# HELICOPTER ENGINEERING (R15A2127)

## COURSE FILE

## IV B. Tech II Semester

## (2018-2019)

**Prepared By**

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**MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY**

**(Autonomous Institution – UGC, Govt. of India)**

Affiliated to JNTU, Hyderabad, Approved by AICTE - Accredited by NBA & NAAC – A Grade - ISO 9001:2015 Certified)

Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad – 500100, Telangana State, India.

## MRCET VISION

- To become a model institution in the fields of Engineering, Technology and Management.

- To have a perfect synchronization of the ideologies of MRCET with challenging demands of International Pioneering Organizations.

## MRCET MISSION

To establish a pedestal for the integral innovation, team spirit, originality and competence in the students, expose them to face the global challenges and become pioneers of Indian vision of modern society.

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- To provide state of art infrastructure and expertise to impart the quality education.

# PROGRAM OUTCOMES

# (PO s)

## Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design / development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one s own work, as a member and leader in a team, to manage projects and in multi disciplinary environments.

12. **Life - long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

# DEPARTMENT OF AERONAUTICAL ENGINEERING

## VISION

Department of Aeronautical Engineering aims to be indispensable source in Aeronautical Engineering which has a zeal to provide the value driven platform for the students to acquire knowledge and empower themselves to shoulder higher responsibility in building a strong nation.

## MISSION

The primary mission of the department is to promote engineering education and research. To strive consistently to provide quality education, keeping in pace with time and technology. Department passions to integrate the intellectual, spiritual, ethical and social development of the students for shaping them into dynamic engineers.

## QUALITY POLICY STATEMENT

Impart up-to-date knowledge to the students in Aeronautical area to make them quality engineers. Make the students experience the applications on quality equipment and tools. Provide systems, resources and training opportunities to achieve continuous improvement. Maintain global standards in education, training and services.

## PROGRAM EDUCATIONAL OBJECTIVES – Aeronautical Engineering

1. **PEO1 (PROFESSIONALISM & CITIZENSHIP):** To create and sustain a community of learning in which students acquire knowledge and learn to apply it professionally with due consideration for ethical, ecological and economic issues.

2. **PEO2 (TECHNICAL ACCOMPLISHMENTS):** To provide knowledge based services to satisfy the needs of society and the industry by providing hands on experience in various technologies in core field.

3. **PEO3 (INVENTION, INNOVATION AND CREATIVITY):** To make the students to design, experiment, analyze, and interpret in the core field with the help of other multi disciplinary concepts wherever applicable.

4. **PEO4 (PROFESSIONAL DEVELOPMENT):** To educate the students to disseminate research findings with good soft skills and become a successful entrepreneur.

5. **PEO5 (HUMAN RESOURCE DEVELOPMENT):** To graduate the students in building national capabilities in technology, education and research.

## PROGRAM SPECIFIC OUTCOMES – Aeronautical Engineering

1. To mould students to become a professional with all necessary skills, personality and sound knowledge in basic and advance technological areas.

2. To promote understanding of concepts and develop ability in design manufacture and maintenance of aircraft, aerospace vehicles and associated equipment and develop application capability of the concepts sciences to engineering design and processes.

3. Understanding the current scenario in the field of aeronautics and acquire ability to apply knowledge of engineering, science and mathematics to design and conduct experiments in the field of Aeronautical Engineering.

4. To develop leadership skills in our students necessary to shape the social, intellectual, business and technical worlds.

# MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

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## (R15A2127) HELICOPTER ENGINEERING
## (CORE ELECTIVE – V)

**Objectives:**

- To understand the basic concepts of Helicopter flying, different configurations.
- To understand the difference between aircraft and helicopter principles, mechanisms.
- To understand the principles, theories and stability and control pertaining to it.

**UNIT-I**

**Introduction:** Historical Development of Helicopters, Helicopter configuration, controls Requirements, Types of Rotor Systems, Basic Power Requirements.

**UNIT-II**

**Introduction To Hovering Theory :** Momentum Theory, Blade Element theory, Combined Blade Element and Momentum theories for non –uniform inflow calculation, Ideal Rotor vs. Optimum Rotor.

**UNIT-III**

**Vertical Flight:** Various flow states of Rotor, Autorotation in Vertical Descent, Ground Flight.

**UNIT-IV**

**Forward Flight:** Momentum Theory, Variable Inflow Models, Blade Element theory, Rotor Reference Planes, Hub Loads, Power variation with forward speed, Rotor Blade flapping Motion: Simple Model.

**UNIT-V**

**Helicopter Trim And Stability:** Equilibrium condition of helicopter, Trim analysis, Basics of helicopter stability.

**Outcomes:**

- The Student will be able to identify the key differences between Aircraft and Helicopter
- The analyze the basic concepts , theories regarding forward and hovering Flight
- The significance of stability and control in different conditions

**TEXT BOOKS**

1. Wayne Johnson Helicopter theory, Princeton University pres 1980.

**REFERENCES**

1. Gessow.A and Meyers G.C. Aerodynamics of Helicopter ,Macmillan & co,,N.Y.1987
2. Mccormick B.w. Aerodynamics, Aeronautics & Flight mechanics ,John Wiley , 1995
3. Gupta.L Helicopter Enginering, Himalayan Books 1996.
4. Bramwell A.R.S Helicopter Dynamics Edward Arnold Publications London 1976.
5. Stepniewski W.Z Rotary Rotary wing Aerodynamics Vol 1 & 2 Dover Publications 1984.

## MODEL PAPER I

### PART A

**ANSWER ALL THE QUESTION** **25M**

1. Write the difference between Helicopter and Aircraft. 2M
2. Describe the term "Helicopter" 2M
3. Define Induced Power. 2M
4. Define Profile Drag Power. 2M
5. Define the term "Synchropter". 2M
6. What are the factors considered to fuselage design? 3M
7. Mention the merits of side by side rotor. 3M
8. Write the uses of helicopter. 3M
9. Write the merits of Rotary wing aircraft. 3M
10. What is mean for Drag? Write its types. 3M

### PART B

**ANSWER FIVE QUESTIONS** **5x10=50M**

1. Explain in details about various types of helicopter configuration.

Or

2. Write a detail notes on compound Helicopter.

3. What is a rotorcraft? What are the different types of rotorcrafts?

Or

4. What are the methods of controls of helicopter? Discuss with sketches/drawing.

5. Write a short note on Flapping and Feathering of rotor blades of a helicopter rotor.

Or

6. Explain collective pitch and cyclic pitch in a helicopter. Describe their action in vertical and forward flights.

7. Discuss the advantages and disadvantages of a compound helicopter over a conventional helicopter.

Or

8. Write the difference between compound helicopter and single rotor helicopter.

9. Explain in details about historical development of helicopter.

Or

10. Explain in details about performance characteristics of Rotor.

## MODEL PAPER II

### PART A

**ANSWER ALL THE QUESTION** **25M**

1. Write Newton's second law of motion. 2M
2. Define Propeller efficiency of the rotor. 2M
3. Define Rotor hovering efficiency. 2M
4. What is mean for angle of attack? 2M
5. What is mean for angle of incidence? 2M
6. Mention the assumptions of simple momentum theory. 3M
7. Define Profile Drag. 3M
8. Mention the power losses of rotor in hover. 3M
9. Define Induced Power. 3M
10. What is mean for Rotational velocity? 3M

### PART B

**ANSWER FIVE QUESTIONS** **5x10=50M**

1. i. Explain 'hover'.
   ii. Using ideal actuator disc theory. Find the relationship between power and thrust of the helicopter in hovering flight.

or

2. Derive the Thrust coefficient using blade element theory.

3. Derive the expressions for profile and induced power.

or

4. Describe twist in the context of a helicopter. When do u call it ideal? What are the advantages of having ideal twist?

5. i. Discuss rotor speeds and tip speeds.
   ii. What are the limitations on the rotor speeds?

or

6. Using ideal actuator disc theory. Find the relationship between thrust and power of the helicopter in hovering flight.

7. How does the blade element theory become superior to overcome actuator disc Theory? Hence define (i) Thrust Coefficient (ii) Torque Coefficient

or

8. Describe the mechanism of ground effect in hover. How does ground effect influence the performance of helicopter during hovering flight?

9. Explain the different types of hovercraft with suitable diagram.

or

10. Describe the types of jet machines used in hovercraft, explain briefly with diagrams.

## MODEL PAPER III

### PART A

**ANSWER ALL THE QUESTION** **25M**

1. What is mean for normal working state of Rotor? 2M
2. Define Autorotation. 2M
3. Define Induced velocity. 2M
4. Define Rotor Drag Coefficient. 2M
5. Write shaft power equation for vertical descent. 2M
6. Write the momentum equation of vertical descent. 3M
7. What is Parasite Drag? 3M
8. Define Inflow angle for Autorotation? 3M
9. What is Vortex? 3M
10. Define Rate Of Climb 3M

### PART B

**ANSWER FIVE QUESTIONS** **5x10=50M**

1. Explain Autorotation with help of Schrenk's diagram.

Or

2. Explain in details about various flow states of Rotor.
3. Derive and explain Performance calculation of vertical descent.

Or

4. Derive the expression for Rotor drag coefficient for vertical descent.
5. Illustrate with sketches, the vortex ring flow in vertical descent of a helicopter at fast rate of descent.

Or

6. Illustrate with sketches, the vortex ring flow in vertical descent of a helicopter at slow rate of descent.
7. What is the purpose of using equivalent solidities in helicopter rotor performance studies? Explain pitfalls using such "equivalent" factors with Rotors

Or

8. Write the difference between compound helicopter and single Rotor helicopter.
9. What do you understand by ground effect machine and how do you classify it.

Or

10. How the proximity of ground affects the performance of helicopter during hovering and forward flight.

# UNIT-I

## INTRODUCTION

**Historical Development of Helicopter:**

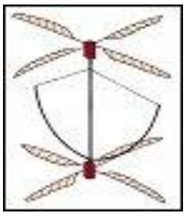
It has often been said regarding new inventions and advances in technical fields that there is very little that is actually new. What is meant by that, of course, is that somewhere, sometime, along civilization's march of progress, an idea considered a modern day original had already been thought of.

This may be true about some things but not all. For example, atomic energy is certainly a completely new scientific development. The marvelous so-called wonder drugs for curing many of mankind's ills are another. On the other hand the helicopter, that unique and most youthful of all aerial transports, can trace its origins to the hazy years of antiquity. This is so at least to the extent of the craft's basic means of flight, if not to its detailed engineering and mechanical structure.

Many who delight in gleaning facts from the dusty files of aviation's history have come to the conclusion that the Chinese were the first to fly a helicopter. Creators of many of civilization's milestones of progress, the Chinese are said to have built the granddaddy of all rotary-winged aircraft centuries ago. Of course, this was not a real helicopter in the sense that it could carry passengers or even that it looked like any of these craft as we know them today. Rather it was a toy, which has since become known as the Chinese top.

Whose happy mind first conceived this flying toy which has entranced children for many generations the world over is unknown. Exactly how this child's plaything looked when first put together by its inventor is also a bit of a mystery, since many variations of it have been described and flown after it left the Orient for the Western World. Perhaps closest to the original was the one built and demonstrated by Launoy and Bienvenu before the French Academy of Sciences in 1784.

Their top was made of two rotors, string and wood. Each of the rotors had four feathers and each rotor was about a foot in diameter. The rotors were fastened to opposite ends of a revolving shaft which was slipped through a hole in another piece of wood formed like a bow. The whole unit was a sort of T-shaped affair. The rotors were spun by cord that had first been fastened to the tips of the bow and then twisted around the shaft. As the cord became entwined around the shaft it pulled the ends of the bow upward and itself became very taut. When the top was launched, the pressure of the bow straightening out pulled on the string. This action spun the shaft and rotors very rapidly, causing the device to fly into the air.



**Launoy & Bienvenu helicopter project**

Some models of these tops were made in which the whirling force was supplied by human hands. In that case the rod was twirled swiftly between the palms of the hands until the fan became airborne. Later, rubber bands, whale bone, and small but powerful springs were also used for motive power.

Another version of the Chinese top had a two-bladed rotor fastened to the end of a wooden rod. A triangular shaped wing was also fixed to the top side of this wood. The rotor fan was spun about by hand until the rubber-band motor was twisted tight. When the toy was released, it shot into the air with great speed. This toy was sold by Chinese merchants in America about the turn of the century and proved very popular among children.

