A

ACOUSTICS

FIELDS OF STUDY

Electrical, chemical, and mechanical engineering; architecture; music; speech; psychology; physiology; medicine; atmospheric physics; geology; oceanography.

SUMMARY

Acoustics is the science dealing with the production, transmission, and effects of vibration in material media. If the medium is air and the vibration frequency is between 18 and 18,000 hertz (Hz), the vibration is termed "sound." Sound is used in a broader context to describe sounds in solids and underwater and structure-borne sounds. Because mechanical vibrations, whether natural or human induced, have accompanied humans through the long course of human evolution, acoustics is the most interdisciplinary science. For humans, hearing is a very important sense, and the ability to vocalize greatly facilitates communication and social interaction. Sound can have profound psychological effects; music may soothe or relax a troubled mind, and noise can induce anxiety and hypertension.

KEY TERMS AND CONCEPTS

- **cochlea:** Inner ear, which converts pressure waves of sound into electric impulses that are transmitted to the brain via the auditory nerves.
- **decibel (db):** Unit of sound intensity used to quantify the loudness of a vibration.
- **destructive interference:** Interference that occurs when two waves having the same amplitude in opposite directions come together and cancel each other.
- **Doppler effect:** Apparent change in frequency of a wave because of the relative motions of the source and an observer. Wavelengths of approaching objects are shortened, and those of receding objects are lengthened.
- **hertz (Hz):** Unit of frequency; the number of vibrations per second of an oscillation.
- **infrasound:** Air vibration below 20 hertz; perceived as vibration.
- **physical acoustics:** Theoretical area concerned with the fundamental physics of wave propagation and the use of acoustics to probe the physical properties of matter.
- **pesonance:** Large amplitude of vibration that occurs when an oscillator is driven at its natural frequency.
- **sound:** Vibrations in air having frequencies between 20 and 20,000 hertz and intensities between 0 and 135 decibels and therefore perceptible to humans.
- **sound spectrum:** Representation of a sound in terms of the amount of vibration at a each individual frequency. Usually presented as a graph of amplitude (plotted vertically) versus frequency (plotted horizontally).
- **spectrogram:** Graph used in speech research that plots frequency (vertical axis) versus the time of the utterance (horizontal axis). The amplitude of each frequency component is represented by its darkness.
- **transducer:** Device that transmutes one form of energy into another. Acoustic examples include microphones and loudspeakers.
- **ultrasound:** Frequencies above 20,000 hertz used by bats for navigation and by humans for industrial applications and nonradiative ultrasonic imaging.

Definition and Basic Principles

The words "acoustics," and "phonics" evolved from ancient Greek roots for hearing and speaking, respectively. Thus, acoustics began with human communication, making it one of the oldest if not the most basic of sciences. Because acoustics is ubiquitous in human endeavors, it is the broadest and most interdisciplinary of sciences; its most profound contributions have occurred when it is commingled with an independent field. The interdisciplinary nature of acoustics has often consigned it to a subsidiary role as an minor subdivision of mechanics, hydrodynamics, or electrical engineering. Certainly, the various technical aspects of acoustics could be parceled out to larger and better established divisions of science, but then acoustics would lose its unique strengths and its source of dynamic creativity. The main difference between acoustics and more self-sufficient branches of science is that acoustics depends on physical laws developed in and borrowed from other fields. Therefore, the primary task of acoustics is to take these divergent principles and integrate them into a coherent whole in order to understand, measure, and control vibration phenomena.

The Acoustical Society of America subdivides acoustics into fifteen main areas, the most important of which are ultrasonics, which examines high-frequency waves not audible to humans; psychological acoustics, which studies how sound is perceived in the brain; physiological acoustics, which looks at human and animal hearing mechanisms; speech acoustics, which focuses on the human vocal apparatus and oral communication; musical acoustics, which involves the physics of musical instruments; underwater sound, which examines the production and propagation of sound in liquids; and noise, which concentrates on the control and suppression of unwanted sound. Two other important areas of applied acoustics are architectural acoustics (the acoustical design of concert halls and sound reinforcement systems) and audio engineering (recording and reproducing sound).

Background and History

Acoustics arguably originated with human communication and music. The caves in which the prehistoric Cro-Magnons displayed their most elaborate paintings have resonances easily excited by the human voice, and stalactites emit musical tones when struck or rubbed with a stick. Paleolithic societies constructed flutes of bird bone, used animal horns to produce drones, and employed rattles and scrapers to provide rhythm.

In the sixth century BCE, Pythagoras was the first to correlate musical sounds and mathematics by relating consonant musical intervals to simple ratios of integers. In the fourth century BCE, Aristotle deduced that the medium that carries a sound must be compressed by the sounding body, and the third century BCE philosopher Chrysippus correctly depicted the propagation of sound waves with an expanding spherical pattern. In the first century BCE, the Roman architect and engineer Marcus Vitruvius Pollio explained the acoustical characteristics of Greek theaters, but when the Roman civilization declined in the fourth century, scientific inquiry in the West ceased for the next millennium.

In the seventeenth century, modern experimental acoustics originated when the Italian mathematician Galileo explained resonance as well as musical consonance and dissonance, and theoretical acoustics got its start with Sir Isaac Newton's derivation of an expression for the velocity of sound. Although this yielded a value considerably lower than the experimental result, a more rigorous derivation by Pierre-Simon Laplace in 1816 obtained an equation yielding values in complete agreement with experimental results.

During the eighteenth century, many famous mathematicians studied vibration. In 1700, French mathematician Joseph Sauveur observed that strings vibrate in sections consisting of stationary nodes located between aggressively vibrating antinodes and that these vibrations have integer multiple frequencies, or harmonics, of the lowest frequency. He also noted that a vibrating string could simultaneously produce the sounds of several harmonics. In 1755, Daniel Bernoulli proved that this resultant vibration was the independent algebraic sum of the various harmonics. In 1750, Jean le Rond d'Alembert used calculus to obtain the wave equation for a vibrating string. By the end of the eighteenth century, the basic experimental results and theoretical underpinnings of acoustics were extant and in reasonable agreement, but it was not until the following century that theory and a concomitant advance of technology led to the evolution of the major divisions of acoustics.

Although mathematical theory is central to all acoustics, the two major divisions, physical and applied acoustics, evolved from the central theoretical core. In the late nineteenth century, Hermann von Helmholtz and Lord Rayleigh (John William Strutt), two polymaths, developed the theoretical aspects. Helmholtz's contributions to acoustics were primarily in explaining the physiological aspects of the ear. Rayleigh, a well-educated wealthy English baron, synthesized virtually all previous knowledge of acoustics and also formulated an appreciable corpus of experiment and theory.

Experiments by Georg Simon Ohm indicated that all musical tones arise from simple harmonic vibrations of definite frequency, with the constituent components determining the sound quality. This gave birth to the field of musical acoustics. Helmholtz's studies of instruments and Rayleigh's work contributed to the nascent area of musical acoustics. Helmholtz's knowledge of ear physiology shaped the field that was to become physiological acoustics.

Underwater acoustics commenced with theories developed by the nineteenth-century mathematician Siméon-Denis Poisson, but further development had to await the invention of underwater transducers in the next century.

