Maneuver Load Control and Relaxed Static Stability Applied to a Contemporary Fighter Aircraft

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Fighter aircraft maneuvering performance improvements attainable through the application of maneuver load control and relaxed static stability have been established analytically. Relaxing static stability and using combinations of horizontal canards and high lift control surfaces improve maneuvering performance characteristics such as specific excess power and lift-limited load factor. Optimal control techniques are used to determine control system compensating network parameters to provide desired system performance and stability. These control characteristics are achievable with an existing fly-by-wire flight control system. Maneuver load control and relaxed static stability are shown to be compatible and complementary fighter design concepts.

Introduction

DURING the past several years, advancements in flight control system technology have led to the emergence of a new aircraft design concept, the Control Configured Vehicle (CCV), in which control design technology is integrated throughout the configuration design stages. It has been shown that significant performance benefits may be realized when advanced control concepts are integrally included in formulating the design of a new aircraft. Two CCV concepts which show particular promise for fighter aircraft performance improvements are Maneuver Load Control (MLC) and Relaxed Static Stability (RSS).

In January 1971, McDonnell Aircraft Co. (MCAIR) began a research program entitled "Compatibility of Maneuver Load Control and Relaxed Static Stability Applied to Military Aircraft" under sponsorship of the Air Force Flight Dynamics Laboratory. The purpose of this research program is to determine the performance benefits which can be obtained for a fighter aircraft through the application of MLC and RSS and to evaluate the resulting impact on aircraft handling qualities. Analytical results were to be obtained in this study to indicate whether significant fighter aircraft performance benefits can be realized through the use of MLC and RSS, and whether these aircraft design concepts are compatible for all configurations selected for study. These study results were to show whether desirable handling qualities and adequate stability margins are attainable using existing fly-by-wire flight control system hardware with relatively minor modifications.

The aircraft selected for study is the F-4, which has been equipped for fly-by-wire in the Survivable Flight Control System (SFCS) program sponsored by the Air Force Flight Dynamics Laboratory (USAF Contract F33615-69-C-1827). The SFCS aircraft was selected because of the large amount of credible data for this aircraft which were available to MCAIR.

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Index categories: Aircraft Performance; Airplane and Component Aerodynamics; Aircraft Handling, Stability, and Control.

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MLC and RSS Design Concepts as Applied to Fighter Aircraft

The basic performance improvement objectives to be achieved through the use of MLC and RSS are not the same for fighter aircraft as they are for bomber/transport aircraft. The objective for bomber/transport aircraft is to improve cruise efficiency as measured by performance parameters such as range and payload. For fighter aircraft, the design objective is to improve maneuvering performance as measured by performance parameters such as specific excess power (P_s) and maximum normal load factor ($n_{z_{max}}$). While the RSS design concepts are essentially the same for both fighter and bomber/transport aircraft, the MLC design concepts are notably different.

A MLC system is one which employs control surfaces and maneuvering devices automatically positioned by an active feedback control system to redistribute the loading on a wing in maneuvering flight. The large bomber or transport aircraft is designed so that the wing lift distribution associated with minimum drag is obtained at one-*g* flight. Since this type of aircraft is usually at one-*g* flight, there is no reason to minimize drag during maneuvers. Therefore, for a bomber/transport, MLC is used to reduce the wing root bending moments during maneuvering flight, thereby alleviating structural fatigue of the wing and enabling structural weight reduction to be achieved for fixed load factor requirements. This reduction in wing root bending is obtained by shifting the wing lift distribution inboard, as shown in Fig. 1a, through the proper deflection of inboard trailing edge flaps and possibly other wing control surfaces such as outboard spoilers.

In contrast, the fighter aircraft must maintain an efficient wing lift distribution in maneuvering flight, as illustrated in Fig. 1b. To achieve this distribution, a fighter MLC system can employ aerodynamic devices such as leading edge slats to redistribute the wing loading in maneuvers, thereby deriving performance benefits through drag reduction and delayed buffet onset.

For the conventionally designed aircraft, static stability and acceptable handling characteristics must be obtained through aerodynamic design and judicious location of the center of gravity. In maneuvering subsonic flight and especially in supersonic flight this usually results in significant down tail loads to provide the required moment balance for the aircraft. However, if a high-authority feedback control system is used to provide artificial stability, the unaugmented aircraft's longitudinal static stability can be relaxed. Relaxing the aircraft's static stability by shifting the c. aft can result in a significant reduction g. in down tail loads or can even result in an up-loaded tail.

The wing loads are reduced since the tail loads are aiding instead of opposing the wing's lift, so the aircraft's drag is reduced and its maneuvering capability enhanced.

Relaxing longitudinal static stability with horizontal canards can also be used to provide similar drag reductions. The lift from the canards is ahead of the c.g., and with proper design an up-loaded tail will also result. Shifting c.g. aft and using horizontal canards are both means of obtaining RSS since they tend to reduce the aircraft static margin.

Configurations Selection

Five MLC devices were used in the analytical studies: operable canards; leading edge slats; leading edge Krueger flaps; trailing edge flaps; and flaperons (drooped ailerons). An F-4 configuration containing these MLC devices is shown in Fig. 2.

All possible combinations of these MLC devices were considered in the configuration selection phase of this program. The configuration selection was based on anticipated potential for performance improvement as well as on the availability of credible wind-tunnel and/or flight test data. The configurations selected for detailed study were: 1) basic F-4 with operable canards; 2) basic F-4 with operable canards and wing trailing edge flaps; 3) basic F-4 with wing leading edge slats; 4) basic F-4 with wing leading edge slats, flaperons, and trailing edge flaps; 5) basic F-4 with wing leading edge Krueger flaps; and 6) basic F-4 with wing leading edge Krueger flaps and trailing edge flaps.