The author recalls many moments of pleasure he obtained from a metal Chinese top during his boyhood. This toy consisted of three separate parts—a small propeller, a short length of twisted metal, and a piece of tubing about an inch long. The tube and propeller, in that order, were slipped over the twisted rod. One hand held the bottom end of the rod and the other the length of tube. Then the propeller was pushed off the rod with great force. It twirled around at high speed and, once free of its attachment, it rose to a great height in the sky. When the rod was slightly tilted forward, the propeller could be made to fly a good distance from the launching spot.

Sometimes these tops were sold with a string instead of a short length of tube, for spinning the propeller off the shaft. The string had to be wound around a short hub on the prop, and when this was given a quick, hard yank, the propeller whirled off and into the air. What a delight it was to see the spinning wings go flying through the air—and the sad feeling when they failed to return to earth! Sometimes they caught in the upper branches of a tree or rested forever on a rooftop.

Plaything though it was, the Chinese top illustrated perfectly the fundamental principle of the helicopter. Centuries after its appearance in that earliest of civilized nations, it was destined to fire the imagination of scientists and inventors throughout the Western World. Many felt it held the answer to man's age-old dream of rising from his earth-bound realm to that of his feathered friends in the sky above.

Among the ancients this desire to fly was first given expression in the telling of extraordinary legends. These described the strange and wonderful adventures of human flyers who in some mysterious fashion were given birdlike wings to soar and swoop through the sky. Many told of unhappy endings like that of Daedalus and Icarus, perhaps the most famous of all such fantasies.

Icarus had fitted to his back a pair of wings made of waxed bird feathers. Just before he left the earth, his father warned him about flying too high lest the heat of the sun melt the wax and Icarus tumble to earth. But the young man, completely absorbed with the delight of his aerial movements, forgot his father's words of caution. His sky journey ended exactly as his parent had predicted. Icarus flew too close to the sun, which melted the wax. The wings came apart and Icarus fell to his death on the earth below.

From legends, mankind progressed ever so slowly to more serious observations about flying. Perhaps among the earliest that history records are those of Roger Bacon. This thirteenth-century English philosopher was a man of great learning and intellectual ability. He was a prolific writer on scientific subjects, and many of his ideas were greatly in advance of his time. For example, he predicted on numerous occasions that someday man would build a successful flying machine. Bacon even offered a suggestion as to how this machine might look: "a device for flying shall be made such that a man sitting in the middle of it and turning a crank shall cause artificial wings to beat the air after the manner of a bird's flight."

Although we may look with amusement on this early scientist's description of a proposed aircraft, his writings had an important effect as they slowly made their way through the countries of Europe. They stimulated the minds of other scientists and philosophers on the subject of flying machines and the fascinating prospects they offered. One of the world's most famous of this select group of gentlemen was Leonardo da Vinci.

This great Italian who lived in the golden Renaissance of the fifteen and sixteenth centuries was a versatile genius. Although his greatest and most enduring fame lies in the realm of art, he was equally at home in the world of science, engineering, architecture, and natural philosophy. He left lasting contributions in all these fields of intellectual activity. As he had so many widespread interests, it is little wonder that his mind should be attracted to the magic of mechanical flight. Indeed, aside from his art, the lure of flying occupied more of his mental energies than any of his other interests.

For his study of aeronautics, Leonardo turned to a readily available source provided by nature—bird-life. He spent countless hours roaming the fields, observing the flight of these feathery creatures. His notebooks are filled with dozens of sketches of wing structures, done with great skill and detail. The story is told that on his numerous strolls through the market place of Florence, he would buy several cages of birds from their happy vendors. Walking to an uncrowded area, Leonardo would open the cage doors and watch with great attention as the birds took wing and freedom. Those close to him who witnessed this unusual procedure gaped with puzzled expressions. Some even tapped their heads with a finger, saying in effect, "The poor old gentleman must be slightly out of his mind."

But Leonardo was undisturbed by the glances and remarks of the onlookers. In the fleeting instant when his newly bought birds flew off, he caught perhaps an unusual motion of a wing or a new position of the feathers, and these were soon added to his growing collection of data and sketches. A tiny measure of progress was made in his mind towards the creation of a successful flying machine.

When at last Leonardo had exhausted his study of bird flight and had drunk deeply of the writings of Bacon, he was firmly convinced that human flight was possible. He began designs for his first flying machine, which he modeled after the structure and flight of birds. It was essentially a mechanical arrangement for flapping wings up and down, power to be supplied by the pilot, who was then supposed to be taken aloft by the craft. This type of aircraft has since been classified as an ornithopter, because of its resemblance to bird flight. Many of aviation's first experimenters could think of no better way to propel their flying machines than after the manner of birds. They were convinced if birds could do it, so could men. It was simply a case of duplicating mechanically the same wing motion for human flight—or so they thought. No aircraft of this type has ever been known to fly.

Before becoming amused at these pioneer aircraft builders and their fanciful designs, it is good to remember that the ornithopter airplane has never completely left the minds of inventors. Long after the Wright brothers pointed out the most practical means of heavier-than-air flight, tinkerers with a serious gleam in their eyes pursued the old idea, and in fact are still thinking of a successful ornithopter. Perhaps someday an ingenious individual will hit upon the right combination of power plant and wing structure to bring this about.

As for Leonardo and his ornithopter, he designed and built in model form many variations of this flying machine. With some of these the pilot was to lie prone on a board to which movable wings were attached. By pulling on strings with an arm motion and treading with his legs, the flyer was supposed to make the wings beat up and down and carry him to lofty heights. On other models Leonardo added hand cranks and a rudder shaped like a bird's tail. The rudder was to be fastened to the pilot's neck. When he turned his head to the right, he was supposed to fly to the right and vice-versa when he moved it to the left.

It is quite certain that Leonardo never advanced out of the model-making stage with his ornithopter. As he became more deeply involved with this particular type of flying machine, he met with innumerable knotty mechanical problems which gradually discouraged him. It was about this time that the idea for a helicopter flying machine entered Leonardo's mind.

Just how Leonardo came to think of the helicopter flying principle is not quite clear. In view of his enormous mental powers, it is conceivable that this could have welled up from his own creative pools of genius. Of course the possibility of his having come in contact with the Chinese top either through his widespread reading or contact with travelers must also be considered. However this may have been, the fact remains that this great Italian designed and built models of the first helicopters intended for human flight.

One of the first of Leonardo's helicopter designs called for a shallow saucer-like gondola on which two upright posts were attached. Each of the posts carried a double set of wings. By means of a rather complicated system of cords, cylinders, and foot pedals, the pilot set the wings in motion with movements of his feet, hands, and head! Alas, the poor flyer, if he suddenly developed a cramp in his leg!

**Leonardo da Vinci's helicopter project**

The wings of this craft were not of the flapping variety, but rather they moved in a horizontal plane, criss-crossing one another. This motion compressed the air between the wings and gave the craft lift. Leonardo provided his helicopter with a landing gear in the form of a pair of ladders about twenty-four feet long. These were intended not only to help the take-offs but also to cushion the craft when it landed. During flight they were supposed to be hauled into the gondola or fuselage.

Unlike many inventors, Leonardo was not above feeling that perhaps, should his helicopter ever reach the flying stage, an accident might occur. Therefore, along with a description of his craft, he also included the very wise suggestion that during the helicopter's test flight, the pilot fly it over water. In the event of an accident, he would thus be tumbled onto this yielding surface and unharmed.

While speaking of Leonardo's caution about flying, it is interesting to note that in connection with his helicopter studies he also devised what was perhaps the world's first parachute. The Italian genius was quite optimistic about his life-saving device; he showed this when he said, "If a man have a tent roof of caulked linen 24 feet broad and 24 feet high, he will be able to let himself fall from any great height without danger to himself."

The helicopter experiments also led Leonardo to design what many believe to be the first airplane instrument. This was a pendulum device that hung within a glass ring. "This ball within the ring will enable you to guide the apparatus straight ahead or aslant as you wish."

Craving perfection in all that he did, Leonardo soon began to feel unhappy with his first helicopter models. One of the major causes of his dissatisfaction was the manner of powering his flying machine. He came to the conclusion—one that was to profoundly affect aircraft experiments in the years ahead—that mechanical rather than human power must be used before a successful flying machine could be built.

With this thought in mind, he undertook some new experiments before designing a different model helicopter. Standing in the center of his studio one day, he took a large, thin ruler and swung it in rapid circles above his head. He felt a distinctive upward pull on his arm. From this he reasoned that if he could build a flying machine having a rapidly rotating wing above it— powered by mechanical means—he would achieve a successful aircraft. Leonardo proceeded to build a model of his new helicopter design, powering it with a spring motor.

Many of the helicopter models which he built are said to have taken to the air successfully. It is quite likely they were fashioned along the lines of those using a coiled spring for a motor. These craft had a wing-like rotor for rising into the air.

Among the last of the helicopter models designed by Leonardo was one which had the appearance of an artificial Christmas tree. More important to the great Italian, it is the design which historians say made him the partial originator of the word "helicopter." He described the craft with a good deal of confidence in its flying ability. "I say that this instrument made with a helix and is well made, that is to say, of flaxed linen of which one has closed the pores with starch and is turned with a great speed, the said helix is able to make a screw in the air and to climb high."

The helix he mentions is a Greek word meaning "spiral" or "twist." This was combined later with another Greek word, pteron, meaning "wing." In still later years through much usage, the words were fused in such a manner that the term "helicopter" came to be born.

As in his many other fields of endeavor, Leonardo da Vinci left his imprint on the very infant subject of aeronautics. By his work with ornithopters and helicopter models he is said to have begun the first sound experiments in search of a practical heavier-than-air flying machine. Leonardo was strongly convinced that if man were to accomplish his long desired goal of traveling in the sky above him, it would be by a flying machine based on the principle of the helicopter. A little more than two hundred years were to pass before Leonardo's ideas on flying machines were to be picked up and carried forward by a whole host of helicopter experimenters. Alas for this band of aeronautical pioneers, man's first ascent into the sky was made by an entirely different type of aircraft, the hot-air balloon.

This historic event took place in 1783 just outside of Paris when two courageous young Frenchmen, Jean-Francois Pilatre de Rozier and Marquis d'Arlandes, rose into a November sky in their hot-air balloon craft. It wasn't many years since the Montgolfier brothers had startled the French people and those of the neighboring countries with the world's first hot-air balloon flights. When word of these pioneering sky journeys spread far and wide, they inspired experimenters and inventors struggling to build flying machines as nothing had stirred them since the days of Leonardo da Vinci.

About this time another event took place that was far less dramatic but was eventually to prove almost as powerful a stimulant to technically minded people absorbed with the youthful science of aviation as the hot-air balloons. This was a demonstration of the flying Chinese top before members of the French Academy of Sciences, probably Europe's first glimpse of this Oriental aerial toy. Normally, these gentlemen were not easily stirred by exhibitions of unusual mechanical devices. But after the flying top had flown gracefully above their heads from one end of the room to the other and then, its energy spent, settled gently to the floor, the hall broke out with a buzz of excitement. What a superb performance! Launoy, a naturalist, and his partner, Bienvenu, a mechanic, who put the top through its paces, were surrounded by the learned gentlemen, all seemingly talking at once with great animation. They were stormed with questions, and the little toy was minutely examined by dozens of hands.

Leaving the Academy at the close of that day's session, many of the scientists were still under the spell of the fascinating aerial plaything. This was especially true of those who were deeply interested in aeronautics. Talking with great animation and gesturing rapidly with their hands, they were convinced they had just been shown the key that would unlock the door leading towards a successful flying machine.

Although the Montgolfier brothers had already shown how man might travel through the air with one type of aerial vehicle, there were many experimenters who felt that a better way would be by some sort of craft having wings, one or more propellers, a body or fuselage, and a mechanical source of power. This, of course, was the heavier-than-air aircraft they were thinking about.

It is interesting to note that in the early nineteenth century the helicopter, as a means of achieving heavier-than-air aircraft flight, was thought of as much as airplanes having fixed wings. And even though the latter won the race of getting into the sky first, the supporters of the helicopter never gave up in their struggle to build a workable machine. Their great loyalty to this type of aircraft and the many superior qualities which they felt it had over other forms, would someday be vindicated.

