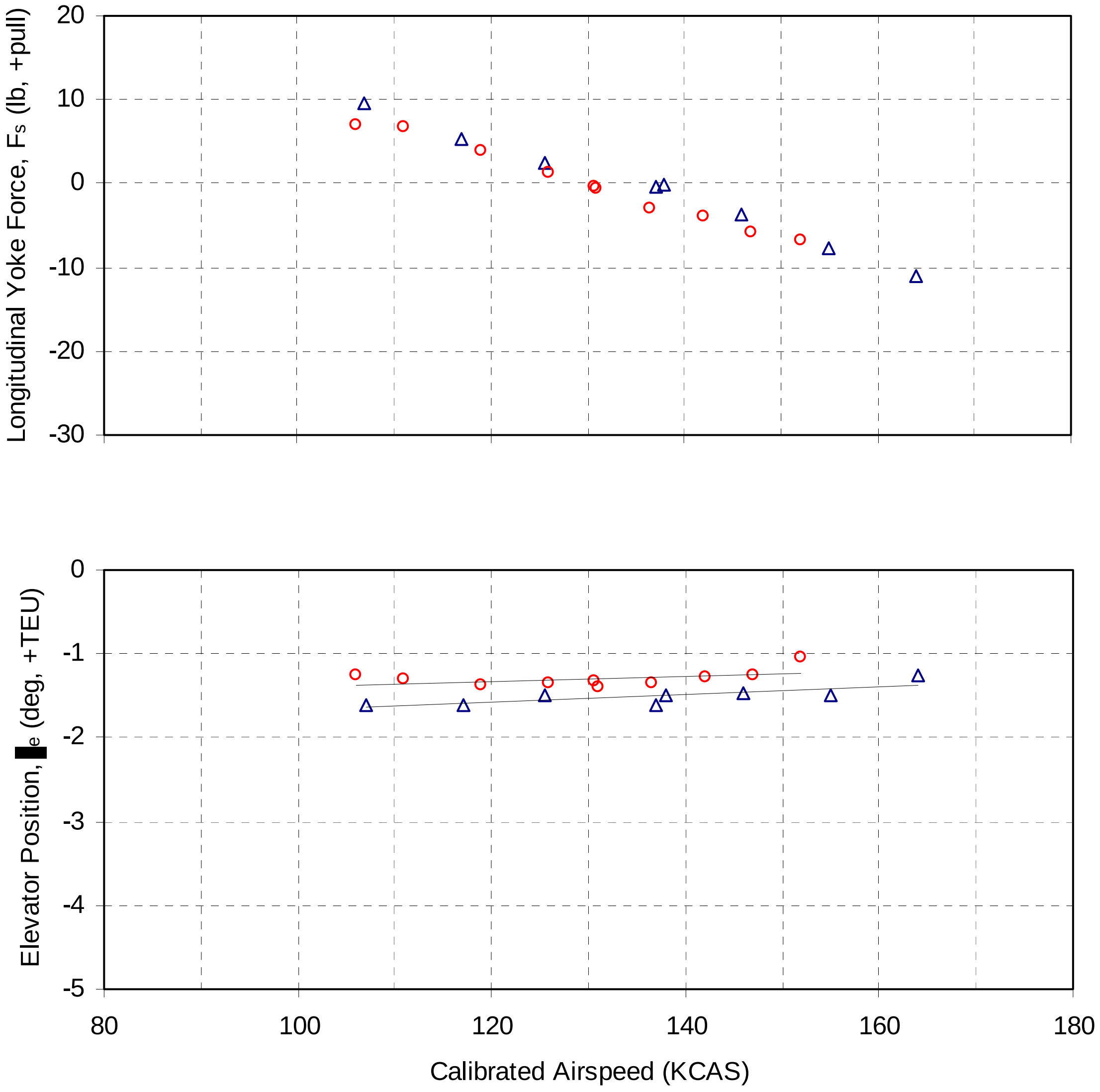

Figure B-10. Static Longitudinal Stability, 130 KCAS,
Configuration PA(30)

Model E-2C Aircraft, BuNo 163535, Trim Conditions:

Symbol	Propeller	Gross Weight (lb)	CG (%MAC)	Pressure Altitude (ft)	Pitch Feel Setting	Trim Airspeed (KCAS)	Avg. Eng. Power (ISHP)
△	NP2000	48,140	22.8	5,170	AUTO	106	1,540
○	NP2000	50,760	24.5	4,940	AUTO	108	1,810
□	NP2000	48,090	25.8	5,170	AUTO	108	1,590
◊	NP2000	48,190	26.3	4,940	AUTO	105	1,590

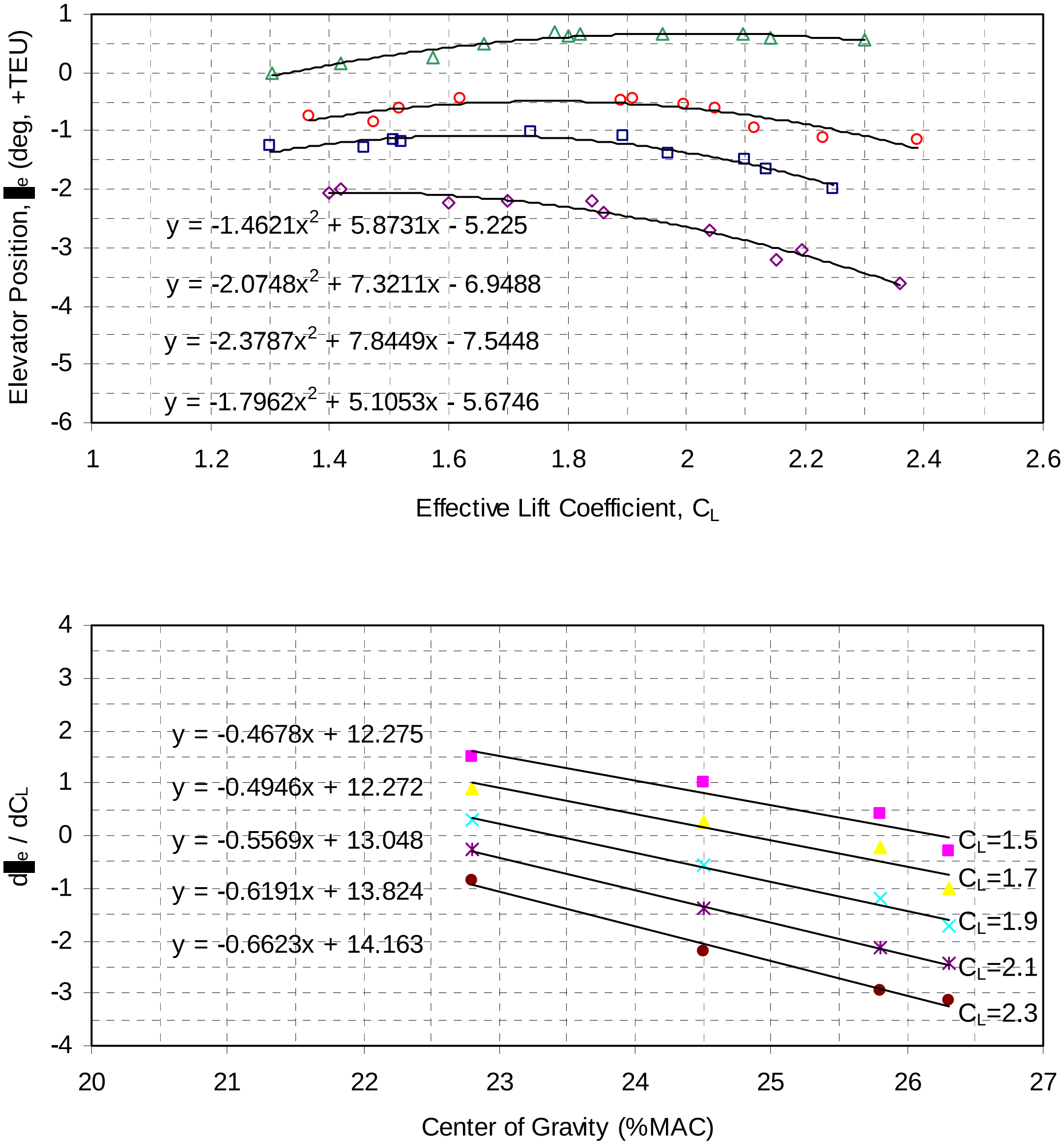

Figure B-11. Static Elevator Position Neutral Points, E-2C with NP2000 Propellers, Configuration PA(30)

