Elements of aviation acoustics

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CONTENTS

PREFACE

ABOUT THE CONTENTS

Quieting cabin and flight deck noise, and reducing the impact of noise on conunununities near airports are matters of great importance to air-manufacturers and airline operators for already more than four decades.

Undoubtedly, knowledge of both aeronautics and acoustics is essential for a clear understanding of any aviation noise problem. Such understandmg is a necessary prerequisite to the control of interior and exterior noise.

In view of the importance of education in dealing with noise control, this book is devoted to the branch of aerospace engineering known as aviation acoustics.

The book contains twelve chapters and three appendixes which originate from an annual course on airplane noise given by the author to aerospace engineering students at Delft University of Technology (DUT).

The book is intended to be useful to undergraduate students of aerospace engineering, and also to researchers and practicing engineers who wish to improve their understanding of the topic.

The text assumes little or no previous knowledge of acoustics. For this reason, the first chapter introduces basic facts and concepts about the generation, propagation and specification of sound. The second chapter describes the dynamics of sound waves. Since acoustics can be seen as a fluid mechanics discipline, this chapter starts with deriving the three basic equations of classical aerodynamic theory. These equations are then linearized to obtain their acoustic equivalents and combined into a single wave equation. Also the solutions of plane and spherical wave propagation are presented.

The third chapter develops the free-field radiation properties of the three principal sources of sound, i.e., the acoustic monopole, dipole, and quadrupole. In Chapter the manner four is considered in which the propagation of sound away from the source is influenced by distance, atmospheric absorption losses, and refractive conditions due to vertical wind and temperature gradients. Also a procedure for the determination of atmospheric attenuation rate has been included.

Chapter five outlines, in a concise form, the types of sound field occurring in enclosures and the absorption of sound energy by the walls. Chapter six briefly describes the attenuation of sound in ducts provided by cross-sectional area changes and wall cavities. In Chapter seven certain practical aspects of ftequency analysis are treated, and Chapter eight is concerned with the effects of ground reflection on observed noise levels.

Chapter nine deals with the subjective assessment of airplane noise. The chapter is supplemented by Appendix A, providing data for the calculation of the perceived noisiness of sounds.

A review of the international standards and reconmended practices for civil aircraft as published in Annex 16 to the Chicago Convention on International Civil Aviation is given in Chapter ten.

The effects of forward motion on the radiation characteristics of a sound source is the subject of discussion in Chapter eleven. This chapter also includes sections on sonic boom and microphone selection.

The concluding chapter (12) examines the various noise sources found on the different types of airplane.

Experimental results throughout the book are presented in order to illustrate the basic theory enunciated in the text.

References to the literature are indicated in the text and listed at the end of the text. In the book the International System of Units (Système International d'Unités) is used. Besides these metric units, in international civil aviation the use of certain English units is prescribed, such as foot for altitude, and so these are also cited in the text.

In Appendix B information is given about the SI-units. Also a number of factors with which English units can be converted into metric SI-units are tabulated.

In bringing the book to a close, a glossary of terms that appear in the text are collected in Appendix F.

ACKNOWLEDGMENTS

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Delft, The Netherlands
G.J.J. Ruijgrok 15 July 1993

This second edition includes three new appendices C, D and E, that describe the assessment of aircraft noise in the vicinity of Dutch airfields, an improved method for the prediction of lateral noise attenuation and existing noise abatement procedures, respectively.

Also the errors found in the first edition have been corrected.

Delft, The Netherlands
G.J.J. Ruijgrok 1 August 2000

The Greek alphabet

NAME	SMALL LETTER	CAPITAL	NAME	SMALL LETTER	CAPITAL
alpha (a)	α	Α	nu (n)	ν	Ν
beta (b)	β	Β	xi (ks)	ξ	Ξ
gamma (g)	γ	Γ	omicron (o)	ο	Ο
delta (d)	δ	Δ	pi (p)	π (ϖ)	Π
epsilon (e)	ε (ϵ)	Ε	rho (r)	ρ (ϱ)	Ρ
zeta (z)	ζ	Ζ	sigma (s)	σ	Σ
eta (e)	η	Η	tau (t)	τ	Τ
theta (th)	θ (ϑ)	Θ	upsilon (y)	υ	Υ
iota (i)	ι	Ι	phi (ph)	ϕ (φ)	Φ
kappa (k)	κ (ϰ)	Κ	chi (ch)	χ	Χ
lambda (l)	λ	Λ	psi (ps)	ψ	Ψ
mu (m)	μ	Μ	omega (o)	ω	Ω

Standard multiples and decimal fractions

MULTIPLE / FRACTION	PREFIX	SYMBOL
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

1 BASIC FACTS

1.1 INTRODUCTION

Sound is a physical disturbance in the air, produced by a sound source. If the disturbance reaches a listener, a sound is heard.

