



Review on Flight Control Law Technologies of Fighter Jets for Flying Qualities

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Received: 25 May 2022 / Revised: 16 October 2022 / Accepted: 30 November 2022 / Published online: 31 December 2022
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Abstract

Since the 1970s, designing flight control laws to ensure good flying qualities and increase mission efficiency has been an issue for many years. This is still regarded as a core technology challenge in aircraft development. When a fly-by-wire flight control system (FBW FCS) technology was adopted to the aircraft, the classical control technique in the form of single-input single-output (SISO) type was applied in early years. Meanwhile, a modern control theory tied with classical control in the form of multi-input multi-output (MIMO) such as eigenstructure assignment (EA) was recently applied, and the nonlinear dynamic inversion (NDI) has been also applied to the highly maneuverable fighters. In this paper, we identify major technologies such as aerodynamics, control stick and sensors, including flight control technologies which have been applied to the production fighter aircrafts so far, and analyze the trend of development of control law technologies. To the extent of education, these reviews regarding the prospects on flight control technologies would be most helpful to engineering.

Keywords Flight control law · Fighter jet · Flying qualities · Airworthiness · Flight control sensor · Envelope protection · Automatic recovery function

List of Symbols

α	Angle of attack (°)
β	Angle of sideslip (°)
$C_{l\beta}$	Dihedral effect derivatives
$C_{n\beta}$	Kinematics, directional stability derivatives
$C_{n\beta_{dyn}}$	Directional control departure parameter of the stability axis
δ	Control surface deflection (°)
I_{ii}	Principal moment of inertia (slug-ft ²) ($i = x, y, z$)
N_n	Normal acceleration (g)
N_z	Body-axis normal load factor (g)
P_B	Body-axis roll rate (°/s)
Q	Dynamic pressure (lb/ft ²)
R_b	Body-axis yaw rate (°/s)
R_s	Stability-axis yaw rate (°/s)

1 Introduction

The fighter aircrafts have been designed to have high maneuverability for preoccupying strategic superiority in the air-to-air and air-to-ground combat situations. For this, most of the fighter aircrafts have adopted digital fly-by-wire flight control system (DFBW FCS) to provide good flying qualities and mission performance, and ensure flight safety for all mission task elements (MTEs) over the entire flight envelope.

A DFBW FCS [1] is an electrical primary flight control system which utilizes feedback of aircraft motion sensing signals as controlled parameters. In 1972, the F-8 Crusader [2] which uses the first DFBW FCS without a mechanical backup was successfully flown at National Aeronautics and Space Administration (NASA) Dryden Flight Research Center. Since then, the major advance in the development of Fly-By-Wire system for the fighter aircrafts were adopted to the F-16 Fighting Falcon,^{1,2} which was a multi-role combat

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¹ David, B., How the F-16 Became the World's First Fly-By-Wire Combat Airplane, 2009. http://www.f-16.net/articles_article13.html.

² L. Cloer, What Is Fly-By-Wire? Nov 1, 2014. <https://duotechservices.com/what-is-fly-by-wire>.

aircraft with a single engine developed by General Dynamics (now Lockheed Martin) in 1976. The F-16 was the first production combat aircraft to use fly-by-wire flight control system technology. Since the first flight of F-16A [3], most combat aircrafts have adopted the DFBW FCS with various control functions to ensure good flying qualities and improve mission performance.

In the early 1990s, the military flight control system for the F-16 [4] was focused on single-input single-output control based on the classical control method ignoring problems of the multivariable nature of the flight control which include multiple control surfaces, multiple sensors, multiple disturbances, and multiple uncertainties occurring in the entire flight envelope. In the 1990s, the multivariable control design guideline [5] was written by Honeywell, Lockheed Ft Worth and Lockheed Advanced Development company. The guideline described the use of multivariable control law design techniques including eigenstructure assignment (EA), dynamic inversion, and μ -synthesis, for three military aircrafts such as F-117 Nighthawk, YF-22 and the MCT/F-16. After that, the advanced flight control law design technology was obtained through technical demonstration with the flight control computer of having the improved computational throughput. The more advanced multi-variable control methods have been applied to fighter aircrafts such as F-35 joint strike fighter (JSF) [6], F-22 Raptor [7], Eurofighter 2000 [8], JAS-39 Gripen [9], vectored thrust aircraft advanced control (VAAC) Harrier [10], and F/A-18E/F Super Hornet [11], which have resulted in the improved flying qualities and flight performance. Moreover, from 1987 to 1996, thrust vectoring control (TVC) [7, 12–14] was implemented to the fighter aircraft to extend the operational flight envelope (OFE) to high post-stall angles of attack and to secure air superiority in dog fighting by providing better nose pointing.

Since World War II, the application of various flight control functions to improve the safety of flight and increase mission success rate in the combat aircraft has been considered in earnest. The representative flight safety functions adopted in modern combat aircrafts are as follows: the envelope protections [15–17] such as warning and flight control limiters with the automatic low speed recovery (ALSR) [18] and the automatic recovery functions such as anti-spin control and automatic pitch rocker (APR) [15, 19], and so on.

This paper reviews the features currently levied on key flight control technologies to assure good flying qualities and achieve better aerodynamic performance of the fighter aircraft throughout entire flight envelope in industry's perspective. And based on the assessments of where they are, the authors speculate where the technologies are headed. This review result will be a useful resource for students majoring in flight control and for beginners who are new to fighter aircraft development to understand the history of flight control and core flight control technologies that should be considered

when developing aircraft. Also, it is possible to reduce trial and error in the aircraft development process by suggesting useful tips that should be considered when developing production aircraft based on development experience in the industrial aspect.

The rest of this article is organized as follows: Sect. 2 introduces a standardized flight control system design and verification process (FCSDVP). Section 3 describes the specification and airworthiness documents for flight control design. Section 4 presents the aerodynamic characteristics to have better performance and flying qualities in the high angle-of-attack (AoA). Section 5 presents flight control technologies which address the major inner-loop control technologies including envelope protection and recovery functions to guarantee the flight safety. Section 6 presents the control law design considerations in selecting the best flight control method. And Sect. 7 presents conclusions.

2 Flight Control Design and Validation Process

The development of flight control systems takes a lot of time to be designed and verified due to the complexity and importance. Therefore, a standardized development and verification process is required to efficiently not only develop the complex and important systems but also solve various problems that arise in the development process. For this reason, advanced airlines not only apply a standardized FCSDVP, but also have their own in-house software programs which are necessary in the control law development. Figure 1 shows the design and verification process of the flight control system from requirement of customer (ROC) to flight test. Aircraft development requirements are defined according to the needs of military consumers. The design requirements for flight control systems to satisfy them are established as criteria of flying qualities based on MIL-STD-1797A [20] and control system stability margin against uncertainty based on MIL-F-9490D [21]. Moreover, the flight safety is simultaneously proven in accordance with the verification process of the airworthiness certification criteria, MIL-HDBK-516 [22], in Engineering and Manufacturing Development (EMD).

The flight control law is based on the mathematical model of the aircraft, in which an appropriate control method capable of satisfying these requirements is selected. In recent years, a model-based design (MBD) method [23] method has been universally applied to the flight control law development. With this, the control law designer optimizes a control gain which could satisfy the flying qualities and stability requirement based on a linear control system including linear models of the aircraft, sensors, actuator, and simplified control structure. The flying qualities requirement [24] takes into

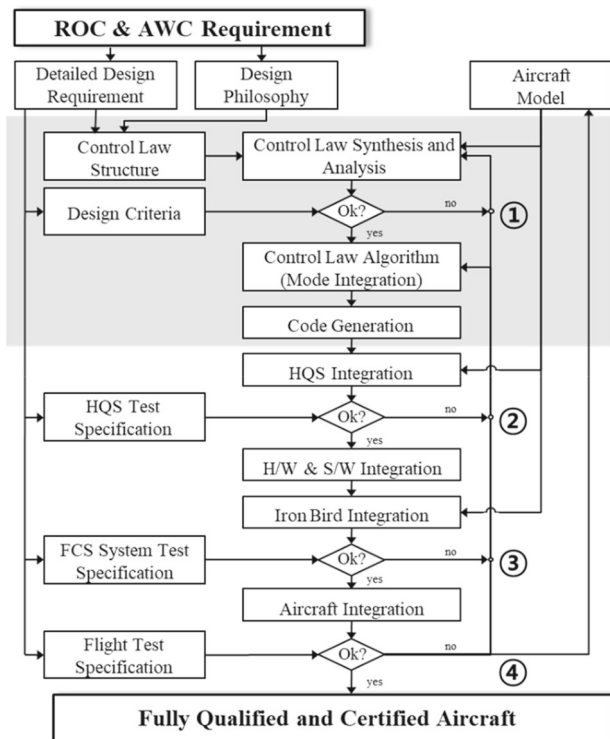


Fig. 1 Flight control system development process

account of Tier#1 criteria such as the short-period and dutch-roll mode frequency and damping ratio, the roll mode time constant and spiral stability, and the stability requirement which is of gain and phase margin [21]. In addition, Tier#2 criteria such as bandwidth, Gibson's phase rate and dropback [25, 26], and Neal-Smith criteria [27] are also evaluated to be used as design guidelines. In this design process, commercial programs such as Control Designer's Unified Interface (CONDUIT®) [28] are used, but advanced aerospace companies have an in-house software based on MATRIXx [29] or MATLAB Simulink [30] to design the control law. The control gains optimized for each design point are scheduled over the entire flight conditions and applied to the nonlinear control law. On the other hand, the nonlinear control law is designed in a graphic user interface (GUI) environment based on commercial programs such as MATLAB Simulink and MATRIXx, in which various software filters, flight control limiters and structural coupling filters (SCFs) are implemented. And the nonlinear control law designed in the GUI environment is automatically generated into a C-code using an automatic code generator.

The generated control law C-code is implemented to nonlinear 6-degree of freedom (DOF) simulation environments including database and aircraft's subsystem models such as landing gear, actuator, inertial measurement unit (IMU) and air-data sensor models. The database consists of aerodynamic, mass properties, propulsion, and hinge moment of

the aircraft based on the data obtained from the wind tunnel test. In nonlinear simulation environment, the time domain response characteristics of the aircraft, such as the frequency and damping, to the open-loop control input are evaluated. And roll performance, load, and departure resistance of the aircraft against maximum maneuver are also evaluated. After the evaluation of aircraft response characteristics in the frequency- and time-domain is completed, the operational flight program (OFP) [31] with flight control laws is applied to flight control computer (FLCC) and integrated into hardware in-the-loop simulator (HILS) [32] including actuator and hydraulic subsystem to evaluate handling qualities (HQ) for closed-loop responses. The evaluation maneuver consists of several MTEs such as take-off and landing, pitch and roll attitude capture, air-to-air tracking, and aerial refueling. The HQ are evaluated based on cooper-harper rating (CHR) [33] and pilot-in-the-loop oscillation (PIO) rating [34]. In addition, failure modes and effects test (FMET) for control surfaces and air-data sensors are performed to verify the flight safety.

After verifying the FLCC OFP in the laboratory test environment, the aircraft ground tests are performed. Ground tests related to flight control systems typically include structural coupling test (SCT) [35]. The SCT is a test to verify whether a gain margin criterion of the control system is satisfied from signals measured at IMU sensors in the structural flexible mode in representative flight conditions with the highest gain of the control law. In other words, it is a test to evaluate the suitability of a SCF [36] designed based on the structural flexible mode of the aircraft. The main design methods in this regard are detailed in Chapter 5.3.

Finally, the flight test consists of several tests such as stability and control (S&C) test, load test, HQ test and high angle-of-attack (AoA) test including intentional departure test, departure resistance test in the final stage to validate development requirements. If the requirement is not satisfied in the flight test, the control gain is precisely tuned or the control gain is reoptimized with the aerodynamic database update. By finally verifying the requirements at the end of the flight test phase, the aircraft development is completed and the airworthiness certification for production is obtained.

3 Specification and Airworthiness Documents

On December 17, 1903, Wilbur and Orville Wright flew an engine-power-driven flyer for 12 s at Kitty Hawk, starting the first history of the airplane [37]. At the same time, there has been a development of specifications to evaluate flying qualities of the aircraft in conjunction with the aircraft development history and these documents have been continuously modified and updated to date. Figure 2 shows the history of