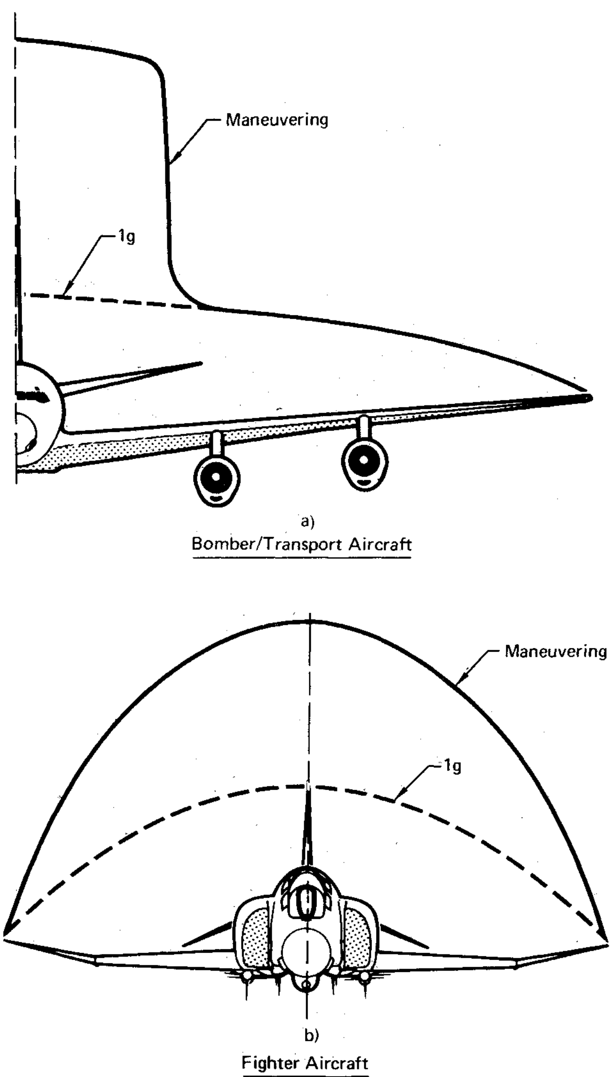

Fig. 1 Maneuver load control ideal lift distribution.

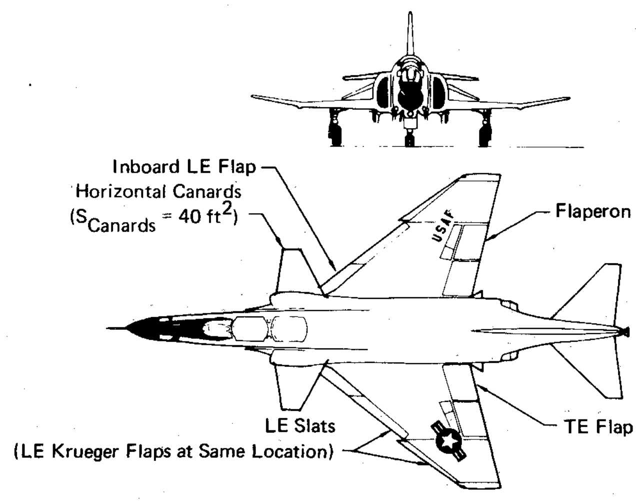

Fig. 2 Model F-4E with maneuver load control devices.

Two methods were also selected for relaxing the aircraft's static stability. One method was shifting the aircraft's c.g. aft. The other method was using the canards to move the aircraft's control-fixed neutral point forward. The effect on the basic aircraft's static longitudinal stability is shown in Fig. 3. It can be seen that addition of the canards used in this study (40 ft^2 exposed area) moved the aircraft's neutral point forward as much as 13.5% of the mean aerodynamic chord ($\bar{c}$) subsonically and 9.5%$\bar{c}$ supersonically.

A maximum negative stabilator limit of $\delta_s = -16°$, as compared with $\delta_s = -21°$ for the SFCS aircraft, was used for this study because of the necessity for more positive stabilator deflection when the aircraft's static longitudinal stability is relaxed. Design studies have shown that for this aircraft the amount of stabilator travel cannot be increased conveniently without requiring a new actuator. The stabilator stops, however, can be changed. Therefore, instead of a stabilator travel of $\delta_s = -21°\text{–}+7°$ as on the normal F-4, a travel of $\delta_s = -16°\text{–}+12°$ was chosen to allow for RSS.

Aerodynamic Characteristics of the MLC and RSS Configurations

The drag penalty at maneuvering combat flight conditions is of paramount importance for a fighter aircraft. The wing area is dictated by transonic or supersonic maneuverability, and the wing is optimized for minimum attainable drag at high lift coefficients during high-g maneuvers. Also of importance is the fighter aircraft's lifting

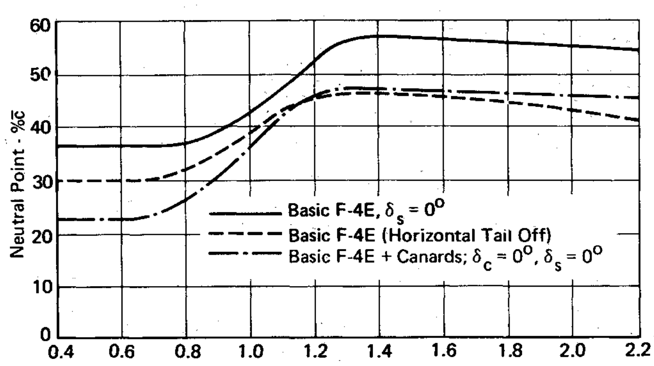

Fig. 3 Model F-4E—Effect of horizontal canards on control fixed neutral point.

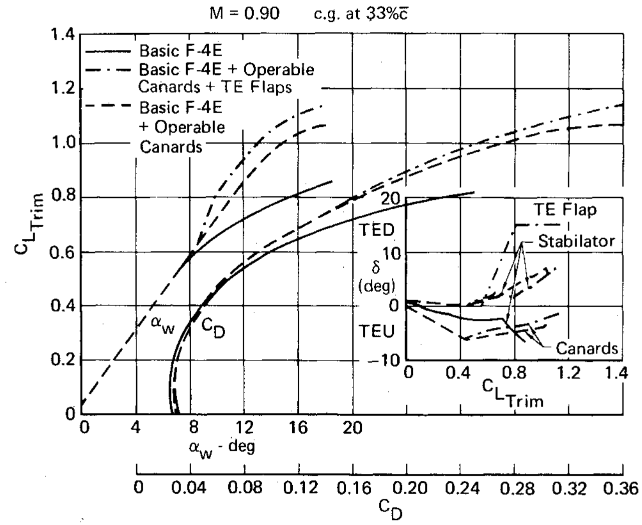

Fig. 4 Model F-4E—Trim lift and drag characteristics with operable canards and TE flaps.

capability at high maneuvering angles-of-attack because the more lift capability it has, the more g's it can pull in combat maneuvers. Therefore, the primary aerodynamic parameters used to evaluate the MLC and RSS configurations were the lift and drag at representative combat maneuvering flight conditions.

The trim lift and drag characteristics of each configuration were determined at several Mach numbers using wind-tunnel and flight test data. Trim characteristics were calculated for several center of gravity locations for each configuration to aid in evaluating the effect of relaxed static stability on performance.

Two of the configurations studied were the basic F-4 with operable canards and the basic F-4 with operable canards and wing trailing edge flaps. From a previous canards wind-tunnel test, described in Ref. 1, it was found that subsonically, close-coupled canards such as the ones shown in Fig. 2 have a high lift effect at high angles-of-attack on the basic aircraft much the same as wing leading edge slats. Figure 4 shows typical transonic trim lift and drag characteristics of the two canards configurations. It can be seen that the canards provide significant reductions in trim drag at maneuvering lift conditions, and that further reduction in trim drag can be obtained by using the wing trailing edge flaps.

