# Digital Flight Control Systems

## For Practising Engineers


**Defence Research & Development Organisation**
**Ministry of Defence, New Delhi - 110 011**

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**Defence Research and Development Organisation**
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# Contents

# Foreword

This book is, in many ways, the most unusual technical account I have seen or read of any subject, for it is reader-friendly, enthusiastic, practical and history-loving. It is one of the many outcomes of the LCA project, for it teaches the reader how to analyse, design and develop a digital flight control system, by narrating the story of how it was done for the LCA by a National team headed by ADE and how a family of flight control systems for the Indian stable of UAVs was also developed alongside.

For those who have been associated with the LCA from the beginning (or even earlier, as in my case), the first 10-15 years were an exciting period. New technologies were being developed, national teams were working together on various projects and the NAL wind tunnels ran on two shifts to get aerodynamic data on time. I recall an article which appeared in the AIAA magazine Aerospace America in the late 1990s, based on a report by an AIAA Committee that visited major Asian countries to assess their aero-space programmes. The Committee concluded that, to their surprise, the fastest developments in aerospace technologies seemed to be taking place in India (rather than in Japan, Korea or China). This was a reflection of the spirit in which the aerospace community in India was pushing its projects at the time, in particular the LCA which made its first flight some 40 years after the previous indigenous fighter HF-24 had done. (I wonder if that AIAA assessment of Indian aerospace is true now, as far as new aircraft are concerned!)

Coming back to the monograph, it begins with a colourful first line about the climate of the hometown of Indian aeronautics: "The sun shines brightly in the blue sky during the crisp winter months in Bangalore. So it did on 4 January 2001", as the LCA made its maiden flight before a large group of people who had worked on it for years. And the rest of the book gives detailed accounts of how it all happened, what problems the engineers had to face and how they were solved, and how there had been no incident in the LCA-Tejas in all of nearly 5000 flights. (Indeed, the last few words mark a very impressive achievement at international

level, as such a flawless record of flight control performance in the development phase has eluded countries with much longer experience in fighter aircraft design). Of the many technologies that the Indian engineers had to develop for LCA, digital flight control system and carbon-fibre composite structures were unanimously considered the most challenging (besides the engine), by a Committee (chaired by me) whose task was to identify the most critical technologies. This book on Digital Flight Control Systems, often called 'the heart and soul of an aircraft', is an outcome of what was actually achieved in LCA.

The book is structured in a very practical and (again) unusual way, as it is intended for use not only by already practising engineers but also by those young graduates who have been taught the principles of flight control and the mathematical tools for handling them, but not how the working system is actually designed for the aircraft. Chapter 2 is a brief presentation of such basic principles of control engineering in general and ends with a mention of more modern Artificial Intelligence techniques as a future possibility. Chapter 3 goes a step further, describing the dynamics of the aircraft and how the flight control system operates to keep the relevant forces in the requisite balance to keep the aircraft from going unstable – using classical analysis tools like Laplace transforms and Bode plots. The possible use of state-space theory in coming years is mentioned.

Chapter 4 is an interesting interlude which turns to the history of the development of flight control technology, starting with the flights of the Wright Brothers with simple manually operated control systems (even the shift in pilot's body mass was used cleverly to control the attitude of aircraft), all the way to the present technology of employing highly advanced digital electronic systems for agile aircraft that preserve stability when the pilot's 'human' power is not adequate to intercede.

Chapter 5 explains the setting up of mathematical models to describe aircraft dynamics in all six degrees of freedom that are required to design control laws as well as tests to check whether the aircraft retains its stability. A typical design process of determining the control laws for a fixed wing aircraft is described in Chapter 6, through the example of an UAV designed to operate as a pilotless target aircraft, and demonstration of how computer simulation studies help in designing a control system tailored to handle the aerodynamic characteristics of the vehicle.