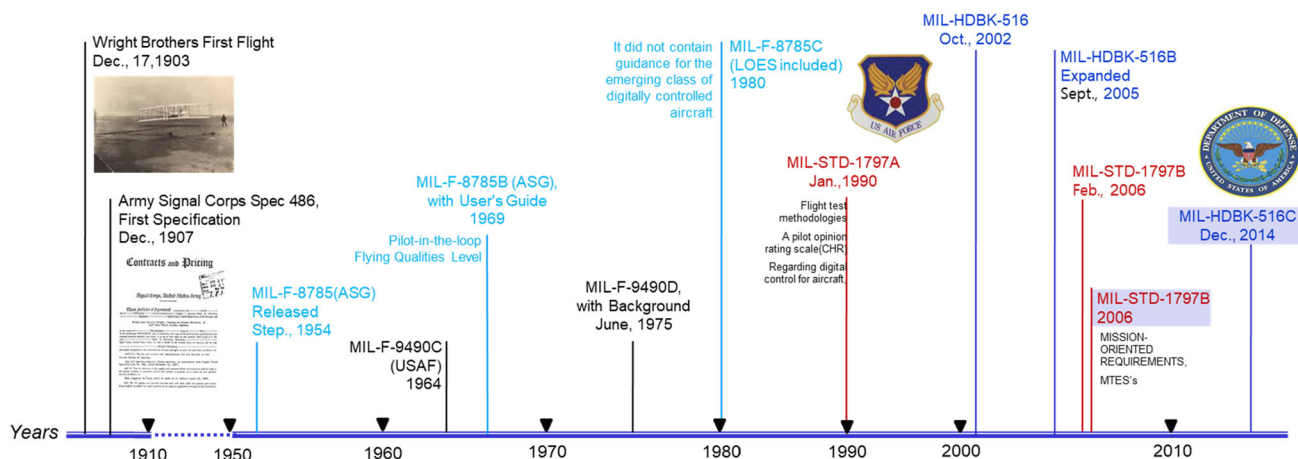


Fig. 2 Historical review for specification and airworthiness documents of the fixed-wing aircraft

flight control design specification and airworthiness documents. Military procurement of the aircraft had begun shortly after the Wright brothers' first powered flight. But the aircraft, in terms of flying qualities, had evolved relatively slowly until military specifications for stability and control requirements were announced during World War II. The first specification was the army signal corps spec 486 [38] announced in December 1907. Although this standard was simply a criterion for evaluating machines, it served as an opportunity to present the Army Air Forces Specification No. C-1815 'stability and control requirements for airplanes', which includes quantitative requirements in 1943, and there have been several revisions. The MIL-F-8785 [39] was published in 1954 and presented more requirements in terms of the evaluation criteria rather than the design criteria considered in the previous specifications. As a concern for dynamic responses moved from cycles and times to damp to modal parameters as well as turbulence models, a major change occurred with the launch of the MIL-F-8785B (ASG) [40] in 1969, suggesting the stability and control parameters of the aircraft with flying qualities based on 'pilot-in-the loop'. The requirements were presented as three levels of flying qualities in consideration of various levels of pilot workload and performance. As a revision to the fixed-wing specification, MIL-F-8785C [24] announced in 1980 contained flight simulation results supported by a fairly large database. The MIL-F-8785C was remarkable for first containing the low order equivalent system (LOES) approach that the equivalent classical system has responses most closely matching those of the actual complex aircraft [41]. The MIL-F-9490D [42] in 1975 was released to establish general performance, design, test development and qualities assurance requirements for the flight control systems of the military piloted aircraft, in which the gain and phase margin requirements were listed. This document was updated to Notice 2 [21] in 2007. In the 1990s, MIL-STD-1797A [43], an integrated specification for the third

division, was announced. MIL-STD-1797 includes guideline from research regarding digital controls, as well as revisions to criteria of the LOES and time delay. In this specification, alternatives were provided with sufficient explanation so that users could select appropriate criteria, without explicitly presenting the requirements. In 2006, MIL-STD-1797B [20], a mission-oriented requirement based on MTEs rather than flight phase categories, was announced, but the distribution is authorized to the Department of Defense and U.S. DoD contractors only.

Recently, military aircraft has been through the process of obtaining airworthiness certification to prove safe flight. Starting with MIL-HDBK-516B [44] in 2002, MIL-HDBK-516B expanded version [45] in 2005 and MIL-HDBK-516B Change 1 [46] in 2008, and MIL-HDBK-516C [22] in 2014 were announced. Chapter 6.1 flight technology of MIL-HDBK-516C, the recent airworthiness certification document, differs in how to describe the criteria compared to the conventional document, MIL-HDBK-516B.

For example, the MIL-HDBK-516B described the criteria from the safety perspective of the aircraft, in which the user had to prepare detailed standards on his own by referring only to the relevant sections of the DoD and military specification since the criteria are referenced without detailed standards. Meanwhile, and in the MIL-HDBK-516B expanded version the specified standards are additionally described. However, Chapter 6.1 flight technology of MIL-HDBK-516C directly cited the detailed section of MIL-STD-1797B without standard description, for considering aircraft performance as well as aircraft safety factors from the early stages of aircraft development in conjunction with development specifications. However, MIL-STD-1797B is currently an undisclosed document and is limited to identify details.

4 Aerodynamics Characteristics

Since the control law is designed based on a database including aerodynamics, propulsion, mass properties and hinge moment, the design results of the control law reflect the characteristics of the aircraft. For this reason, the level of flying qualities as a top-level requirement in the aircraft development is determined not only by the design philosophy of the control law but also by the characteristics of the aircraft in the configuration design stage of the aircraft. Therefore, before the flight control law engineer is participated in the configuration design stage, the configuration should be essentially designed to have aerodynamic characteristics such as adequate control power and departure resistance to successfully perform mission tasks within the operation flight envelope.

The aerodynamics of the aircraft is strongly influenced by the unsteady dynamic flow fields and vortices shed from forebody shapes, wing geometric, engine inlet shape causing inlet flow distortion, canopies, fuselage- and wing-mounted loadings such as weapons and external fuel tanks, any discontinuity in the airframe and control surfaces, etc. In consideration of these characteristics, the various configuration design methods [47], such as forebodies geometrics [48], engine inlet configuration optimization [49], leading- and trailing-edge flap (LEF/TEF) schedule [50, 51] to optimize the wing camber, wing-root leading-edge extension (LEX) [52, 53], wing-fuselage strake [54, 55], and upper surface spoiler device [56], have been researched for many years to enable the aircraft to have excellent aerodynamic characteristics. And these results have been adopted to modern highly manoeuvrable fighter aircraft.

This section describes the longitudinal and lateral-directional aerodynamic characteristics of the F-16 Fighting Falcon [57, 58], F-22 Raptor [7, 19, 59] and F-35 JSF [60, 61], representatively. Most of the highly performance fighter aircraft are designed to have unstable configuration in the longitudinal axis by adopting the design concept of relaxed static stability (RSS) [62] to improve maneuverability and performance. By applying this design concept, maneuverability can be dramatically improved in the subsonic and transonic flight conditions for air-to-air combat mission although the static stability becomes stable due to aft movement of the aerodynamic center (AC) [63] in the supersonic flight condition that requires supersonic cruise.

The conventional fighter aircraft such as F-16 could not perform a tactical post stall (PST) [64] maneuver due to factors such as a lack of control power, so the FBW FCS adopts angle-off-attack (AoA) limiter to prevent aircraft from entering the departure, with an AoA limit of 25 degrees for the F-16 fighters. On the other hand, supermaneuverable [65] fighters such as F-22 Raptor and F-35 JSF can operate PST maneuver, so the F-22 Raptor has no deep stall

mode and no limitation on the operating AoA by applying a one-dimensional TVC [7] that uses propulsive control in longitudinal axis at the high AoA conditions. And the maneuverability of the lateral-direction axis is significantly improved by utilizing the asymmetric horizontal tail control surface in lateral-direction control in the high AoA conditions. The F-35 JSF, which recently succeeded in production, can maneuver up to 50 degrees AoA below deep stall AoA without applying the TVC considered by the conventional supermaneuverable fighters. Such a design method of fighter jets with supermaneuvering capabilities has never been disclosed in detail, but it is at least known that this is due to aerodynamic improvement [66] and the application of nonlinear dynamic inversion (NDI) [6] control. As can be seen from the case of aircraft development, the supermaneuverability is closely related to the unique aerodynamic improvement and control power characteristics of the aircraft as well as the design method of flight control laws. The detailed design concept and major technologies of NDI control are presented in Chapter 5.4.2.

The aerodynamic characteristics of the aircraft are designed differently according to the mission requirements. If PST maneuver is required at low speed and high angle of attack, the aircraft should be designed to have the similar aerodynamic characteristics of the lateral-directional axis as F-35 JSF and F-22 Raptor since the maneuverability in the PST flight condition is closely related to not only the control power, but also the deep stall AoA characteristics and stability in the lateral-directional axis. Generally, the AoA limit is set in consideration of the stability margin due to uncertainties in case of the air data sensor failure at the AoA at which the characteristics of C_{l_β} and $C_{n_{\beta, \text{dyn}}}$ become unstable. The directional control departure parameter of the stability axis, $C_{n_{\beta, \text{dyn}}} (= C_{n_\beta} \cos - (I_z/I_x) C_{l_\beta} \sin)$, representing the departure resistance characteristics of the aircraft, is a function of inertia ratio, I_z/I_x , kinematics, directional stability derivatives, C_{n_β} , and dihedral effect derivatives, C_{l_β} , of the body axis. Here, the aircraft is stable if C_{n_β} has a positive value and C_{l_β} has a negative value, that is, it has a departure resistance if $C_{n_{\beta, \text{dyn}}}$ has a positive value. Generally, the modern version of fighters has a large value of inertia ratio, I_z/I_x , so even if C_{n_β} has a negative value, $C_{n_{\beta, \text{dyn}}}$ has a positive value as long as C_{l_β} has a negative value, then the aircraft can have a departure resistance characteristics [67]. Figure 3 shows the lateral-directional aerodynamic characteristics of the F-16 Falcon [67], F-18 Hornet [68], F-22 [19] Raptor and the F-35 JSF [15]. The $C_{n_{\beta, \text{dyn}}}$ characteristics developed by Lockheed Martin company and McDonnell Douglas company are similar in such a way that the neutral stability is ensured by the LEF scheduling method so that the stability can be improved in designing the augmented control law of the lateral-directional axis.

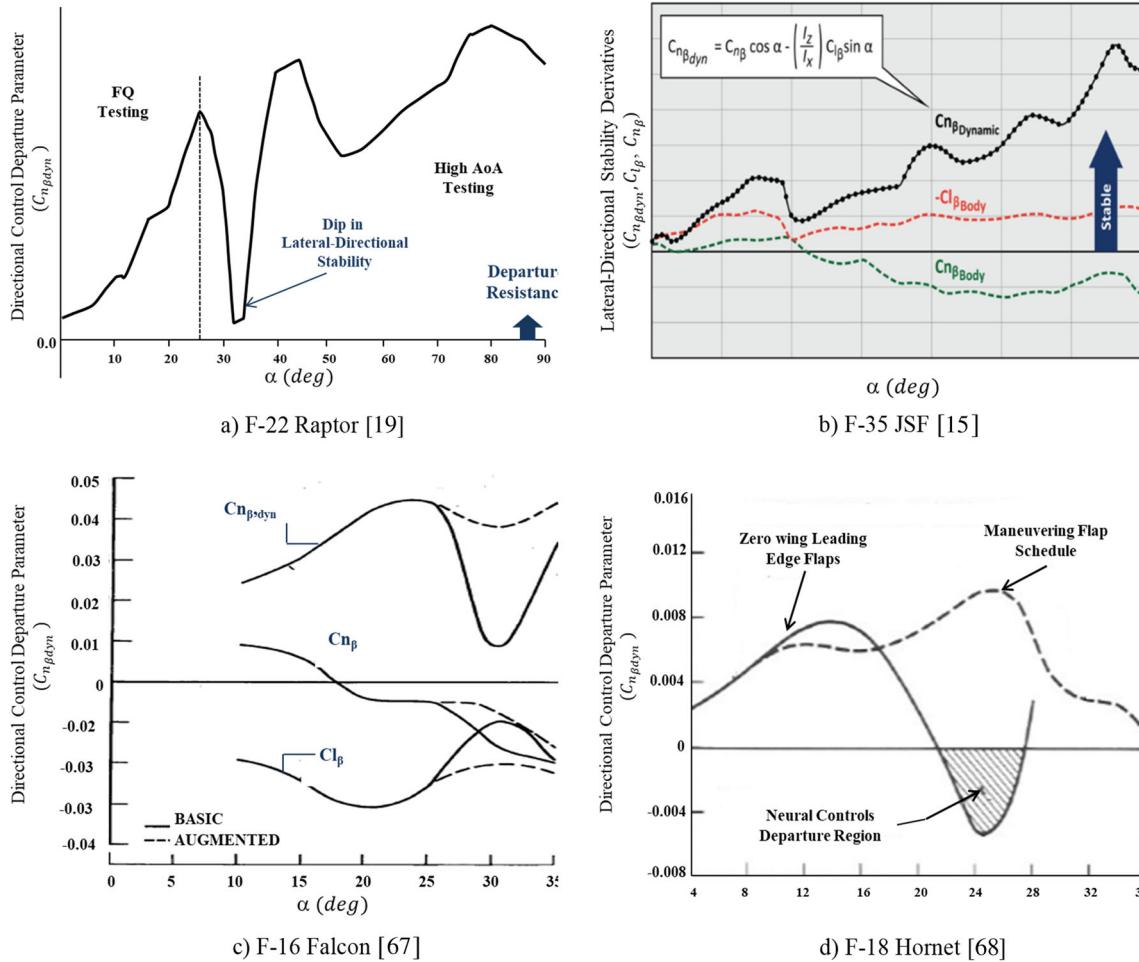


Fig. 3 $C_{n_{\beta dyn}}$ characteristics for the advanced fighters

5 Flight Control Technologies

5.1 Historical Background

After World War II, many countries around the world have spurred the development of high-performance fighters to take air superiority on the battlefield. Figure 4 shows the history review regarding the aerodynamic characteristics of representative high-performance fighters and their flight control system design concept, starting with the F-16 Fight Falcon. Most of the fighters are designed to be statically unstable in the longitudinal axis in the subsonic flight condition for the purpose of applying the RSS configuration design concept to improve maneuverability in aerial warfare. Also, as previously mentioned in Sect. 4, most of the fighters are designed to have the $C_{l_{\beta}}$ characteristic to be stable and the $C_{n_{\beta}}$ characteristic to be neutral or unstable. In this way, the $C_{n_{\beta, dyn}}$ characteristic can be designed to be stable in the entire AoA regime to ensure the departure resistance of the aircraft which is one of the most aggressive maneuvers. For this reason,

high-maneuverable fighters are needed to adopt redundant flight control system to not only stabilize the aircraft designed with unstable flight characteristics but also improve handling qualities.

Thanks to the upgrade of flight control computers' performance, and the advance on the sensors performance and the technology development that can obtain more accurate aerodynamic data, more advanced flight control law techniques have been applied to flight control systems with the RSS configuration design. Adequate control techniques are generally selected in consideration of the mission performance required for the target aircraft. In other words, in a case of a target aircraft maneuvering at the high AoA in post-stall region outside the normal flight conditions, not only the aerodynamic design and flight control method appropriate to the mission requirement should be selected, but also the flight control law should be designed to effectively control the nonlinear flight characteristics of the aircraft even in the post stall flight conditions and to have robust characteristics against model uncertainties with various sensor feedbacks.