The trim lift is also increased significantly at high angles-of-attack. Above $\alpha_w = 16°$, trim lift is increased by $\Delta C_L = 0.2$ with canards alone and by $\Delta C_L = 0.3$ using the horizontal canards and wing trailing edge flaps. The same characteristics were found at $M = 0.60$, and for the basic F-4 with canards configuration, trim drag was reduced significantly at $M = 1.45$. The trailing edge flaps were not investigated supersonically since they are not supersonic control devices. The relaxed static longitudinal stability caused by the canards accounted for a large part of the trim drag reduction at high lift coefficients, but the high lift effect of the canards also was a primary factor. The ability to pull the same lift coefficient at lower angles-of-attack greatly reduces the aircraft's induced drag. The trim deflection of the control surfaces can also be seen in Fig. 4. It is interesting to note that the optimum trim deflections of the canards, on the basis of minimum drag, are negative (trailing edge up) and the stabilator deflections are positive (trailing edge down), especially at the higher lift coefficients. The positive stabilator deflections account for a part of the increased trim lift at the higher angles-of-attack because the stabilator is an up-lifting tail as compared with the down-lifting tail on the basic aircraft. The optimum desired trailing edge flap deflection as a function of lift coefficient is also shown in Fig. 4. It was found in this study that the flaps could be fully deflected ($\delta_{F_{TE}} = 15°$ in this study), or retracted, depending on angle-of-attack, to most effectively reduce trim drag.

Two other configurations studied were the basic F-4 with leading edge slats and the basic F-4 with leading edge slats, trailing edge flaps, and flaperons. The locations of the slats (midboard and outboard wing panels) and the flaps and flaperons are shown in Fig. 2. Figure 5 shows the effect of the slats, flaps, and flaperons on trim lift and drag at $M = 0.90$. It can be seen that the slats provide a significant trim drag reduction at maneuvering lift coefficients. The addition of the trailing edge flaps and flaperons further reduces trim drag and results in a significant increase in trim lift at the higher angles-of-attack. the flaps and flaperons increase the trim lift by $\Delta C_L = 0.12$ at $\alpha_w = 16°$. It can also be seen in Fig. 5 that, as with the horizontal canards configuration, the optimum deflection of the flaps and flaperons for maximum trim drag reduction is either fully deflected ($\delta_{F_{TE}} = 15°$) or fully retracted, depending on angle-of-attack. The same trim lift and drag characteristics were observed at $M = 0.60$. Since the slats, flaps and flaperons are subsonic and transonic maneuvering devices, they were not investigated supersonically.

The last two configurations investigated in this study were the basic F-4 with wing leading edge Krueger flaps and the basic F-4 with wing leading edge Krueger flaps and trailing edge flaps. The locations of these devices can be seen in Fig. 2. These maneuvering devices provide a trim drag reduction at maneuvering lift coefficients and an increased trim lift capability at high angles-of-attack. It was also found that they should be either extended or retracted depending on the angle-of-attack. These devices also were not investigated supersonically as Krueger flaps and trailing edge flaps are not supersonic devices.

All the MLC configurations resulted in increases in trim lift capability at the higher angles-of-attack. These increases in lift indicate that maximum usable normal force capability of the basic aircraft increases when the MLC devices are utilized. Some of these devices, however, not only increase lift at the higher angles-of-attack but delay buffet onset to higher angles-of-attack, thereby increasing the maximum usable angle-of-attack of the aircraft. For a fighter aircraft, such as the one used in this study, the subsonic and transonic maximum usable angle-of-attack is determined by "wing-rock" or handling qualities considerations. Thus any delay in buffet onset will increase the maximum usable angle-of-attack and, therefore, the maximum usable normal force capability of the aircraft.

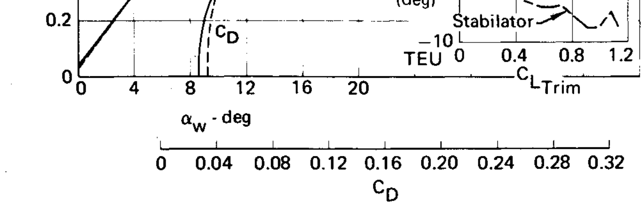

Fig. 5 Model F-4E—Trim lift and drag characteristics with slats, TE flaps, and flaperons.

Supersonically, the maximum usable angle-of-attack is control-limited. It was found that subsonically and transonically the configurations utilizing the leading edge slats result in the largest increases in maximum usable normal force. At $M = 0.90$ it was found that the leading edge slats by themselves increase the maximum usable normal force by $\Delta C_N = 0.35$, and when the trailing edge flap and flaperons are added, this increased to $\Delta C_N = 0.47$. Supersonically, the horizontal canards configuration results in a significant increase in maximum usable normal force because of the aircraft's ability to rotate to a higher maximum usable angle-of-attack. At $M = 1.60$ an increase in maximum usable force of $\Delta C_N = 0.13$ was found for the horizontal canards configuration with $\delta_s = -16°$ and $\delta_c = +10°$.

Part of the trim lift and drag improvements associated with the two canard configurations were due to the reduction in static longitudinal stability resulting from the control-fixed neutral point being moved forward by the canards. This reduced trim drag and increased lift resulted from the stabilator becoming a lifting tail.

The other method of relaxing static longitudinal stability that was investigated in this study was moving the c.g. aft, thus reducing the control-fixed static margin. For this case the trim drag is reduced significantly, especially at maneuvering normal load factors. Maximum usable normal force capability is also increased by moving the c.g. aft. The increase was found to be especially significant supersonically. At $M = 1.6$, maximum usable normal force was increased by $\Delta C_N = 0.35$ for an 11%$\bar{c}$ aft c.g. shift (31%$\bar{c}$–42%$\bar{c}$).

The extent that the static longitudinal stability can be relaxed is a direct function of the amount of nose down control capability available. For the basic F-4 aircraft, the c.g. cannot be moved further aft than 44%$\bar{c}$ or there would be an angle-of-attack region where the aircraft could not be trimmed. This c.g. limit is for a stabilator deflection of $\delta_s = +12°$. For the canards configuration with its resulting forward neutral point shift, the c.g. can only be moved aft to 38%$\bar{c}$ with $\delta_s = +12°$ and $\delta_c = -10°$. This is the stabilator/canards deflection combination that provides maximum nose down control. The aft c.g. limit was evaluated for all the MLC configurations, but the canards configurations were the only ones to significantly change the aft c.g. limit from that of the SFCS aircraft.