Two important nineteenth-century inventions, the telephone (patented 1876) and the mechanical phonograph (invented 1877), commingled and evolved into twentieth-century audio acoustics when united with electronics. Some products in which sound production and reception are combined are microphones, loudspeakers, radios, talking motion pictures, high-fidelity stereo systems, and public sound-reinforcement systems. Improved instrumentation for the study of speech and hearing has stimulated the areas of physiological and psychology acoustics, and ultrasonic devices are routinely used for medical diagnosis and therapy, as well as for burglar alarms and rodent repellants. Underwater transducers are employed to detect and measure moving objects in the water, while audio engineering technology has transformed music performance as well as sound reproduction. Virtually no area of human activity has remained unaffected by continually evolving technology based on acoustics.

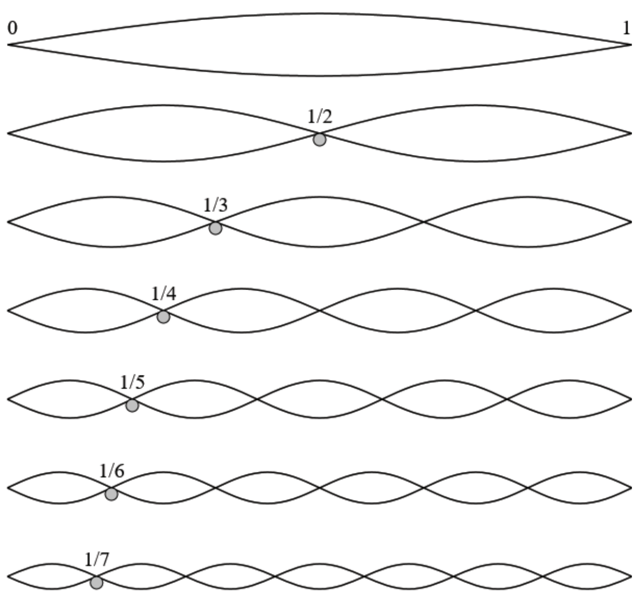
How it Works

Ultrasonics. Dog whistles, which can be heard by dogs but not by humans, can generate ultrasonic frequencies of about 25 kilohertz (kHz). Two types of transducers, magnetostrictive and piezoelectric, are used to generate higher frequencies and greater power. Magnetostrictive devices convert magnetic energy into ultrasound by subjecting ferric material (iron or nickel) to a strong oscillating magnetic field. The field causes the material to alternately expand and contract, thus creating sound waves of the same frequency as that of the field. The resulting sound waves have frequencies between 20 Hz and 50 kHz and several thousand watts of power. Such transducers operate at the mechanical resonance frequency where the energy transfer is most efficient.

Piezoelectric transducers convert electric energy into ultrasound by applying an oscillating electric field to a piezoelectric crystal (such as quartz). These transducers, which work in liquids or air, can generate frequencies in the megahertz region with considerable power. In addition to natural crystals, ceramic piezoelectric materials, which can be fabricated into any desired shape, have been developed.

Physiological and psychological acoustics. Physiological acoustics studies auditory responses of the ear and its associated neural pathways, and psychological acoustics is the subjective perception of sounds through human auditory physiology. Mechanical, electrical, optical, radiological, or biochemical techniques are used to study neural responses to various aural stimuli. Because these techniques are typically invasive, experiments are performed on animals with auditory systems that are similar to the human system. In contrast, psychological acoustic studies are noninvasive and typically use human subjects.

A primary objective of psychological acoustics is



The fundamental and the first 6 overtones of a vibrating string. The earliest records of the study of this phenomenon are attributed to the philosopher Pythagoras in the 6th century BCE to define the psychological correlates to the physical parameters of sound waves. Sound waves in air may be characterized by three physical parameters: frequency, intensity, and their spectrum. When a sound wave impinges on the ear, the pressure variations in the air are transformed by the middle ear to mechanical vibrations in the inner ear. The cochlea then decomposes the sound into its constituent frequencies and transforms these into neural action potentials, which travel to the brain where the sound is evidenced. Frequency is perceived as pitch, the intensity level as loudness, and the spectrum determines the timbre, or tone quality, of a note.

Another psychoacoustic effect is masking. When a person listens to a noisy version of recorded music, the noise virtually disappears if the music is being enjoyed. This ability of the brain to selectively listen has had important applications in digitally recorded music. When the sounds are digitally compressed, such as in MP3 (MPEG-1 audio layer 3) systems, the brain compensates for the loss of information; thus one experiences higher fidelity sound than the stored content would imply. Also, the brain creates information when the incoming signal is masked or nonexistent, producing a psychoacoustic phantom effect. This phantom effect is particularly prevalent when heightened perceptions are imperative, as when danger is lurking.

Psychoacoustic studies have determined that the frequency range of hearing is from 20 to about 20,000 Hz for young people, and the upper limit progressively decreases with age. The rate at which hearing acuity declines depends on several factors, not the least of which is lifetime exposure to loud sounds, which progressively deteriorate the hair cells of the cochlea. Moderate hearing loss can be compensated for by a hearing aid; severe loss requires a cochlear implant.

Speech acoustics. Also known as acoustic phonetics, speech acoustics deals with speech production and recognition. The scientific study of speech began with Thomas Alva Edison's phonograph, which allowed a speech signal to be recorded and stored for later analysis. Replaying the same short speech segment several times using consecutive filters passing through a limited range of frequencies creates a spectrogram, which visualizes the spectral properties of vowels and consonants. During the first half of the twentieth century, Bell Telephone Laboratories invested considerable time and resources to the systematic understanding of all aspects of speech, including vocal tract resonances, voice quality, and prosodic features of speech. For the first time, electric circuit theory was applied to speech acoustics, and analogue electric circuits were used to investigate synthetic speech.

Musical acoustics. A conjunction of music, craftsmanship, auditory science, and vibration physics, musical acoustics analyzes musical instruments to better understand how the instruments are crafted, the physical principles of their tone production, and why each instrument has a unique timbre. Musical instruments are studied by analyzing their tones and then creating computer models to synthesize these sounds. When the sounds can be recreated with minimal software complications, a synthesizer featuring realistic orchestral tones may be constructed. The second method of study is to assemble an instrument or modify an existing instrument to perform nondestructive (or on occasion destructive) testing so that the effects of various modifications may be gauged.

Underwater sound. Also know as hydroacoustics, this field uses frequencies between 10 Hz and 1 megahertz (MHz). Although the origin of hydroacoustics can be traced back to Rayleigh, the deployment of submarines in World War I provided the impetus for the rapid development of underwater listening devices (hydrophones) and sonar (sound navigation ranging), the acoustic equivalent of radar. Pulses of sound are emitted and the echoes are processed to extract information about submerged objects. When the speed of underwater sound is known, the reflection time for a pulse determines the distance to an object. If the object is moving, its speed of approach or recession is deduced from the frequency shift of the reflection, or the Doppler effect. Returning pulses have a higher frequency when the object approaches and lower frequency when it moves away.

Noise. Physically, noise may be defined as an intermittent or random oscillation with multiple frequency components, but psychologically, noise is any unwanted sound. Noise can adversely affect human health and well-being by inducing stress, interfering with sleep, increasing heart rate, raising blood pressure, modifying hormone secretion, and even inducing depression. The physical effects of noise are no less severe. The vibrations in irregular road surfaces caused by large rapid vehicles can cause adjacent buildings to vibrate to an extent that is intolerable to the buildings' inhabitants, even without structural damage. Machinery noise in industry is a serious problem because continuous exposure to loud sounds will induce hearing loss. In apartment buildings, noise transmitted through walls is always problematic; the goal is to obtain adequate sound insulation using lightweight construction materials.