Chapter 7, certainly unique (again) and in many ways the most enlightening part of the book, is all about the exciting history of how the digital flight control system was designed at ADE for the LCA. There are detailed descriptions of total system design followed by individual subsystems such as air data sensors, hydraulic actuators, the digital flight control computer and related software. DFCS development demands an extensive control law development programme

described in greater detail in Annexure 3. This Chapter goes on to describe the processes of verification and validation of both software and subsystems at various levels, and validation of the integrated system on the Iron Bird. Other essential test activities such as coupling of structural vibration modes to flight controls, EMI/EMC tests, engine ground-run tests and the final 50-hour fault-free tests on the Iron Bird, leading to clearance for first flight, are described in some detail. Thus, we have a total description of the LCA digital flight control system development experience summarised in about 100 pages. References to more detailed technical descriptions available elsewhere have also been provided.

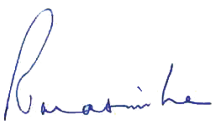
Chapter 8 discusses flight control systems of UAVs, back-tracking a little in time to describe those which were developed in ADE in the decade before the beginning of the LCA project. These projects had given very valuable experience to many of their engineers who went on to design advanced UAVs such as long endurance surveillance platforms and cruise vehicles, besides the far more complex LCA system. Chapter 9 lists helpful 'better practices' – a compilation of friendly advice on developing the technology of flight control systems, based on the experience with LCA-Tejas and UAVs.

The book concludes with another special feature. There are a set of technical annexures containing contributions by domain experts who add unusual value to the book by bringing in the fruits of their rich experience. Air Marshal P Rajkumar discusses the handling qualities of the four generations of IAF aircraft he has flown, in terms of a rating system. "Team Tejas must be justifiably proud", is his concluding line. A summary of the careful and comprehensive work done by the National CLAW (control law) Team, headed originally by Srinath Kumar and subsequently by Shyam Chetty, appears as an Annexure. Wg. Cdr. P K Raveendran (NFTC) confirms the global record of zero failure in over 4986 flights, in his account of the flight testing of LCA – FCS. UAV-related topics are elaborated in a description of integration experience of UAV control systems by Ajoy Raman (ex-ADE), and in two Annexures contributed by Shri PS Krishnan (also ex-ADE, one of the authors of this Monograph). One of them provides the MATLAB program listing for a typical UAV control design which the reader can run on the computer; the other describes a solution to the problem of designing control laws taking into account the significant flexibility of wings in a solar powered UAV with large wing span necessary for collection of energy. The last of the annexures provides an annotated list of the more useful references with brief comments on each of them, so a reader can get more information whenever needed.

Thus, we have a remarkably 'complete' text– from theory and mathematics to test flights, and from the Wright Flier to Tejas of the 4+ generation. It also makes a great contribution to reducing the concern in the Indian aeronautical profession about losing the knowledge and experience gained, as experts retire during the

long intervals between approval of indigenous projects (at an extrapolated rate of three indigenous fighter aircraft types in a century!). After all, the experience of HF-24 was lost irretrievably. The Indian fighter to succeed Tejas is not in the air yet, nearly two decades after the first flight of LCA. This book does the next best thing by passing on the lessons learnt from the extensive experience on the LCA to the next generation. It offers a brief discussion of fundamental principles and enriches it with the lessons of hard experience and narrates interesting historical accounts of problems, solutions and successes.

The account of the journey made by ADE from building India's first automatic flight control system for an air launched drone (1974) to a Tejas fly-by-wire supersonic fighter (2001) and to a fully autonomous low level cruise platform Nirbhay (2013) is fascinating indeed. The authors have rendered a great service to the profession and to the nation, with a book that is always interesting reading. Thank you, PSK and KGN!



Bangalore, 05 September 2019

Roddam Narasimha F.R.S.
Honorary Professor
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Advanced Scientific Research

# Preface

A great deal of the technology described in this Monograph is a compilation of the work done by two generations of scientists and engineers at the Aeronautical Development Establishment (ADE), Bengaluru and a few other co-operating institutions, on the subject of Flight Controls. The thrust areas of the mandate of ADE, a constituent of the Defence Research and Development Organisation (DRDO), are Flight Simulation, Unmanned Aircraft, and Combat Aircraft Systems. This Monograph traces how expertise in these three domains converged synergistically to produce strengths in developing Digital Flight Control Systems, thorough a succession of engineering development programmes.