Operation of the Maneuver Load Control Devices

In every configuration studied it was found that all of the maneuvering devices, with the exception of the canards, should be either fully extended or fully retracted and should be deflected as functions of wing angle-of-attack. The optimum deflection for trimming the canards as a function of lift coefficient was determined at each of the three Mach numbers studied for the horizontal canards

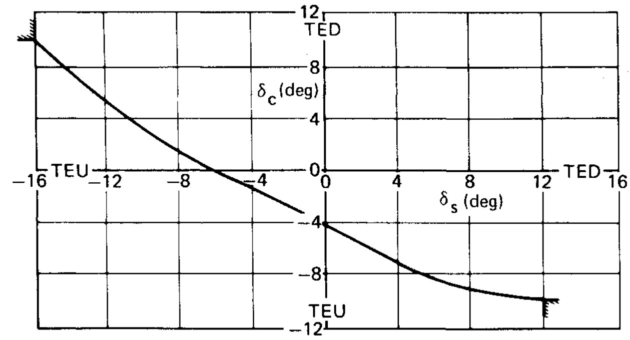

Fig. 6 Model F-4E with operable canards—control surface deflection schedule.

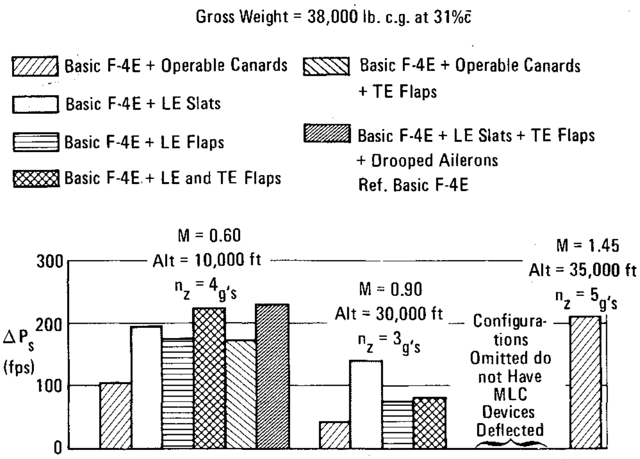

Fig. 7 Model F-4E—effect of MLC devices on energy maneuverability.

alone and also for the horizontal canards with the trailing edge flaps. Figure 4 shows the variation of canards deflection with C_L at $M = 0.90$. It can be seen that this deflection schedule is nonlinear with C_L, and it also changes with Mach number, c.g. location, and trailing edge flap deflection. It was desirable to develop a simple canards deflection schedule that would be good for all Mach num-

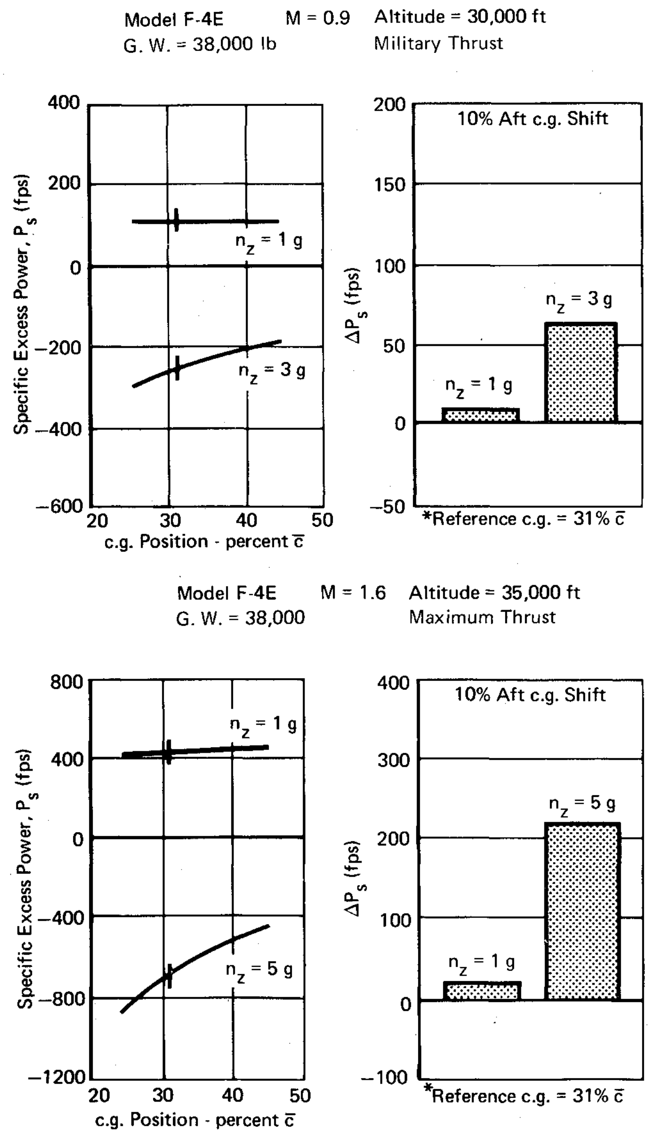

Fig. 8 Effect of aft c.g. on specific excess power.

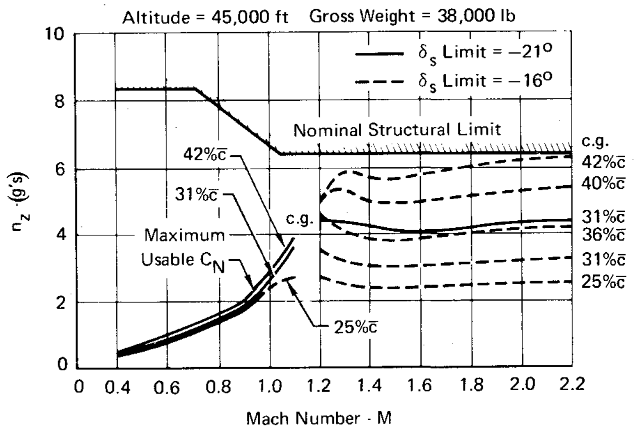

Fig. 9 Model F-4E—load factor variation with c.g. position.

bers, c.g. locations, and flap deflections and still be able to realize the full trim drag benefits of the horizontal canards. Such a schedule was developed and is shown in Fig. 6. In this schedule canards deflection is a function of stabilator deflection. It is valid for all Mach numbers from M = 0.60 to 1.45, c.g. positions from 28%c̄ to 37%c̄, and trailing edge flap deflections from 0° to 15°.

MLC and RSS Performance Benefits

The aerodynamic benefits previously discussed can be expressed in terms that more readily show the performance benefits of MLC at maneuvering combat flight conditions. The trim drag benefits can be shown in terms of specific excess power, P_s, where

$$P_s = [(T - D)/W]V \tag{1}$$

and T = thrust (lb), D = drag (lb), W = aricraft weight (lb), and V = aircraft velocity (fps).

