Aircraft Instrumentation
and Systems
Aircraft Instrumentation and Systems

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This book is intended for the undergraduates studying Aircraft Instrumentation and Avionic Systems. This happens to be a core subject of various branches of engineering such as: Instrumentation Technology, Electronics Instrumentation Engineering, Aeronautical Engineering as well as Aerospace Engineering.

One of the prime objectives of this book is to present a contemporary approach to the subject, stressing the importance of basic principles, clarity and objectivity. The complex systems are described in simpler terms for students to comprehend the basic principles and operation, without losing sight in details. The authors have taught the subject for several years to the undergraduate students and thus have written the book in a style to match with their needs. At the end of each chapter, review questions have been included for practice and self-study.

It is worth noting that most of the aircraft technology has remained, somewhat stagnant for the past 50 years. For example, jet engines rely on gas turbines developed in late 1930s; aircraft structures have reached a stable and saturated level. However, significant advances are still made in instrumentation systems and avionics with the primary objective of reducing the pilot's workload, as well as increasing the safety of flight to remarkably high levels. The other advantage of using semiconductor VLSI technology has resulted in significantly reducing the size and weight of equipment. The cockpit no longer looks like conventional old clock-type instruments; on the other hand, they appear more like a computer workstation now. This book emphasises on covering the contemporary developments rather than dwelling more on outdated systems. For example, attitude measurements were traditionally done using mechanical gyros, which have now been almost been replaced by ring-laser or fibre optic gyros in modern aircraft. We have included latest advances in strap-down angular sensors using the RLG and FOG. Similarly air data computers using microprocessor technology have replaced the older all-pneumatic conventional indicators such as air speed indicator, altimeter, vertical speed indicator, which have certain serious limitations.

The chapters are arranged in such a way as to cover the subject from simple topics to more complex and sophisticated systems. The book starts with a broad overview of the basics of aircraft, instruments and cockpit layout in modern aircraft. Chapters 2 to 7 deal with the conventional flight instruments as well as advanced flight instruments, and their location in the main instrument panel. Chapter 8 describes modern electronic flight instrument system. Navigation system, whose primary function is to fly the aircraft from point A to point B on the surface of earth, is covered in chapter 9. Basics of flight control system, autopilot and auto-throttle are discussed in Chapter 10. Modern aircraft
uses many primary and secondary types of radar such as radio altimeter, weather radar, surveillance radar, etc; basics of airborne radars are presented in Chapter 11. Flight management systems have been developed to increase the situational awareness and reduce the pilot’s workload remarkably, without compromising the safety of flight; Chapter 12 is concerned with the basic principles and operation of flight management systems. Chapter 13 explains the basics of aircraft communication and addressing systems using satellite links, as well as future air navigation systems. Whenever an aircraft is involved in an incident/accident, it will be necessary to find out the cause and take corrective measures by learning from the past mistakes, so that such incidents do not recur; the data stored in “black-boxes” are used for reconstructing the flight during the final critical moments of an accident – Chapter 14 introduces the fundamentals of modern black-boxes or flight data recorders. Chapter 15 covers many safety, warning and alerting systems, which include altitude alerting system, speed/Mach warning systems, ground proximity warning systems, and collision avoidance systems. These systems have greatly reduced the number of accidents since their introduction in 1980s. Aerial warfare is not restricted to ammunitions and missiles, but uses electromagnetic waves for surveillance, protection and attack; Chapter 16 briefly introduces electronics warfare techniques. We have tried to present the details on the subjects covered in the book, without undue cross-referencing; we hope that this feature as well as a comprehensive index and a detailed glossary of terms will enhance the usability of the book.

While writing this book, we have received strong encouragement from Prof. H. N. Shivashankar, Director R. N. Shetty Institute of Technology, and Prof. K. R. Suresh, Principal of Bangalore Institute of Technology. The book was exhaustively reviewed by Mr. N. N. Murthy of Moog Controls for which we are extremely thankful to him. The authors had the privilege of discussing certain subtle physics points with Prof. N. Prabhu of Purdue University, USA., and we are extremely grateful to him for his help.

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S. Nagabhushana  
L.K. Sudha
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1.1 Introduction

An aircraft is truly a multidisciplinary system involving almost all branches of physics, chemistry and engineering. Modern aircraft tends to be highly efficient, very reliable and eco-friendly, with all branches of science contributing synergistically to achieve the optimum flying machine, capable of transporting more than 600 passengers non-stop from Bombay to Los Angeles.

An aircraft consists of (i) main frame—fuselage to carry passengers or payloads, (ii) wings to provide lifting force to overcome weight of the aircraft, (iii) propulsion system (jet engine or turboprop or propeller engine) and (iv) sophisticated avionics system including instrumentation system, navigation systems, communication systems and warning systems. Modern avionics suite includes many digital computers to increase safety, reduce pilot workload and enhance reliability.