Traffic noise, both external and internal, is ubiquitous in modern life. The first line of defense is to reduce noise at its source by improving engine enclosures, mufflers, and tires. The next method, used primarily when interstate highways are adjacent to residential areas, is to block the noise by the construction of concrete barriers or the planting of sound-absorbing vegetation. Internal automobile noise has been greatly abated by designing more aerodynamically efficient vehicles to reduce air turbulence, using better sound isolation materials, and improving vibration isolation.

Aircraft noise, particularly in the vicinity of airports, is a serious problem exacerbated by the fact that as modern airplanes have become more powerful, the noise they generate has risen concomitantly. The noise radiated by jet engines is reduced by two structural modifications. Acoustic linings are placed around the moving parts to absorb the high frequencies caused by jet whine and turbulence, but this modification is limited by size and weight constraints. The second modification is to reduce the number of rotor blades and stator vanes, but this is somewhat inhibited by the desired power output. Special noise problems occur when aircraft travel at supersonic speeds (faster than the speed of sound), as this propagates a large pressure wave toward the ground that is experienced as an explosion. The unexpected sonic boom startles people, breaks windows, and damages houses. Sonic booms have been known to destroy rock structures in national parks. Because of these concerns, commercial aircraft are prohibited from flying at supersonic speeds over land areas.

Construction equipment (such as earthmoving machines) creates high noise levels both internally and externally. When the cabs of these machines are not closed, the only feasible manner of protecting operators' hearing is by using ear plugs. By carefully designing an enclosed cabin, structural vibration can be reduced and sound leaks made less significant, thus quieting the operator's environment. Although manufacturers are attempting to reduce the external noise, it is a daunting task because the rubber tractor treads occasionally used to replace metal are not as durable.

Applications and Products

Ultrasonics. High-intensity ultrasonic applications include ultrasonic cleaning, mixing, welding, drilling, and various chemical processes. Ultrasonic cleaners use waves in the 150 to 400 kHz range on items (such as jewelry, watches, lenses, and surgical instruments) placed in an appropriate solution. Ultrasonic cleaners have proven to be particularly effective in cleaning surgical devices because they loosen contaminants by aggressive agitation irrespective of an instrument's size or shape, and disassembly is not required. Ultrasonic waves are effective in cleaning most metals and alloys, as well as wood, plastic, rubber, and cloth.

Ultrasonic waves are used to emulsify two nonmiscible liquids, such as oil and water, by forming the liquids into finely dispersed particles that then remain in homogeneous suspension. Many paints, cosmetics, and foods are emulsions formed by this process.

Although aluminum cannot be soldered by conventional means, two surfaces subjected to intense ultrasonic vibration will bond—without the application of heat—in a strong and precise weld. Ultrasonic drilling is effective where conventional drilling is problematic, for instance, drilling square holes in glass. The drill bit, a transducer having the required shape and size, is used with an abrasive slurry that chips away the material when the suspended powder oscillates. Some of the chemical applications of ultrasonics are in the atomization of liquids, in electroplating, and as a catalyst in chemical reactions.

Low-intensity ultrasonic waves are used for nondestructive probing to locate flaws in materials for which complete reliability is mandatory, such as those used in spacecraft components and nuclear reactor vessels. When an ultrasonic transducer emits a pulse of energy into the test object, flaws reflect the wave and are detected. Because objects subjected to stress emit ultrasonic waves, these signals may be used to interpret the condition of the material as it is increasingly stressed. Another application is ultrasonic emission testing, which records the ultrasound emitted by porous rock when natural gas is pumped into cavities formed by the rock to determine the maximum pressure these natural holding tanks can withstand.

Low-intensity ultrasonics is used for medical diagnostics in two different applications. First, ultrasonic waves penetrate body tissues but are reflected by moving internal organs, such as the heart. The frequency of waves reflected from a moving structure is Doppler-shifted, thus causing beats with the original wave, which can be heard. This procedure is particularly useful for performing fetal examinations on a pregnant woman; because sound waves are not electromagnetic, they will not harm the fetus. The second application is to create a sonogram image of the body's interior. A complete cross-sectional image may be produced by superimposing the images scanned by successive ultrasonic waves passing through different regions. This procedure, unlike an X ray, displays all the tissues in the cross section and also avoids any danger posed by the radiation involved in X-ray imaging.

Physiological and psychological acoustics. Because the ear is a nonlinear system, it produces beat tones that are the sum and difference of two frequencies. For example, if two sinusoidal frequencies of 100 and 150 Hz simultaneously arrive at the ear, the brain will, in addition to these two tones, create tones of 250 and 50 Hz (sum and difference, respectively). Thus, although a small speaker cannot reproduce the fundamental frequencies of bass tones, the difference between the harmonics of that pitch will re-create the missing fundamental in the listener's brain.

Another psychoacoustic effect is masking. When a person listens to a noisy version of recorded music, the noise virtually disappears if the individual is enjoying the music. This ability of the brain to selectively listen has had important applications in digitally recorded music. When sounds are digitally compressed, as in MP3 systems, the brain compensates for the loss of information, thus creating a higher fidelity sound than that conveyed by the stored content alone.

As twentieth-century technology evolved, environmental noise increased concomitantly; lifetime exposure to loud sounds, commercial and recreational, has created an epidemic of hearing loss, most noticeable in the elderly because the effects are cumulative. Wearing a hearing aid, fitted adjacent to or inside the ear canal, is an effectual means of counteracting this handicap. The device consists of one or several microphones, which create electric signals that are amplified and transduced into sound waves redirected back into the ear. More sophisticated hearing aids incorporate an integrated circuit to control volume, either manually or automatically, or to switch to volume contours designed for various listening environments, such conversations on the telephone or where excessive background noise is present.

Speech acoustics. With the advent of the computer age, speech synthesis moved to digital processing, either by bandwidth compression of stored speech or by using a speech synthesizer. The synthesizer reads a text and then produces the appropriate phonemes on demand from their basic acoustic parameters, such as the vibration frequency of the vocal cords and the frequencies and amplitudes of the vowel formants. This method of generating speech is considerably more efficient in terms of data storage than archiving a dictionary of prerecorded phrases.

Another important, and probably the most difficult, area of speech acoustics is the machine recognition of spoken language. When machine recognition programs are sufficiently advanced, the computer will be able to listen to a sentence in any reasonable dialect and produce a printed text of the utterance. Two basic recognition strategies exist, one dealing with words spoken in isolation and the other with continuous speech. In both cases, it is desirable to teach the computer to recognize the speech of different people through a training program. Because recognition of continuous speech is considerably more difficult than the identification of isolated words, very sophisticated pattern-matching models must be employed. One example of a machine recognition system is a word-driven dictation system that uses sophisticated software to process input speech. This system is somewhat adaptable to different voices and is able to recognize 30,000 words at a rate of 30 words per minute. The ideal machine recognition system would translate a spoken input language into another language in real time with correct grammar. Although some progress is being made, such a device has remained in the realm of speculative fantasy.

Musical acoustics. The importance of musical acoustics to manufacturers of quality instruments is apparent. During the last decades of the twentieth century, fundamental research led, for example, to vastly improved French horns, organ pipes, orchestral strings, and the creation of an entirely new family of violins.

Underwater sound. Applications for underwater acoustics include devices for underwater communication by acoustic means, remote control devices, underwater navigation and positioning systems, acoustic thermometers to measure ocean temperature, and echo sounders to locate schools of fish or other biota. Low-frequency devices can be used to explore the seabed for seismic research.