Aircraft	F-16 [4, 57, 58, 67, 124]	F-18 [125, 126]	JAS-39 [18]	YF-23 [90, 91]	EF-2000 [8, 92]	F-22 [7, 116, 117, 119, 127]	T-50 [115, 120, 128, 129]	F-35 [6, 15, 66, 130]
National	United States	USA	Sweden	USA	Multinational	United States	Korea	United States
Manufacturer	Lockheed Martin	Boeing	SAAB AB	Northrop	Eurofighter	Lockheed Martin	KAI	Lockheed Martin
First Flight	1974.1.20	1978.11.18	1988.12.9	1990.8.27	1994.3.27	1997.9/7	2002.8.20	2006.12.15
Production	1978.8.17	1983.1.7	1997.11.1	-	2003.8.4	2005.12.15	2005.2.22	2016.8.2
Redundancy	Quadruplex	Quadruplex	Triplex	Quadruplex	Quadruplex	Triplex	Triplex	Triplex
Control Stick	Passive Side Stick	Center Stick	Center Stick	Center Stick	Center Stick	Active Side Stick	Active Side Stick	Active Side Stick
Bare-airframe Stability (Subsonic)	Long($C_{m\alpha}$)	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable
	Lateral($C_{l\beta}$)	Stable, $\forall \alpha$	Stable, $\forall \alpha$	Not Published	Not Published	Stable, $\forall \alpha$	Stable, $\forall \alpha$	Unstable in specific α regime
	Dir. (C_{np})	Unstable in specific α regime	Unstable in specific α regime	Not Published	Not Published	Unstable in specific α regime	Unstable in specific α regime	Stable, $\forall \alpha$
Control Surfaces	Primary	Horizontal Tails Flaperons Single Rudder	Horizontal Tails Ailerons Twin Rudders	Canard Flaperons Single Rudder	V-tail. Inboard/ outboard TEF	Canard IB/OB Flaperons Single Rudder	Horizontal Tails Flaperons Single Rudder	Horizontal Tails Flaperons Single Rudder
	Secondary	LEF, Dedicate SB	LEFs, TEFs, Spoilers Virtual SB, LEX	LEF, Dedicate SB	LEF, Virtual SB	LEF, Dedicate SB	LEF, Virtual SB	LEF, Dedicate SB
State Feedback Variables	Airdata, Rate, Acceleration	Airdata, Rate, Acceleration, AoA, AoS, AoS Rate	Airdata, Rate, Acceleration, AoA, AoS, AoS Rate	Airdata, Rate, Acceleration, CG and Weight, etc	Airdata, Rate, Acceleration, AoA, AoS, AoS Rate	Airdata, Rate, Acceleration, AoS, AoS Rate, etc	Airdata, Rate, Acceleration, Inertial Attitudes, AoA, AoS, AoS Rate	Airdata, Rate, Acceleration, AoS Rate, CG and Weight, etc
Stability & Control Augmentation	Proportional plus Integral	Proportional plus Integral	Linear Quadratic	Proportional, Integral plus derivatives	Differential PI	Eigen-structure Assignment	Simplified Dynamic Inversion	Nonlinear Dynamic Inversion
Envelope Protection	AoA-G limiter, Roll and Yaw Command Limiter							

Fig. 4 Historical review of flight control system for representative fighter aircrafts

As a representative development example, the JSF program does not use TVC in its design but applies an NDI control technique combined with classical control to maneuver the aircraft in the post stall flight conditions. The several development cases and the representative control design technologies for flight control law design are addressed in Sect. 5.

Most fighter aircrafts such as the F-16 Fight Falcon have applied automatic control functions to improve flight safety and enhance mission performance at continuous subsequent performance improvement projects after initial production. And the fighter is designed to have a flight control limiter to prevent loss of aircraft in many uncontrollable situations in which it can enter the departure in the operational flight condition. It is a trend to apply advanced automatic control functions such as APR, ALSR, pilot activated recovery system (PARS), and automatic ground collision avoidance system (AGCAS) to avoid dangerous flight conditions caused by pilot’s disorientation, ground collision situations, deep stall, and so on. The flight control system integrated with avionics and propulsion systems also provides automatic control functions such as automatic throttle control (ATC), automatic terrain following (ATF), and automatic carrier landing system (ACLS) to improve mission performance. Section 5 covers several development cases of advanced automatic control functions and key technologies that should be considered, in detail, in the control laws design phase.

5.2 Control Stick

The control stick is one of line replaceable units (LRUs) constituting the flight control system, which plays a significant role in handling qualities and flying qualities during high gain closed-loop maneuvers such as takeoff and landing [69]. For this reason, adequate control stick characteristics have been researched to improve handling qualities throughout various research and development (R&D) programs over the years as shown in Fig. 5.

Each different type of control stick has been applied to the aircraft depending on the required mission tasks and class of the aircraft. The yoke-type control stick, which is mainly applied to relatively large military transport and light civil aircraft, has relatively low control sensitivity but makes it easy for pilots to precisely control and visually recognize the amount of control input. However, this type is not suitable for the fighter jets that require agile maneuvering since the pilot has also difficulty in reading the instrument as the flight instrument panel is obscured by the yoke-type control stick. To compensate for these shortcomings, the center control stick was applied between both legs of the pilot in the cockpit to secure a view of the flight instrument panel and improve the achievement of high gravity acceleration. However, the center stick has the disadvantage of causing mechanical cracks during high-g maneuvering and control harmony problems in which one direction of control input by the pilot is coupled to

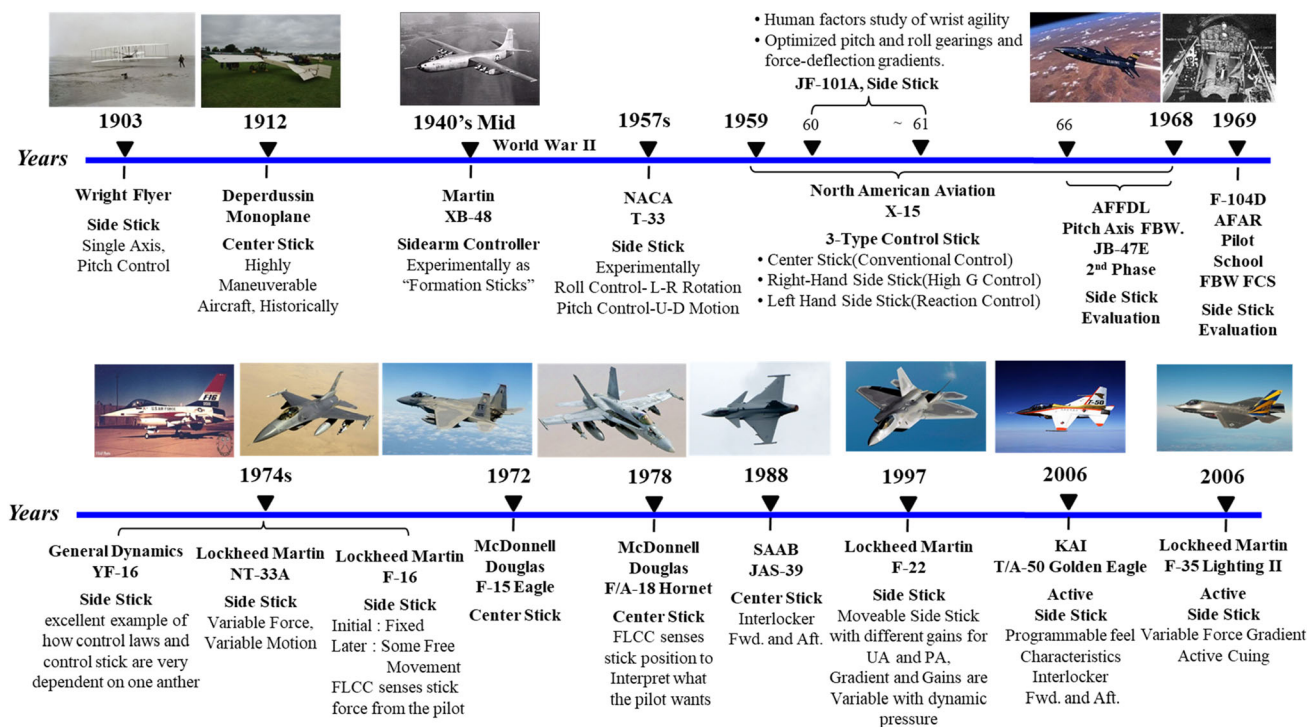


Fig. 5 Historical review of control stick for representative fighter aircrafts

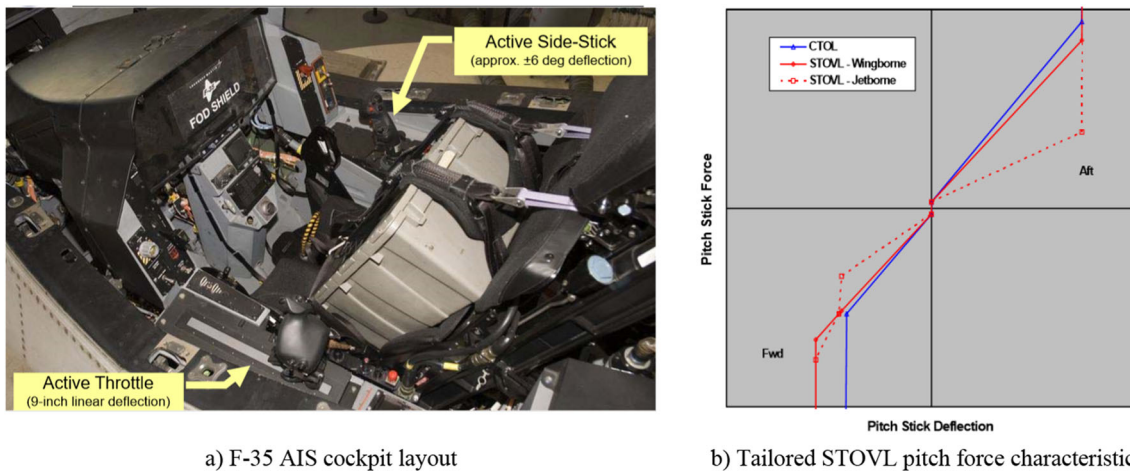
an unintended direction of control input [70] due to its wide range of movement. Both the yoke-type and center control sticks are heavy and bulky so that requires a large space in the cockpit to be mounted. JAS-39 Gripen adopted mini center control stick [71] to overcome the weakness of these control sticks. Additionally, there is another type of control stick like sidestick which has the advantage of reducing the weight and volume of the control stick and minimizing mounting space in the cockpit. The sidestick is mainly mounted on the right-side panel of the cockpit, enabling efficient arrangement. It has the additional advantage of being able to achieve high-g maneuver without blocking the view of the pilot operating the flight instrument panel [72]. Considering these advantages, sidesticks can be easily found in application cases of highly maneuverable fighter jets employing an FBW flight control system.

According to the driving method, the control stick can be classified into a passive type and an active type. While the passive-type control stick is designed mechanically with mass-spring structure, the active-type control stick can visually and tactilely convey information such as aircraft condition to the pilot with transmitting force or position to the flight control computer in an electric motor-driven manner [74]. Representative fighter jets with active control stick are F-35 JSF, and Fig. 6 shows the cockpit layout including the control stick and throttle, and the tailored pitch force gradient for short take-off/vertical landing (STOVL) of F-35 [73]. The F-35 JSF has adopted an active inceptor system (AIS) [6]

developed by British Aerospace (BAe) systems and applied it in common to three variants of F-35s, so the force–displacement slope of the control stick could be designed variably to have optimal control performance in consideration of various mission tasks. In addition, if all programmable active functions do not work due to defects in the AIS, the AIS is switched from active mode to passive mode which is operated as a backup with a basic spring damper characteristic to ensure flight safety. Also, based on the aircraft’s state information, tactile cueing can be demonstrated by the control stick so that envelope protection function can be applied for the pilot to immediately recognize the situation and to prevent the aircraft entering dangerous flight conditions in dangerous situations such as departure or deep stall. The programmable features of control stick allow the control law designer a significant amount of flexibility to adjust the characteristics in various flight conditions and modes, although it has the disadvantage of increasing the complexity of reconfiguration logic within the control law to accommodate system failures.

5.3 Flight Control Sensors

Among the sensors mounted on the aircraft, there are the IMUs and the air data sensors. The IMUs measure motion of the aircraft such as angular rate, angular acceleration and linear acceleration, and the air data sensors measure air data information such as AoA, angle-of-sideslip (AoS), airspeed, Mach number and altitude. Since the information measured



a) F-35 AIS cockpit layout

b) Tailored STOVL pitch force characteristic

Fig. 6 Active-type sidestick and throttle for F-35 [73]

by the sensors are inputted to the flight control system as feedback signals of aircraft state information, the measurement accuracy and reliability directly affect the performance of the flight control system. Therefore, the control designer should consider the method to obtain the more accurate sensor information. This section describes some design considerations for measuring the information from IMUs and air data sensors.

The structural coupling characteristic is a major concern to flight control system engineers, known as aeroservoelasticity [75] which is a phenomenon caused by interactions among structural dynamics, aerodynamics, and flight control system. The undesirable vibration from the control surfaces affects flight safety since the vibration signals at frequencies in flexible structural modes of the aircraft are introduced into the flight control system. The structural coupling characteristics can have an effect on most of aircrafts, especially highly maneuverable fighters that require very strict stability margin requirements [21] as well as rapid maneuverability.