It did not take long for word of the Chinese top and the principle of rotary flight which it demonstrated to reach scientists in other lands. They, too, were equally enthusiastic about its offering a rather simple solution to what had long been a most baffling problem. Now that the way had been shown, the next step was to try to build an aircraft using its principles that would really fly. Soon the lamps in workshops throughout Europe were burning to the wee hours of the morning as inventors struggled hopefully over their aerial creations. Each felt that his machine would be the first to rise successfully from Mother Earth.

The English Channel was no barrier to the spreading of the news concerning the flying Oriental toy. As elsewhere, it created quite a stir when shown to the scientists and inventors of Great Britain interested in aviation matters. It made a particularly deep impression on Sir George Cayley, who has been fondly called the "father of English aeronautics."

Ever since he was a boy of nine, Cayley had been fascinated with the possibilities of flying. His imagination soared during the late 1700's because of the wonderful hot-air balloon flights of the Montgolfier brothers. Some day, he dreamed, he too would build a flying machine that would astound the world and make his name famous in many lands.

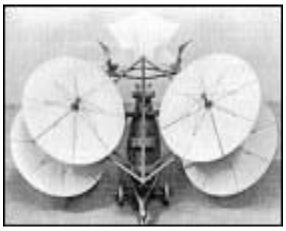
Although he never quite reached his goal, Cayley in time came to be one of England's leading men of science and especially well informed about aeronautics as it existed during his lifetime. For almost half a century he busied himself with aerial experiments, mostly with the balloon type aircraft. He is said to be the first to have begun experiments with gliders which were an important initial step leading towards the successful fixed-wing aircraft.

Cayley was about twenty-three years old when he first came in contact with the top. He was fascinated by the flying toy and in 1796 began building models of his own design, using different means of powering them. Most were driven by springs and rubber bands—the latter a power source familiar to all aircraft model builders of today. Some of Cayley's models were said to have risen almost ninety feet into the air, which was no mean achievement at the time. However, his interest in these models soon waned, and the Englishman gave most of his attention to balloon aircraft.

It wasn't until he was well along in years that Cayley again switched his emphasis in aeronautical studies from the balloon to the heavier-than-air flying machines. It is significant that when he did this, the helicopter was among the more important of the types which he investigated. As evidence that the rotary wing airplane had now deeply impressed the English scientist, he revealed to the public in 1843 his design for a flying machine based on the helicopter principle. He called his sky vehicle an "aerial carriage."

In a sense, Cayley was correct in labeling his aircraft a "carriage." It bore a strong resemblance to a baby's vehicle elaborately decorated for a May Day children's parade. Had it ever been built, his design called for two sets of huge rotors, positioned one above the other and connected to the body of the craft by a system of booms. A belt drive, connecting the craft's steam engine and the rotors, spun the latter and supposedly gave the machine its lifting power. When the craft was airborne, two propellers fixed to the stern were intended to power it in a forward direction. The body of the helicopter had a shape somewhat like that of a bird and was canvas-covered. Indeed, a bird's head was used as the design for the front of the helicopter's body.

However, the craft had a very unbird-like interior, since its inventor called for a steam engine to be placed within it. The engine powered not only the rotors but the two directional propellers as well. Cayley equipped his helicopter with a four-wheel landing gear together with a broad horizontal rudder to control its upward and downward flight actions. He also included a small vertical rudder for guiding the machine to the right or left.



**Cayley helicopter project**

Cayley's helicopter never actually reached the construction stage. It is quite likely that in the process of working out various engineering features of his craft, especially the power plant, he realized that a much more efficient engine would have to be created—one that produced a great deal more power in relation to its weight than the steam engines of that period—before a flying machine could successfully leave the ground. This stumbling block to a practical flying machine of these early years—either helicopter or fixed-wing aircraft—was to dawn slowly on each individual experimenter as one by one they met with discouraging failure.

Cayley died at the age of eighty-four. It is said that his interest in aeronautical matters was just as keen during the fading days of his life as it was in his youth. For the fine pioneering work he accomplished in a field of science still in its infancy during his day, he was honored with knighthood.

About the time that Sir George was experiencing a new interest in helicopters, a countryman of his, W. H. Phillips, was busying himself with similar studies. Like the knighted Sir George, Phillips was a scientist who had a strong curiosity in aeronautics—a curiosity that was intensified by Cayley's achievements. Just a year before the latter revealed his plans for a helicopter "aerial carriage," Phillips went a step further and produced an actual flying model of a steam-powered rotary wing aircraft. Driven by a midget-sized steam-engine, the entire device weighed about twenty pounds. Phillips' miniature helicopter was remarkably successful. It made a number of fine nights. One of the last of these the inventor described in his notes with some pride: "The steam was up in a few seconds, when the whole apparatus spun around like a top and mounted into the air faster than any bird; to what height it ascended I had no means of ascertaining. The distance traveled was across two fields where, after a long search, I found the machine minus the wings, which had been torn off from contact with the ground." The English inventor's helicopter was a substantial contribution to the science of aeronautics of that day. It was the first steam-powered model helicopter to fly successfully. The aerial contrivance was also outstanding because its system of propulsion was based on the jet principle. Steam was made to squirt out of tiny openings in the arms of the rotor, spinning them around and carrying the machine into the sky.

When news of the model rotary wing airplane circulated among scientific groups, it was considered nothing short of sensational. Some engineers became overly enthusiastic about Phillips' flying machine, and soon there was talk of building large passenger-carrying helicopters. These bold ideas quickly faded when it was realized that a much more suitable power unit other than the bulky steam engine would be needed before their dreams could become a reality.

Cayley and Phillips were probably unaware of it, but at about the same time of their helicopter experimental activities, another gentleman with scientific interests was also thinking of this aerial machine for transportation purposes. Vittorio Sarti was his name. He lived in the same country where a little more than two hundred years earlier, Leonardo da Vinci was busily laying the groundwork for the science of aeronautics. Indeed, it is quite likely that Sarti was a student of the work of his famous countryman, since his version of an aircraft embodied many of the basic ideas of Leonardo.

Sarti's flying machine was a combination of the ornithopter and the helicopter. He was obviously determined to make his, craft fly by one means or another. It had huge square blades— three of these being grouped in each rotor. The latter were positioned on a vertical shaft one above the other, an arrangement described by present-day helicopter engineers as a coaxial system. The blades were hinged to the shaft in order that they could flap up and down, similar in action to a bird's wing. This motion was supposed to lift the inventor's craft straight up off the ground.

The remainder of the Italian engineer's helicopter had a large triangular-shaped rudder for steering in forward flight. This was fastened to a boom which extended from the rear of the pilot's compartment, a circular structure that hung below the flapping rotor blades. There is no record that Sarti's helicopter flying machine ever left the ground.

While the work of the three helicopter experimenters just described might have little value as far as contributing anything important towards the building of a successful rotary wing aircraft is concerned, it had historical significance. Their efforts .were among the first of more than a hundred years of painfully slow and often bitterly disappointing work before the first really successful helicopter was created. Throughout the nineteenth and twentieth centuries, helicopter study, experiment and development work proceeded, first at a snail's pace and then at an ever accelerated rate. At first this activity was concentrated in a few countries in Europe, with France the main workshop. French scientists and technical men had a particular fondness for flying craft of all sorts and for a long time their country was considered the world's center of aviation developments. It wasn't unusual, therefore, when Gabriel de la Landelle along with two associates, Gustave Ponton d'Amecourt and Felix Tournachon more popularly known as Nadar) designed a helicopter flying machine that astounded the public of their day.

This craft was intended to be a real leviathan of the skies Which the aeronauts aptly called the "steam air-liner." The designers were lavish with the creation of their brain-child by including not only all the features they considered necessary to make it fly, but also many others for the comfort and safety of the passengers.

To start with, it had a boat-shaped hull or fuselage from either side of which the builders fixed large rectangular wings. These were kept in a rigid position by wires which were fastened to two tall masts. These last were imbedded vertically in the fuselage. On the upper portions of the masts were the rotors—four of them—one above the other. The optimistic designers felt that these would be sufficient to lift the giant hulk off the ground.

Passengers inside the cabin who felt the air getting too stuffy for their comfort could climb a stairway to a rail-enclosed upper deck. At the fore and aft ends of the hull, the designers placed triangular-shaped fins which were probably intended to guide the craft in horizontal as well as up and down flight. A propeller was also placed at the front of the airliner which was supposed to pull it in a forward direction.

Taking no chances in the event their omnibus of the sky should develop mechanical difficulty, the investors included parachutes and a life boat as safety devices. The parachutes were attached to the tops of each of the masts, and while the craft was sailing serenely on its aerial journey, they were collapsed like the arms of an umbrella. In fact when the parachutes were opened, they resembled giant umbrellas. It was hoped, of course, that the 'chutes would ease the massive helicopter back to earth gently in case of emergency.

The life-boat hung below the fuselage. It was probably thought valuable in case the helicopter ran into trouble while flying over water. The inventors certainly could not be accused of lacking foresight.

Landelle and his associates intended their sky giant to be powered with the only available means of that day for driving mechanical contrivances, the steam engine. This spun not only the rotors but the forward propeller as well.

As events turned out, the steam air liner never reached the construction stage. It became a symbol of lofty plans that failed of accomplishment both because of material and human shortcomings.

While the three French helicopter designers were busy working out the details for their air giant, one of the group, Gustave Ponton d'Amecourt, had an additional helicopter project under way which he was handling all by himself. In comparison with the air liner, this craft, a model, incidentally, was about the size of a beetle. The Frenchman's flying machine had two sets of small rotors of two blades each. They were placed one above the other on top of the machine and were spun about by a small steam engine. Gustave Ponton d'Amecourt was a clever mechanic, and his tiny helicopter was an extremely neat and efficient looking affair. Perhaps more important than its aircraft features was the tiny steam engine. This unit was considered quite advanced for its day since its creator had made considerable use throughout its construction of a new metal, aluminum.

In 1868 scientists and engineers of Great Britain who were deeply engrossed with aeronautical matters put their heads together one day to discuss the status of that youthful science. The majority agreed that, on the whole, many wonderful accomplishments had been made up to that time. Someone then made the suggestion that it would be nice if an exhibition were held where many of aviation's achievements—mostly in the form of flying machines—could be seen by the public. Exhibits would be shown from other countries along with those of Great Britain.

The idea was received with great enthusiasm, and shortly thereafter, in June of 1868, the world's first aeronautical exhibition was held in the Crystal Palace in London. Crowds poured into the great hall to see the varied shaped balloons and aircraft which their inventors had hoped would open up a brand new field of transportation. The d'Amecourt helicopter model was one of the craft on display and it drew more than its share of curious onlookers.

Paucton was still another French engineer who, at the time of the London air exhibit, sought to solve the problem of heavier-than-air flight with a helicopter. However, he would have no part of the word "helicopter" to describe his aircraft, although its basic principles were of that type. Instead, he called his aerial vehicle a "pterophore." Further, Paucton decided not to follow in the steps of his contemporaries and use mechanical power to drive his craft. The method of the ancient experimenters with their human energy for propulsion was good enough for him.

The helicopter was to have two propellers, or "pterophores" as the inventor identified them, one to provide the craft with lift and the other forward motion. These were hooked up with cords and pulleys to a crank arrangement. The pilot, seated in Ira chair, was supposed to turn the crank as fast as he was physically able, and this in turn spun the rotor overhead to lift him off the ground. Also this motion turned the propeller at the rear for movement forward.

Paucton called for a unique feature in his lifting rotor or "pterophore." The blades of this unit were to be made adjust-» able so that from a spoke-shaped position they could be moved to form a continuously closed surface. Thus, in the event the pilot met with trouble while aloft, the inventor felt confident that this solid disc parachute would "resist the flow of air and retard the fall of the machine to a considerable degree."

There is no record that Paucton ever built or attempted a flight with his hand-powered helicopter or even that he put his unique parachuting device to a test. If he did, he probably made the rueful discovery that man is poorly equipped physically to imitate the birds for propelling himself through the air. Paucton's machine contributed little if anything to the art of building a successful helicopter. The same could not be said for a rotary wing aircraft model built several years later by Enrico Forlanini of Italy.