Although primitive measuring devices were developed in the 1920's, it was during the 1930's that sonar systems began incorporating piezoelectric transducers to increase their accuracy. These improved systems and their increasingly more sophisticated progeny became essential for the submarine warfare of World War II. After the war, theoretical advances in underwater acoustics coupled with computer technology have raised sonar systems to ever more sophisticated levels.

Noise. One system for abating unwanted sound is active noise control. The first successful application of active noise control was noise-canceling headphones, which reduce unwanted sound by using microphones placed in proximity to the ear to record the incoming noise. Electronic circuitry then generates a signal, exactly opposite to the incoming sound, which is reproduced in the earphones, thus canceling the noise by destructive interference. This system enables listeners to enjoy music without having to use excessive volume levels to mask outside noise and allows people to sleep in noisy vehicles such as airplanes. Because active noise suppression is more effective with low frequencies, most commercial systems rely on soundproofing the earphone to attenuate high frequencies. To effectively cancel high frequencies, the microphone and emitter would have to be situated adjacent to the user's eardrum, but this is not technically feasible. Active noise control is also being considered as a means of controlling low-frequency airport noise, but because of its complexity and expense, this is not yet commercially feasible.

Impact On Industry

Acoustics is the focus of research at numerous governmental agencies and academic institutions, as well as some private industries. Acoustics also plays an important role in many industries, often as part of product design (hearing aids and musical instruments) or as an element in a service (noise control consulting).

Government research. Acoustics is studied in many government laboratories in the United States, including the U.S. Naval Research Laboratory (NRL), the Air Force Research Laboratory (AFRL), the Los Alamos National Laboratory, and the Lawrence Livermore National Laboratory. Research at the NRL and the AFRL is primarily in the applied acoustics area, and Los Alamos and Lawrence Livermore are oriented toward physical acoustics. The NRL emphasizes fundamental multidisciplinary research focused on creating and applying new materials and technologies to maritime applications. In particular, the applied acoustics division, using ongoing basic scientific research, develops improved signal processing systems for detecting and tracking underwater targets. The AFRL is heavily invested in research on auditory localization (spatial hearing), virtual auditory display technologies, and speech intelligibility in noisy environments. The effects of high-intensity noise on humans, as well as methods of attenuation, constitute a significant area of investigation at this facility. Another important area of research is the problem of providing intelligible voice communication in extremely noisy situations, such as those encountered by military or emergency personnel using low data rate narrowband radios, which compromise signal quality.

Academic research. Research in acoustics is conducted at many colleges and universities in the United States, usually through physics or engineering departments, but, in the case of physiological and psychological acoustics, in groups that draw from multiple departments, including psychology, neurology, and linguistics. The Speech Research Laboratory at Indiana University investigates speech perception and processing through a broad interdisciplinary research program. The Speech Research Lab, a collaboration between the University of Delaware and the A. I. duPont Hospital for Children, creates speech synthesizers for the vocally impaired. A human speaker records a data bank of words and phrases that can be concatenated on demand to produce natural-sounding speech.

Academic research in acoustics is also being conducted in laboratories in Europe and other parts of the world. The Laboratoire d'Acoustique at the Université de Maine in Le Mans, France, specializes in research in vibration in materials, transducers, and musical instruments. The Andreyev Acoustics Institute of the Russian Acoustical Society brings together researchers from Russian universities, agencies, and businesses to conduct fundamental and applied research in ocean acoustics, ultrasonics, signal processing, noise and vibration, electroacoustics, and bioacoustics. The Speech and Acoustics Laboratory at the Nara Institute of Science and Technology in Nara, Japan, studies diverse aspects of human-machine communication through speech-oriented multimodal interaction. The Acoustics Research Centre, part of the National Institute of Creative Arts and Industries in New Zealand, is concerned with the impact of noise on humans. A section of this group, Acoustic Testing Service, provides commercial testing of building materials for their noise attenuation properties.

Industry and business. Many businesses (such as the manufacturers of hearing aids, ultrasound medical devices, and musical instruments) use acoustics in their products or services and therefore employ experts in acoustics. Businesses also are involved in many aspects of acoustic research, particularly controlling noise and facilitating communication. Raytheon BBN technologies (Cambridge, Massachusetts) has developed low data rate Noise Robust Vocoders (electronic speech synthesizers) that generate comprehensible speech at data rates considerably below other state-of-the-art devices. Acoustic Research Laboratories in Sydney, Australia, designs and manufactures specialized equipment for measuring environmental noise and vibration, in addition to providing contract research and development services.

Fascinating Facts About Acoustics

- Scientists have created an acoustic refrigerator, which uses a standing sound wave in a resonator to provide the motive power for operation. Oscillating gas particles increase the local temperature, causing heat to be transferred to the container walls, where it is expelled to the environment, cooling the interior.
- A cochlear implant, an electronic device surgically implanted in the inner ear, provides some hearing ability to those with damaged cochlea or those with congenital deafness. Because the implants use only about two dozen electrodes to replace 16,000 hair cells, speech sounds, although intelligible, have a robotic quality.
- MP3 files contain audio that is digitally encoded using an algorithm that compresses the data by a factor of about eleven but yields a reasonably faithful reproduction. The quality of sound reproduced depends on the data sampling rate, the quality of the encoder, and the complexity of the signal.
- Sound cannot travel through a vacuum, but it can travel four times faster through water than through air.
- The cocktail party effect refers to a person's ability to direct attention to one conversation at a time despite the many conversations taking place in the room.
- Continued exposure to noise over 85 decibels will gradually cause hearing loss. The noise level on a quiet residential street is 40 decibels, a vacuum cleaner 60-85, a leafblower 110, an ambulance siren 120, a rifle 163, and a rocket launching from its pad 180.

Careers and Course Work

Career opportunities occur in academia (teaching and research), industry, and national laboratories. Academic positions dedicated to acoustics are few, as are the numbers of qualified applicants. Most graduates of acoustics programs find employment in research-based industries in which acoustical aspects of products are important, and others work for government laboratories.

Although the subfields of acoustics are integrated into multiple disciplines, most aspects of acoustics can be learned by obtaining a broad background in a scientific or technological field, such as physics, engineering, meteorology, geology, or oceanography. Physics probably provides the best training for almost any area of acoustics. An electrical engineering major is useful for signal processing and synthetic speech research, and a mechanical engineering background is requisite for comprehending vibration. Training in biology is expedient for physiological acoustic research, and psychology course work provides essential background for psychological acoustics. Architects often employ acoustical consultants to advise on the proper acoustical design of concert halls, auditoriums, or conference rooms. Acoustical consultants also assist with noise reduction problems and help design soundproofing structures for rooms. Although background in architecture is not a prerequisite for becoming this type of acoustical consultant, engineering or physics is.

Acoustics is not a university major; therefore, specialized knowledge is best acquired at the graduate level. Many electrical engineering departments have at least one undergraduate course in acoustics, but most physics departments do not. Nevertheless, a firm foundation in classical mechanics (through physics programs) or a mechanical engineering vibration course will provide, along with numerous courses in mathematics, sufficient underpinning for successful graduate study in acoustics.