ADE entered the area of flight simulation in the early 1970s with the aim of establishing a piloted simulation facility which would be used for aeronautical research and systems development. Although a major aircraft development programme to exploit this facility would come into being only a decade later, the work done in the interim period not only resulted in very valuable experience in using piloted simulation in flight control system design; it also produced outputs of developing crew training simulators for some of the fighters and trainers of IAF.

ADE flew its first air launched target drone with two axis stabilisations in its control loop implemented in analog electronics, in 1974. Autonomous controlled flights were achieved at high altitudes including supersonic speeds and at low levels. Considering the state of infancy of FCS technologies in India and non-availability of critical elements needed, successful flights of this drone in the late 1970s were indeed a pioneering start for Indian automatic flight control systems[#].

This was followed by a succession of UAVs spanning reusable pilotless target aircraft, UAVs for tactical surveillance, long endurance aircraft for persistent

# SLV-3 satellite launch vehicle developed by ISRO (1980), employed an open loop guidance (with stored pitch programme) to steer the vehicle in flight along a pre-determined trajectory. Prithvi surface to surface guided missile flew with a closed loop strap-down navigation and flight control system, in 1988.

missions at medium altitudes and a cruise flight platform, in response to a variety of needs expressed by the Indian Armed Forces over the next three decades. As global technology developments rendered digital implementation as the technology of choice for flight control functions, ADE teams built and tested digital flight control systems of progressively increasing technological sophistication for these vehicles.

Big opportunity, however, came when the LCA fighter development Programme entered the system definition phase. ADE was assigned the responsibility for the development of the DFCS as the System House to develop the central Digital Flight Control Computer (DFCC) and SW, to integrate them with the hydraulic actuators and sensor elements and to prove the DFCS through Verification and Validation tests in Test rigs. ADE also took up the task of establishing the pilot-in-loop simulation facility to design and validate the control laws and their incorporation in the DFCC SW. Indeed, a convergent culmination of competences generated over a decade in simulation, UAVs and flight test technologies was put to application in the high performance fighter aircraft programme. It was certainly "the" opportunity that ADE teams were waiting for.

The authors of this volume have been active participants in the truly exciting technology development programmes described above, in different capacities. Therefore, when the suggestion was made by DESIDOC for us to a write a monograph, it took us very little time to select 'digital flight controls' as the theme. We decided that it will not aim to be a text book for graduate or post graduate courses, as there are very many books written by teaching professionals of great competence. We set ourselves two objectives based on what ADE had experienced in the previous decades. We recalled how difficult it had been for young graduate or post-graduate engineers to equip themselves to handle practical problem solving tasks. Often, we found that the obstacles to their quicker adaptation arose from unfamiliarity with the way practical engineering problems presented themselves and with the methodologies available to solve them. We decided therefore to spend our energies in writing a Monograph that would document the "projects experience" gained so far with the hope it would make the future generation of fresh entrants to flight control research and development programmes adapt themselves to their roles more easily.

There was also a need to review and consolidate all the work related to flight control done by different ADE teams and record them in an integrated fashion. This would enable one to see the track clearly including the zigzags and some blind alleys. When we discussed the subject with the Director and other senior scientists of ADE, there was positive enthusiasm as that would be part of ADE's Knowledge Management initiatives. So that became another strong motivator for writing this Monograph.

We have made every effort to adhere closely to these objectives while formulating the contents and in writing the chapters. Introductory material and explanation of the fundamental principles are kept to the minimum. Well over three fourths of the book is devoted to discussion of practical engineering features, challenges and solutions as encountered in specific UAV and fighter aircraft FCS projects. An effort has been made to trace the common features among diverse projects and draw lessons for the future designs in the form of 'Better Practices'.

A distinguishing feature of this Monograph is the inclusion of detailed notes by several experts on topics of immediate relevance to the general theme of digital flight control. These topics range from pilot perspectives of flight controls of fighter aircraft in IAF, sample computer programs used in UAV control system design, development process of control laws for Tejas fighter, flight testing experience of Tejas, special issues in the design and integration of UAVs. These articles written by domain experts are included as Annexures. The authors of this Monograph gratefully acknowledge the efforts of these contributors.