Mostly we appreciate sound. It enables conversation and many other forms of communication. Sound furnishes pleasant experiences such as listening to music. It also permits us to evaluate the condition of man and machine, and to make diagnoses.

On the contrary, sound can be undesired and annoying when it interferes with specific activities such as speech communication and recreation.

It also can induce stress and prevent sleep, it can produce irritation, disturb concentration, and it can cause a decrement in human performance. There are indications that exposure to intense sound may be a contributing factor to physical illness. Repeated exposure to very intense sound can even harm the human ear, leading to a temporary or permanent loss of hearing. In all these cases it is called *noise*, accepting the definition of noise as *sound that is unwanted by the observer*. This definition emphasizes the admitted fact that noise is a subjective phenomenon. In other words, the question or a given sound is experienced as noise and what its level of annoyance is, is influenced by personal feelings and depends also on our attitude toward the source.

Since the number of noise sources is continually increasing in our technological society, it has become necessary to control and reduce the noise levels to which we are subjected in every day life.

In aeronautical engineering, obviously, we are faced with two kinds of noise problems; (a) flight deck and cabin noise (*interior noise*) of which the control is required as an element in providing a safe and comfortable environment for crew and passengers, and (b) community noise impact as one of the most serious problems of aircraft operations (*exterior noise*).

Aviation noise introduces a complex problem that consists of three main parts; (1) the production of noise by the aircraft (*the source*), (2) the propagation of noise through the atmosphere and the influences of obstacles and/or ground surface on sound propagation (the transmission path), and (3) the effect of noise on man, the reactions of the occupants of the airplane and the people working at or living in the vicinity of civilian airports and military airfields (*the receivers of the noise*).

A clear appreciation of the nature of these component parts is a prerequisite to a sensible approach and subsequent process of finding an adequate answer to the various noise problems as related to aviation.

A complicating factor is that we are concerned with many types of aircraft which all have their own noise radiation characteristics, and which are heard under various atmospheric, meteorological and terrain conditions. We also have to consider the many kinds of people and the many kinds of reaction from each individual.

The aim of this book is to treat the most important theories, quantities and procedures necessary for describing the features of emission, propagation and reception of aviation noise. In preparing the text, emphasis has been placed on those noise problems that are related to the operations of airplanes. By definition, an airplane is a mechanically driven aircraft, heavier than air, which is supported chiefly by aerodynamic reaction forces on surfaces which remain fixed under given conditions of flight.

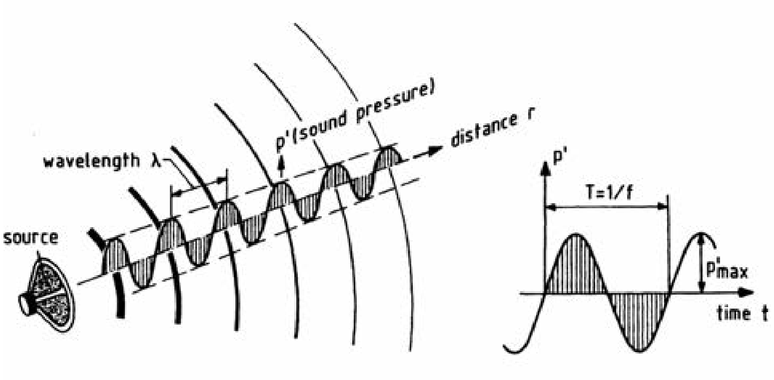
As little previous knowledge of the subject is assumed, some basic concepts of acoustics will be introduced subsequently in this first chapter.

1.2 SOUND AND SOUND WAVES

A sound source sets the nearest particles of air into vibration through which acoustic energy is transmitted from the source to the surrounding air. The movement gradually spreads to air particles further away from the source since energy is transferred from one vibrating particle to the next.

Thus sound is a form of energy which propagates through the air as progressive waves, as illustrated in Figure 1.2-1a.

Sound generally travels in longitudinal waves in which the particle displacements take place in the same direction as the movement of the wave. The region in



a. effect of distance b. effect of time

Figure 1.2-1. Progressive sound waves

which the wave travels is termed the *sound field*. In a space where the sound waves can propagate freely without reflection they are termed *free progressive waves* traveling in a *free field*.

The motion of the air particles about their equilibrium position produces a local compression followed by a local rarefaction and so on. The instantaneous value of the fluctuating pressure disturbance on the ambient pressure is called the *sound pressure* and is given the symbol p'.