Forlanini was a professor of civil engineering who, like many others in his profession, was fascinated with the flying possibilities of the helicopter. Studiously quiet, he loved to tinker in his little workshop after classroom lectures. It was here, after good deal of thought and effort, that the helicopter model took form. In due time the flying machine created much excited comment with its graceful aerial antics.

The Italian engineer's craft weighed almost eight pounds, which, in view of the fact that he powered it with a steam engine, was a splendid technical accomplishment. Indeed, this unit, cleverly designed by Forlanini, was as outstanding a part of the model aircraft as its flight performances. The propulsive force of the engine was created by super-heated water contained in a hollow globe hanging beneath the apparatus. This globe was two-thirds filled with water and then heated. When the desired pressure was obtained, a valve was opened which permitted the steam to flow to the engine's cylinders. Their movement spun the large rotor overhead.

To the delight and astonished gasps from many of those who saw it, the professor's little helicopter would rise from the ground and fly along for a distance of many feet. On some of these flights it rose to a height of forty feet and stayed aloft for as long as twenty seconds. Following the footsteps of the Englishman Phillips, Forlanini had succeeded in building the world's second successful steam-powered helicopter model.

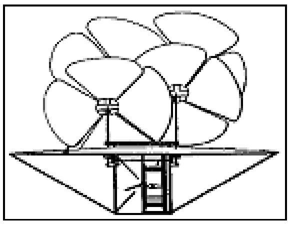
It is not to be supposed that helicopter development activity of the nineteenth century was confined to the gentlemen discussed thus far. It wasn't. There were a host of others in other countries of Europe each contributing a tiny measure of additional knowledge that some day would bring into being a successful helicopter. What is more, this engineering work was not restricted to the old world. The United States, youthful, vigorous and growing, also had its scientific, mechanically-minded men who were intrigued with the idea of building a flying machine. Destiny, indeed, selected this country as the scene where man would some day achieve his long sought goal of building the first successful flying machine.

Long before the Wright brothers were sailing in their experimental gliders over the sand dunes of Kitty Hawk, a lonely figure of a scientist was bent over his drafting board in a New York City home putting finishing touches to his design for an aerial machine. At last Mortimer Nelson straightened up. This was it, and at once he dispatched his brain child to the United States Patent Office. Nelson was granted a patent on his flying device on May 21, 1861, and as far as is known, this is the earliest record of an American attempt to build a helicopter.

The New York scientist's aerial invention at first was merely considered an improvement for balloon aircraft. His helicopter device, which he called an "aerial car" was to be used along with a balloon. He explained, "The nature of my . . . invention consists in revolving fans, applied to balloons and arranged in such a manner that they can be used for communicating a vertical ascending movement, or a forward propulsion." Later he developed more confidence in his flying machine, so that he felt it could be operated by itself.

Nelson's combination helicopter-balloon aircraft consisted of a body which tapered fore and aft, a pear-shaped rudder at the stern, a parachute canopy over the top of the fuselage and two vertical shafts rising out of the body, each equipped with a pair of rotors. A canvas material or oiled silk was suggested for covering the car, rudder, and parachute. He arranged the rudder in such fashion that it could control the craft's upward, downward, and sidewise flying directions.

Nelson's helicopter had several very advanced engineering features for its day. One of these concerned the rotors. Nelson didn't care particularly how many were placed on his aerial car just so long as there was a minimum of two and that others were added in pairs. The rotors and their shafts could be fixed in an upright position or inclined forward. In describing them, he said, "when the shafts stand vertically . . . the revolution of them will tend to raise the balloon or car and that when . . . inclined forward their action on the air will give propulsion to the car." This was anticipating by almost a hundred years another type of aircraft, the convertiplane.



**Nelson helicopter project**

Nelson also realized that the rotors had to spin in opposite directions; otherwise a peculiar force of physics which engineers call "torque" would turn his car in one direction while the fans revolved in another. It is for that reason that Nelson insisted on rotors being installed in pairs.

The other feature which distinguished Nelson's helicopter design was his recommendation for the use of aluminum for all the craft's metal parts. Aluminum was scarcely as well known then as it is now; iron and steel were more commonly used for mechanical apparatus. Nelson was aware, however, that its light weight in comparison to iron and steel would be a great advantage in helping his craft to fly better. In this connection, he wrote, "I have discovered that by making the framework . . . of aluminum, a sufficient strength can be obtained, and the great weight usually in such parts so much removed that the sustaining power has not as much weight to lift as would be the case in any engine . . . made of iron, steel or other metals." Nelson had again anticipated modern day airplane builders by many decades.

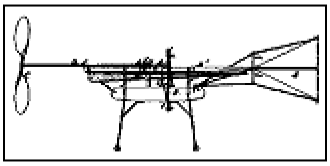
The parachute or awning device which Nelson called for in his design was not meant for safety. This was to be installed over the top of the car at an angle and serve the same purpose as a wing to give the craft lift. According to Nelson's own explanation of this feature, "The parachute . . . gives outstanding power to the car in moving through the air and forms a buoyant sail."

Nelson failed to provide one very essential item for his helicopter as described in his patent. He didn't say how the aerial vehicle was to be powered. Perhaps this was because the inventor was aware that some means of propulsion other than the heavy steam engine would be necessary before his craft could fly. Evidence of this is shown by the fact that Nelson conducted experiments on a revolutionary lightweight internal combustion engine. As a result of his efforts along this line, he obtained still another patent on a chemical mixture to be used in his new engine. He called it "carbo-sulphethal."

Nelson made some very optimistic claims for his new fuel mixture and engine. Not only would his new engine be far lighter than the conventional steam power unit, but it would also burn a good deal less fuel while producing the same amount of energy. Mortimer Nelson, alas, never transformed his paper-designed helicopter into real life substance.

In West Dennis, Massachusetts, meanwhile, another inventor was pressing the New Yorker for the honor of obtaining this country's first patented helicopter design. He was Luther C. Crowell, and his aerial device was recognized by the Patent Office on June 3, 1862.

Crowell's machine called for some unique mechanical features. For example, the two propellers with which it was equipped were fastened to shafts that could be swung from a vertical position to a horizontal. Thus, when it was flying as a helicopter, that is, in a vertical direction, the propellers would be above the aircraft's body. For forward flight they were supposed to be lowered to a horizontal position. Incidentally, he also realized that these had to rotate in opposite directions to counteract torque. In addition to the movable propellers, the designer also equipped the craft with adjustable wings. For up and down flight the wings could be lowered to a vertical position. After reaching the desired altitude, the pilot was then supposed to bring the wings up horizontally for flying in a forward direction. Another curious thing about the wings was the fact that they were hollow and were to be filled with hydrogen or some other lifting gas. Wood and a covering of either oiled cloth or silk was suggested for their construction. Once aloft, the helicopter was supposed to be steered in any desired direction by a pyramid-shape rudder fixed to the stern of the fuselage. This was accomplished by means of cords and pulleys extending into the pilot's compartment.



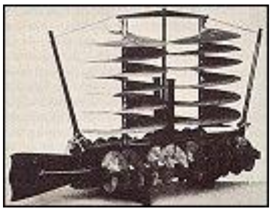
**Crowell helicopter project**

Like most of his contemporary aircraft inventors, Crowell was precise with his directions for building the structure of his flying machine. About ways of powering his helicopter, however, he was quite vague. He merely called for a steam engine. The inventor probably felt that the problems of installing a power plant as bulky as this was so great, they had better be left to someone else.

Crowell worked out his helicopter design just as the American Civil War was getting under way, which undoubtedly influenced his thoughts concerning possible uses for his flying machine. He suggested that it could be used for bombing purposes. "When it is desired to employ this aerial machine as an engine of war, it could be elevated, loaded with shell, and when arrived over the desired spot the shell could be discharged," he commented.

The New England inventor, however, was not the only one thinking of the flying machine, more particularly the helicopter, as a means for waging war. In the South with similar ideas was Captain William C. Powers.

Captain Powers was inspired to invent his flying machine by the Union blockade of Confederate ports. He thought of it as a wonderful means to get around the Union Navy which was preventing the import of badly needed war supplies. In addition, he also saw his invention as an excellent device for observation and reconnaissance work. It was a crude-looking machine and had hardly any resemblance to an aircraft. The helicopter had two rotor units in the form of spiralling screws which were supposed to lift the craft vertically, and a series of similar units on the sides for propelling it through the skies. Presumably a steam engine was to be the power source.

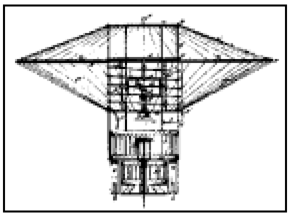


**Powers helicopter project**

The Confederate officer's helicopter design is a comparatively recent discovery. It is said that he never tried to build a full-scale model of his flying machine because he was afraid it might fall into Union hands and be used against the Southerners. He need not have troubled himself with this thought. According to aviation authorities, his helicopter never would have left the ground under any circumstances.

The mid-1800's was a banner time for American inventors to try their hand at designing flying machines. To those of Nelson, Crowell, and others, John Wooton added his in 1866.

A native of Boonton, New Jersey, he invented a machine featuring a large ring-shaped wing beneath which hung two circular compartments. One of these held the power plant and the other, directly beneath it, was for passengers. The cautious inventor designed his wing in this fashion with the thought in mind that its parachute-like qualities would help bring the machine back to earth in one piece if anything went wrong while aloft.



**Wootton helicopter project**

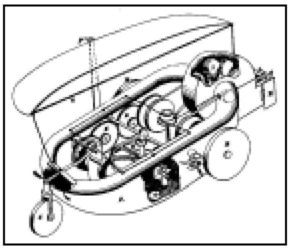
The helicopter was supposedly powered with a steam engine which turned two or more propellers that were fixed between the wing and the topmost gondola. Again we see an American inventor anticipating the convertiplane by designing the propellers to tilt either vertically or horizontally. Indeed, Wooton had many features in his design aside from the one above that were not to be seen again until the modern days of aviation.

For example, his flying machine had a hoisting device within it by which the passenger's compartment could be raised or lowered while the machine hovered over one spot. Present-day helicopters are equipped with similar mechanical hoists capable of doing the same thing. He also called for catapulting apparatus to launch his aircraft into the skies. This was a sort of roller-coaster affair on which the helicopter was supposed to be hauled to a high point at one end. With everything set for the take-off, the machine was released and left to roll down one incline and up the next, at which time, by the combination of lift given by the parachute-wing and whirling propellers, the machine was to become airborne.

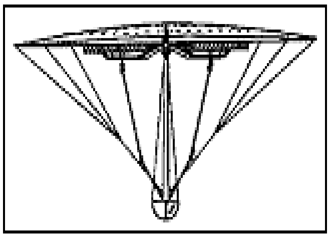
Landing and stopping the helicopter after a flight called for still greater skill on the part of the flyer. Although designed to descend vertically, the vehicle was expected to roll after its wheels touched the ground. To stop the craft, the pilot had to aim it between two upright poles. A hook fastened to the topmost portion of the flying machine grabbed ropes which stretched between the uprights and halted the craft. Although the method is different, basically, the present-day navies of the world use somewhat the same means of bringing aircraft to a stop on the decks of carriers.

Even though the New Jersey inventor never reached the stage of building his helicopter, his work can be considered important in the rotary-wing field if only for the many novel and advanced engineering features which he called for in his design.

Other American inventors during this era who sought to solve the problem of mechanical flight by means of the helicopter, included John Ward of California, who obtained a patent on his contrivance in 1876. With its multiplicity of tubes, gears, and whirling propellers, Ward's aircraft resembled most closely a flying pipe organ.



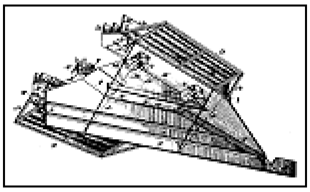
**Ward helicopter project**



**Greenough helicopter project**

Three years later John Greenough came out with a patented design that was a slight improvement. Calling his machine an aerobat, this Syracuse inventor fashioned his helicopter in the form of a giant bird's wing. The craft's two lifting rotors whirled around in two large circular openings cut into the wings. A boat-shaped fuselage was suspended beneath the wing.