*Unavoidably, there are limitations in discussing details of performance of systems developed for military applications. We have therefore designed the presentations in this volume strictly around the technical and operational information which has been released in the public domain. Some of the specifications and technical features are assumed and are illustrative. The technical features of the aircraft and other equipment developed under these programmes and which are in service with the Indian defence services might differ from what is described here, owing to upgrades and other factors.*

We are very grateful to the Chairman DRDO, Director General (Aeronautics), Director General (HR) at DRDO Headquarters and to Director DESIDOC for approving our proposal and supporting us throughout. We are particularly thankful to Director ADE and Programme Director, ADA for their generous support and help in accessing data and other resources which were required for this project. Lastly and most importantly, we would like to sincerely acknowledge the most encouraging support and highly knowledgeable technical inputs from several colleagues, presently and formerly from ADE, ADA, NAL and other institutions received in formal and informal reviews. A detailed list of those who helped appears elsewhere in this volume.

As authors, we enjoyed the writing exercise which refreshed us. We have had to dig quite deeply into records and our memories to construct a coherent description of flight controls engineering implemented across platforms. The Monograph enabled us to understand some of the technical issues even better than before and in a new and interesting light. We had to fine tune our abilities of communication to be suitable for transfer of knowledge succinctly to new entrants to the field.

Recall of experiences and some nostalgia were pleasant experiences. All these are positive gains from our efforts.

More than anything, it is our expectation of the impact of the book which keeps us excited. We earnestly hope that this Monograph will, in fact, meet the objectives laid down for it substantially. We also hope that some among the coming generations of practicing flight control engineers will be helped in countering the big challenges which await them.We will be grateful to the readers of this Monograph for any suggestions which will lead to its improvement.

January 2020 PS Krishnan & KG Narayanan

When Dr KG Narayanan approached me to co-author this monograph, I was very excited at the prospect of re-living my practical experiences of over three decades in the design of flight control systems. At the same time, I was also apprehensive of my abilities to communicate the subject adequately to the fresh learners. However, as I dived deeper into the writing project, driven by a passion of creating a record of what had been accomplished in ADE on FCS for UAVs and LCA and to provide a short and easy introduction to the basic elements of flight mechanics and control engineering for the younger generation of engineers, I gained comfort and confidence. The final output also reflects the impact of several tutoring and learning sessions I have had with practising engineers currently working in ADE and in other organisations. I sincerely hope that the readers will find in this book a practical mix of theory and practice of the several disciplines which FCS encompasses.

– PS Krishnan

It is really fortunate that Shri PS Krishnan was able to find the time to join me in this effort, over the last 3 years. It is difficult to think of a more appropriate and competent collaborator to enrich the volume with the technology details which are so essential to convey the depth of the subject to the readers. I owe him a special thanks for accommodating most of my suggestions for modifications in his drafts, made for the sake of providing greater clarity.

– KG Narayanan

## We Are Very Grateful

We received technical and managerial assistance generously from several colleagues and friends from ADE, ADA and DRDO, drawing from the experience gained by them in Tejas LCA, UAVs and other programmes, in the preparation of this Monograph. We are deeply conscious how valuable their inputs have been. We have great pleasure in acknowledging their help individually here.

- *Air Marshal P Rajkumar*, *Shyam Chetty*, *Wing Commander P Raveendran* and *Ajoy Raman* for authoring the technical essays included as Annexures.
- *Y. Dilip*, *V Kala*, *S Balasubramanian*, *C Ruba*, *G Sankar* and *Christie V Jacob*, for sharing technical inputs from their rich experience in ADE which have been incorporated in various chapters.
- *Kishan Singh* for drawing our attention to several important sources of reference.
- *Asha Garg* and *NH Satyaraja* for reviewing the text and providing constructive technical inputs.
- *BN Suresh, Shyam Chetty, Girish Deodhare, J Jayaraman, R Krishnan* for reviewing the E-book most carefully and suggesting corrections and improvements.
- *JV Ramprasad* and *SK Raviray* for assistance in preparation of drawings.
- *R Nagamma* for assistance in preparation of the text and list of references,
- *Gunjan Bakshi* and *Alka Bansal* for creative editorial support, *NK Chawla* for project management, *Gopal Bhushan* and *Alka Suri* for guidance at Directors' level, at DESIDOC.
- *MVKV Prasad and S Venugopal* (both Directors of ADE during this period) and *Girish S Deodhare*, Program Director (CA) and Director, ADA for their enthusiastic support for the project.