The action of the pressure variations on the eardrum of a listener produces neural impulses in the inner ear, which are transmitted to the brain, where they are experienced as a hearing sensation.

The oscillating line in Figure 1.2-1b represents a periodic variation of the local sound pressure with time. The time history of the sound pressure repeats itself exactly. Each unique sequence of variations is a cycle. The time required to complete one cycle is the *period T*. In symbols:

$$p'(t) = p'(t+T) \quad .$$

The number of oscillations per second is the *frequency f* of the disturbance expressed in terms of cycles per second (cps) or more recently referred to as *Hertz*, abbreviated Hz.

Clearly the frequency is the reciprocal of the period,

$$f = \frac{1}{T} \quad . \tag{1.2-1}$$

At low frequencies the air particles oscillate slowly producing low or bass tones. At high frequencies the air particles vibrate quickly giving high tones (Figure 1.2-2).

The frequencies audible to the human ear may range from about 20 Hz to 20,000 Hz.

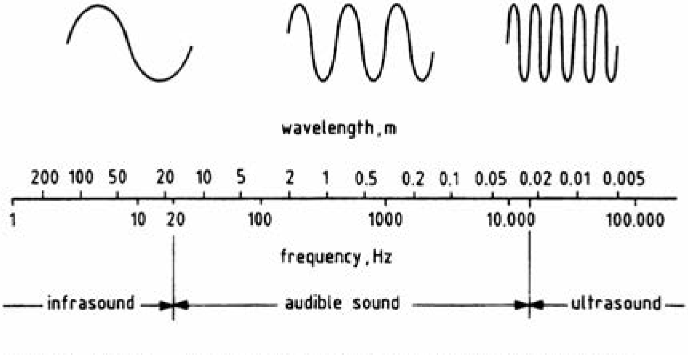


Figure 1.2-2. Frequency and wavelength (0 m I.S.A.)

The inaudible sound with frequencies under 20 Hz is named *infrasound*. Sound over 20,000 Hz which is also normally inaudible is termed *ultrasound*.
Especially the highest perceptible frequency decays with age. However, it appears that, independent of age, frequencies higher than ca 11,000 Hz hardly contribute to the *loudness*, i.e., the way in which a listener reacts to a sound in terms of how quiet or how loud. Moreover, it is known that the great majority of sound sources radiate very little energy in the frequency range above 11,000 Hz.

The sound pressure variation in Figure 1.2-1b may have the form of a sinusoid. An oscillation that can be described by the sine function is called *simple harmonic motion*.
Generally, the sound pressure is a function of both time and distance from the source,

$$p' = p'(r,t) \quad , \tag{1.2-2}$$

where r is the distance from the acoustic center of the source.
Returning to Figure 1.2-1a, we see that in the sound field around the source the acoustic energy spreads out in all directions through which the *peak value* or *amplitude* of the sound pressure decreases as the distance from the source increases.
Anticipating later derivations in Chapter 2, for simple harmonic motion of a point sound source, the variations of the sound pressure with time and distance can be expressed as

$$p'(r,t) = \frac{A}{r}\cos\omega(t - r/c) \quad , \tag{1.2-3}$$

where A is the strength of the source and ω the angular frequency in radians per second, $\omega = 2\pi f$. The ratio A/r is the amplitude of the local sound pressure.
Since the pressure disturbance propagates with the speed c, the time r/c is taken for the sound wave to travel to a point at distance r from the source.
For this reason, the pressure variations reaching a distance r at time t are determined by a value of p' at an earlier time $(t - r/c)$.
Noting that $\cos x + i \sin x = e^{ix}$, alternatively, we can write

$$p'(r,t) = Re\left[\frac{A}{r}e^{i\omega(t-r/c)}\right] \quad , \tag{1.2-4}$$

where Re stands for the real part. Normally, however, this prefix is dropped.
Using this complex notation for the sound pressure has the advantage that it is easier to manipulate mathematically than the trigonometric notation of Equation (1.2-3).

As depicted in Figure 1.2-1b, the magnitude of a sound signal can be expressed by the amplitude, p'_{max}, of the instantaneous sound pressure. However, the most often used measure of magnitude is the *effective (sound) pressure*, which is the *root-mean-square* value of the instantaneous sound pressures over one period or an integral number of periods at the point under consideration,

$$p_e = \left[\frac{1}{T} \int_0^T [p'(t)]^2 \, \mathrm{d}t \right]^{1/2} \quad . \tag{1.2-5}$$

Using Equation (1.2-3) we find

$$p_e = \left[\frac{1}{T} \int_0^T \left[\frac{A}{r} \cos \omega (t - r/c) \right]^2 \mathrm{d}t \right]^{1/2} = \frac{A}{r\sqrt{2}} \quad . \tag{1.2-6}$$

Equation (1.2-6) shows that for a sinusoidally varying sound pressure the amplitude of the sound pressure and the effective pressure are simply related by the factor $\sqrt{2} = 1.414$. This ratio is known as the *crest factor* of a sound signal.