A month before Greenough received his helicopter patent, another was issued to Watson Quinby on August 12, 1879. A native of Wilmington, Delaware, Quinby had long been interested in aviation experiments and built many unsuccessful machines patterned after the mechanics of bird flight. For his last attempts at building a practical flying machine he turned to the helicopter, which he was confident offered the easiest solution to a long sought goal. Quinby's helicopter, with its four rigid legs for a landing gear, inclined body, and a long nose boom to which were fastened two small sails for a propeller, looked more like an aerial steed than a flying vehicle. The lifting propeller or rotor was also made of a pair of small sails, which were supposed to whirl around a vertical shaft, above the body of the machine.



**Johnston helicopter project**

In 1888 another Southerner, Edward Johnston of Alabama, entered the aviation field with his ideas for a workable helicopter. His design was patented in June of that year and resembled for allthe world the paper aircraft models which school boys make to plague their teachers.

Johnston's flying machine had six propellers, four for vertical flying and two for giving it directional flight. An interesting detail about these propellers was the fact they had their own individual motors. In addition to being capable of flying in up and down and forward directions, the inventor claimed, his machine could also hover, like a humming-bird, over one area.

Of all the helicopter experimenters during these last years of the nineteenth century, Thomas Edison was unquestionably the best known. He was interested for a long time in the great variety of mechanical problems which a successful flying machine offered. He was convinced from the start, that the helicopter would be the best means of achieving man's dream of conquering the sky.

In 1880 Edison began his experiments with rotary-wing aircraft. To aid him in his work financially, James Gordon Bennett, a famous newspaper publisher of that day and an enthusiastic supporter of aviation activities, provided him with one thousand dollars. First the famous inventor investigated the characteristics of various designs of rotor blades, to discover those having the best lifting power. To do this he erected a rather cumbersome apparatus having a vertical shaft to which the test rotors were attached. He powered these vertically mounted propellers with an electric motor, since the internal combustion engine was not yet in existence.

The electric motor in turn was placed on a wooden base, and the entire unit connected to weight-measuring scales. Thus, as the rotors spun overhead, Edison could tell by reading the scales how many pounds the propellers were able to lift. After prolonged tests with various styles of rotor blades, the inventor discovered that with the only means of powering them at his command, they could only raise a small part of the total weight of his testing apparatus which added up to 160 pounds. He came to the conclusion, therefore, that helicopter flight could be solved only after a suitable engine was created. He was thinking of one that had little weight, yet could produce a good deal of horsepower. Edison had run afoul of the same obstacle that had tripped many other aircraft experimenters before him.

The renowned American inventor was not one to give up easily, however, when faced with a brow-knitting technical problem. He set to work building his own engine and soon was ready to try it. Along with his other notes on helicopter experiments, he wrote, "I used stock-ticker paper made into guncotton and fed the paper into the cylinder of the engine and exploded it with a spark. I got good results, but burned one of my men pretty badly and burned off some of my own hair and didn't get much further."

Following this near-fatal incident, Edison was forced to abandon his helicopter experiments for other more pressing work. However, he never lost his strong feeling that some day the world would see a workable helicopter, as he showed when he said, "I knew that it was only a matter of experimenting and I reported to Mr. Bennett that when an engine could be made that would weigh only three or four pounds to the horsepower, the helicopter would be a success."

More than fifty years later Edison's prediction was to come true but not quite the way he imagined. Helicopter experimenters who followed in his footsteps had to solve problems just as difficult as his before the first successful helicopter could take to the sky.

**Helicopter configuration** :

A helicopter is a heavier-than-air aircraft supported in flight chiefly by the reactions of the air on one or more power driven rotors.
A gyroplane is a heavier-than-air aircraft supported in flight by the reactions of the air on one or more rotors which rotate freely.
A rotor provides lift, which can be employed to keep the aircraft airborne and to provide thrust.
A rotor can also counteract torque (tail rotors).
Several rotor designs and configurations have been implemented over time.

**Single Main Rotor:**

Single main rotor helicopters are the most common type of helicopter They need an anti-torque device (tail rotor or other anti-torque system) to counteract the twisting momentum produced by the main rotor, which is powered by one or more engine(s). In a single main rotor helicopter part of the power generated by the powerplant(s) is employed to counteract torque. The most common anti-torque device is a tail rotor, which is designed to compensate the torque produced by the main rotor.

**EC25 single main rotor helicopter**

**Tandem rotor (or dual rotor):**

A tandem rotor helicopter has two main rotor systems and no tail rotor. Usually the rear rotor is mounted at a higher position than the front rotor, and the two are designed to avoid the blades colliding, should they flex into the other rotor's pathway. The rotor discs are slightly tilted toward each other to provide control along the vertical axis during the hover. This configuration, which is mainly used for larger helicopters, has the advantage of being able to support more weight with shorter blades. The smaller rotor disc area is compensated by having two rotors. The anti-torque function is performed by the counter-rotating rotors, with each cancelling out the other's torque, so all of the power from the power-plants is employed for lift. Tandem helicopters are typically powerful and fast. The design of the drive and control system are more complicated than the ones of a single main rotor helicopter.

Ch47 Chinook helicopter with tandem rotors

**Coaxial:**

Coaxial rotors are two main rotors mounted on one mast, sharing the same axis of rotation but turning in opposite directions, one on top of the other. The control along the vertical axis is produced as a result of different lifts, thus differential torque, of the two rotor discs. The helicopter will yaw to the left if the clock wise rotating rotor produces more lift, and it will yaw to the right if more lift is produced by the counter-clock wise rotating rotor. The drag produced by the rotors is quite large due to the interference of airflows, so these helicopters do not normally have a high cruising speed. Mounting rotors closer together, which is possible only with rigid rotors, reduces the amount of drag produced.

KAMOV Ka-50 "Black Shark" with distinctive coaxial rotor system

**Intermeshing rotors (synchropter):**

A helicopter with two rotors turning in opposite directions and mounted on two masts slightly inclined towards each other, so that the blades intermesh (without colliding), is called a synchropter. The two rotors mesh with one another, like a gearwheel. This configuration does not require a tail rotor, since the anti-torque action is performed by the counter-rotation of the rotors. Synchropters have high stability and powerful lifting capabilities.

KAMAN K-1200 K-Max Synchropter

**Side by side:**

In a side by side rotor configuration, two horizontal, counter-rotating rotors are mounted side-by-side on a helicopter (or transverse rotorcraft). The anti-torque effect is provided by the opposing rotation of the two main rotors. The side-by-side configuration is one of the possible flight configurations of a tilt-rotor aircraft, when the rotors are in the vertical position to provide vertical lift.

**The Rotors:**

The rotors are mounted at the edge of the wings, on nacelles that rotate in order to transition the rotors from the vertical position (to provide vertical lift like a side by side rotor configuration helicopter), to the horizontal position (where they provide horizontal lift, or thrust, just like in airplanes). Both lift and propulsion are then generated by the rotors, which act as helicopter main rotors when in the vertical position, and as airplane propellers when in the horizontal position. Lift is then provided by fixed wings.

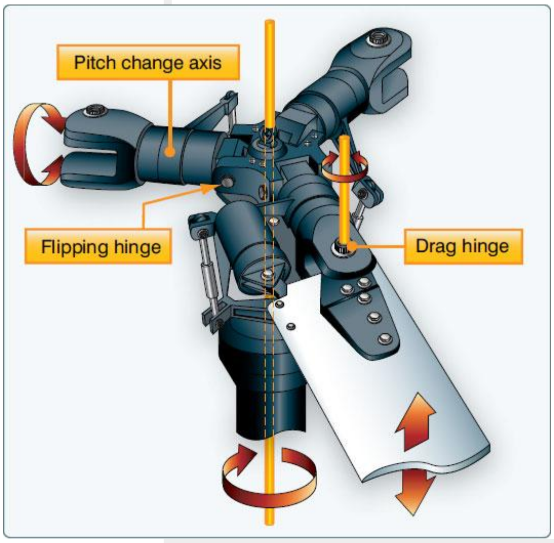
**Control Requirements:**

In many piston engine-powered helicopters, the pilot manipulates the throttle to maintain rotor speed. Turbine engine helicopters, and some piston helicopters, use governors or other electro-mechanical control systems to maintain rotor speed and relieve the pilot of routine responsibility for that task. (There is normally also a manual reversion available in the event of a governor failure.)

| **Name** | **Directly Controls** | **Primary Effect** | **Secondary Effect** | **Used in Forward Flight** | **Used in hover Flight** |
|---|---|---|---|---|---|
| Cyclic (longitudinal) | Varies main rotor blade pitch with fore and aft movement | Tilts main rotor disk forward and back via the swashplate | Induces pitch nose down or up | To adjust forward speed and control rolled-turn | To move forwards/backward |
| Cyclic (lateral) | Varies main rotor blade pitch with left and right movement | Tilts main rotor disk left and right through the swashplate | Induces roll in direction moved | To create movement to sides | To move sideways |
| Collective | Collective angle of attack for the rotor main blades via the swashplate | Increase/decrease pitch angle of all main rotor blades equally, causing the aircraft to ascend/descend | Increase/decrease torque. Note: in some helicopters the throttle control(s) is a part of the collective stick. Rotor speed is kept basically constant throughout the flight. | To adjust power through rotor blade pitch setting | To adjust skid height/vertical speed |
| Anti-torque pedals | Collective pitch supplied to tail rotorblades | Yaw rate | Increase/decrease torque and engine speed (less than collective) | To adjust sideslip angle | To control yaw rate/heading |

**Types of Rotor Systems: Fully Articulated Rotor**

A fully articulated rotor is found on aircraft with more than two blades and allows movement of each individual blade in three directions. In this design, each blade can rotate about the pitch axis to change lift; each blade can move back and forth in plane, lead and lag; and flap up and down through a hinge independent of the other blades. [Figure 2-27]




***Articulated rotor head.***

**Semirigid Rotor**

The semirigid rotor design is found on aircraft with two rotor blades. The blades are connected in a manner such that as one blade flaps up, the opposite blade flaps down.

**Rigid Rotor**

The rigid rotor system is a rare design but potentially offers the best properties of both the fully articulated and semirigid rotors. In this design, the blade roots are rigidly attached to the rotor hub. The blades do not have hinges to allow lead-lag or flapping. Instead, the blades accommodate these motions by using elastomeric bearings. Elastomeric bearings are molded, rubber-like materials that are bonded to the appropriate parts. Instead of rotating like conventional bearings, they twist and flex to allow proper movement of the blades.

**Basic Power Requirements:**

The performance envelope of every helicopter is defined by the relationship between the power required and the power available at some flight condition. Power required can be thought of as being airframe dependent, while power available is engine dependent. In other words, the helicopter does not care what kind of engine powers it, any more than the engine cares what it supplies power to.

It takes the same amount of force to hold a 5,000-pound helicopter one foot off the ground as it does to hold it at any cruising altitude. But to create that lift force, we need to turn the rotor and accelerate a mass of air. In the physics world, it is said that the rotor does work on the air. It takes power (the rate at which work is done) to overcome the drag of the rotors and

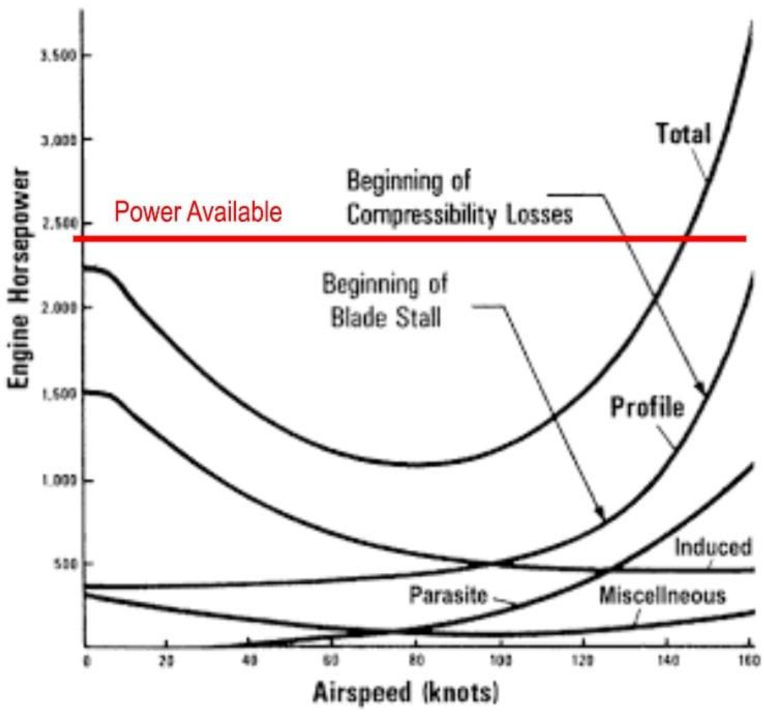
create lift. Power is that parameter that we can measure in the cockpit, and changing conditions of air density, airspeed and flight condition will all cause a change in power requirement.
Generally speaking, the maximum power available from the engine can be assumed to be constant. Circling back to the idea that power required is airframe dependent, it can be further broken down into the subcategories of profile, induced and parasitic.