Specific excess power is a measure of the aircraft's acceleration along its flight path. The lift benefits of MLC can be shown in terms of normal load factor, n_z, where

$$n_z = C_N qS/W \tag{2}$$

with C_N = normal force coefficient, q = dynamic pressure (lb/ft²), S = wing area (ft²), and W = aircraft weight (lb).

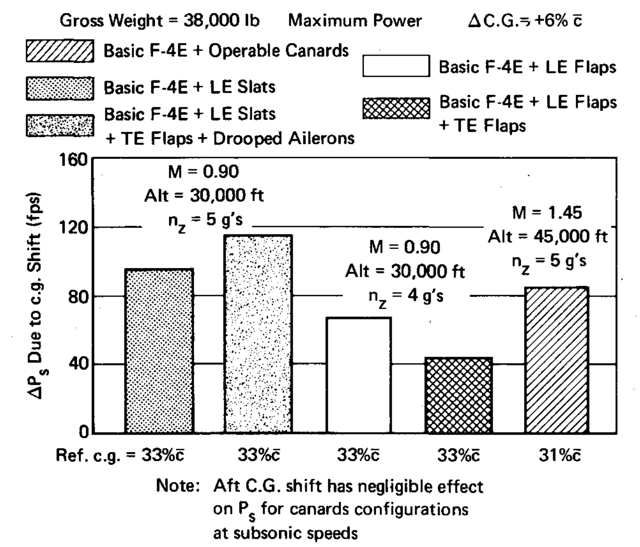

Fig. 10 Model F-4E—compatibility of maneuver load control and relaxed static-stability.

Table 1 Model F-4E—improvements in maximum normal load factor

Configuration	Lift limited, Alt = 35,000 ft, M = 0.60	Lift limited, Alt = 35,000 ft, M = 0.90	Control limited, Alt = 45,000 ft, M = 1.45
Basic F-4E + operable canards	0.32g	0.89 g	1.0g
Basic F-4E + operable canards + TE flaps	0.55	1.19	NA[a]
Basic F-4E + LE slats	0.44	1.30	NA
Basic F-4E + LE slats + TE flaps + drooped ailerons	0.65	1.75	NA
Basic F-4E + LE flaps	0.11	0.11	NA
Basic F-4E + LE flaps + TE flaps	0.30	0.43	NA

[a]NA = not applicable.

Figure 7 shows the effect of the MLC configurations on specific excess power at three typical combat flight conditions. It can be seen that the configurations with leading edge slats provide the best subsonic improvements in specific excess power. At M = 0.90, alt = 30,000 ft and n_z = 3 g, the leading edge slats result in an improvement in P_s of 140 fps. Supersonically, the canards increase specific excess power by 210 fps at M = 1.45, alt = 35,000 ft and $n_z = 5\,g$.

Table 1 shows the improvement in maximum normal load factor of the MLC configurations at three typical combat flight conditions. For M = 0.90 and 35,000 ft, the two MLC configurations with leading edge slats result in the largest improvements in maximum usable normal load factor. The two horizontal canards configurations also show significant improvements in $n_{z_{max}}$. Supersonically, the only configuration that is applicable is the horizontal canards configuration and it results in a one-g improvement in control-limited n_z as compared with the basic aircraft with $\delta_s = -21°$.

The performance benefits shown for the canards configurations summarize the benefits which can be expected from relaxing static longitudinal stability by using canards. The other means studied for obtaining RSS is moving the c.g. aft. Figure 8 shows the effect on specific excess power of moving the c.g. aft on the basic aircraft at one subsonic and one supersonic combat flight condition. Supersonically an aft shift in c.g. location results in a significant increase in P_s at n_z = 5 g. Figure 9 shows the effect of moving the c.g. aft on maximum usable normal load factor. Supersonically, an 11%c̄ aft shift in c.g. (31%c̄–42%c̄) results in a significant increase (40%) in control-limited normal load factor capability.

Compatibility studies revealed that all the MLC configurations were compatible with RSS in the sense that performance improvements were greater employing RSS and MLC simultaneously than employing either RSS or MLC independently. This is shown in Fig. 10 in terms of improvement in specific excess power for a 6%c̄ aft shift in c.g. location. Further significant increases in P_s at the high load factor conditions occur as a result of applying RSS to the MLC configurations. It should be noted that this aft shift in c.g. location had a negligible effect on P_s for the canards configurations at subsonic Mach numbers. As previously mentioned this was due to the fact that the

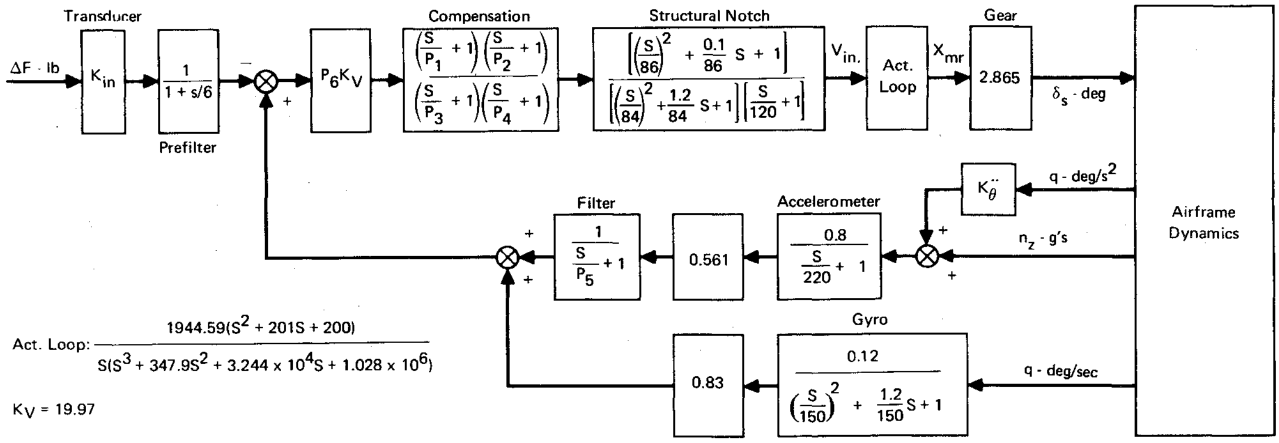

Fig. 11 Longitudinal flight control system.

static longitudinal stability had already been relaxed significantly by the canards.