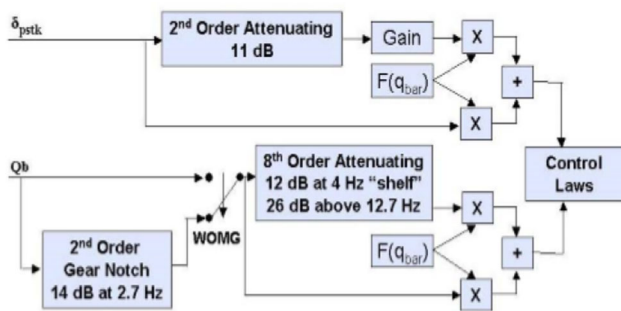
This section discusses two representative aspects to consider in design aspect that can minimize structural coupling. The first aspect is to design aircraft structure and select IMU location. By mounting the IMU at an ideal position or “sweet spot” with the least motion as a whole in the structure of the aircraft [76] the amount of structural coupling can be reduced. In other words, the motion sensor is ideally mounted at a position where no local vibration [77] occurs within the aircraft structure. In general, a gyro sensor measuring an angular rate is located at an anti-node position where the least angular motion occurs, meanwhile an acceleration sensor measuring a linear acceleration is located at a node position where the least linear motion occurs [76]. And the natural frequency of the structure on which the IMU sensor is mounted should be quite high. If the first natural frequency of the structure

around IMU including bracket and tray is low, the structural vibration characteristics may affect the signal of low frequency signal band due to the aliasing characteristics by digital sampling of the flight control computer. Also, when the IMU sensor location is selected the actual manufacturing sensitivity should be accounted for [46]. For this reason, the sensor mounted structure should be designed to have a natural frequency in the high frequency band of 140 Hz or higher [78]. The second aspect is to design the control law to minimize structural coupling. The control law engineer should not ignore the structural coupling characteristics when designing the control law. The structural coupling characteristics are closely related to both the structural mode vibration of the aircraft and the high control gain of the control law because the structural mode vibration signal measured from the IMU is multiplied by the control gain within the control law and is transmitted directly to a control surface deflection. Therefore, the control law engineer must optimize the control gain and limit the maximum control gain within a range satisfying the flying qualities requirements when scheduling control gain in all flight envelopes. In general, high control gains are used in low-speed flight conditions, but it is possible that the control gain can be reduced by the control gain optimization since the flying qualities in low-speed flight condition is not greatly affected by the magnitude of the control gains.

Highly maneuverable fighter jets with a wide range operational flight envelope should significantly take into account the structural coupling impact. Currently, the most widely used design method to ensure the coupling stability between FCS and structural flexibilities is to apply notch filters [79] to the sensor feedback path of the control system to attenuate the problematic high frequency signal component out of the sensor signal. However, the notch filter has a disadvantage of increasing the phase lag [80] in the low frequency band, reducing the phase margin of the control system and



a) BF-3 during Structural Coupling Test



b) Pitch Axis Structural Filters for F-35 STOVL

Fig. 7 Structural coupling test and pitch axis control law including for F-35 [82]. a) BF-3 during Structural Coupling Test (Doug H (2010) F-35 Weapon System Overview. <https://www.f-16.net/forum/download/file.php?id=21525>). b) Pitch Axis Structural Filters for F-35 STOVL

increasing the equivalent time delay, thereby degrading the level of flying qualities of the aircraft. FCS performance is generally related to high control gains in the flight control law that can cause structural coupling and require additional filtering and phase lag [81]. In the SCF design, there are two approaches to reduce the phase lag in the low frequency band for the SCF design. The first is to remove only specific structural vibration characteristics of the frequency band of interest by increasing the order of SCF such as a notch filter. But this design method has the disadvantage of increasing the computational throughput of the flight control computer by increasing the order of SCF. Another design approach is to schedule the characteristics of the SCF as a function of state variables such as airspeed at each flight condition as shown in Fig. 7 [82]. This design approach has the advantage of selectively solving structural coupling characteristics in the problematic flight condition. In particular, in a case that the aircraft has aircraft-pilot-coupling (APC) characteristics, which is coupling phenomenon between the pilot and the structural vibration mode, it is useful to design this SCF which applies to the control command path although a large amount of phase lag may result in. Here, it is possible to minimize the deterioration of flying qualities if this design

method of scheduling the SCF is used according to the flight state of the aircraft.

Additionally, there is another consideration for testing environment in SCT. If the frequency of the structural mode of interest is in a fairly low frequency band, it should be noted that the vibration in low frequency band carried from the ground through the landing gear will affect the test results. One way to solve this problem is to use a kind of “soft support” system [82] to support the aircraft during structural mode testing. The concept of a soft support system is introduced to make it lower than the frequency of interest, allowing reliable test data to be obtained without interfering with the test as well as saving analysis time.

The air data sensors constituting air data system (ADS) are placed on different position around forebody of the aircraft to provide identical measurements. There are a variety of types of the sensors. The T-50 [83] uses three integrated multi-function probes (IMFPs) and two AoS cones, and the F-35 [15] uses two dog-leg multifunction probes and two flush-mount ports which are located on the forebody below the chine and just aft of the radome as shown in Fig. 8. As the ADS is used to measure AoA, AoS, static pressure (P_s), and total pressure (P_t), the air data should be corrected and inputted to the flight control law. The information of these states is used for control law feedback and control gain scheduling, so its accuracy and reliability directly affect the performance of the control system. In general, legacy fighter jets operating in low- and medium-AoA flight region with relatively stable flow fields achieve desired performance and flying qualities with the conventional ADS systems. But the conventional pneumatic-type ADS cannot guarantee reliability and accuracy in the flight regimes of unstable flow fields at low speed, high AoA or large AoS. Therefore, an alternative system capable of estimating air data information can be considered in the ADS design. For example, the F-35 JSF [15] maneuvering beyond stall AoA uses the estimated AoA, AoS, and total pressure based on inertial information at specific AoA or higher. To support this estimation method using these inertial parameters, the air data is continuously calculated whenever the aircraft is in the specific air data envelope, where the stored wind information collected in this manner is used with inertial attitude and velocity which are computed from tactical navigation system (TNS). The TNS mounted in the F-35 is used as a redundant system so that it can provide very accurate and reliable aircraft attitude and inertial velocity information.

5.4 Stability and Control Augmentation System

Over the past 50 years in aircraft development, many flight control methods have been proposed for the aircraft to successfully achieve missions and ensure good flying qualities

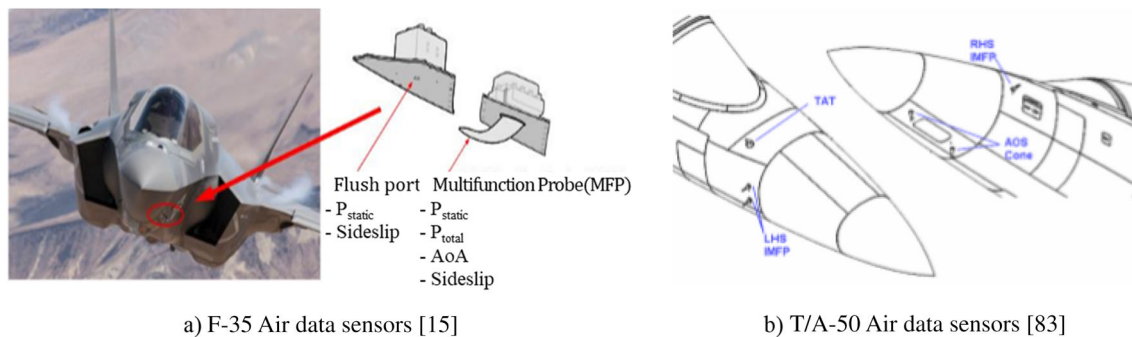


Fig. 8 Air Data System for F-35 JSF [15] and T/A-50 [83]

[84]. The advance of flight control methods applied to the aircraft was relatively slow compared to the rapid evolution in control theory. This is because the aircraft requires a control method that prioritizes flight safety and provides a deterministic solution that can make it readily to obtain airworthiness certification. This section describes the criteria for selecting a control method for successful mission accomplishment in developing aircraft while effectively using development costs and schedules. The key techniques for designing the control laws actually applied to representative modern fighter jets should be carefully selected.

5.4.1 Perspective of Fighter Jets Control Law Concept

Modern fighter jets aimed at production should not only meet customer's requirements, but also obtain airworthiness certification to verify flight safety. For these goals, the control method applied to the aircraft should provide a deterministic solution in the control law output to the input. And the control methods should be suitable for verifying the quantitative flying qualities criteria presented in MIL-STD-1797, the flying qualities specification for piloted aircraft. Taking all these factors into account, the modern highly maneuverable fighter jets adopt a redundant FBW control system with modern control techniques based on classical control to guarantee the stability and improve the flying qualities of the aircraft as shown in Fig. 4.

The F-16 Fight Falcon [4] widely known as the best seller, has been upgrading its performance over the many years, since its first flight in 1974. The F-16 has all-moveable horizontal tails (HTs), flaperons, and a single rudder to generate the motion of the aircraft to the control stick inputs. In addition, by adopting a triplex redundancy flight control system, the flight control law of the classical proportional plus integral (PI) control is designed to guarantee more stability and improve flying qualities.

Developed for the U.S. Navy around the same time as the F-16, the F-18 Hornet is the fighter that can maneuver in high AoA flight regime above the stall AoA by upgrading

the configuration and flight control performance for several years, since first flight in 1978. In terms of longitudinal static stability, the latest E/F version of the F-18 was designed to be neutral or slightly unstable to improve maneuverability with a quadruple redundant flight control system to ensure stability of the aircraft, while the early version was designed to be stable. The F-18 E/F was additionally designed to have the LEX fence, and modify leading-edge-flap (LEF) schedule and LEX alterations [85] to enhance departure resistance characteristics in the high AoA flight regime, and has been improved flying qualities characteristics using sideslip and sideslip rate as feedbacks [86].

Sweden SAAB AB's JAS-39 Gripen, which succeeded in its first flight in late 1988, is the first case of applying a canard-shaped control surface to a production fighter jets. Most fighter jets generally fix several problems that occur during the development period through design changes such as flight control software upgrades. The JAS-39 also encountered several problems during the flight test, and even crashed due to PIO tendency during landing, which was widely known as a case in point [87]. The cause of the PIO tendency was the phase lag of the control system, and SAAB AB solved it by designing a phase compensation logic of rate limiters [9] at the actuator command path. Meanwhile, the control method applied to the JAS-39 Gripen has improved the flying qualities and robustness against various uncertainties by designing the control gains with optimal control technique like linear quadratic (LQ) [18] as shown in Fig. 9. And the flying qualities were improved even in wide Xcg travel due to external store loading through additional control design improvement [88] with AoA and pitch rate as feedback variables. In addition, the auto trim function of all the axes was provided to reduce the pilot's workload in asymmetric store loading.

In the 1990s, the United States launched an Advanced Tactical Fighter (ATF) program for developing fifth-generation fighter jets. In the ATF program, Northrop Grumman's YF-23 and Lockheed Martin's YF-22 competed, and Air Force finally selected Lockheed Martin's YF-22 design for full-scale development, which is now called System Development

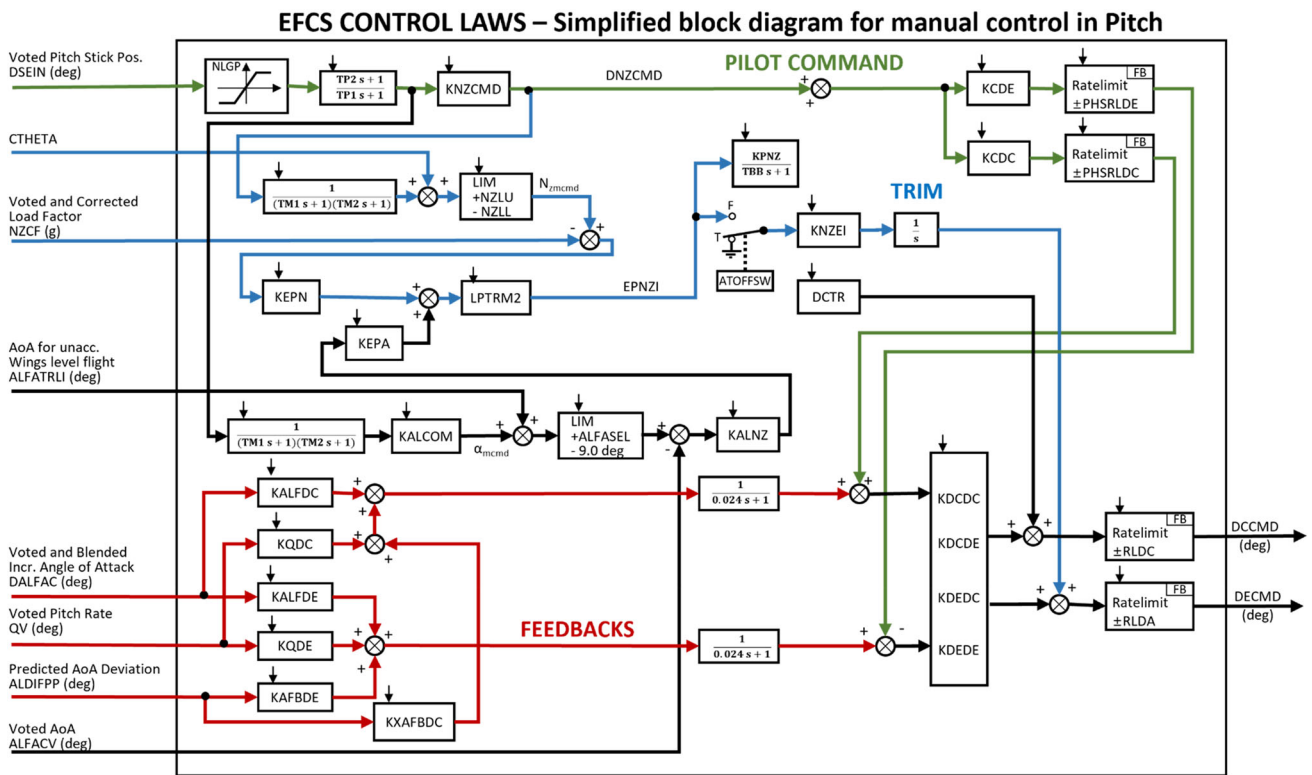


Fig. 9 Longitudinal control laws of SAAV AB's JAS-39 Gripen [18]

and Demonstration (SDD) [89]. In the middle of 1997, the F-22 succeeded in first flight and began to be produced from the end of 2005, as the strongest 5th generation fighter in existence. On the other hand, the excellent performance of Northrop Grumman's YF-23 has been recently re-evaluated. Both the YF-23 and F-22 managed and monitored all subsystems of the aircraft by adopting the vehicle management system (VMS) [90] function. With this design concept, center-of-gravity (Xcg) was managed using the active fuel transfer function during in-flight [29, 91]. And the YF-23 had the capability to control the weight and Xcg position calculated during in-flight as a control law feedback variable, provide more precise vehicle control, and improve flying qualities and maneuverability performance over the achievable ones in conventional control law design [91]. It is known as the first case of applying Xcg and weight information control technique to the design of the control law of the fighter jets. And the latest fighter F-35 JSF [6] is known to use Xcg and weight information to on-board models (OBMs).