Profile power is the power required to overcome the friction drag on the blades and push the rotor's shape through the viscous air. It does not change significantly with a change in angle of attack and accounts for 15% to 40% of the main rotor power required in a hover. It stays relatively constant with airspeed until at high speeds compressibility and/or blade stall drive it up.

Induced power is the power required to overcome the drag developed during the creation of rotor thrust. With an increase in angle of attack, the airflow that moves down through the rotor causes the total reaction lift vector of the blade to tilt rearwards, creating induced drag. It takes around 60% to 85% of the total main rotor power in a hover to overcome it.

Parasitic power is the additional power required to move everything else attached to the rotor through the air — that's the fuselage and everything attached to it. It rises with the cube of airspeed.

Adding up these three components of power, as well as miscellaneous power consumers like the tail rotor, hydraulic pumps, gearbox losses, generators, etc., results in the familiar total power required curve that defines our flight envelope.




Moving from hover into forward flight brings a rapid decrease in required power, due to a change in inflow angle of oncoming air. This is the induced power decreasing as the rotor becomes more efficient (translational lift).

Total power continues to decrease with increasing airspeed, until you reach the “bucket” speed. This is the point of greatest difference between power required and power available, which can be translated into maximum rate of climb. Beyond this speed, the rotor continues to become more efficient, but wind resistance begins to prevail and parasite power swaps places with induced power as the main contributor to total rotor power required. Total power then begins to rise until it meets with power available, defining the helicopter’s maximum horizontal speed.

Although the blades and airframe move easier through the thinner air of higher altitudes, more pitch in the blades is required to create thrust, and an overall increase in total power required can be expected with altitude increase.

Having a keen understanding of your aircraft’s power requirements can help you perfect technique, maximize performance and minimize maintenance. Knowing that induced power will decrease with greater airflow through the rotor disk in forward flight — and similarly in a max performance vertical takeoff — a pilot can finesse a heavy aircraft into the air by watching their power margin increase on a decreasing torque meter allowing more “pitch pull,” while still staying within limits. Knowing that left pedal or a left cyclic roll will drive power requirements up on rotors rotating clockwise (looking up), a pilot can avoid an overtorque by not operating too close to a limit while maneuvering. Opposite pedal/cyclic will, of course, do the same on opposite spinning rotors.

Multi-engine helicopters bring even more need to understand power, especially in one-engine-inoperative flight, and require their own discussion. Suffice to say, when it comes to helicopters, power may be important, but knowledge will always be power.

# UNIT-II

## INTRODUCTION TO HOVERING THEORY

### Momentum Theory:

In fluid dynamics, the **momentum theory** or **disk actuator theory** is a theory describing a mathematical model of an ideal actuator disk, such as a propeller or helicopter rotor, by W.J.M. Rankine (1865), Alfred George Greenhill (1888) and Robert Edmund Froude (1889).

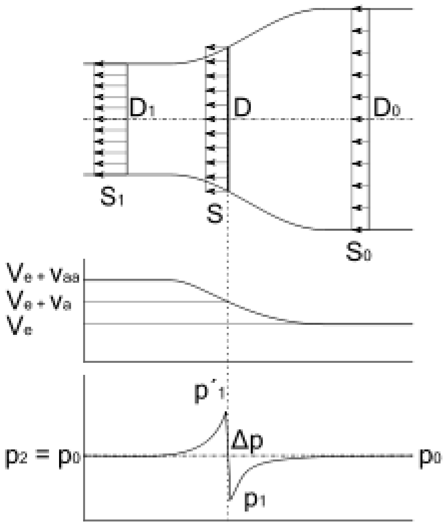
The rotor is modeled as an infinitely thin disc, inducing a constant velocity along the axis of rotation. The basic state of a helicopter is hovering. This disc creates a flow around the rotor. Under certain mathematical premises of the fluid, there can be extracted a mathematical connection between power, radius of the rotor, torque and induced velocity. Friction is not included.

For a stationary rotor, such as a helicopter in hover, the power required to produce a given thrust is:

Where:

- T is the thrust
- is the density of air (or other medium)
- A is the area of the rotor disc

A device which converts the translational energy of the fluid into rotational energy of the axis or vice versa is called a **Rankine disk actuator**. The real life implementations of such devices are e.g. marine and aviation propellers, windmills, helicopter rotors, centrifugal pumps, wind turbines, turbochargers and chemical agitators.



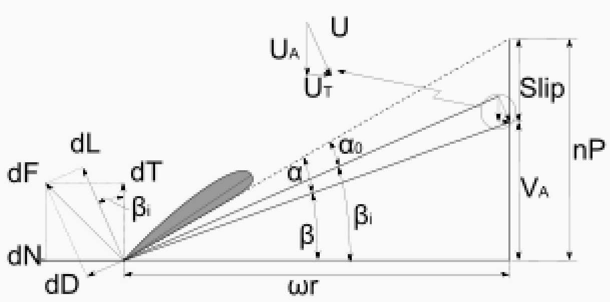

### Blade Element Theory:

**I**t is a mathematical process originally designed by William Froude (1878), David W. Taylor (1893) and Stefan Drzewiecki to determine the behavior of propellers. It involves breaking a blade down into several small parts then determining the forces on each of these small blade elements. These forces are then integrated along the entire blade and over one rotor revolution in order to obtain the forces and moments produced by the entire propeller or rotor. One of the key difficulties lies in modelling the induced velocity on the rotor disk. Because of this the blade element theory is often combined with the momentum theory to provide additional relationships necessary to describe the induced velocity on the rotor disk (for further details see Blade Element Momentum Theory). At the most basic level of approximation a uniform induced velocity on the disk is assumed:

Alternatively the variation of the induced velocity along the radius can be modeled by breaking the blade down into small annuli and applying the conservation of mass, momentum and energy to every annulus. This approach is sometimes called the Froude-Finsterwalder equation.

If the blade element method is applied to helicopter rotors in forward flight it is necessary to consider the flapping motion of the blades as well as the longitudinal and lateral distribution of the induced velocity on the rotor disk. The most simple forward flight inflow models are first harmonic models.

**Velocities and forces for a blade element**




dT = Thrust
dL = Lift
dF = Force
dN = Torque / radius
dD = Drag
U = Induced speed
$U_A$ = Axial induced speed

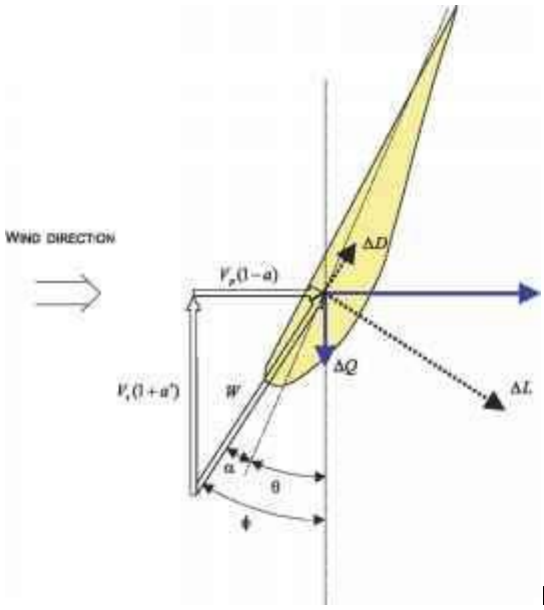
$U_T$ = Tangential induced speed
$V_A$ = Translation speed
nP = Pitch speed
ωr = Blade tip speed
α = Angle of attack
β = Inflow angle

**Combined Blade Element and Momentum Theories For Non-Uniform Inflow Calculation**

## Blade element momentum model:

The combined blade element and momentum theory is an extension of the Rankine-Froude actuator disk theory described in Section 3.3.2. The blade element momentum theory divides the rotor blades into a number of radial blade sections (elements), each at a particular angle of attack. These blade elements are assumed to have the same aerodynamic properties as an infinitely long (or 2-D) rotor blade with the same chord, and aerofoils. This implies that 2-D aerofoil data (i.e. lift, drag and moment coefficients) obtained from wind tunnel experiments may be used. The airflow from upstream to downstream of the elements is, in turn, divided into annular stream tubes. It is assumed that each stream tube can be treated independently from adjacent ones. Subsequently, the theory outlined in the preceding section is applied to each blade element, instead of to the rotor disk as a whole. The velocity component in the span-wise direction (i.e. perpendicular to the blade cross-section) is ignored. Finally, the total load is calculated by adding up the forces from all the elements.

The contribution of each blade element to the lift and drag force can be derived as follows. Consider an annular cross-section of a rotor blade as depicted in Fig. 3.11, and examine an element of length Ar of one blade.




ROTATING DIRECTION

Blade element velocities, and aerodynamic forces w.r.t the blade local coordinate frame with the chord line as reference.

AL Blade element lift force

AD Blade element drag force

AF Axial components of aerodynamic forces

AQ Tangential components of aerodynamic forces a Angle of attack of aerodynamic (or resultant) velocity

0 Pitch angle of rotor blade

6 Direction of aerodynamic velocity related to the rotor plane

Vp Local, undisturbed, perpendicular wind velocity

Vt Local, undisturbed, tangential wind velocity

W Local, undisturbed, aerodynamic wind velocity Axial induction factor: represents the fractional decrease in wind velocity between the free stream and rotor plane a' Tangential induction factor: represents the swirl velocity of the air.

The net effect on air flowing through this annular section of the rotor disk results from the forces and moments on all the blades. The instantaneous relative undisturbed wind velocity experienced by a blade element is under an angle.

It must be noted that the tangential induction factor a' in the above equation is as a rule an order smaller than the axial induction factor a.

Due to the special profile of a rotor blade, higher velocities will occur at the top of the blade rather than on the bottom side. According to the Bernoulli theorem, this leads to an under pressure at the first mentioned side of the blade and an overpressure at the latter. This air pressure difference is the driving force behind the rotation of the rotor. More precisely, the pressure distribution around an aerofoil can be represented by two forces, a lift L and a drag D force, and one torque, the pitching moment M. Both forces and the pitching moment are usually applied at a location 4 chord back from the leading edge (i.e. the so-called aerodynamic center) since, on most low speed aerofoils, the magnitude of the pitching moment is essentially constant up to maximum lift at that specific location. For symmetric aerofoils, the aerodynamic moment about the aerodynamic center is zero for all angles of attack. With camber, the moment is non-zero (normally negative for positive camber) and constant for thin aerofoils. Using the aerodynamic center as the location where the aerodynamic forces are applied simplifies the aerodynamic analysis. The effect of the pitching moment, however, is neglected in most design codes.

The angle of attack of the relative wind velocity (a) is determined by the difference between the angle of inflow (6) and the pitch angle (0):

Due to the resultant velocity W the blade cross-section exerts a quasi-steady aerodynamic lift force (AL ± W) and a quasi-steady aerodynamic drag force (AD || W) with c Local blade chord (varies along the blade: c = f (r))

C|2D] Blade element 2-D lift coefficient cdD] Blade element 2-D drag coefficient p Air density

## Ar Length of blade section:

The dimensionless aerodynamic coefficients C\, Cd, and Cm are - among other things - functions of the angle of attack a, Reynolds number Re and Mach number Ma (compressibility of the airflow). These coefficients have to be either determined for each type of aerofoil separately by means of stationary wind tunnel experiments and/or CFD computations or can be obtained from a database. An example of such a database is the Aerodynamische Tabel Generator (ATG) described by Timmer et al. [290].