Flight Control Systems Configurations

The unaugmented airframes for many of the configurations that were examined are longitudinally statically unstable in subsonic flight. Therefore, practical considerations for basic flight safety require that a reliable full-time, high-authority flight control system be employed in the longitudinal axis to provide artificial stability. Fully augmented fly-by-wire longitudinal and lateral-directional flight control systems were developed in the SFCS program for the unmodified configuration of the subject aircraft, and representative forms of these control systems were employed for all configurations investigated. A control system design goal was to achieve the same handling qualities and stability margins as the SFCS aircraft with as few modifications in the basic flight control systems as possible.

A functional block diagram of the SFCS longitudinal flight control system is shown in Fig. 11. Detailed descriptions of the SFCS longitudinal and lateral-directional flight control systems are contained in Ref. 2. Two degree-of-freedom longitudinal and three degree-of-freedom lateral-directional linearized airframe dynamics were used in the control system optimization studies. The RSS configurations employing aft shifted c.g. required only parameter changes in the SFCS flight control systems. All other configurations required additional control loops to position the MLC surfaces.

Six parameters in the basic SFCS longitudinal control system and six in the basic SFCS lateral-directional control system were selected for adjustment on the basis of anticipated system sensitivity to the parameter values. From a practical standpoint, it was desirable to adjust only electronic components. Parameters selected in the longitudinal axis are denoted as P_1 through P_6 in the longitudinal SFCS block diagram in Fig. 11. Adjustment of these parameters is equivalent to selecting the forward loop gain and defining the forward loop compensation networks and the accelerometer feedback filter. Adjustments of these parameters were made to provide each of the MLC F-4 configurations with longitudinal handling qualities and stability margins that satisfactorily met the basic SFCS design requirements. Lateral-directional aerodynamics were not altered as significantly as longitudinal aerodynamics, so it was not necessary to make major parameter changes in the SFCS lateral-direction flight control system.

As discussed previously, it was found that all MLC surfaces except the horizontal canards should be either fully extended or fully retracted depending on the angle-of-attack. In the case of the leading edge slats, trailing edge flaps, and flaperons, positioning was accomplished by scheduling surface deflection with angle-of-attack as shown in Fig. 12. The small surface deflection ramp was

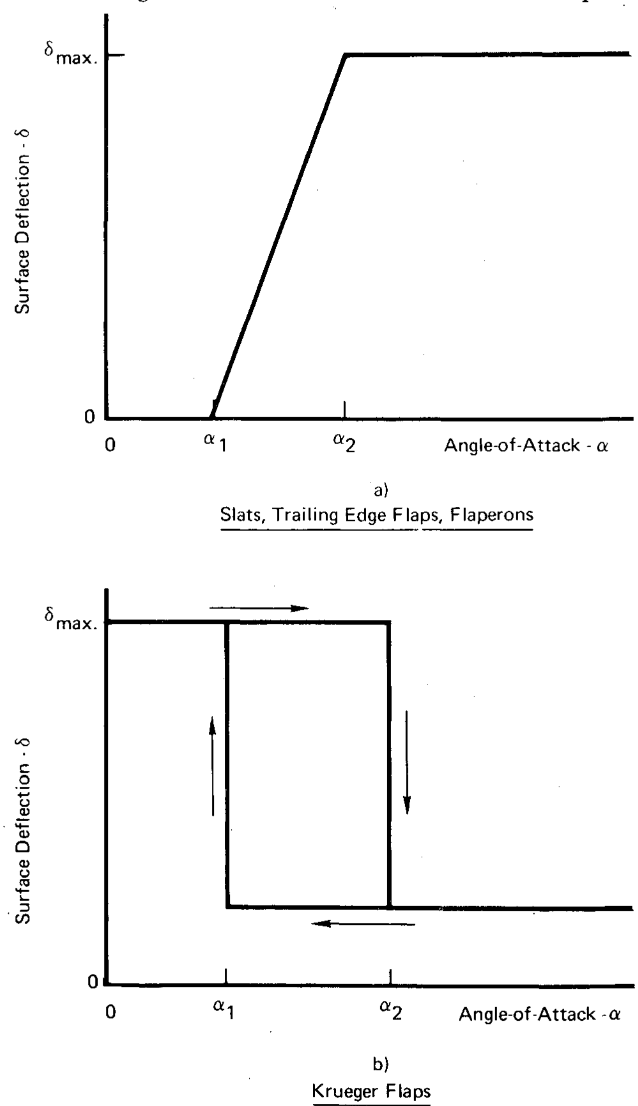

Fig. 12 Deflection schedules of MLC surfaces other than canards.

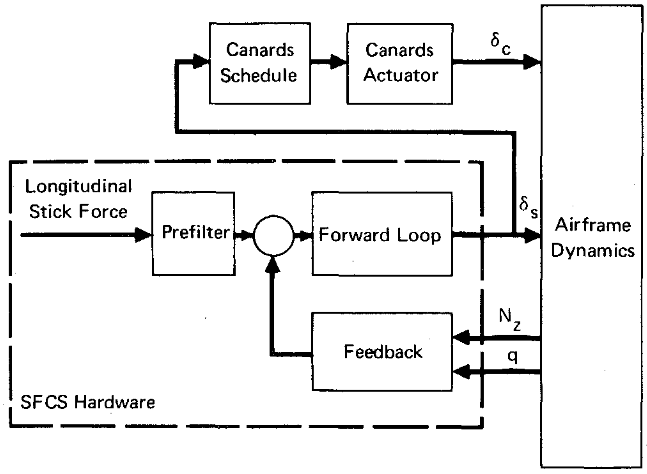

Fig. 13 Longitudinal flight control system with canards.

provided to prevent chatter, a common drawback of "bang-bang" control systems. Optimum deflection of the leading edge Krueger flaps is also essentially "bang-bang". However, these surfaces must unfold from the fully retracted position beneath the wing and swing forward to the fully deflected position. Unlike the other surfaces, deflection of the Krueger flaps midway between retracted and fully extended positions results in severe drag penalties, so it is desirable to deflect and retract the surfaces as quickly as possible. This was accomplished by employing hysteresis in the surface deflection schedule, as illustrated in Fig. 12, to prevent chatter. For MLC configurations utilizing the canards, near optimum combinations of stabilator and canards deflections illustrated in Fig. 6 were achieved by "slaving" the canards to the stabilator using a nonlinear electronic component which implemented the optimum canards/stabilator deflection schedule. This arrangement is shown in Fig. 13, where stabilator position is sensed to provide a reference for the canards positioning control path.

No additional control paths were required in the basic SFCS lateral-directional control system. The relatively minor modification to the aircraft lateral-directional dynamics attributable to the configuration changes required only minor changes in the lateral-directional flight control system parameters.