The Eurofighter Typhoon, EF-2000, which succeeded in first flight in early 1994, began to be produced in 2003. The EF-2000 used a differential PI algorithm (DPIA) [8, 92] control that was modified from the classical control of the PI control method to the flight control system, as shown in Fig. 10. This control method is known to have the

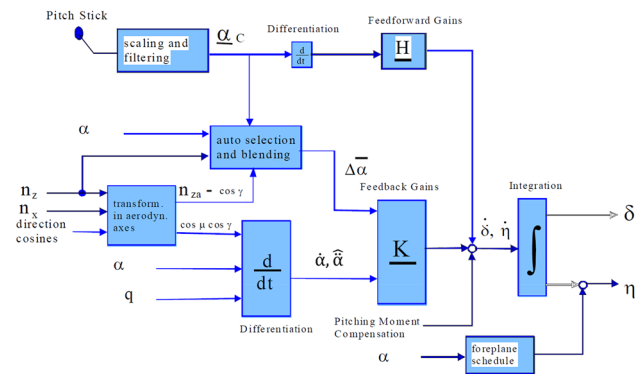


Fig. 10 Longitudinal control laws of Eurofighter Typhoon, EF-2000 [8]

following several advantages by having a concept of differentiating all feedbacks and inputs of the command loop and then re-integrating at the control surface command path. The differentiation provides zero input under steady-state conditions, allowing you to schedule control gains downstream of a differentiation without causing parameter excitation and unwanted feedback loops. The integration in the control surface command path serves to smooth the command signal, and the control gain upstream of the integrator can be scheduled against signal noise and disturbance. The EF-2000 is designed with DPIA control for lateral-direction axis as well as longitudinal axis, providing automatic trim so that it can

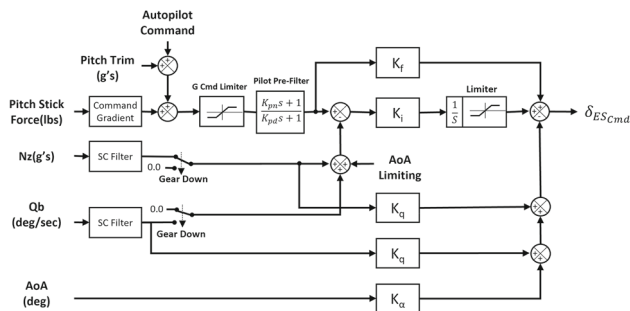


Fig. 11 Longitudinal control laws of Black Eagle, T-50 [17]

reduce the pilot’s workloads by eliminating the need for the pilots to use manual trim button even in asymmetric loading operations.

The F-22 Raptor, which succeeded in its first flight in 1997, is the world’s strongest fifth-generation fighter, but there was an accident in which the F-22 crashed due to PIO characteristics during the flight test. To solve this problem, additional guidelines [7] such as Gibson, Neal-Smith, Bandwidth and Smith Geddes which could predict PIO characteristics in advance in the process of designing control law, were introduced in the process of designing and analyzing control law, and were applied to the structure of control law to be modified [93]. The control techniques adopted to the F-22 were an EA [7] combined with the classical control theory. In addition to the existing control surface design, the F-22 Raptor designed the TVC [7] control with a longitudinal axis to compensate for the lack of control power in the high AoA flight regime. In the high AoA flight regime, the TVC is used as an effector of longitudinal control, and the asymmetry of the horizontal tail control surface is used to control the yawing of the aircraft, thereby ensuring control for the directional axis. In this design method, there is no limitation on the operating flight envelope in which the F-22 maneuvers.

In recent years, a nonlinear dynamic inversion (NDI) control technique as a multivariable control method has been applied in earnest to flight control of the fighter jets aimed at production. Starting with first flight in 2002, the T-50 Black Eagle, a supersonic advanced trainer went into production, provided the further improved flying qualities by adopting simplified dynamic inversion control [17] based on linear model of the aircraft, as a longitudinal axis control technique, as shown in Fig. 11. The T-50 has succeeded in production of the supersonic fighter FA-50 through subsequent performance upgrades.

The recently produced F-35 JSF [15, 61] has been developed efficiently by reducing the requirements for design and verification by applying more advanced control theory of NDI tied with classical control in common to three versions of F-35s. First of all, the F-35 is a fighter jet capable of post-stall maneuvering up to 50° without an additional effector

such as a TVC. Although no detailed design method of the F-35 has currently been disclosed, it is known that it was possible to maneuver in the high AoA beyond stall area with more improved aerodynamic characteristics and advanced control techniques in the F-35.

The next chapter introduces the advantages of NDI control techniques and the related technologies to be considered in the design stage, by analyzing the current published documents for F-35 JSF from the perspective of response type, the efficient use of control power, and the special nonlinear control techniques.

5.4.2 Realization of Nonlinear Dynamic Inversion Control

The control law designer should pay attention to high-order effects that cause high-frequency phase lag and large equivalent time delay that may consequently cause PIO. And, in particular, the control law of the fighter jets maneuvering in the high AoA flight regimes should be designed in consideration of the cross-coupling characteristics between the aircraft axes and control surfaces, the uncommanded motions such as wing rock due to flow separation around main wings, the departure susceptibility, and the control saturation. Traditionally, flight control law for low-to-medium AoA flight regimes can obtain the desired level of flying qualities using linear design methods based on linearized models of the aircraft. But the aircraft designed with a linear design method cannot be effectively controlled in the high AoA regime where higher-order nonlinearities increase. Due to these restrictions, many control law researchers have begun research to apply nonlinear control technologies such as an NDI control to the highly maneuverable fighter jets. With many years of research and technological advances, the recently developed F-35 JSF was successfully produced by adopting the NDI control within the operational flight envelope.

Figure 12 shows the research and development histories related to the NDI control until F-35 succeeds in production [94]. The NDI control is classified into model- and sensor-based design concept, depending on how it acquires the angular acceleration signals. The development of model-based NDI algorithms had begun at NASA in the early 1990s with the participation of Honeywell, Boeing, and Lockheed Martin, and now the NDI control theory is widely studied in the aerospace industry. Using a model-based NDI method as a viable control methodology has been demonstrated in a variety of flight control research aircraft such as F-18 high angle-of-attack research vehicle (HARV) [95], X-38 [96, 97], X-36 reconfigurable control for tailless aircraft (RESTORE) [98], and X-35B short take-off/vertical landing (STOVL) [29] in the limited flight envelope. As a more advanced result, the F-35 JSF [6] is the first production fighter to incorporate the model-based incremental nonlinear dynamic inversion (INDI) into flight in the full flight envelope. As another type

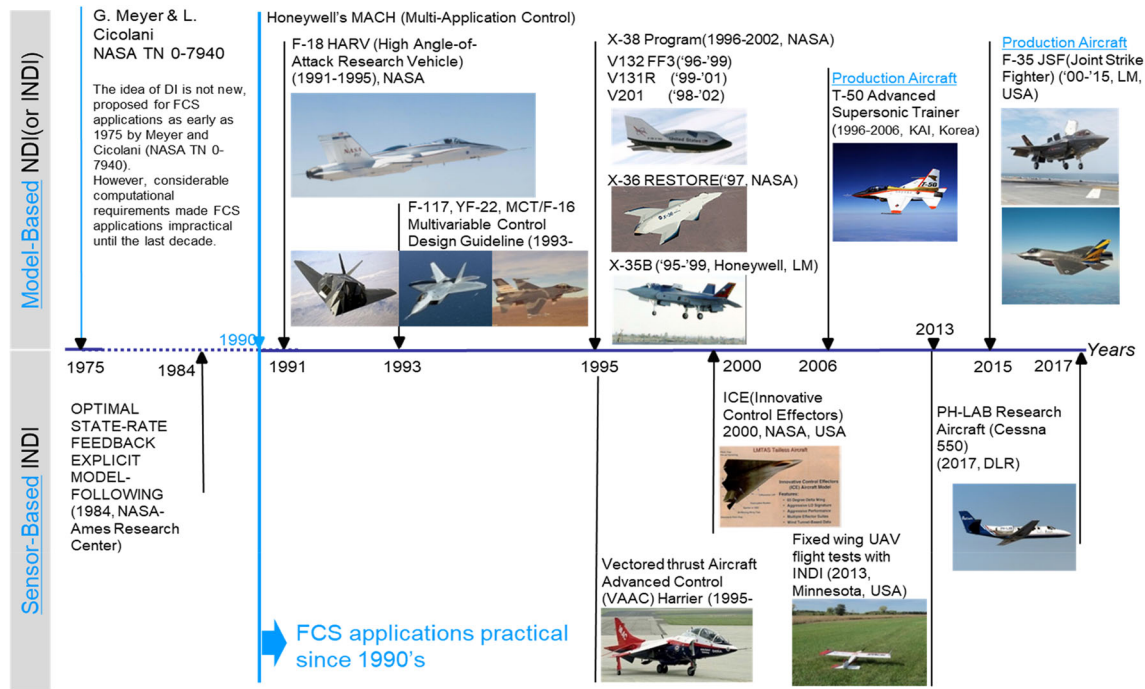


Fig. 12 Timeline for nonlinear dynamic inversion control [94]

of NDI, a sensor-based INDI control which uses angular acceleration measured by an inertial measuring device (IMU) sensor and control surface position as feedback parameters was at first evaluated in VAAC Harrier in 1999 [10, 99]. In 2000, NASA applied this control method to innovative control effector tailless aircraft [100], and recently the German Aerospace Center (DLR) and Netherlands Aerospace Centre (NLR) applied it to Cessna 550 demonstrator with Delft University of Technology and proved the performance of the developed control law [101].

Figure 13 shows the control structure of the NDI including an additional augmentation control using error between estimated and measured angular accelerations which is applied in a case of the F-35 JSF. The NDI has internally two portions in the control structure, which are an aircraft dynamic dependent portion and a flying qualities dependent portion. The aircraft dynamics dependent portion consists of on-board model (OBM) and effector blender (EB) which is also called CA [102] to reflect how the aircraft does fly. Meanwhile, the flying qualities dependent portion has the desired dynamics including command shaping and regulator calculating the desired angular acceleration, to reflect how the aircraft should fly in response to the pilot’s control input. The command shaping aims to translate the pilot’s control stick input to the desired aircraft movement, and the regulator is designed to be directly set by the LOES parameter values such as a short-period mode damping and frequency, and a bandwidth to comply with the classical flying qualities requirements.

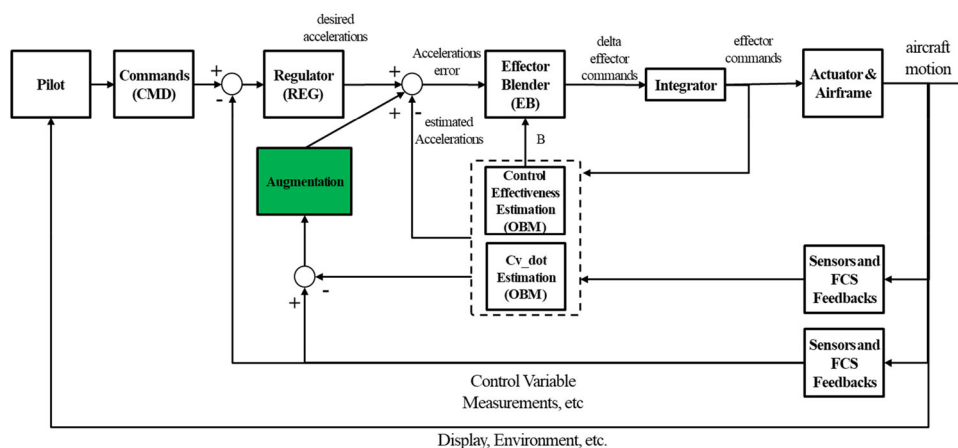
The OBM provides the estimated angular acceleration to the inversion loop and control effectiveness matrix.

This section introduces three representative control technologies, which are the additional augmentation control, control allocation, and response type, that must be considered in the design of the flight control law of a highly maneuverable fighter which flies greater than a stall AoA.

(1) Additional Augmentation Control

The performance of the model-based NDI control depends on the precise aerodynamics model of the aircraft, perfect sensors and actuators, and the ability to invert the control effectiveness matrix. However, it is not only almost impossible to accurately model the aerodynamic, mass properties, and propulsion characteristics of the aircraft, but also it is quite difficult to accurately model the high-order nonlinear effects. Due to these restrictions, the NDI control does not completely cancel out the aircraft dynamics, and the resulting mismatches have a significantly adverse effect on the closed-loop dynamics, which can degrade flying qualities and performance of the aircraft. Therefore, control law designers should design a very detailed and sophisticated OBM throughout the entire flight envelope to maximize the NDI control performance in consideration of the memory and computational throughput of the flight control computer. In particular, the OBM is modeled at relatively dense Mach number and AoA breakpoints in transonic flight regimes where

Fig. 13 Nonlinear dynamic inversion control architecture including additional augmentation control for F-35 [6]



aerodynamic characteristics change rapidly. Considering these matters in the design, the F-35 JSF designed the OBM with approximately 3 million data points [6] using wind tunnel test data.

Despite this design, it is quite difficult to achieve the desired aircraft performance with the model-based OBM design due to the complex and unpredictable aerodynamic characteristics generated by elevated G and AoA maneuvering in the transonic flight regimes. Flow separation on the main wing occurring in high G maneuvering under transonic flight also shows a very irregular aerodynamic characteristics and complex flow field. The wing flow separation occurs due to the unstable flow field in these flight conditions and the asymmetrical flow separation may generate a sudden large imbalance in lift between wing panels, which creates uncommanded lateral motions such as wing heavy, wing drop and wing rock [103, 104]. The uncommanded lateral motion significantly reduces mission effectiveness, such as the precise tracking capability of the aircraft for air-to-air combat maneuvering. In addition, if roll attitude angle increases excessively as these characteristics become even worse, it can cause serious problems in flight safety of the aircraft. Therefore, to improve aircraft robustness against such nonlinearities, the F-35 applies a special control algorithm called “additional augmentation [15]” control, which is implemented using the error signal between the measured angular acceleration from sensor and the estimated angular acceleration from a mathematical model as a feedback variable.