Typical variation of these coefficients is shown in Fig. 3.12. The sudden change in the coefficients at 14° is due to flow separation from the suction side of the aerofoil; this is called stall.

The Reynolds number varies in practice between zero and 2 • 10 6 [119] depending on chord and undisturbed wind velocity of a blade-element. However, this dependency is often neglected, although the Reynolds number significantly affects the values for the lift and drag coefficients (see either Sharpe [259] or the aerofoil data option on DAWIDUM's Plot menu for the variation of aerofoil characteristics with the Reynolds number).

From the above discussion it follows that the quasi-steady aerodynamic lift and drag forces are proportional to the local blade chord c, are quadratic in resultant wind velocity W, and are approximately linear in the angle of attack a in the attached flow region.

In order to calculate the lift AL, and drag AD on a section of a rotor blade it suffices to determine the local, undisturbed, resultant wind velocity W, which consists of four components: the undisturbed wind velocity Vw (including yawed flow, wind shear, and tower shadow, see Section 2.3.4), the velocity of the blade element itself (including rotor shaft rotation, flap motion, lead-lag motion and the velocity of the tower top, resulting from the mechanical model which will be discussed in Section 3.4) and the induced velocities. Next, the determination of the induced wind velocities shall be described.

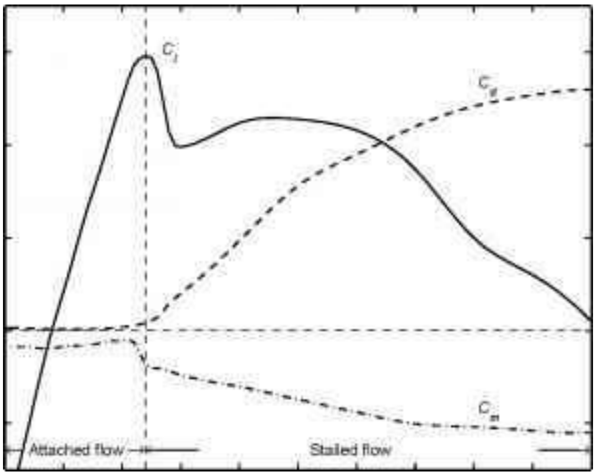



Figure 3.12: Typical variation of the 2-D lift, drag, and moment coefficient as function of the angle of attack a. ¡Solid! curve: lift coefficient Ci, dashed curve: drag coefficient Cd, and dashed-dotted curve: moment coefficient Cm about the aerodynamic center.

## Induced velocities:

In the equilibrium situation, the axial flow in the rotor plane of a wind turbine, depends on the wind velocity, and on the degree of loading (i.e. the size of axial force Dax = ^ AF) of the turbine. For instance, for a turbine with zero loading, the wind velocity at the rotor disk position (Vax) is equal to the undisturbed wind velocity (Vw), while an operating, and hence loaded turbine slows down the wind velocity to a lower value (see Fig. 3.7 on page 51). The difference between the axial component of the wind velocity and the axial flow velocity in the rotor plane is usually called the "axial induced" velocity, the velocity induced by the presence of the turbine. The tangential flow, on the other hand, is induced by the swirl velocity of the air flow around the blade.

Horizontal-axis wind turbine rotors are usually not aligned with the wind due to the continuously changing wind direction and the fact that no rotor is capable of following this variability. Furthermore, upwind rotors are sometimes tilted in order to increase the tower clearance, and hence to reduce tower shadow. In effect, the rotor is then yawed about a horizontal axis. For all these reasons it is thus necessary to include in the blade element momentum theory the effects of yaw. Here we will consider only the simple case of perpendicular flow.

The axial induced velocity can be determined by expressing the axial thrust AF on a blade element either as the rate of change of momentum in the annular ring swept out by this element using Eq. (3.22) with A ~ n(r + 2Ar)2 — n(r — 2Ar)2 = 2nrAr the area of the annular ring, or as the force exerted by the wind on a blade element Cn where Nb is the number of rotor blades. Assuming equality of Eqs. (3.32) and (3.33) gives Cdax

The right-hand side term is defined as the dimensionless thrust coefficient Cdax (see Eq. (3.25)). Solving the above equation gives as an expression for the axial induction factor in case of perpendicular flow. Alternatively, the axial induction factor can be calculated as arCN (3.36) by substituting Nb c 2nr in Eq. (3.34) and solving for a. The term ar (which is a function of the radius r) is called the local solidity or chord solidity.

The tangential induced velocity can, on the other hand, be determined by expressing the torque AQ on a blade element either as the rate of change of angular momentum or as the torque exerted by the wind on a blade element assuming Nb blades. Again assuming equality between the above expressions of the torque on a blade element we have as an expression for the tangential induction factor. Alternatively, the tangential induction factor can be calculated as ar Ct with and Nb c 2nr.

Thus, Eqs. (3.35)/(3.36) and (3.39)/(3.40) are the set of non-linear relations that determine the dimensionless induced velocities a, and a' in case of perpendicular flow. Before these equations can be used, however, the local thrust coefficient must be modified to account for two effects: the departure of the local thrust coefficient from the momentum relation, and the non-uniformity of the induced velocities in the flow. These so-called tip losses will be considered after the treatment of the turbulent wake state.

## Turbulent wake state:

For heavily loaded wind turbines, which implies a high axial induction factor a as well as a high tangential induction factor a', the momentum and vortex theory are no longer applicable because of the predicted reversal of flow in the turbine wake. The vortex structure disintegrates and the wake becomes turbulent and, in doing so, entrains energetic air from outside the wake by a mixing process. Thereby thus altering the mass flow rate from that flowing through the actuator disk. The turbine is now operating in the so-called "turbulent wake state", which is an intermediate state between windmill, and propellor state (see Appendix B for an overview of the different flow states of a wind turbine rotor).

In the turbulent wake state the relationship between the axial induction factor and the thrust coefficient according to the momentum theory, Eq. (3.35), has to be replaced by an empirical relation. The explanation for this is that the momentum theory predicts a decreasing thrust coefficient with an increasing axial induction factor, while data obtained from wind turbines show an increasing thrust coefficient [279]. Thus, the momentum theory is considered to be invalid for axial induction factors larger than 0.5. This is consistent with the fact that when a = 0.5 the far wake velocity vanishes (i.e. a condition at which streamlines no longer exist), thereby violating the assumptions on which the momentum theory is based. The following approximations are implemented in DAWIDUM:

1. Anderson [2]. The empirical relation of Anderson is defined as:

   or equivalently

   Cdax =4(aT)2 +4(1 - 2aT) • a for Cdax > 4aT(1 - aT) (3.42)

   where aT =1 — fV Cdaxl with Cdax1 = 1.816 as "best" fit [21]. Thus aT = 0.3262 and Cdax(aT) = 0.8792. The empirical relation of Anderson is a straight line in the Cdax - a diagram, and this line lies tangential to the momentum theory parabola at the transition point aT (marked * in Fig. 2.1);

2. Garrad Hassan [29]. The empirical relation of Garrad Hassan is defined as:

   or equivalently

   a = 7ZE + 7ZE V-15239 + 31600 • Cdax for Cdax > 0.96 (3.44) 158 158

3. Glauert [55, 82]. The empirical relation of Glauert is defined as:

   a = 0.143 +^0.6427 • Cdax - 0.55106 for Cdax > 0.96 (3.45)

4. Johnson [118]. The empirical relation of Johnson is obtained from interpolation of the expressions for the wind turbine and propellor state by a third order polynomial:

   1.491Cdax or equivalently

5. Wilson [280, 308]. The empirical relation of Wilson is defined as:

   or equivalently a = 1 , Cdax -4aC for Cdax > 4ac(1 - ac) (3.49)

This is a linear extrapolation of the from the momentum theory parabola at the transition point aC (marked o in Fig. 2.1);

Observe that the empirical relation of Wilson is identical to that of Anderson, only the location of the transition point is different. The five mentioned approximations were already compared in Fig. 2.1 on page 25 for perpendicular flow. From the observed differences it has been concluded that the listed empirical approximations must be regarded as being only approximate at best. The prediction is, nevertheless, more realistic than the one from the momentum theory as illustrated in Fig. B.1 on page 228. It must be noted that, in general, the value of the axial induction factor rarely exceeds 0.6 and for a well-designed blade it will be in the vicinity of 0.33 for much of its operating range [37].

Thus for values of Cdax greater than the (empirical model dependent) transition point, the right-hand side term of Eq. (3.34) needs to be substituted in one of the above mentioned empirical relations (i.e. either Eq. (3.41), (3.44), (3.45), (3.46), or (3.49)) to compute a.

## Blade tip and root effects:

The blade momentum theory, as previously developed, does not account for the effect of a finite number of rotor blades. Therefore a correction has to be applied for the interaction of the shed vorticity with the blade's bound vorticity. This effect is usually greatest near the blade tip, and it significantly affects the rotor torque and thrust.

Either an approximate solution by Prandtl or a more exact solution by Goldstein can be used to account for the non-uniformity of the induced axial velocity [55]. Both approximations give similar results. The expression obtained by Prandtl is however commonly used, since this has a simple closed form, whereas the Goldstein solution is represented by an infinite series of modified Bessel functions.

This expression is in literature denoted with the misleading term tip-loss factor. Misleading because it corrects for the fact that induction is not uniform over the annulus under consideration owing to the finite number of blades, and not for the finiteness of the blades. Prandtl's tip-loss factor is defined as

n a c with R Length of rotor blade ri Radial position of blade section i N b Number of blades

6i Angle between relative wind vector and the plane of rotation at blade section i

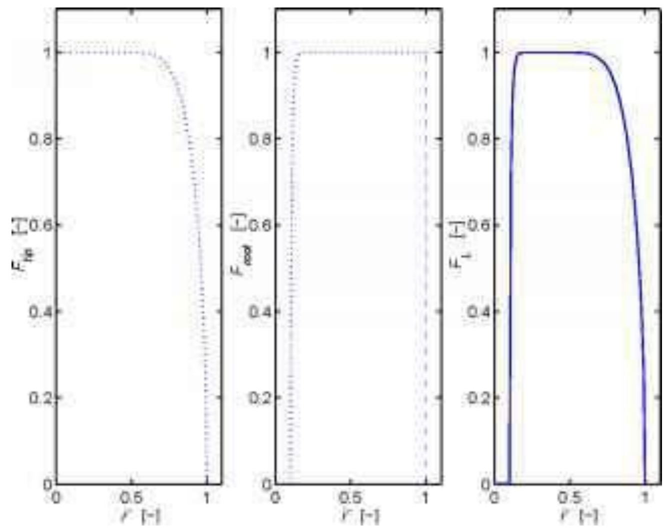
Note that at the blade tips, where T = R, the factor equals zero, as can be reasoned by the fact that the circulation at the blade tips is reduced to zero by the wake vorticity.

A similar loss takes place at the blade root where, as at the blade tip, the bound circulation must fall to zero, and therefore a vortex must be trailed into the wake. The blade root-loss factor is defined as n with to the radial position of start root loss (typically 10% to 30% of the blade radius [118]).

The effective total loss factor at any blade section is, according to Eggleston and Stoddard [55], then the product of the two:

Figure 3.13 shows Prandtl's combined blade tip and blade root loss factor FL as a function of the normalized radius T = t/R.

The incorporation of the combined blade tip and root loss factor FL into the expressions for the induction factors depends upon whether the azimuthal averaged values of the induction factors, or the maximum values (local to a blade element) are to be determined. If the former alternative is chosen then, in the momentum terms the induction factors remain unmodified, but in the blade element terms the induction factors must appear as the average value divided by FL. The latter choice, however, allows the simplest modification of Eqs. (3.35)/(3.36) and (3.39)/(3.40). In this case, the induction factors in the momentum terms are to be multiplied by FL while the values of 6 and CN that are obtained from the blade element calculations are not multiplied by FL. Equation (3.35) then becomes a = 1 - ^l- Cdax (3.53) for a wind turbine operating in windmill state or, when the turbine is operating in turbulent wake state, by dividing the right-hand side of either Eq. (3.41), (3.44), (3.45), (3.46), or (3.49) by FL. In addition, Eq. (3.39) becomes root.