Handling Qualities and Stability Criteria

The handling qualities and stability criteria used in this study were the same as used in the design of the flight control systems for the SFCS aircraft. The familiar C^* criteria were applied for optimizing the longitudinal flight control system parameters. The D^* criteria, developed

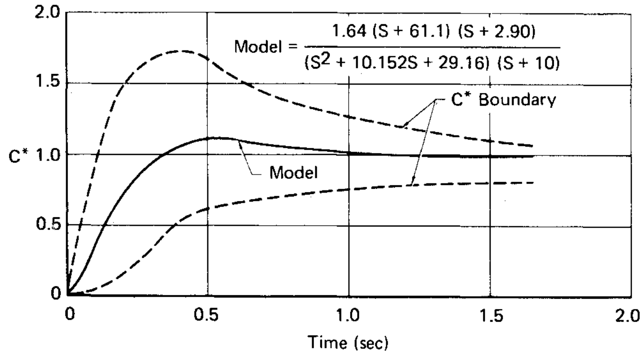

Fig. 14 Desired C^* response.

Table 2 Optimum parameters—aft c.g. and canards configurations

Mach = 0.9, 35,000 ft		
Configuration	Aft c.g.	Canards
c.g. (%$\bar{c}$)	44.0	33.0
P_1	2.28	4.0
P_2	27.0	27.0
P_3	1.52	1.0
P_4	80.0	80.0
P_5	7.52	3.62
P_6	0.57	1.05

during the SFCS program, were used in optimizing the lateral-directional flight control system parameters. Complete descriptions of the longitudinal and lateral-directional handling qualities criteria used in the SFCS program and the subject program are contained in Ref. 2. Since the SFCS aircraft configuration changes studied in this program primarily affected longitudinal dynamic characteristics, descriptions of the lateral-directional handling qualities criteria are not repeated here.

The C^* criteria were used in the selection of the longitudinal control system parameters for each configuration studied. As discussed in Ref. 2, C^* is a blend of the pitch rate and normal acceleration and is defined by the equation

$$C^* = \Delta n_{z_p} + 12.43q \tag{3}$$

where Δn_{z_p} is the incremental normal load factor at the pilot station in g and q is the pitch rate in rad/sec. Figure 14 gives the boundaries for the normalized C^* step response used to evaluate the longitudinal dynamics. To satisfy the C^* criteria, C^* time histories should fall within the boundaries given in Fig. 14 with the response free of high-frequency, poorly damped oscillatory modes.

The stability margin goals used in optimizing the compensation parameters for the longitudinal and lateral-directional flight control systems for each configuration studied were at least a 6-db gain margin and a 45° phase margin at all flight conditions. Three symmetrical and three asymmetrical structural modes were included in the gain and phase margin calculations. A description of these modes and a discussion of their significance is available in Ref. 2. Maintaining these stability margins tended to minimize high-frequency, poorly damped oscillations in the aircraft responses.

Control System Optimization

The previously described aerodynamic characteristics of the various additional control surfaces employed in the MLC configurations determined the optimum bang-bang

Table 3 Aft c.g. fixed parameter values and stability margins

Mach number	Alt, ft	c.g., %$\bar{c}$	P_1	P_2	P_3	P_4	P_5	P_6	Gain margin, db	Phase margin, deg
0.5	5000	36	3.84	27.0	1.59	80.0	3.90	0.52	15.6	61
0.9	35,000	36	3.84	27.0	1.59	80.0	3.90	0.52	13.0	57
1.5	35,000	36	3.84	27.0	1.59	80.0	3.90	0.52	17.6	67
0.5	5000	44	2.71	27.0	1.33	80.0	6.63	0.55	13.6	62
0.9	35,000	44	2.71	27.0	1.33	80.0	6.63	0.55	8.3	67
1.5	35,000	44	2.71	27.0	1.33	80.0	6.63	0.55	10.4	53

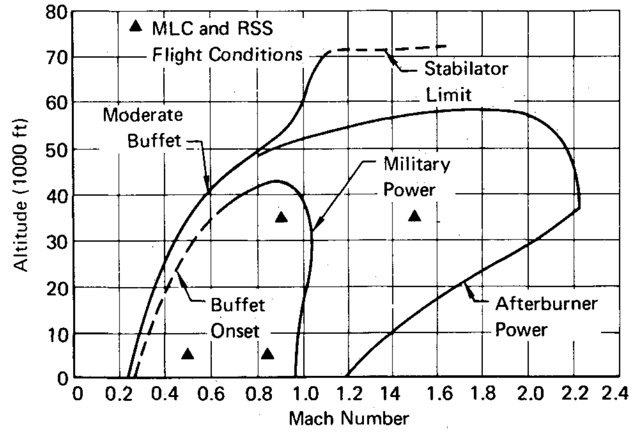

Fig. 15 F-4E operational envelope.

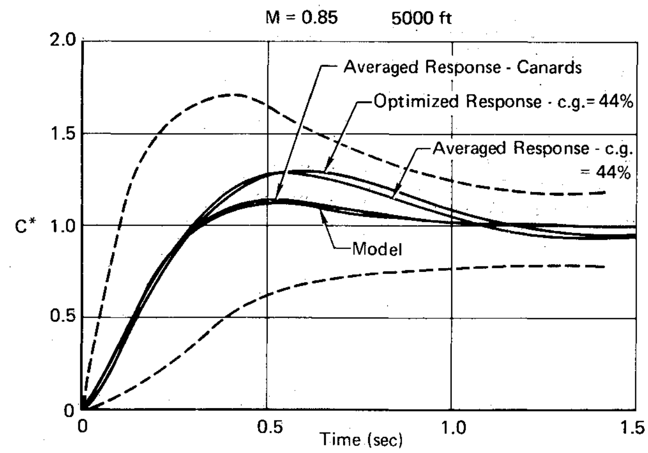

Fig. 16 Typical averaged fixed parameter C^* responses.

design of the control loops used to position the MLC devices. Therefore, control system parameter optimization for the various configurations was limited to selecting parameter values within the basic longitudinal and lateral-directional flight control systems. Classic control system parameter optimization techniques were utilized for this task.

Cost functionals were defined for each control axis based on the handling qualities and stability criteria summarized in the previous section. These functionals were of the classic integral squared error (ISE) quadratic form, and parameter optimization was performed by using digital computer steepest-descent techniques to minimize the cost functionals.

The cost functional used for the longitudinal flight control systems was

$$\text{ISE} = \int_0^\infty [(C^* - C^*_m)^2 + 10(\dot{\delta}_s)^2]dt \qquad (4)$$

where C^* is the aircraft C^* step response, C^*_m is the desired (or model) C^* step response which is shown in Fig. 14, and $\dot{\delta}_s$ is the stabilator rate. The value of the stabilator rate weighting factor was selected to be 10 primarily because this value tended to produce systems which met the desired gain and phase margins in initial optimization trials. A similar parameter optimization procedure was used for the lateral-directional flight control system for each configuration.