Model E-2C Aircraft, BuNo 163535

Symbol	Propeller	Description
○	54460-1	Points derived from calculations in figure B-1[1]
Δ	NP2000	Points derived from calculations in figure B-11[1]
- - - - - - -	--	Estimated trend with decreasing C_L
— —	--	Airplane fwd and aft CG limits
▮	--	Effective C_L corresponding to 20u AOA

1. Data presented are derived values where $d\delta_e/dC_L$ was calculated to equal zero for each CG and C_L combination.

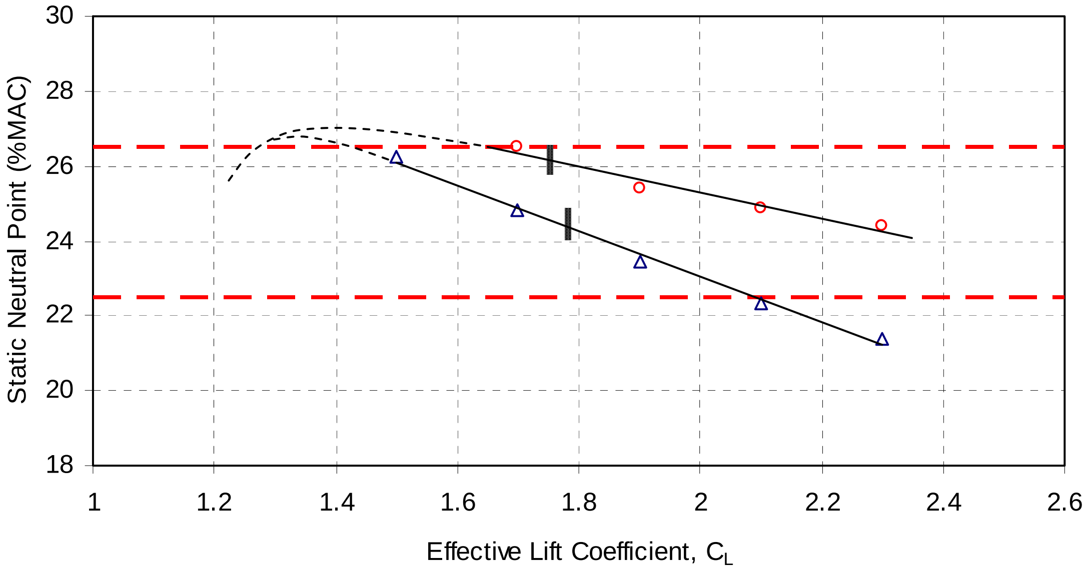

Figure B-12. Static Neutral Point Summary,
Configuration PA(30)

VITA

Glenn Jamison was born October 24, 1968 in Edison Township, New Jersey. In 1978, he moved with his family to Lisbon Falls, Maine. After graduating from Kents Hill School in 1986, he attended Duke University on academic and NROTC scholarships, graduating in 1990 with a BSE in Civil and Environmental Engineering and a commission in the United States Navy. Following graduation, he reported to Pensacola, Florida for U.S. Navy flight training, earning his Naval Aviator Wings in 1992. From 1993 to 1998 he served as a pilot and instructor in the E-2C Hawkeye, and then was selected to attend the U.S. Naval Test Pilot School at NAS Patuxent River, Maryland. After completing test pilot school, he served as the Project Officer for E-2C and C-2A programs at Naval Force Aircraft Test Squadron, during which time he successfully completed the first flight of the prototype NP2000 eight-bladed propeller system. From 2002 to 2004 he was assigned to Carrier Airborne Early Warning Squadron 112 and deployed overseas in support of Operations Enduring Freedom and Iraqi Freedom. In 2005, Glenn graduated from the Naval War College in Newport, Rhode Island with a Master's degree in National Security and Strategic Studies, and currently serves as the Air Warning Center Commander at Cheyenne Mountain AFB in Colorado Springs, Colorado. In 2007, Glenn will report as Executive Officer to a fleet E-2C squadron stationed at Point Mugu NAS, California. To date, he has accumulated over 3,400 flight hours in 47 different aircraft.