At this juncture, we also recall the contributions of some former leaders and colleagues in the development projects referred to in this Monograph. Although

they were not directly involved in the preparation of this Monograph, it is our pleasure to record and acknowledge here, from our personal experience, the great impact made by each one of them to the growth of flight controls technology.

- *Air Vice Marshal HN Krishnamurthy* for his technologically motivating leadership as Director ADE (1974 – 1985)
- *Vice Admiral SK Ray,* IN and NH Satyaraja who provided able and efficient leadership to flight control development teams for UAVs and LCA
- *PK Panda* who was the designer and analyst of flight mechanics of UAVs and a passionate mentor for many in ADE
- *KV Srivatsan* (HAL), *Srinathkumar* (NAL), *TS Prahlad* (ADA), *Air Marshal P Rajkumar* (NFTC), *K. Nagaraj* (CEMILAC) and *Kota Harinarayana* (ADA) for their deep and extended involvement in the development of IFCS for LCA.

We are also very grateful to *Prof Roddam Narasimha*, a doyen of the aeronautical engineering community, for finding the time to read through the draft and for writing the Foreword. We could scarcely have asked for a better introduction of this Monograph to the readers.

Of course, we are immensely grateful to our wives and other members of our immediate families for their understanding and unstinting support to our commitment to this book over an extended period of our lives.

PS Krishnan & KG Narayanan

## CHAPTER 1

# Introduction

This chapter explains the objectives of the authors in writing the monograph. It provides information on the foreground knowledge and experience on which this monograph is based. It also summarises the contents of subsequent chapters.

### 1.1 FIGHTER AIRBORNE

The sun shines brightly in the blue sky during the crisp winter months in Bangalore. So, it did on 4th January 2001. It might have appeared brighter than usual to a large team of people on the tarmac at the airfield of Hindustan Aeronautics Limited (HAL), assembled there with great hopes and anticipation. They were the design engineers, manufacturing technologists, flight test engineers and pilots who had been dreaming of this day for over a decade. The first technology demonstrator of a new fighter plane, called Light Combat Aircraft (LCA), painted in livery which suggested the Indian national flag, was ready for its maiden test flight. As the LCA taxied out, excitement among those gathered there was almost palpable.

The LCA development programme had acquired high visibility not only as a future weapon system for Indian Air Force (IAF) but also as a potential game changer in Indian aeronautics. LCA programme[#1] was seen as an opportunity for resurgence of Indian aeronautics. Quite appropriately so, because the last fighter aircraft designed in India was almost 40 years ago. HF-24, Marut, designed by HAL made its maiden flight from the same airfield in 1961 and entered IAF operational service in 1967. However, it faded into history thereafter. There had been no successor variants and no follow-on fighter aircraft programmes to engage

[#1] LCA development programme was managed by Department of Defence Research and Development of Government of India through its Aeronautical Development Agency (ADA) and several other development partners including HAL as the Aircraft Prime. For the development of the Digital Fly-By-Wire flight controls, Aeronautical Development Establishment (ADE) was chosen as the Systems lead. Indian Air Force (IAF) is the prime user and launch customer.

and challenge the talents of two generations of Indian aeronautics community. Hence the big excitement on this day.