Control System Optimization Results

Optimization of the longitudinal and lateral-directional parameters was performed for each of the four flight conditions depicted on the F-4 operational envelope in Fig. 15. Parameters for the configurations not employing bang-bang controlled MLC surfaces were optimized for one-g load factor flight. Parameters for the other configurations were optimized at aircraft load factors of one and 3.5 g. This procedure was followed in order to examine optimal parameter values and system performance with MLC surfaces both in the retracted and in the extended positions. With the exception of the canards, effects of MLC surface deflection transients on handling qualities were not considered in the control system optimization. It is again noted that the only MLC control surface operated supersonically was the horizontal canards; the other MLC surfaces are subsonic devices.

In general, it was found that to meet handling qualities and stability requirements, only the forward loop gain (parameter P_6) and the accelerometer filter pole (parameter P_5) needed to be changed significantly from the values used in the SFCS longitudinal flight control system. Typical examples of the values of optimum parameters are listed for the aft c.g. and the F-4 with horizontal canards configurations in Table 2. Longitudinal gain and phase margins for the configurations and flight condition listed were 7.4 db, 68°, and 14.1 db, 49° for aft c.g. and canards configurations, respectively. Lateral and directional stability margins for all configurations did not vary significantly from the values for the SFCS aircraft presented in Ref. 2. All six longitudinal parameters were optimized for the aft c.g. configuration; however, only P_5 and P_6 were optimized for the horizontal canards configurations.

To avoid in-flight adaptive parameter adjustment, optimum parameter values for the various flight conditions were averaged for each configuration. These fixed sets of averaged parameter values were then used to preclude the need for adaptively changing parameters during flight. In all cases the C^* responses deviated slightly more from the desirable model responses than did the optimum-parameter handling qualities responses, but the fixed parameter responses met the handling criteria very well at the various flight conditions. Typical parameter results are illustrated in Table 3 which presents representative fixed longitudinal parameter values and stability margins for the aft c.g. configurations examined, and by Fig. 16 which presents a typical handling qualities response comparison for a relaxed stability configuration and a canards configuration.

These parameter optimization studies were performed on all MLC configurations including the canards with aircraft c.g. locations at 37% $\bar{c}$, the canards configuration control limited aft c.g. location, as well as the more conventional location of 33% of the mean aerodynamic chord. The 37%$\bar{c}$ configurations represented a combination of the MLC and RSS concepts, and the resulting excellent handling qualities and stability characteristics that were achieved for the two concepts individually were also achieved for the two concepts employed simultaneously.

Conclusion

In conclusion, analytical studies have been performed to establish the fighter aircraft maneuvering performance improvements attainable through the application of MLC and RSS aircraft design concepts. These studies have shown that 1) significant performance benefits can be realized for a fighter aircraft through judicious application of MLC and RSS aircraft design concepts; 2) these design concepts are compatible; and 3) aircraft configured using these design concepts can be adequately controlled using existing control system technology.

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Evaluation of the Selection and Training of Fighter Pilots

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Analysis of historical combat data indicates that the fraction of fighter pilots killed (pilot hazard rate) decreases as the number of decisive air-to-air combats increases. This could be a result of two groups of pilots being present; a superior group represented by those who learn from experience and an inferior group represented by those with no learning. A proposed plan for pilot selection and training, based on this hypothesis, is presented. The purpose of the plan is to lower the hazard rate that pilots would experience in real combat by first subjecting these pilots to a selection and training process based on successive simulated combats. Using a mathematical model, based on renewal theory, the paper shows how such a program can have significant payoff in terms of improved force effectiveness and reduced pilot losses.

Introduction

HERBERT Weiss[1] has written a paper which includes some statistics and analysis on pilot survival in air-to-air combat. In his paper, Weiss states that in past wars involving extensive air-to-air combat, a small number of pilots—the aces—were responsible for most of the kills. He therefore hypothesizes that fighter force capability depends on the performance of a few top pilots rather than on the collective skills of all oilots.

A "decisive combat" is defined by Weiss as one in which a pilot is either killed or adds one to his score. Mathematically, the hazard rate h_i on decisive combat i, is

$$h_i = K_{i-1}/(S_i + K_{i-1}) \qquad (1)$$

where K_i = number of pilots downed by enemy aircraft with score i; S_i = total number of pilots (living or dead) with at least score i.

Of particular interest in the Weiss paper is data giving the probability of being killed as a function of the decisive combat number for the German squadron Jagdgeschwader JG26 in World War II. These data show a decrease in the probability of being killed as the number of encounters increases. This probability, being a conditional probability, is defined as the hazard rate as given by Eq. (1).

The question arises whether the initial decline in hazard rate with score represents learning, or the elimination of the least skilled pilots. One interesting hypothesis concerning the JG26 data can be made by reference to Fig. 1 which gives the hazard rate for the JG26 plotted on a semilog scale. One hypothesis is that two straight-line segments are prominent on this chart. The first line segment represents a composite of two dominant groups of individuals; one group is represented by a constant learning slope and an initial hazard rate of roughly 0.2; the other group, exhibits a higher initial hazard rate and essentially zero learning. This latter group quickly dies out of the population and is almost completely gone by the 5th decisive combat if no replacement takes place. This is shown by the progression of circles at the bottom of the chart. The size of the circles represent the reduction in total population, there being about a 50% reduction in total population with the first decisive combat.

Two points of consequence emerge from this hypothesis. First, we have both survival of the fittest and learning going on in the process; the learning seems to be largely restricted to the superior group of pilots; second, the loss of almost half of the pilots in their first decisive combat is a situation we could do much to improve.

Thus, our task is twofold: to identify potential aces early and to allow the learning process to proceed sufficiently so that a maturing effect is already in existence by the time combat takes place. The use of training simulators can do this for us. The effect in improving force effectiveness and pilot replacement rate can be dramatic, as will now be illustrated.

Payoff of the Program

A training program for fighter pilots should include both initial screening of candidates and retention of selected candidates throughout the program for progressive development. These two aspects depend on the degree of innate vs acquired skills which pilots display in actual (or simulated) air-to-air encounters. Controlled experimentation through flight tests and training simulators is necessary to isolate and identify those factors which account for these effects on sequential air-to-air encounters.

We now examine the impact of using a proper scheme of selection and training of pilots. The effects we will examine are in terms of replacement rates demanded of a training program (pilots lost in combat) and the fighter force effectiveness in terms of exchange ratio (ratio of expected enemy losses to expected friendly losses).

To demonstrate these effects, we will present a model and analysis based on the theory of renewals, or recurrent events.[2] Before doing this, however, let us first examine a

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