1.2 Control Surfaces

An aircraft has two types of control surface:

1. Primary control surfaces and
2. Secondary control surfaces.

The primary control surfaces are shown in Figure 1.1(a) and these control the pitch, roll and yaw of the aircraft. The secondary control surfaces include air brakes spoilers, trims for roll, pitch and yaw, as shown in Figure 1.1(b).
1.3 Forces, Moments and Angle of Attack (AOA)

There are three forces and three moments as shown in Figure 1.2, that should be considered. In order to deal with the motion of an aircraft, it is essential to define a suitable coordinate system.
There are two coordinate systems:

(i) First coordinate system—*inertial coordinate system* is fixed to the earth and is used for aircraft motion analysis, with respect to earth.
(ii) Second coordinate system—*body coordinate system* is fixed to the moving aircraft.

Figure 1.3 shows the two right-handed coordinate systems.
Coordinate System Three Forces

The aircraft experiences longitudinal force, lateral force and vertical (normal) force. Likewise, there are three moments:

1. Pitching moment about lateral axis,
2. Rolling moment about longitudinal axis, and
3. Yawing moment about vertical axis.

The three forces and moments are shown in Figure 1.2.

Angle of Attack (AOA)

Angle of attack (AOA) is one of the most important parameters in the aircraft. Angle of attack (AOA, $\alpha$ Greek letter alpha) is the angle between the chord line (see Figure 1.4) of an aerofoil and the vector representing the relative motion of aerofoil and the surrounding air.

![Fig. 1.4 Angle of attack of an aerofoil (wing cross-section).](image)

There is another related angle, called pitch angle which is different from angle of attack—pitch angle is measured with respect to the horizon, whereas AOA is measured with respect to the direction of local airflow.

The lift coefficient, $C_L$ of a fixed-wing aircraft is directly related to AOA. Increasing $\alpha$ increases $C_L$ up to the maximum lift, after which lift decreases as shown in Figure 1.5.

As the AOA increases beyond $\alpha_{max}$, separation of the airflow from the upper surface of the wing becomes more significant, causing the reduction of $C_L$. At the critical AOA, the wing is unable to support the weight of the aircraft, causing the aircraft to descend, which in turn, causes the AOA to increase further. This is known as STALL.
An aircraft always stalls at the same $\alpha_{\text{crit}}$, rather than at the same airspeed. The airspeed at which the aircraft stalls depends on many factors like—weight of the aircraft, the load factor* at the time and the thrust from engine. The critical AOA is typically at 15° for many aerofoils.

Stall condition is a very dangerous situation, particularly at low flight altitude. Most of the modern aircraft have a stall warning system typically a tactile (control column shaking) and aural synthesised voice warning. Sometime, stall conditions are automatically corrected by a stick pusher system, which acts on the elevator control to prevent the AOA reaching $\alpha_{\text{crit}}$. The stall warning system gives warning about the incipient stall condition, by alerting the pilot even before stall conditions are reached.

**High Alpha**

Very high angles of attack in fighter aircraft give an unsurpassing agility to evade missile hits. Indian–Russian fighter aircraft SU-30MKI has the highest AOA of 123° for a duration of 3 seconds. The manoeuvre is called Pugachev’s (after the Russian pilot) Cobra manoeuvre.

Using additional control surfaces, vectored thrust by engines, and the high-lift devices, like leading extensions, flyable AOA has been substantially increased from about 20° to over 45°, and in some aircraft AOA can become 90°, i.e. wing is perpendicular to the direction of motion. On civil transport aircraft like Boeing 777 or Airbus 330 angle of attack is well below those in military fighter aircraft.

Pitch, roll and yaw angles are controlled by using variable control surfaces. Elevators in the horizontal tail control the pitching, ailerons at the tip of wings (to get maximum leverage) control the aircraft roll and the rudder in the vertical tail change the yawing of the aircraft. These are shown in Figure 1.1. On addition to these three PRIMARY control surfaces, there are few secondary surfaces.

* Load factor is the ratio of aerodynamic lift to weight of the aircraft.
The secondary control surfaces include: (a) flaps (to increase lift at low aircraft speed) (b) air brakes or spoilers (to reduce/wash-off speed while landing), (c) trimming surfaces (for all primary control surfaces).

1.4 Engines

Modern commercial jet liners have two, or three or even four turbofan engines to provide forward thrust. Engines perform with unprecedented reliability, so that in-flight engine failures are very rare, and even if one of the engines fails, on-board computers reconfigure the aircraft to land the aircraft in the nearest airfield. Of late, turboprops are becoming popular again due to its lower fuel consumption.