In addition to excitement, there was anxiety. The LCA was pushing the boundaries of technical competence of Indian aeronautics industry hugely forward. LCA was designed to meet a far more challenging set of performance goals than those of Marut and even of the Russia designed MiG 21 it was to replace in IAF inventory. Learning from experience, LCA was designed to fight future wars and also be competitive in performance and cost with globally available alternatives. With supersonic speed capability and outstanding agility for air combat, LCA was designed with an aerodynamic configuration of relaxed stability. As the lightest by weight amongst contemporary fighters, it would have composite materials in primary structural components. An engine with proven record of performance and reliability had been acquired to power the prototype aircraft. It was also to be provided with advanced mission sensors and weapons. *Most of the systems on the aircraft–airframe with composite structures, hydraulics, electrics, utility systems, integrated digital avionics including mission computers and glass cockpit display systems and the crucial flight control system–all of these were custom designed and built in research and development centres and industries across India*.

Digital Flight Control System (DFCS) topped the list of flight safety critical elements in the aircraft. Primary control surface actuation employed cutting edge technology of Direct Drive Valves (DDVs) with quadruplex redundancy, operating at 4000 pounds per square inch (280 bar) hydraulic pressure. The custom designed 4-channel Digital Flight Control Computer (DFCC) based on a 32-bit microprocessor was, perhaps, the most complex, most densely packaged, avionics equipment built in India till then. For the first time in the history of Indian aeronautics, a manned fighter plane would be controlled in flight by thousands of lines of digital software code executing control law algorithms and redundancy management functions in its Digital Fly-By-Wire (DFBW) flight control system. Technologically, it was absolutely new to Indian industry and a huge leap forward.

Pre-flight testing and evaluation of the flight control system had to be thorough, rigorous and disciplined to ensure flight safety. Every element in the aircraft, small and big, had been tested thoroughly and certified to be airworthy, by a group independent of the designers. All the elements of DFCS, with the DFCC running the final approved version of software, had been tested together with all control actuators for 50 hours of defect free, pilot-in-loop flight in the "Iron Bird" test rig, to uncover hidden defects that might have escaped detection. But what of the "unknown - unknown" in this programme without a local industry precedent? It was not surprising that the excitement of the team was laced with anxiety.

## About the Book

This Monograph is a fascinating account of the journey made by Aeronautical Development Establishment (ADE), Bengaluru from its first analog automatic flight control system for an air launched drone (1974) to sophisticated digital Flight Control System (FCS) for the fly-by-wire supersonic fighter (2001) and to the autonomous low-level cruise platform (2013). Distinguishing features of this Monograph include the documentation of 'projects experience', inclusion of technical essays by domain experts and annotation of the contents of important references. A great deal of the technology described is a compilation of the work done by two generations of scientists and engineers at ADE and other co-operating institutions. The authors who have been active participants in these development projects hope that this Monograph would help the future entrants to flight control research and development programmes to adapt themselves to their roles more easily.

## About the Authors

**Shri PS Krishnan** began his research career in DRDO in 1972 in the area of Inertial Navigation Systems at DRDL, Hyderabad and moved to the ADE, Bengaluru in 1976. At ADE, he has developed Flight Control Systems for all the UAVs. He was a member of the development team of Digital Flight Control System (DFCS) for the Light Combat Aircraft (LCA), and went on to become its Project Director. In 2007, he was elevated to the position of Director, ADE which he held till he retired in 2013. Shri Krishnan has served as Independent Director of the Board of Directors of Hindustan Aeronautics Limited (HAL) from 2014 to 2017. He is now the Chairman of Unmanned Aero Systems panel of AR&DB. Shri Krishnan holds BTech and MS degrees from IIT Madras. He is a Fellow of Aeronautical Society of India and a Fellow of Systems Society of India.

**Dr KG Narayanan** was engaged in research and development activities in solid state devices, avionics systems and flight simulation besides management of large aeronautical systems development programmes, during his career in DRDO from 1965 to 2002. He served as the Director of ADE, DARE and the Chief Adviser of DRDO where he guided the development of several UAVs, LCA flight controls and avionics systems. Dr Narayanan holds an engineering degree from IIT, Kharagpur and PhD from the Indian Institute of Science, Bangalore. He is a Fellow of the Indian National Academy of Engineering.

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