Social Context and Future Prospects

Acoustics affects virtually every aspect of modern life; its contributions to societal needs are incalculable. Ultrasonic waves clean objects, are routinely employed to probe matter, and are used in medical diagnosis. Cochlear implants restore people's ability to hear, and active noise control helps provide quieter listening environments. New concert halls are routinely designed with excellent acoustical properties, and vastly improved or entirely new musical instruments have made their debut. Infrasound from earthquakes is used to study the composition of Earth's mantle, and sonar is essential to locate submarines and aquatic life. Sound waves are used to explore the effects of structural vibrations. Automatic speech recognition devices and hearing aid technology are constantly improving.

Many societal problems related to acoustics remain to be tackled. The technological advances that made modern life possible have also resulted in more people with hearing loss. Environmental noise is ubiquitous and increasing despite efforts to design quieter machinery and pains taken to contain unwanted sound or to isolate it from people. Also, although medical technology has been able to help many hearing- and speech-impaired people, other individuals still lack appropriate treatments. For example, although voice generators exist, there is considerable room for improvement.

—George R. Plitnik, MA, PhD

Further Reading

Bass, Henry E., and William J. Cavanaugh, eds. *ASA at Seventy-five.* Melville, N.Y.: Acoustical Society of America, 2004. An overview of the history, progress, and future possibilities for each of the fifteen major subdivisions of acoustics as defined by the Acoustical Society of America.

Beyer, Robert T. *Sounds of Our Times: Two Hundred Years of Acoustics.* New York: Springer-Verlag, 1999. A history of the development of all areas of acoustics. Organized into chapters covering twenty-five to fifty years. Virtually all subfields of acoustics are covered.

Crocker, Malcolm J., ed. *The Encyclopedia of Acoustics.* 4 vols. New York: Wiley, 1997. A comprehensive work detailing virtually all aspects of acoustics.

Everest, F. Alton, and Ken C. Pohlmann. *Master Handbook of Acoustics.* 5th ed., New York: McGraw-Hill, 2009. A revision of a classic reference work designed for those who desire accurate information on a level accessible to the layperson with limited technical ability.

Rossing, Thomas, and Neville Fletcher. *Principles of Vibration and Sound.* 2d ed. New York: Springer-Verlag, 2004. A basic introduction to the physics of sound and vibration.

Rumsey, Francis, and Tim McCormick. *Sound and Recording: An Introduction.* 5th ed. Boston: Elsevier/Focal Press, 2004. Presents basic information on the principles of sound, sound perception, and audio technology and systems.

Strong, William J., and George R. Plitnik. *Music, Speech, Audio.* 3d ed. Provo, Utah: Brigham Young University Academic Publishing, 2007. A comprehensive text, written for the layperson, which covers vibration, the ear and hearing, noise, architectural acoustics, speech, musical instruments, and sound recording and reproduction.

Swift, Gregory. "Thermoacoustic Engines and Refrigerators." *Physics Today* (July, 1995): 22-28. Explains how sound waves may be used to create more efficient refrigerators with no moving parts.

Web Sites

Acoustical Society of America
http://asa.aip.org

Institute of Noise Control Engineering
http://www.inceusa.org

International Commission for Acoustics
http://www.icacommission.org

National Council of Acoustical Consultants
http://www.ncac.com

See also: Applied Physics; Communication; Noise Control; Pattern Recognition.

AERONAUTICS AND AVIATION

FIELDS OF STUDY

Algebra; calculus; inorganic chemistry; organic chemistry; physical chemistry; optics; modern physics; statics; aerodynamics; thermodynamics; strength of materials; propulsion; propeller and rotor theory; vehicle performance; aircraft design; avionics; orbital mechanics; spacecraft design.

SUMMARY

Aeronautics is the science of atmospheric flight. Aviation is the design, development, production, and operation of flight vehicles. Aerospace engineering extends these fields to space vehicles. Transonic airliners, airships, space launch vehicles, satellites, helicopters, interplanetary probes, and fighter planes are all applications of aerospace engineering.

KEY TERMS AND CONCEPTS

- **airfoil:** Structure, such as a wing or a propeller, designed to interact, in motion, with the surrounding airflow in a manner that optimizes the desired reaction, whether that be to minimize air resistance or to maximize lift.
- **boundary layer:** Thin region near a surface of an aircraft where the flow slows down because of viscous friction.
- **bypass ratio:** Ratio of turbofan engine mass flow rate bypassing the hot core, to that through the core.
- **Delta V:** Speed difference corresponding to the difference in energies between two orbital states.
- **fuselage:** Body of an aircraft, other than engines, wings, tails, or control surfaces.
- **lift to drag ratio:** Ratio of the lift to drag in cruise; the aerodynamic efficiency metric for transport aircraft and gliders.
- **oblique shock:** Thin wave in a supersonic flow through which flow turns and decelerates sharply.
- **Prandtl-Meyer expansion:** Ideal model of a supersonic flow accelerating through a turn.
- **stall:** Condition in which flow separates from most of a lifting surface, sharply lowering lift and raising drag.
- **takeoff gross weight:** Mass or weight of an aircraft at takeoff with full payload and fuel load; the highest design weight for liftoff.
- **wind tunnel:** Facility where a smooth, uniform flow helps simulate flow around an object in flight.
- **wing:** Object that generates lift with low drag and supports the weight of the aircraft in flight.

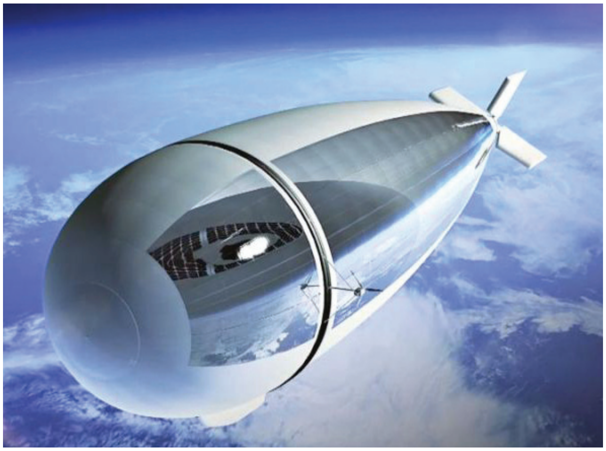
Definition and Basic Principles

Aeronautics is the science of atmospheric flight. The term ("aero" referring to flight and "nautics" referring to ships or sailing) originated from the activities of pioneers who aspired to navigate the sky. These early engineers designed, tested, and flew their own creations, many of which were lighter-than-air balloons. Modern aeronautics encompasses the science and engineering of designing and analyzing all areas associated with flying machines.

Aviation (based on the Latin word for "bird") originated with the idea of flying like the birds using heavier-than-air vehicles. "Aviation" refers to the field of operating aircraft, while the term "aeronautics" has been superseded by "aerospace engineering," which specifically includes the science and engineering of spacecraft in the design, development, production, and operation of flight vehicles.

A fundamental tenet of aerospace engineering is to deal with uncertainty by tying analyses closely to what is definitely known, for example, the laws of physics and mathematical proofs. Lighter-than-air airships are based on the principle of buoyancy, which derives from the law of gravitation. An object that weighs less than the equivalent volume of air experiences a net upward force as the air sinks around it.