In studies for the additional augmentation control method, C Kim et al. [105–107], Jiali et al. [108, 109] and Kumtepe et al. [110] proposed a hybrid control method that combines the model- and sensor-based INDI control. For highly maneuverable fighters having wide operational flight envelope, it is difficult to

accurately model a dynamic system in very unstable and unpredictable flow fields such as a transonic speed or high AoA flight regime so that the development cost and development program period of the aircraft can increase significantly due to the increased number of flight test sorties to acquire the accurate models in the existing model-based INDI, which eventually not only increase the price of production aircraft, but also reduce price competitiveness. Meanwhile, the hybrid INDI control may not increase the development cost and time because it simply uses the angular acceleration with higher accuracy depending on flight conditions. In the hybrid INDI control, the weight ratio of estimated angular acceleration, \dot{x}_{obm} , is increased in the subsonic and supersonic flight areas where a rather accurate model estimation can be obtained, and the weight ratio of measured angular acceleration, \dot{x}_{meas} , is increased in the very high AoA and supersonic flight conditions where it is difficult to estimate the model. In this way, this control method is presented to provide uniform and constant flying qualities without relying on the flight conditions, improve the dynamic response characteristics of the system, and ensure the robustness.

(2) Mission Oriented Response Type

The response type determines the aircraft response to the pilot’s input. It can provide the more improved handling qualities by designing the flight control law considering flight phases and MTE. In this regard, ADS-33E-PRF [111], the latest specification for flying qualities of rotorcraft, presents the response types as applicable to the usable cue environment (UCE). On the other hand, for the response type of fixed-wing aircraft there is no published document with guidelines defined. But, in the cases of fighter development, it can be seen so far that the concept of response type according to flight phases and MTE is also widely applied, as in fixed-wing aircraft.

Table 1 F-35A response type and control surfaces usage in up and away (UA) mode [15, 29, 61, 112]

	Flight condition	Response type	Feedback variables	Control surfaces						
				Lateral-directional			Longitudinal			
				δRS	δFA	δHA	$\delta LEFS$	δFS	δRA	
Pitch	Low speed	Q	N_n, Q, \dots	-	-	-	Sched	Sched	✓	-
	High speed	N_n		δFS & $\delta LEFS$: Followed performance schedule set by aerodynamics group						
Roll	Low- to moderate- α	P_s	P_s, \dots	✓	✓ (FAHA*)	-	-	-	-	-
	Transient	Blended		Blend						
	High α	P_s, R_b if large pedal input		✓	-	-	-	-	-	-
Yaw	Low- to moderate- α	β	β, β_{dot}, R_s or R_b, \dots	✓	✓ (FAHA*)	-	-	-	-	-
	Transient	Blend		Blend						
	High α	β, R_b if large pedal input		✓	-	-	-	-	-	-
SB	Limited operational flight envelope	Exact feedback variables cannot find in public domain		* FA and HA are ganged (treated as a single effector) at high speeds for structural load consideration In Low Speed, Roll-Yaw control by RS, HA and FA based on control allocation						
		Performance schedule set by aerodynamics group in UA Mode				-	-	-	✓	✓

δRS symmetric rudder deflection, δFA asymmetric flap deflection, δHA asymmetric horizontal deflection, $\delta LEFS$ symmetric leading-edge deflection, δFS symmetric flap deflection, δRA symmetric horizontal deflection, δRA asymmetric rudder deflection, Q pitch rate, N_n normal load factor, P_s stability-axis roll rate, R_b body-axis yaw rate, SB speed brake

This section briefly introduces the case of the response type of the F-35A [15, 29, 61, 112], as presented in Table 1. The NDI control in which a flying qualities dependent portion and an aircraft dependent portion are separated has the advantage of being able to be applied by mixing various response types when the control law designer designs desired dynamics. And the designers can directly reflect the flying qualities specifications presented in MIL-STD-1797 using a classical control method with desired dynamics with multiple state feedbacks. The F-35A is designed in the response types depending on flight states such as AoA and airspeed. In UA mode, the F-35A adopts response types with a design concept similar to a conventional fighter jets in a low- and medium-AoA flight regime as follows: The pitch responses to pitch control stick input are pitch rate to have the precise control at low speed, the normal acceleration to enhance the fast maneuverability at high speed. And the roll response to roll control stick input is the roll rate to achieve the fast roll performance, and the yaw response to rudder pedal input is AoS to improve the directional stability.

Meanwhile, the response type of the roll and yaw axis is changed as the AoA increases. To achieve fast nose pointing, the response type in the yaw axis will be changed from AoS to body-axis yaw rate for the large rudder pedal input, in which the pilot cannot directly control the roll axis. And, by controlling the rolling and yawing under the control law using the aircraft's unique stability characteristics, the rolling and yawing performance of the aircraft can be greatly improved.

(3) Control Allocation

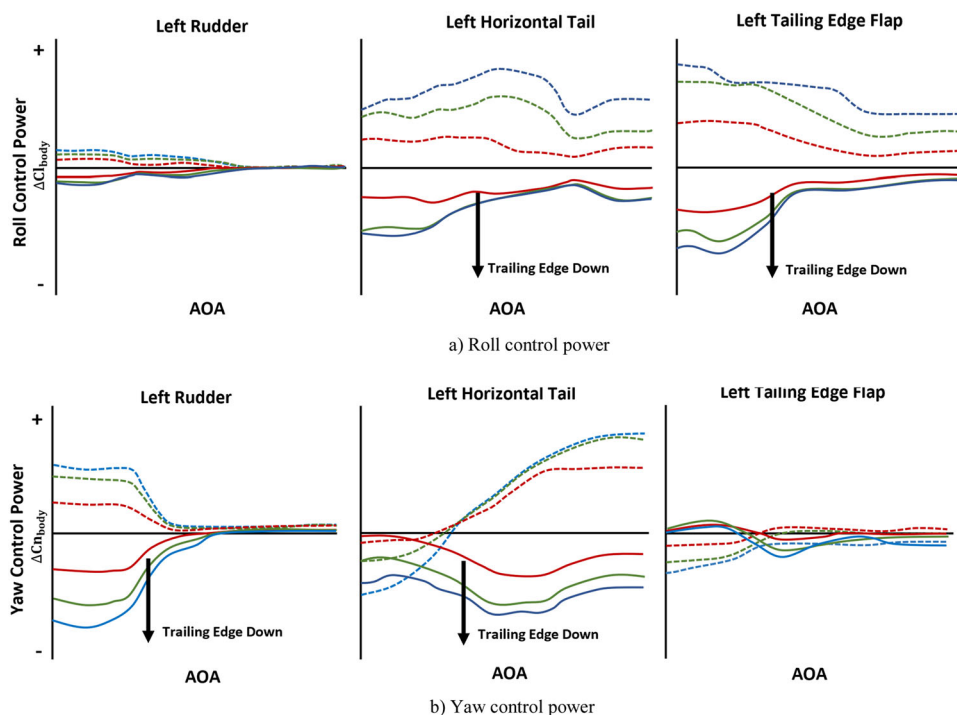
The effectiveness of the control surfaces is significantly reduced due to flow separation in an unstable flow field around the main wing and the immersion of the rudder control surface in the fuselage wake in the high AoA flight regime. Therefore, it is essential to apply the CA algorithm in consideration of the control effectiveness characteristics of each control surface in the high AoA flight regime which has a different aspect from the control surface operation in a low- and medium-AoA flight regime with sufficient control power. The CA algorithm can be implemented by easily integrating with the NDI control, and its main functions can be divided into two categories as follows [113]. The first is to normalize the control effectiveness by converting the generalized 3-axes angular acceleration commands into the actuator deflection angles. The second is to redistribute the control effectiveness of each control surface without deteriorating the performance of the closed-loop system, thereby ensuring flight performance and safe flight by providing control redundancy in case of reduction of control effectiveness or failure of control surfaces.

The fighter jet that applied the CA algorithm to the EMD program is three variants of F-35, and Table 1 shows the response type and control surface usage method of the F-35A according to the flight regime in up and away (UA) mode [15, 29, 61, 112]. The CA is designed at the lateral-directional axis considering the computational throughput and memory of the flight control computer, the design complexity, and the roll performance at high AoA, etc. Asymmetric HTs (δ HA) are used as a control surface for lateral-directional axis control in consideration of control effectiveness characteristics according to the flight regime. But the HTs still have priority for longitudinal axis control to ensure stability and maneuverability for longitudinal since they are the primary control surface of the longitudinal axis control. The function of the CA algorithm is designed in two following main concepts according to changes of AoA or dynamic pressure.

First, the roll maneuvering is performed by dividing the control surfaces into the asymmetric flaperon (δ FA) and the asymmetric horizontal tails at a predetermined ratio in the low- and moderate-AoA and medium- and high-speed flight regimes with relatively sufficient control power. The reason for applying this design concept is that roll maneuvering using asymmetric flaperon in high-speed flight regime increases the structural load on the main wing of the aircraft. In addition, when the aircraft maneuvers a high g turning flight in the transonic flight regime, an unstable flow field causes a flow separation throughout the main wing, including the flaperon control surfaces. Therefore, in high-speed flight regime, performing a roll command with asymmetric flaperons not only reduces roll performance, but also causes uncommanded lateral motion such as wing rock, heaving wing and wing drop. For solving these problems, asymmetric HT, which is relatively unaffected by the stream of the main wing, is used to ensure the roll performance of the aircraft.

Second, the CA algorithm in the high AoA flight regime which lacks control power, is designed in consideration of the control effectiveness on the control surface deflection and the aircraft's motion characteristics. In general, agility of the aircraft in flight regime is determined by the amount of control power that can generate rolling and yawing moments. The F-35 integrally used the asymmetric flaperon, the asymmetric horizontal tail, and the symmetric rudder in consideration of the control effectiveness characteristics of each control surface for agile maneuvering at the high AoA as shown in Fig. 14. In this flight regime, the yawing moment generated by rudder deflection is significantly reduced, so the rudder control effectiveness does not function as

Fig. 14 Roll and yaw control power of the left rudder, HT, and flap of the F-35 [15]



a control surface. In contrast, the yaw control effectiveness by asymmetric horizontal tails significantly increases as the AoA increases, while asymmetric horizontal tails have little yaw control effectiveness at a low and moderate-AoA. Therefore, asymmetric horizontal tails as control surfaces for generating yawing moments at a high AoA are considered in the allocation of control power. However, when the horizontal tails are at down deflection, the yawing moment for the asymmetric horizontal tails is significantly reduced. The amount of asymmetric horizontal tails that can be used to generate yawing moments in the high AoA flight regime may be limited according to the longitudinal axis control priority of the horizontal tails. Therefore, it is important to maximize maneuverability in high AoA with an appropriate CA algorithm design between the longitudinal and directional axis. And, since the authority of CA applied to the F-35 takes yaw control over the roll even if the yaw control effectiveness of asymmetric horizontal tails is small, the asymmetric horizontal tails are used for the yaw control command which generates undesirable rolling motion. In this case, it is possible to conditionally alleviate the priority of the yaw and prevent undesirable rolling motion due to the asymmetric horizontal tails use by adjusting the weighing factor in the CA algorithm.

Lastly, ill-conditioned control power data, such as a large change in control effectiveness and a local

maximum/minimum value caused by a nonmonotonic change in control power, generates chattering problem in the actuator command. Thus, the OBM dataset should be monotonically designed for each axis. Figure 15 shows the simulation results that the departure at the pitch axis occurs due to the local maximum of the horizontal tails control effectiveness of F-35. That is, the zero control-effectiveness derivatives are calculated by computing a value of “0” due to the non-monotonic control power data of the OBM so that the control surface cannot move from a local maximum value or a minimum value. These characteristics can potentially not only degrade the flying qualities of the aircraft, but also affect flight safety.

5.5 Flight Envelope Protection Functions

The highly maneuverable fighter jets require maximum maneuverability to preoccupy a superior position over the enemy’s aircraft or to avoid enemy’s missiles. Therefore, the pilots should have control the aircraft very close to the possible limits of flight envelope without structural overload, departure situation, or air intake and engine envelope limit while focusing on tactical missions. To ease the pilot workload, in the advanced flight control systems, automated and active flight envelope protection functions are adopted such as AoA-G limiter, roll rate limiter, rudder fader and anti-spin

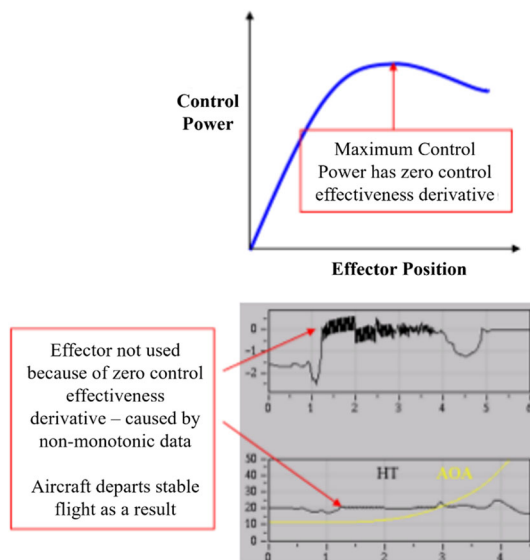


Fig. 15 Local maximum of the horizontal tails control effectiveness [6]

control including warning systems. However, the flight envelope protection functions should not unnecessarily prevent the pilot's capability to obtain the maximum maneuverability of the aircraft, without sacrificing performance in any part of the flight envelope. So, the design method requires increasing the computing capability of FLCC and reflecting various aircraft status information such as Mach number, dynamic pressure, angular rates, mass properties and control surface positions. In addition, a more adaptive control approach can be applied so that it sets baseline limiters for each axis, feeds back information such as control commands and angular rate on other axes, and modifies the baseline limiter in real time for in-flight. This chapter introduces the representative envelope protection functions of AoA-G limiter, and roll and yaw command limiter.