Prandtl's combined blade tip and blade root loss factor Fl as function of the normalized radius r. It is assumed that the inflow angle fa is constant over the radius of the blade, and ro is taken as 0.10 • r.

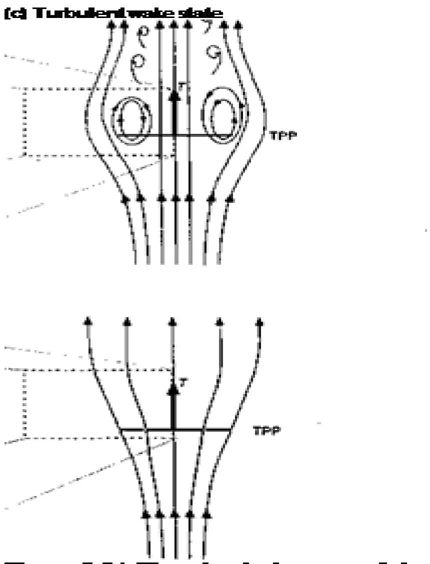
# UNIT-III
# VERTICAL FLIGHT

## Various Flow States Of Rotor:

A description of the four working states of the rotor were first put forward by Lock and his colleagues (1926,1928) and are summarized by Glauert (1935) and Hafner (1946). Figures 2.18 and 2.20 show the lines representing Vc + u* = 0 and Vc + 2i>; = 0. Johnson (1980) shows that these lines are best used to help demarcate four axial operating states of the rotor. For points above the line Vc + vL = 0, the rotor is absorbing power supplied from the rotor shaft. Below this line, the rotor is extracting power from the relative airstream, which does work on the rotor shaft. To help understand the complicated physical nature of the rotor wake under these conditions, The flow visualization images of the wake at various descent velocities. Unlike some of the earlier work by Lock (1928) where smoke was used to visualize the gross flow structure, the individual blade tip vortices were rendered visible here by means of shadowgraphy, which is a density-gradient method (see Section 10.2.3). Because the flow is nominally axisymmetric, only one side of the rotor is shown for clarity.

(a) Normal working state

(b) Vortex ring state



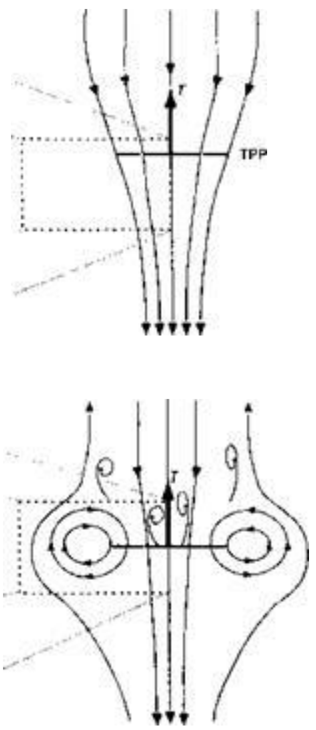




**Figure 2.21 The physical nature of the rotor wake in simulated axial descent: (a) Normal working state, (b) Approaching the vortex ring state, (c) Turbulent wake state, (d) Approaching windmill brake state. Flow visualization source: University of Maryland.**

1. Normal Working State: Figure 2.21(a) shows an image of the flow in the normal working state. Here, the tip vortices follow smooth helicoidal-like trajectories. The flow is highly periodic with a smooth slipstream boundary free of any significant disturbances. A schematic of the mean flow is also shown. The normal working state encompasses climb, with the limit being the hover condition.

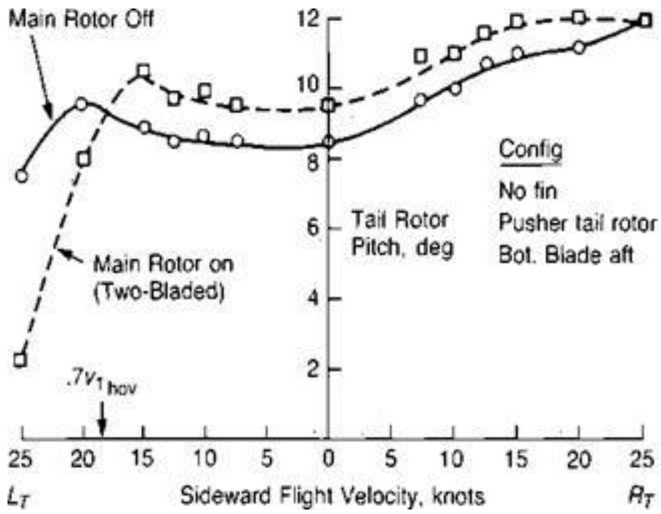
2. Vortex Ring State: For low rates of descent, the tip vortex filaments are convected closer to the plane of the rotor than for the hover case, but they also move radially outward away from the rotor. At higher descent rates, the tip vortices come very close to the rotor plane and considerable unsteadiness (aperiodicity) becomes apparent. This can be seen in Fig. 2.21(b) by the contortions in the tip vortex trajectories and the lack of any distinct slipstream boundary. This is close to the flow condition known as the vortex ring state, where the accumulation of tip vortices in the rotor plane begins to resemble a concentric set of vortex rings.

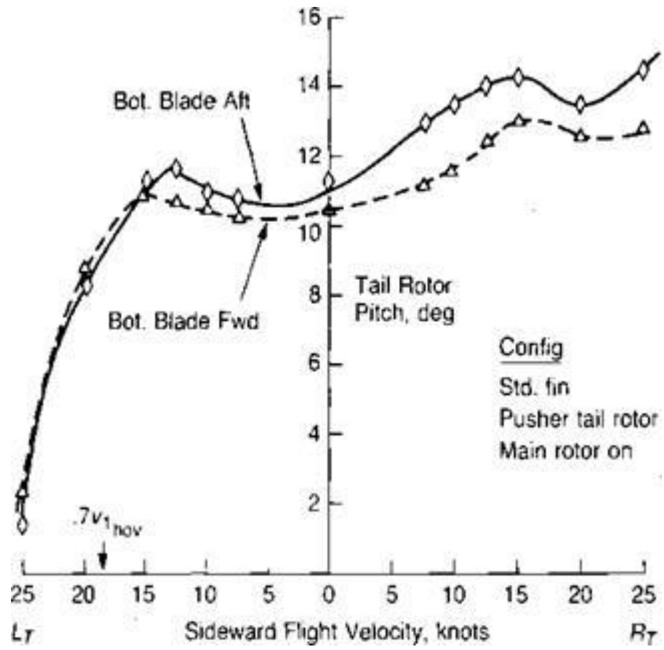
3. Turbulent Wake State: As the descent velocity increases further, the wake above the rotor becomes more turbulent and aperiodic and is representative of the flow conditions known as the turbulent wake state. This state is shown by Fig. 2.21(c) and represents the initial return to a smooth flow with a well-defined slipstream boundary. The flow is similar to that associated with a bluff body.

4. Windmill brake State: At even higher descent velocities, the wake is again observed to develop a more definite slipstream boundary that expands downstream (above) of the rotor. When in this state, the vortical wake structure is found to return to a more regular helical structure, as shown by Fig. 2.21(d). As previously described, this flow condition is known as the windmill brake state because the rotor extracts energy from the flow and brakes the flow velocity like a windmill.

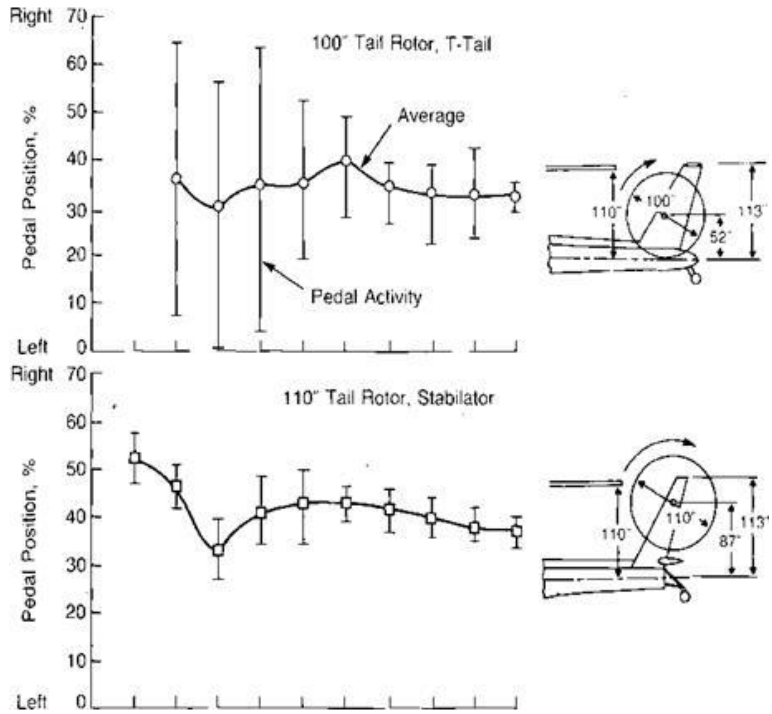
## Autorotation In Vertical Descent:

Even though vertical autorotation occurs in the vortex ring state, a first approximation procedure for calculating the rate of descent may be derived from a combination of blade element and momentum concepts. Setting the torque equation for the ideally twisted rotor to zero gives:






Effect of Main Rotor Wake and Direction of Tail Rotor Rotation at Yaw Trim Conditions.




Pedal Activity in Left Sideward Flight of Hughes AH-64

Source: Prouty, “Development of the Empennage Configuration of the YAH-64 Advanced Attack Helicopter," USAAVRADCOM TR-82-D-22, 1983.

where from the hovering derivation: (0r — ϕr) = CT ——

The inflow angle at the tip, ϕт, is: -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0

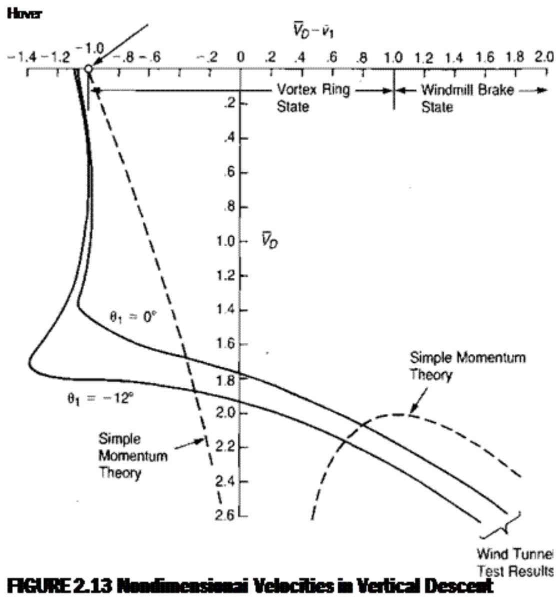


**FIGURE 2.13 Nondimensional Velocities in Vertical Descent**

Source: Castles & Gray, “Empirical Relation between Induced Velocity, Thrust, and Rate of Descent of a Helicopter Rotor as Determined by Wind-Tunnel Tests of Four Model Rotors,” NACA TN 2474, 1951.

This result is so typical that a rule of thumb is that the rate of descent in vertical autorotation is twice the hover-induced velocity. This is also borne out by an examination of Figure 2.8. Figure 2.13 shows that an untwisted rotor is better than a twisted one for vertical autorotation in that a lower rate of descent is required.

The rate of descent is a function of rotor speed; the minimum occurring at the rotor speed that corresponds to the maximum c,/2/q. Figure 2.14 shows the calculated rate of descent of the example helicopter as a function of rotor speed. The minimum rate of descent occurs at a tip speed of about 550 ft/sec. Although this represents a theoretical optimum, it is not a practical condition since the rotor is on the verge of blade stall, which could be triggered by small changes in flight conditions, and because of the relatively low value of kinetic energy stored in the rotor for use in the landing flare. It is more likely that the pilot would try to hold the normal power-on tip speed or even a value slightly higher. The collective pitch required as a function of tip speed can be estimated by combining equations already derived.

## Ground Effect:

The proximity of the ground to the hovering rotor disc constrains the rotor wake and reduces the induced velocity at the rotor, which means a reduction in the power required for a given thrust, this behavior is called ground effect.