1.5 Avionics

Avionics of a modern aircraft includes state-of-the-art instrumentation, navigation, communication and warning systems. Particularly three warning systems—stall warning system, ground proximity warning systems and traffic collision avoidance system have evolved to a high degree of maturity, after learning the hard way about the causes of aircraft accidents (many catastrophic—meaning total loss of aircraft and people). Induction of these warning systems has significantly reduced the accident rate—earlier there were one or two accidents per month in the world. These warning systems are broadly discussed in Chapter 15.

“Isn’t it astonishing that all these secrets have been preserved for so many years, just so that we could discover them.” So said Orville Wright in June 7, 1903.

Wright Brothers (Orville and Wilbur Wright) made the historic first flight on a powered plane at Kitty Hawk, North Carolina, USA on December 17, 1903. Orville Wright made the historic flight, lasting only 12 seconds over a distance of 125 feet. Both Orville and Wilbur made three more flights the same day. The last flight of that day lasted 59 seconds, over a distance of 852 feet. Figure 1.6 shows the historic first flight by Orville Wright.

Wright Brothers found their powered airplane much more responsive than their earlier gliders, unstable and difficult to control. However, they managed to fly the unstable plane with their background experience on gliders.

Fig. 1.6 Kitty Hawk Flyer, making the historic airplane flight, 17 Dec 1903, Kitty Hawk.
Orville Wright took the “FLYER” for a 12-second (over 200 ft) sustained flight on December 17, 1903. This was the first successful, powered, controlled flight in history. They had worked out the key issue for flight control. While other aviators searched in vain for “inherent stability”, they created a method for the pilot to control the aircraft—“wing warping” to provide more lift on left or right wings, to create differential lift in the wings, in order to bank (roll) the aircraft. They even designed and realised an eight-hp engine—4 cylinders 4” bore and 4” stroke, less than 200 lbs—“unless the motor would develop a full brake horse power, it would be useless for our purpose”.

The Wright Brothers began their experimentation in flight in 1896 at their bicycle shop in Dayton, Ohio. They selected the beach Kitty Hawk as their proving ground, because of the constant wind (20 miles head wind) that added lift to their aircraft. Earlier in 1902, they came to the beach with their glider and made more than 700 successful flights.

### 1.6 Modern Aircraft System

In the following chapters, basic instrumentation and avionic systems in a modern aircraft are discussed with special emphasis, wherever possible, on being as contemporary as is possible. Nearly 100 years have passed since Wright Brothers made their first flight at Kitty Hawk in North Carolina and paved the way for aviation breakthroughs. From this very modest beginning, the world has seen a fantastic revolution in aircraft development. Wright Brothers laid the foundation stone for the aircraft design and development by:

- Constructing a wind tunnel (in which aircraft model is held stationary and air moves past the model),
- Developing a comprehensive flight control system with enough control capability,
- Designing a light-weight engine and an efficient propeller, and
- Making finally an aircraft capable of sustained powered flight.

Static stability, manoeuvrability and control are recent terms to characterise handling qualities of an aircraft. Manoeuvrability and stability are two contradicting requirements. A highly stable plane is difficult to manoeuvre and vice versa. In order to obtain equilibrium and perform manoeuvres, the aircraft must have properly designed control surfaces and engine controls.

Stability ensures that the plane automatically returns to original state after a disturbance, which could be pilot-induced, or caused by atmospheric disturbances. Atmosphere is not static and there are wind gusts, wind gradients, turbulence, wind shear, etc. An aircraft must possess inherent stability so that the pilot need not take strenuous and continuous action to stabilise the aircraft (the problem which existed in Wright Brother’s plane).

Modern fighter aircraft have been designed to fly at 3–4 times the speed of sound (Mach 3–4) with capabilities of pin-point weapon delivery systems. Commercial aircraft carry, as a routine, more than 600 passengers non-stop over distances of 16,000 km. Systematic studies on the causes of aircraft accidents over the past 100 years have contributed to realise a flying machine with exceptional reliability. In the event a system malfunctions, computers can reconfigure the existing systems to enable safe landing of the aircraft at the nearest airport. Pioneers in aerospace field have even made possible the commercial space flight.
There has been a paradigm shift of late in the present-day warfare, namely deployment of Unmanned Air Vehicles—UAVs—or also known as Drones. These UAVs are flown safely by “pilots” situated several thousands of miles away, and they are far less expensive than manned fighters. UAVs have played a lead role in Iraq and Afghanistan theatres in fight against terrorism. The UAV “pilots” also have a pseudo cockpit with similar instrument layout.

**Review Questions**

1.1. Explain with a diagram the primary control surfaces in an aircraft.
1.2. What are the secondary control surfaces and their functionalities?
1.3. Discuss the three forces and moments experienced by an aircraft.
1.4. Define the angle-of-attack. Differentiate between angle of attack and pitch angle.
1.5. What are the problems experienced by Wright Brothers in their first ever manned flight?
1.6. What is meant by static stability? What are the disturbing forces to upset the stability of an aircraft?
1.7. Discuss the reconfiguration of aircraft systems.
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