5.5.1 AoA-G Limiter

The AoA-G limiter is designed to prevent excess structural load in the high-speed flight regime above corner speed or out-of-control conditions due to departure into high AoA in low-speed flight regime below corner speed. In most of the fighter jets, their maximum g performance is limited to $+9g$ to protect their structural limitations and the pilots' achievable maximum g is reduced according to the external loading configurations [16, 18, 114].

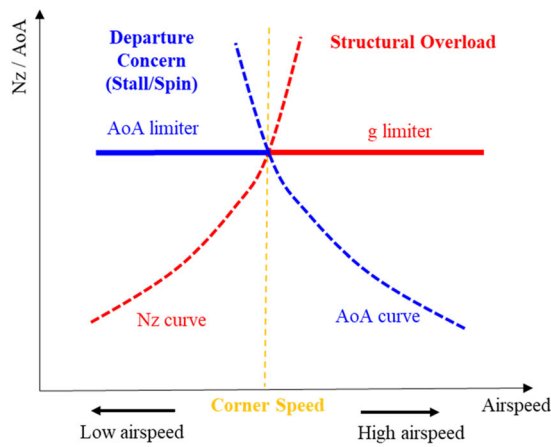
The design criteria for the AoA limiter differ depending on the aircraft characteristics such as pitch margin, directional stability derivatives ($C_{n\beta}$), dihedral effect derivatives ($C_{l\beta}$), directional control departure parameter ($C_{n\beta, dyn}$), control power, and measurement range of air data sensors. Based on these characteristics, the maximum limit value of the AoA

is designed to satisfy safety margin criteria on various uncertainties at the lowest AoA. In addition to these design criteria, the AoA-G limiter is to allow the pilot to attain the limit as quickly as possible, considering acceptable overshoots for maximum pitch control input. Examples of the design of the AoA-G limiter are as follows: As shown in Fig. 16, the F-16 [16] is designed to have a baseline AoA limiter in consideration of directional stability derivatives characteristics that become unstable as the AoA increases and temporarily reduces the AoA limiter as the feedback-based washout pitch rate and roll rate increase to prevent departure of the aircraft. With a similar design concept, the F/A-50 is designed to have the AoA limiter at 25° in consideration of the instability of the dihedral effect derivative [17, 115].

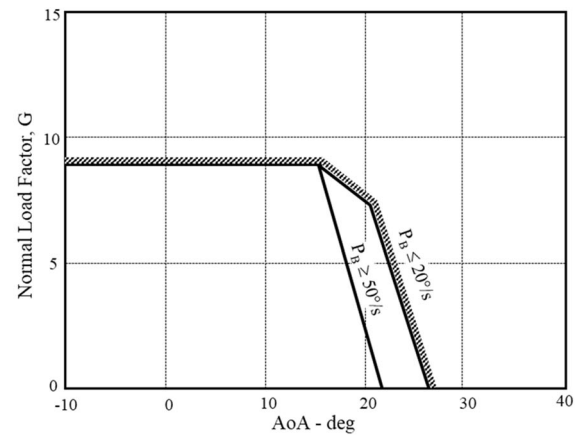
Unlike legacy fighter jets operating in low- and medium-AoA flight regimes, the F-18 E/F, the F-22 and the F-35 is capable of being maneuvered beyond stall AoA. The F-22 has no AoA limit by adopting TVC as an additional pitch control effector in the High AOA flight regime [116, 117]. The baseline AoA limit of F-35 [15, 61] is known to be about 50 degrees, and the primary design criteria for AoA limiter are to ensure nose-down pitch acceleration capability and satisfactory pitch margin in the low-speed flight regimes. The nose-down pitch acceleration design criteria are applied as follows: -0.20 rad/s^2 in the UA and -0.15 rad/s^2 in the power approach (PA). The F-35 adopted design concept similar to the F-22, in which the limiter is a function of CG, weapon bay door (WBD) and other factors affecting pitching moment, and the design has very complex and extensive logic and gain scheduling, but, as a conservative design, does not prevent pilot's capabilities. The two design lessons learned from the AoA-G limiter design of F-35 are as follows: The fuel system ensures that CG positions should be maintained at the forward position to maximize maneuvering capabilities in high AoA. Figure 17 shows the movement of CG according to the fuel consumption and internal store loading of the F-35A [15]. And, in flight maneuvers such as slow down turn (SDT) from high speed where the relationship between normal load factor and AoA changes rapidly, the airspeed and rate of airspeed were applied to the AoA-G limiter logic so that the limitations of both normal load factor and AoA can be attained.

5.5.2 Roll Rate and Yaw Command Limiters

The roll rate command limiter (RCL) is designed by taking into account the characteristics of the aircraft, such as HQ, control surface load limitation and departure response related to gyroscope (inertial) coupling. The command limiters are designed considering HQ rather than DR concerns in the low-speed flight regime where control authority is limited, while it is designed considering control surface load limitation and departure in the high-speed flight regime



a) Design concepts



b) F-16 [16, 123]

Fig. 16 Design concept of AoA-G limiter

where dynamic pressure is high. For most fighters, the pitch control effect of the HT control surface is reduced in the low-speed and high AoA flight regime, so the aircraft may enter the departure due to the inertial pitching moment, $\{(I_{zz} - I_{xx})/I_{yy}\} \times (P_B \times R_B)$, caused by the high roll rate. And the use of uninhibited yaw commands during roll maneuvers can generate a pitch-up characteristic and cause the aircraft to enter a departure. Therefore, the flight control computer should have a yaw command limiter that allows the pilot to command the maximum roll rate that the aircraft can generate without entering departure out of controlled flight.

The roll rate command limiter of the F-16 [16] is a function of dynamic pressure, AoA, and HT position as shown in Fig. 18. Since it limits the maximum roll rate only when the calibrated air speed is 250 knots, AoA is 15°, or HT command is 5° or more, there is no performance degradation. And the rudder command is fadeout at the angle of attack above 20°, and the rudder command is limited further as the roll rate and AoA increase.

The F-35 [15] applied a wider variety of aircraft state variables to the limits logic not to restrict the pilot’s control performance. The logic of roll rate and yaw command limiter were scheduled as a function of AoA, dynamic pressure, Mach number, store loading, and CG, and the limit value was relaxed selectively and temporarily by feeding back state variables such as angular rate and angular acceleration of the aircraft. This adjustment is essential to maximize maneuverability in that it precludes the need for overly restrictive and preemptive command limits.

5.6 Recovery Functions

The flight control system has the flight envelope protection function to prevent the aircraft from entering a departure beyond a limited AoA. However, the pilot’s intentional

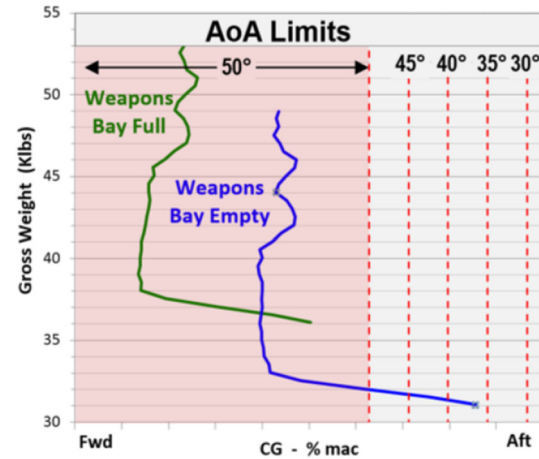


Fig. 17 CG movement as a function of fuel burn and internal store loading for the F-35A [15]

deceleration with sustained high-pitch attitude climbs and the aggressive maneuvering during combat missions disable flight envelope protection so that they can put the aircraft in dangerous situations such as spin and deep stall where it is difficult to recover to normal controlled flight. To ensure flight safety even in this situation, the flight control system provides automated recovery functions such as ALSR, anti-spin control and APR, etc. This chapter briefly introduces these functions.

5.6.1 Automatic Low Speed Recovery (ALSR)

Eurofighter Typhoon’s flight control system has additional safety features to facilitate the care-free handling function called ALSR [18, 118]. This function provides three automatic recovery mechanisms, i.e., roll to inverted and pull, push over, and knife over maneuver depending on the pitch

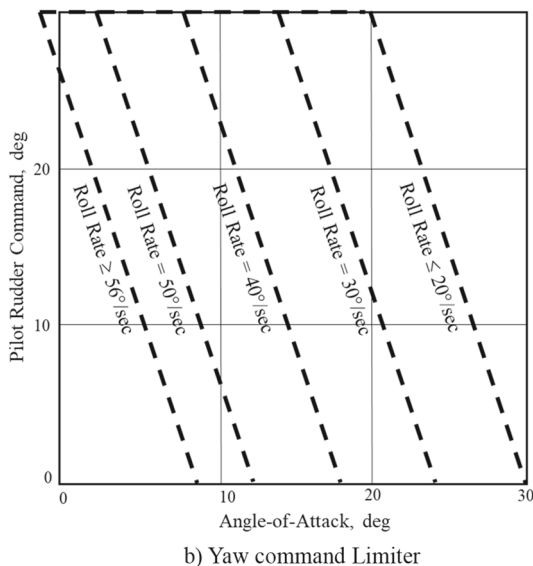
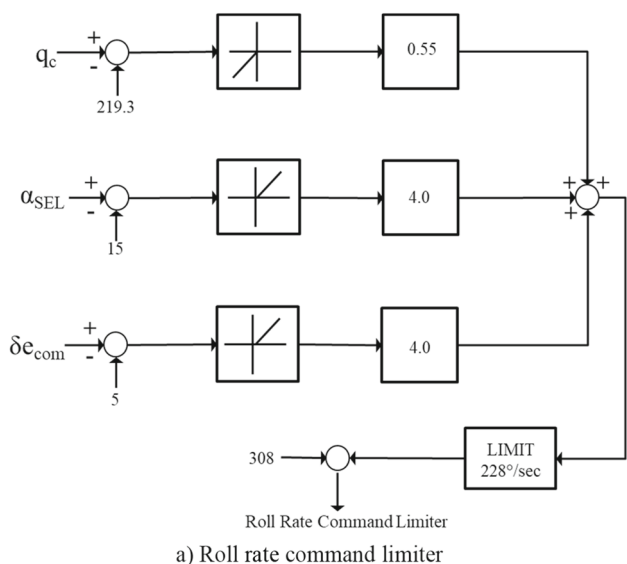


Fig. 18 Roll rate and yaw command limiters for F-16 [16]

and roll attitudes. If the pilot fails to take appropriate action without paying attention to the low speed warning (LSW) when the pilot can initiate manual recovery of the aircraft, the ALSR function takes over control from the pilot about 3 s after the LSW works, and then automatically recovers the aircraft. At the same time when FCS has taken over control of the aircraft to head up display (HUD), the “FCS override” warning is operated with voice warning.

Figure 19 shows the recovery maneuvering procedures for types 1 and 2. While the red symbol indicates that the pilot immediately responded to the LSW and recovered the aircraft manually, the types 1 and 2 of the blue and yellow symbols are cases that the FCS has control authority, and an ALSR takeover (at point T) occurs approximately 3 s after point W is triggered. The first type in blue symbol of

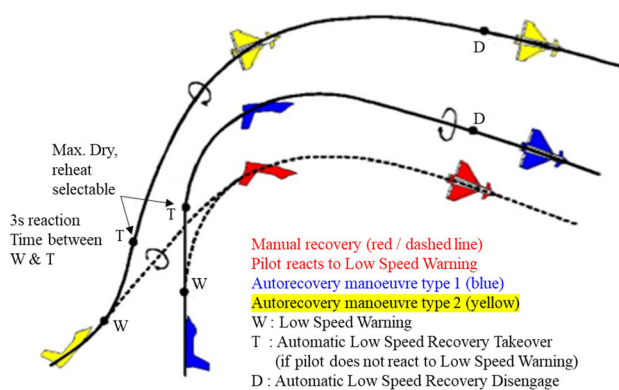


Fig. 19 ALSR sequence of events for type 1 and 2 recovery maneuver [118]

recovery maneuver is applied at pitch attitude close to the vertical with 180° roll and the aircraft recovers its attitude and airspeed by pulling the control stick input toward the horizon while maintaining a positive g. The second type in yellow symbol of recovery maneuver recovers altitude and airspeed with knife-over maneuver if the pitch attitude is larger than moderate and the roll attitude is larger than 45 degrees. This type of recovery usually takes about 15–20 s. ALSR will be disengaged at point D after recovery maneuver is completed.

The envelope protection function including ALSR applied to Eurofighter Typhoons preemptively prevents the aircraft from entering departure out of the controlled flights, further reducing pilot workload and providing maximum performance at the edge of flight envelope. Meanwhile, this function might be also operated as a factor that hinders pilots from utilizing the maximum performance of the aircraft.

5.6.2 Anti-Spin Control

The spin is the motion that the aircraft diverges as it continuously rotates, tilted in one direction, due to the difference in flow between the left and right wings in a high AoA. In general, the spin characteristics such as amplitude and frequency are determined by the aerodynamic characteristics of the aircraft, so it is advantageous to design the aircraft to have spin resistant in aerodynamic configuration design, considering that the control surface effectiveness decreases in these flight regimes. The anti-spin control function to prevent the spin motion is designed taking into account of the effectiveness and primary role of the control surfaces based on aerodynamic characteristics.