Two basic principles that enable the design of heavier-than-air flight vehicles are those of aerodynamic lift and propulsion. Both arise from Sir Isaac Newton's second and third laws of motion. Aerodynamic lift is a force perpendicular to the direction of motion, generated from the turning of flowing air around an object. In propulsion, the reaction to the acceleration of a fluid generates a force that propels an object, whether in air or in the vacuum of space. Understanding these principles allowed aeronauts to design vehicles that could fly steadily despite being much heavier than the air they



Lighter than air geostationary airship telecommunications satellite

displaced and allowed rocket scientists to develop vehicles that could accelerate in space. Spaceflight occurs at speeds so high that the vehicle's kinetic energy is comparable to the potential energy due to gravitation. Here the principles of orbital mechanics derive from the laws of dynamics and gravitation and extend to the regime of relativistic phenomena. The engineering sciences of building vehicles that can fly, keeping them stable, controlling their flight, navigating, communicating, and ensuring the survival, health, and comfort of occupants, draw on every field of science.

Background and History

The intrepid balloonists of the nineteenth century were followed by aeronauts who used the principles of aerodynamics to fly unpowered gliders. The Wright brothers demonstrated sustained, controlled, powered aerodynamic flight of a heavier-than-air aircraft in 1903. The increasing altitude, payload, and speed capabilities of airplanes made them powerful weapons in World War I. Such advances improved flying skills, designs, and performance, though at a terrible cost in lives.

The monoplane design superseded the fabric-and-wire biplane and triplane designs of World War I. The helicopter was developed during World War II and quickly became an indispensable tool for medical evacuation and search and rescue. The jet engine, developed in the 1940's and used on the Messerschmitt 262 and Junkers aircraft by the Luftwaffe and the Gloster Meteor by the British, quickly enabled flight in the stratosphere at speeds sufficient to generate enough lift to climb in the thin air. Such innovations led to smooth, long-range flights in pressurized cabins and shirtsleeve comfort. Fatal crashes of the de Havilland Comet airliner in 1953 and 1954 focused attention on the science of metal fatigue.

The Boeing 707 opened up intercontinental air travel, followed by the Boeing 747, the supersonic Concorde, and the EADS Airbus A380. A series of manned research aircraft designated X-planes since the 1930's investigated various flight regimes and also drove the development of better wind tunnels and high-altitude simulation chambers. German ballistic missiles led to U.S. and Soviet missile programs that grew into a space race, culminating in the first humans landing on the Moon in 1969. Combat-aircraft development enabled advances that resulted in safer and more efficient airliners.

How it Works

Force balance in flight. Five basic forces acting on a flight vehicle are aerodynamic lift, gravity, thrust, drag, and centrifugal force. For a vehicle in steady level flight in the atmosphere, lift and thrust balance gravity (weight) and aerodynamic drag. Centrifugal force due to moving steadily around the Earth is too weak at most airplane flight speeds but is strong for a maneuvering aircraft. Aircraft turn by rolling the lift vector toward the center of curvature of the desired flight path, balancing the centrifugal reaction due to inertia. In the case of a vehicle in space beyond the atmosphere, centrifugal force and thrust counter gravitational force.

Aerodynamic lift. Aerodynamics deals with the forces due to the motion of air and other gaseous fluids relative to bodies. Aerodynamic lift is generated perpendicular to the direction of the free stream as the reaction to the rate of change of momentum of air turning around an object, and, at high speeds, to compression of air by the object. Flow turning is accomplished by changing the angle of attack of the surface, by using the camber of the surface in subsonic flight, or by generating vortices along the leading edges of swept wings.

Propulsion. Propulsive force is generated as a reaction to the rate of change of momentum of a fluid moving through and out of the vehicle. Rockets carry all of the propellant onboard and accelerate it out through a nozzle using chemical heat release, other heat sources, or electromagnetic fields. Jet engines "breathe" air and accelerate it after reaction with fuel. Rotors, propellers, and fans exert lift force on the air and generate thrust from the reaction to this force. Solar sails use the pressure of solar radiation to push large, ultralight surfaces.

Static stability. An aircraft is statically stable if a small perturbation in its attitude causes a restoring aerodynamic moment that erases the perturbation. Typically, the aircraft center of gravity must be ahead of the center of pressure for longitudinal stability. The tails or canards help provide stability about the different axes. Rocket engines are said to be stable if the rate of generation of gases in the combustion chamber does not depend on pressure stronger than by a direct proportionality, such as a pressure exponent of 1.

Flight dynamics and controls. Static stability is not the whole story, as every pilot discovers when the airplane drifts periodically up and down instead of holding a steady altitude and speed. Flight dynamics studies the phenomena associated with aerodynamic loads and the response of the vehicle to control surface deflections and engine-thrust changes. The study begins with writing the equations of motion of the aircraft resolved along the six degrees of freedom: linear movement along the longitudinal, vertical and sideways axes, and roll, yaw, and pitch rotations about them. Maneuvering aircraft must deal with coupling between the different degrees of freedom, so that roll accompanies yaw, and so on.

The autopilot system was an early flight-control achievement. Terrain-following systems combine information about the terrain with rapid updates, enabling military aircraft to fly close to the ground, much faster than a human pilot could do safely. Modern flight-control systems achieve such feats as reconfiguring control surfaces and fuel to compensate for damage and engine failures; or enabling autonomous helicopters to detect, hover over, and pick up small objects and return; or sending a space probe at thousands of kilometers per hour close to a planetary moon or landing it on an asteroid and returning it to Earth. This field makes heavy use of ordinary differential equations and transform techniques, along with simulation software.

Orbital missions. The rocket equation attributed to Russian scientist Konstantin Tsiolkovsky related the speed that a rocket-powered vehicle gains to the amount and speed of the mass that it ejects. A vehicle launched from Earth's surface goes into a trajectory where its kinetic energy is exchanged for gravitational potential energy. At low speeds, the resulting trajectory intersects the Earth, so that the vehicle falls to the surface. At high enough speeds, the vehicle goes so far so fast that its trajectory remains in space and takes the shape of a continuous ellipse around Earth. At even higher kinetic energy levels, the vehicle goes into a hyperbolic trajectory, escaping Earth's orbit into the solar system. The key is thus to achieve enough tangential speed relative to Earth. Most rockets rise rapidly through the atmosphere so that the acceleration to high tangential speed occurs well above the atmosphere, thus minimizing air-drag losses.

Hohmann transfer. Theoretically, the most efficient way to impart kinetic energy to a vehicle is impulsive launch, expending all the propellant instantly so that no energy is wasted lifting or accelerating propellant with the vehicle. Of course, this would destroy any vehicle other than a cannonball, so large rockets use gentle accelerations of no more than 1.4 to 3 times the acceleration due to gravity. The advantage of impulsive thrust is used in the Hohmann transfer maneuver between different orbits in space. A rocket is launched into a highly eccentric elliptical trajectory. At its highest point, more thrust is added quickly. This sends the vehicle into a circular orbit at the desired height or into a new orbit that takes it close to another heavenly body. Reaching the same final orbit using continuous, gradual thrust would require roughly twice as much expenditure of energy. However, continuous thrust is still an attractive option for long missions in space, because a small amount of thrust can be generated using electric propulsion engines that accelerate propellant to extremely high speeds compared with the chemical engines used for the initial ascent from Earth.

Applications and Products

Aerospace structures. Aerospace engineers always seek to minimize the mass required to build the vehicle but still ensure its safety and durability. Unlike buildings, bridges, or even (to some degree) automobiles, aircraft cannot be made safer merely by making them more massive, because they must also be able to overcome Earth's gravity. This exigency has driven development of new materials and detailed, accurate methods of analysis, measurement, and construction. The first aircraft were built mostly from wood frames and fabric skins. These were superseded by all-metal craft, constructed using the monocoque concept (in which the outer skin bears most of the stresses). The Mosquito high-speed bomber in World War II reverted to wood construction for better performance. Woodworkers learned to align the grain (fiber direction) along the principal stress axes. Metal offers the same strength in all directions for the same thickness. Composite structures allow fibers with high tensile strength to be placed along the directions where strength is needed, bonding different layers together.