For a good example, the F-35 anti-spin control function [15] has a spin recovery mode and a yaw rate suspension mode. The main functions of this mode are as follows: the spin recovery mode which is to arrest the large, self-propelling yaw rates associated with incipient or fully

developed spins, and the yaw rate suspension which is to suppress yaw rate during high AoA conditions where sustained spins are possible. First, the spin recovery mode is activated when the yaw rate exceeds the predefined threshold value as a function of airspeed in a positive or negative high AoA where continuous spin can occur, and thereby suppresses large and self-propelling yaw rates related to early or fully developed spin. When the spin recovery logic is enabled, the yaw rate to asymmetric HT is scheduled based on the lateral CG, and the yaw rate and yaw acceleration feedback are used to ensure a quick and smooth recovery. However, it is important to prioritize HTs according to the yaw rate as HT is used simultaneously for pitch and roll-to-yaw axis controls in the high AoA flight regimes. In other words, the yaw rate should be minimized at the departure of the aircraft from the high AoA in a way of applying a small but continuous yaw rate, since it can significantly delay or completely interfere with a successful recovery. At that time, HT priority is changed to the roll and yaw axis control rather than pitch control when spin mode recovery is activated, although a significant portion of symmetric HT is used for APR or manual pitch override (MPO) when yaw rate becomes reduced. Second, the yaw rate suspension mode is engaged when the positive AoA limiter exceeds by the specified amount. The AOA schedule is designed not to respond to minor AoA limiter overshoots. And this mode is not used as the rudders and vertical tails are effective at negative AoA since there is no deep stall characteristic. Another design lesson learned is that the anti-spin control function has reduced the extreme delay in spin recovery by reducing inefficient pitch rocking with designing adaptive filters that respond to steady-state yaw rates but do not overreact to high-frequency yaw rate oscillations.

5.6.3 Automatic Pitch Rocker (APR)

A deep stall, a very dangerous form, that results in a significant reduction or loss in the effectiveness of the HT control surfaces, invalidates normal stall recovery actions. Most fighter jets designed with small HT control surfaces have a deep stall mode in specific AoA regime. For example, the deep stall of the F-16 [16] occurs between AoA 60 and 70 degrees, and that of the F-35 [15] occurs differently by variants. In other words, both STOVL and CTOL versions with relatively small HT control surfaces have the deep stall mode, while the carrier-variant (CV) of the F-35, F-22 [19, 119] and FA-50 [115] have no deep stall mode in all AoA regimes.

If the aircraft enters departure beyond the limited AoA, the AoA-G limiter overrides the control stick pitch command and commands the symmetric HT toward the nose down direction to recover the aircraft from the deep stall. However, the aircraft is stabilized and will still be unable to

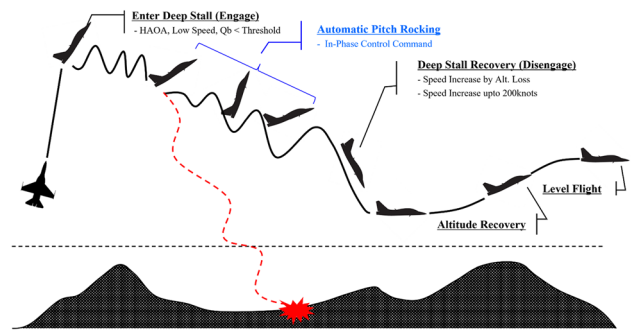


Fig. 20 Deep stall recovery procedure based on pitch rocking maneuver [120, 121]

recover from the deep stall with the nose down command by the AoA-G limiter around deep stall AoA. Under this situation, the MPO switch allows a “pitch rocking maneuver” to override the AoA-G limiter and provide direct control of the HT for the pilot to recover the aircraft from deep stall flight conditions. The pilot overrides the automated in-phase pitch command by operating the MPO switch and then generates pitch oscillations using the HT control surfaces manually until the pitch rate is sufficient for recovery, sufficient nose-down pitch rate is generated and the AoA decreases below the stall AoA with speed increase towards the ground path. Figure 20 shows the deep stall recovery procedure based on pitch rocking maneuver. The pilot begins pitch rocking in-phase with nose movement; i.e., if the nose is pitching up, the pilot pulls back on the stick. And the plot maintains aft stick until the maximum pitch attitude is reached, which is indicated by the nose stopping and reversing direction, and then he pushes the stick full forward to generate a nose down pitch rate. If the nose down pitch rate is high enough to break the deep stall, the aircraft recovers. Deep stall recovery using MPO relies on the pilot who can apply timely inputs, and its success depends on the pilot’s skill and familiarity with the technique. To overcome these shortcomings, the F-35 [15], F-16E/F [58] and F-22 [19, 119] flight control systems provide APR function for automatic deep stall recovery when pitch rate is within a certain threshold in the high AoA. However, no details on the APR applied to the production fighter jets have been disclosed so far.

Kim [120, 121] designed and evaluated the APR function, as a research study, based on the T-50 aircraft simulation environment in consideration of the pilot pitch rocking maneuver pattern using MPO described above.

Figure 21 shows the APR control law structure. The reference parameter for the deep stall recovery command is pitch rate. The control law consists of five elements: lag filter, amplitude gain, deep stall condition selector (inverted or upright), g command limiter, and transient response preventer. The lag filter reflects the effect of delay in the pilot’s situation to determine the proper pitch rate before starting

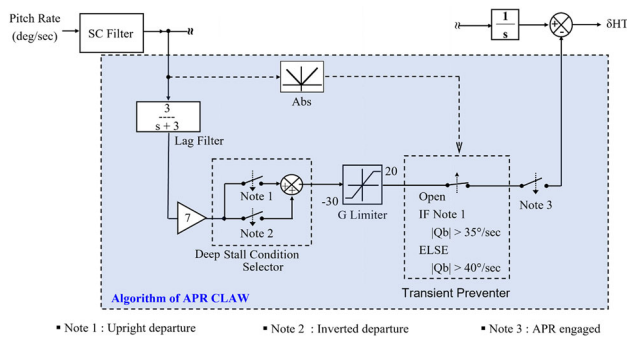


Fig. 21 Control architecture of APR [120, 121]

to perform the pitch rocking, and the amplification gain is applied to convert the pitch rate into g command. The deep stall condition selector determines whether the flight condition of the aircraft is upright or inverted, and the g limiter restricts g command. The transient response preventer was designed to prevent the transition from upright to inverted or from inverted to upright at the time of recovery due to excessive APR commands in situations where the pitch rate is large.

6 Control Law Design Considerations

Modern fighter jets have high-order nonlinear characteristics and significant interactions between subsystems such as aerodynamics, propulsion, and weight, as they are designed with features for low drag and excellent low observability (LO). Considering these characteristics of the aircraft, the subsystems can be integrated into the flight control system to maximize performance by controlling the aircraft. To ensure robustness against nonlinearities and uncertainties, it is becoming common to design flight control systems with nonlinear control of the MIMO control concept. In the MIMO control, various aircraft state variables are feedbacked and more effectors are utilized for aircraft control. By applying this MIMO control concept to the flight control law design, more sensor data acquired from subsystems such as Fuel management system (FMS) and avionics are fed back to improve aircraft performance. The control law design method also introduces more effectors such as TVCs, canards and nose blowing to control the aircraft. The basic characteristics of the aircraft and the design of the flight control system are closely related to the success of the project, so that the flight control methods appropriate to the characteristics can be chosen in the aircraft development project. This section describes the key considerations in selecting the best flight control method for successful and efficient aircraft development, in a way that asks questions and answers them.

First, is the control law structure to be selected suitable for satisfying the aircraft performance goals in the development project? It is directly related to the operational flight envelope (OFE) of the aircraft, and the control law structure can be designed differently according to whether it is possible to maneuver up to or beyond the stall angle-of-attack flight regime. For example, when designing fighter jets such as the F-35 JSF, F-22 Raptor, F-18E/F Super Hornet that require maneuver and mission performance beyond the stall angle-of-attack flight regime are design, the control law engineer should have considered nonlinear control methods including control allocation that effectively utilize the control surface effectiveness, so that he could control the aerodynamic nonlinear characteristics that may occur in the high angle-of-attack. On the other hand, in a case of fighter jets that require maneuver and mission performance in low to medium angle-of-attack flight regime, such as F-16 Falcon and FA-50 Black Eagle, just applying linear control methods based on a linear aircraft model can secure adequate flying qualities and mission performance. Thus, the flight control design engineer can suitably reduce development technical and cost risk to achieve final development goals by adopting a control method appropriate to the OFE and the required mission performance of the development aircraft.

Second, is the output to the input of the controller applied to the control method consistent and predictable? In other words, it means that designers and verifiers should easily predict the output to the input of the controller, thereby minimizing efforts for development. A control method with having a simple structure and predictable control outputs to inputs can significantly reduce efforts for design and verification in the development stage and can easily solve problems that may occur in the development stage, thereby considerably reducing non-recurring engineering (NRE). A reduction in NRE, a cost to be required in the aircraft development stage, leads to a decrease in the manufacturing cost of the aircraft, and an increase in the price competitiveness. For this reason, the selection of adequate control methods in the aircraft development stage is one of the most important things in the entire life cycle of aircraft which constitutes development, production, and export. As a representative development case, it is known that F-35 JSF had reduced NRE [122] by 4–8 times by adopting the nonlinear dynamic model control method.

Third, does the control method apply a design concept that can modularize the control loops and have interdependence between the modules? That the control loop can be developed with multiple modules at the same time means that a partial problem that occurs during the development process does not affect the overall development process. That is, each control function can be independently developed as a module, thereby enabling to efficiently develop

the flight control law within a limited manpower and schedule. In this methodology, the structure of each module can be easily expanded and changed to the control structure of desired dynamics. Another advantage is that the modular development improves portability, making it easy to apply the already developed and verified control functions to the control structure which is being developed in other new aircraft development projects. For example, various ongoing airlines aircraft development projects can reduce the period and cost by reusing the already developed control technologies.

Lastly, does the control structure have readability so that it can be easy to change and modify the control structure? Various unpredictable problems have arisen in the aircraft development process. To solve this problem quickly, the readability of the control structure must be ensured so that the structure can be easily modified. This control method also makes it easy for designers to verify the control law.

7 Conclusion

As modern fighter jets with advanced aerodynamic features adopt full authority digital fly-by-wire (FBW) flight control system, they use multivariable control theories to achieve superior performance and to guarantee good flying qualities. In particular, thanks to the progress of sensor technology, the flight control theory with the multi-input multi-output (MIMO) concept is common, which feedbacks various state variables to control various control surfaces with each augmented control command considering control effectiveness. The most modern fighter jets apply this control theory concept to their flight control systems.

The recently developed f-35 joint strike fighter (JSF) which has advanced aerodynamic features applies the non-linear dynamic inversion (NDI) control to the flight control system, enabling maneuver in high AoA flight regime beyond stall without additional effectors such as thrust vectoring control (TVC). The NDI control effectively utilizes basic aerodynamic characteristics and control of aircraft to achieve maximum maneuverability and performance since it is designed by introducing various state variable feedbacks and control allocation (CA) algorithms based on high fidelity on-board model (OBM) model.

From these points of view, this paper presents the results of reviewing the development cases of flight control systems for representative fighter jets developed since the 1970s, as follows: For the aircraft to achieve maximum performance and good flying qualities, the configuration of the aircraft should be basically designed to have excellent aerodynamic features and sufficient control for maneuvering, with application of advanced control theory. That is, the excellent performance, maneuverability, and flying qualities of the aircraft may be

achieved by organically combining the flight control and the aerodynamic characteristics. Also, the selection of the sensor type and mounting location is important to obtain accurate and reliable aircraft state information in all flight envelopes. Furthermore, by adopting the control stick with software-changeable active control function, it is possible to reduce trial and error for the aircraft development phase since the characteristics of control sticks have a significant effect on flying qualities.

This paper can be used as background knowledge and guidelines to understand flight control, which will be of great help from the aircraft developers to students majoring in aerospace.

Acknowledgements The authors would like to deliver their sincere thanks to the editors and anonymous reviewers.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

Declarations

Conflict of Interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

Appendix

List of acronyms

AC	Aerodynamic center
ACLS	Automatic carrier landing system
ADS	Air data system
AGCAS	Automatic ground collision avoidance system
AIS	Active inceptor system
ALSR	Automatic low speed recovery
AoA	Angle-of-attack
AoS	Angle-of-sideslip
APC	Aircraft-pilot-coupling
APR	Automatic pitch rocker
ATC	Automatic throttle control
ATF	Advanced tactical fighter
ATF	Automatic terrain following
B Ae	British aerospace
CA	Control allocation
CG	Center of gravity
CHR	Cooper-harper rating
CONDUIT	Control designer's unified interface
CV	Carrier-version
DFBW FCS	Digital fly-by-wire flight control system
DLR	German aerospace center

DOF	Degree of freedom
DPIA	Differential proportional plus integral algorithm
EA	Eigenstructure assignment
EB	Effector blender
EMD	Engineering and manufacturing development
FCSDVP	Flight control system design and verification process
FLCC	Flight control computer
FMET	Failure modes and effects test
FMS	Fuel management system
IMFP	Integrated multi-function probe
GUI	Graphic user interface
HARV	High angle-of-attack research vehicle
HILS	Hardware in-the-loop simulator
HQ	Handling qualities
HUD	Head up display
IMU	Inertial measurement unit
JSF	Joint strike fighter
LEF/TEF	Leading- and trailing-edge flap
LEX	Leading-edge extension
LOES	Low order equivalent system
LQ	Linear quadratic
LRU	Line replaceable unit
LSW	Low speed warning
MBD	Model-based design
MIMO	Multi-input multi-output
MPO	Manual pitch override
MTE	Mission task element
NASA	National aeronautics and space administration
NDI	Nonlinear dynamic inversion
NLR	Netherlands aerospace centre
NRE	Non-recurring engineering
OBM	On-board model
OFE	Operational flight envelope
OFP	Operational flight program
PA	Power approach
PARS	Pilot activated recovery system
PIO	Pilot-in-the-loop oscillation
R&D	Research and development
RCL	Roll rate command limiter
RESTORE	Reconfigurable control for tailless aircraft
ROC	Requirement of customer
RSS	Relaxed static stability
S&C	Stability and control
SB	Speed brake
SCF	Structural coupling filter
SCT	Structural coupling test
SDD	System development and demonstration
SDT	Slow down turn
SISO	Single-input single output
STOVL	Short take-off/vertical landing
TNS	Tactical navigation system

TVC	Thrust vectoring control
UA	Up and away
VAAC	Vectored thrust aircraft advanced control
UCE	Useable cue environment
VMS	Vehicle management system
WBD	Weapon bay door
LO	Low observability

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