Aeroelasticity. Aeroelasticity is the study of the response of structurally elastic bodies to aerodynamic loads. Early in the history of aviation, several mysterious and fatal accidents occurred wherein pieces of wings or tails failed in flight, under conditions where the steady loads should have been well below the strength limits of the structure. The intense research to address these disasters showed that beyond some flight speed, small perturbations in lift, such as those due to a gust or a maneuver, would cause the structure to respond in a resonant bending-twisting oscillation, the perturbation amplitude rapidly rising in a "flutter" mode until structural failure occurred. Predicting such aeroelastic instabilities demanded a highly mathematical approach to understand and apply the theories of unsteady aerodynamics and structural dynamics. Modern aircraft are designed so that the flutter speed is well above any possible speed achieved. In the case of helicopter rotor blades and gas turbine engine blades, the problems of ensuring aeroelastic stability are still the focus of leading-edge research. Related advances in structural dynamics have enabled development of composite structures and of highly efficient turbo machines that use counter-rotating stages, such as those in the F135 engines used in the F-35 Joint Strike Fighter. Such advances also made it possible for earthquake-surviving high-rise buildings to be built in cities such as San Francisco, Tokyo, and Los Angeles, where a number of sensors, structural-dynamics-analysis software, and actuators allow the correct response to dampen the effects of earth movements even on the upper floors.

Smart materials. Various composite materials such as carbon fiber and metal matrix composites have come to find application even in primary aircraft structures. The Boeing 787 is the first to use a composite main spar in its wings. Research on nano materials promises the development of materials with hundreds of times as much strength per unit mass as steel. Another leading edge of research in materials is in developing high-temperature or very low-temperature (cryogenic) materials for use inside jet and rocket engines, the spinning blades of turbines, and the impeller blades of liquid hydrogen pumps in rocket engines. Single crystal turbine blades enabled the development of jet engines with very high turbine inlet temperatures and, thus, high thermodynamic efficiency. Ceramic designs that are not brittle are pushing turbine inlet temperatures even higher. Other materials are "smart," meaning they respond actively in some way to inputs. Examples include piezoelectric materials.

Wind tunnels and other physical test facilities. Wind tunnels, used by the Wright brothers to develop airfoil shapes with desirable characteristics, are still used heavily in developing concepts and proving the performance of new designs, investigating causes of problems, and developing solutions and data to validate computational prediction techniques. Generally, a wind tunnel has a fan or a high-pressure reservoir to add work to the air and raise its stagnation pressure. The air then flows through means of reducing turbulence and is accelerated to the maximum speed in the test section, where models and measurement systems operate.

The power required to operate a wind tunnel is proportional to the mass flow rate through the tunnel and to the cube of the flow speed achieved. Low-speed wind tunnels have relatively large test sections and can operate continuously for several minutes at a time. Supersonic tunnels generally operate with air blown from a high-pressure reservoir for short durations. Transonic tunnels are designed with ventilating slots to operate in the difficult regime where there may be both supersonic waves and subsonic flow over the test configuration. Hypersonic tunnels require heaters to avoid liquefying the air and to simulate the high stagnation temperatures of hypersonic flight and operate for millisecond durations. Shock tubes generate a shock from the rupture of a diaphragm, allowing high-energy air to expand into stationary air in the tube. They are used to simulate the extreme conditions across shocks in hypersonic flight. Many other specialized test facilities are used in structural and materials testing, developing jet and rocket engines, and designing control systems.

Avionics and navigation. Condensed from the term "aviation electronics," the term "avionics" has come to include the generation of intelligent software systems and sensors to control unmanned aerial vehicles (UAVs), which may operate autonomously. Avionics also deals with various subsystems such as radar and communications, as well as navigation equipment, and is closely linked to the disciplines of flight dynamics, controls, and navigation.

During World War II, pilots on long-range night missions would navigate celestially. The gyroscopes in their aircrafts would spin at high speed so that their inertia allowed them to maintain a reference position as the aircraft changed altitude or accelerated. Most modern aircraft use the Global Positioning System (GPS), Galileo, or GLONASS satellite constellations to obtain accurate updates of position, altitude, and velocity. The ordinary GPS signal determines position and speed with fair accuracy. Much greater precision and higher rates of updates are available to authorized vehicle systems through the differential GPS signal and military frequencies.

Gravity assist maneuver. Yuri Kondratyuk, the Ukrainian scientist whose work paved the way for the first manned mission to the moon, suggested in 1918 that a spacecraft could use the gravitational attraction of the moons of planets to accelerate and decelerate at the two ends of a journey between planets. The Soviet Luna 3 probe used the gravity of the Moon when photographing the far side of it in 1959. American mathematician Michael Minovitch pointed out that the gravitational pull of planets along the trajectory of a spacecraft could be used to accelerate the craft toward other planets. The Mariner 10 probe used this "gravitational slingshot" maneuver around Venus to reach Mercury at a speed small enough to go into orbit around Mercury. The Voyager missions used the rare alignment of the outer planets to receive gravitational assists from Jupiter and Saturn to go on to Uranus and Neptune, before doing another slingshot around Jupiter and Saturn to escape the solar system. Gravity assist has become part of the mission planning for all exploration missions and even for missions near Earth, where the gravity of the Moon is used.

Impact on Industry

Aeronautics and aviation have had an immeasurable impact on industry and society. Millions of people fly long distances on aircraft every day, going about their business and visiting friends and relatives, at a cost that is far lower in relative terms than the cost of travel a century ago.

Every technical innovation developed for aeronautics and aviation finds its way into improved industrial products. Composite structural materials are found in everything from tennis rackets to industrial machinery. Bridges, stadium domes, and skyscrapers are designed with aerospace structural-element technology and structural-dynamics instrumentation and testing techniques. Electric power is generated in utility power plants using steam generators sharing jet engine turbo machine origins.

Satellite antennae are found everywhere. Much digital signal processing, central to digital music and cell phone communications, came from research projects driven by the need to extract low-level signatures buried in noise. Similarly, image-processing algorithms that enable computed tomography (CT) scans of the human body, eye and cardiac diagnostics, image and video compression, and laser printing came from aerospace image-processing projects. The field of geoinformatics has advanced immensely, with most mapping, navigation, and remote-sensing enterprises assuming the use of space satellites. The GPS has spawned numerous products for terrestrial drivers on land and navigators on the ocean. Aerospace medicine research has developed advances in diagnosing and monitoring the human body and its responses to acceleration, bone marrow loss, muscular degeneration, and their prevention through exercise, hypoxia, radiation protection, heart monitoring, isolation from microorganisms, and drug delivery. Teflon coatings developed for aerospace products are also used in cookware.

Careers and Course Work

Aerospace engineers work on problems that push the frontiers of technology. Typical employers in this Aeronautics and Aviation industry are manufacturers of aircraft or their parts and subsystems, airlines, government agencies and laboratories, and the defense services. Many aerospace engineers are also sought by financial services and other industries seeking those with excellent quantitative (mathematical and scientific) skills and talents.

University curriculum generally starts with a year of mathematics, physics, chemistry, computer graphics, computer science, language courses, and an introduction to aerospace engineering, followed by sophomore-year courses in basic statics, dynamics, materials, and electrical engineering. Core courses include low-speed and high-speed aerodynamics, linear systems analysis, thermodynamics, propulsion, structural analysis, composite materials, vehicle performance, stability, control theory, avionics, orbital mechanics, aeroelasticity and structural dynamics, and a two-semester sequence on capstone design of flight vehicles. High school students aiming for such careers should take courses in mathematics, physics, chemistry and natural sciences, and computer graphics. Aerospace engineers are frequently required to write clear reports and present complex issues to skeptical audiences, which demands excellent communication skills. Taking flying lessons or getting a private pilot license is less important to aerospace engineering, as exhilarating as it is, and should be considered only if one desires a career as a pilot or astronaut.

The defense industry is moving toward using aircraft that do not need a human crew and can perform beyond the limits of what a human can survive, so the glamorous occupation of combat jet pilot may be heading for extinction. Airline pilot salaries are also coming down from levels that compared with surgeons toward those more comparable to bus drivers. Aircraft approach, landing, traffic management, emergency response, and collision avoidance systems may soon become fully automated and will require maneuvering responses that are beyond what a human pilot can provide in time and accuracy.

Opportunities for spaceflight may also be minimal unless commercial and military spaceflight picks up to fill the void left by the end of civilian programs discussed below. This is not a unique situation in aviation history. Early pilots, even much later than the intrepid “aeronauts,” also worked much more for love of the unparalleled experience of flying, rather than for looming prospects of high-profile careers or the salaries paid by struggling startup airline companies. The only reliable prediction that can be made about aerospace careers is that they hold many surprises.

Social Context and Future Prospects

Airline travel is under severe stress in the first part of the twenty-first century. This is variously attributed to airport congestion, security issues, rising fuel prices, predatory competition, reduction of route monopolies, and leadership that appears to offer little vision beyond cost cutting. Meanwhile, the demand for air travel is rising all over the world. Global demand for commercial airliners is estimated at nearly 30,000 aircraft through 2030 and is valued at more than $3.2 trillion—in addition to 17,000 business jets valued at more than $300 billion.

Detailed design and manufacturing of individual aircraft are distributed between suppliers worldwide, with the wings, tails, and engines of a given aircraft often designed and built in different parts of the world. Japan and China are expected to increase their aircraft manufacturing, while major U.S. companies appear to be moving more toward becoming system integrators and away from manufacturing.

The human venture in space is also under stress as the U.S. space shuttle program ends without another human-carrying vehicle to replace it. The future of the one remaining space station is in doubt, and there are no plans to build another.

On the other hand, just over one century into powered flight, the human venture into the air and beyond is just beginning. Aircraft still depend on long runways and can fly only in a very limited range of conditions. Weather delays are still common because of uncertainty about how to deal with fluctuating winds or icing conditions. Most airplanes still consist of long tubes attached to thin wings, because designing blended wing bodies is difficult with the uncertainties in modeling composite structures. The aerospace and aviation industry is a major generator of atmospheric carbon releases. This will change only when the industry switches to renewable hydrogen fuel, which may occur faster than most people anticipate.

The human ability to access, live, and work in space or on extraterrestrial locations is extremely limited, and this prevents development of a large space-based economy. This situation may be expected to change over time, with the advent of commercial space launches. New infrastructure will encourage commercial enterprises beyond Earth.

The advancements in the past century are truly breathtaking and bode well for the breakthroughs that one may hope to see. Hurricanes and cyclonic storms are no longer surprise killers; they are tracked from formation in the far reaches of the oceans, and their paths are accurately predicted, giving people plenty of warning. Crop yields and other resources are accurately tracked by spacecraft, and ground-penetrating radar from Earth-sensing satellites has discovered much about humankind's buried ancient heritage and origins. Even in featureless oceans and deserts, GPS satellites provide accurate, reliable navigation information. The discovery of ever-smaller distant planets by orbiting space telescopes, and of unexpected forms of life on Earth, hint at the possible discovery of life beyond Earth.

—Narayanan M. Komerath, PhD

Further Reading

Anderson, John D., Jr. *Introduction to Flight.* 5th ed. New York: McGraw-Hill, 2005. This popular textbook, setting developments in a historical context, is derived from the author's tenure at the Smithsonian Air and Space Museum.

Bekey, Ivan. *Advanced Space System Concepts and Technologies, 2010-2030+.* Reston, Va.: American Institute of Aeronautics and Astronautics, 2003. Summaries of various advanced concepts and logical arguments used to explore their feasibility.

Design Engineering Technical Committee. *AIAA Aerospace Design Engineers Guide.* 5th ed. Reston, Va.: American Institute of Aeronautics and Astronautics, 2003. A concise book of formulae and numbers that aerospace engineers use frequently or need for reference.

Gann, Ernest K. *Fate Is the Hunter.* 1961. Reprint. New York: Simon and Schuster, 1986. Describes an incident that was the basis for a 1964 film of the same name. Autobiography of a pilot, describing the early days of commercial aviation and coming close to the age of jet travel.

Hill, Philip, and Carl Peterson. *Mechanics and Thermodynamics of Propulsion.* 2d ed. Upper Saddle River, N.J.: Prentice Hall, 1991. A classic textbook on propulsion that covers the basic science and engineering of jet and rocket engines and their components. Also gives excellent sets of problems with answers.

Jenkins, Dennis R. *X-15: Extending the Frontiers of Flight.* NASA SP-2007-562. Washington, D.C.: U.S. Government Printing Office, 2007. Contains various copies of original data sheets, memos, and pictures from the days when the X-15 research vehicle was developed and flown.

Lewis, John S. *Mining the Sky: Untold Riches from the Asteroids, Comets and Planets.* New York: Basic Books, 1997. The most readable answer to the question "What resources are there beyond Earth to make exploration worthwhile?" Written from a strong scientific background, it sets out the reasoning to estimate the presence and accessibility of extraterrestrial water, gases, minerals, and other resources that would enable an immense space-based economy.

Liepmann, H. W., and A. Roshko. *Elements of Gas Dynamics.* Mineola, N.Y.: Dover Publications, 2001. A textbook on the discipline of gas dynamics as applied to high-speed flow phenomena. Contains several photographs of shocks, expansions, and boundary layer phenomena.

O'Neill, Gerard K. *The High Frontier: Human Colonies in Space.* 3d ed. New York: William Morrow & Company, 1977. Reprint. Burlington, Ontario, Canada: Apogee Books, 2000. Sets out the logic, motivations, and general parameters for human settlements in space. This formed the basis for NASA/ASEE (American Society for Engineering Education) studies in 1977-1978 and beyond, to investigate the design of space stations for permanent habitation. Fascinating exposition of how ambitious concepts are systematically analyzed and engineering decisions are made on how to achieve them, or why they cannot yet be achieved.

Peebles, Curtis. *Road to Mach 10: Lessons Learned from the X-43A Flight Research Program.* Reston, Va.: American Institute of Aeronautics and Astronautics, 2008. A contemporary experimental flight-test program description.

Web Sites

Aerospace Digital Library
http://www.adl.gatech.edu

American Institute of Aeronautics and Astronautics
http://www.aiaa.org

Jet Propulsion Laboratory A Gravity Assist Primer
http://www2.jpl.nasa.gov/basics/grav/primer.php