The rate at which the pressure disturbance travels through the medium is the *speed of sound* c. In air we have

$$c = \sqrt{\gamma R T} \quad , \tag{1.2-7}$$

where $\gamma = c_p/c_v = 1.4$ is the *ratio of the specific heats of air*, $R = 287.05$ $\mathrm{m^2/s^2K}$ is the *specific gas constant* and T is the *ambient temperature* in kelvin. At a sea-level temperature of 15°C = 288.15 K the speed of sound is 340.29 m/s.

The *wavefronts* pictured in Figure 1.2-1a are imaginary surfaces around the source which are the loci of points having the same particle displacements at a given instant.

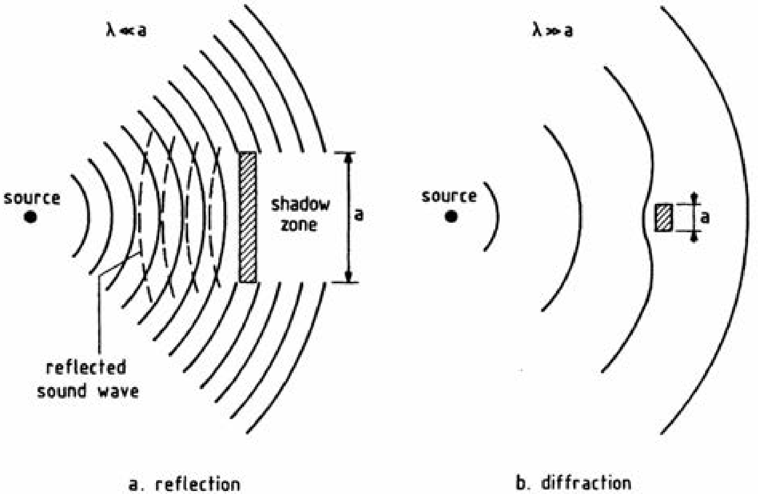
The perpendicular distance between two wavefronts is the *wavelength*, which is thus the distance that a sound wave travels in one period. Using the symbol λ to denote the wavelength, we can write

$$\lambda = cT = \frac{c}{f} \quad . \tag{1.2-8}$$

The directions in which the wave propagates are given by the *sound rays*, which are the imaginary curves directed normally to the wavefronts. The relationship between wavelength and frequency for the speed of sound under standard sea-level conditions is shown in the previous Figure 1.2-2.

Wavelength is a meaningful acoustic quantity. For example, sound having a wavelength much smaller than the size of an obstacle is strongly affected by the presence of the obstacle. The sound will be reflected or scattered in many directions and the obstacle will cast a so-called *shadow zone*. This is suggested in Figure 1.2-3a, where the dashed lines indicate sound reflected back from the obstacle. Thus barriers and screens are effective against high frequency (short-wavelength) sound. If the wavelength is large in comparison with the size of the obstacle the wave behaves almost as if the obstacle does not exist. As sketched in Figure 1.2-3b, the sound will be bent round the obstacle. Hence low frequency (large-wavelength) sound diffuses round obstacles and through holes without losing energy, so barriers and screens are not very effective against it unless they are very large.
In this connection we have the requirement that, when measuring sound, the microphone should be as small as possible. Moreover, a microphone must be designed to compensate for the disturbance caused by its own presence in the sound field.

Acoustic measurements often require the presence of so-called *free-field conditions*, which imply the nonattendance of reflections from obstacles and wall or ground surfaces. For this aim, special rooms have been designed



a. reflection b. diffraction

Figure 1.2-3. Sound wave passing an obstacle in which the sound absorptive construction of the interior surfaces is such that practically no sound is reflected from them. These rooms are called *free-field chambers* or *anechoic chambers*. Rooms having a high wall absorption, but which are not completely echo-free, may be called *dead rooms*.

1.3 DIFFRACTION

As everyone knows, sound can be heard round corners and behind walls. Therefore, it is certainly not true to say that sound waves always travel in straight line.

This bending of sound waves round obstacles is called *diffraction*, and a diffractive wave is thus a sound wave whose wavefront has been changed in direction by an object in the sound field.

As was indicated already in the previous section, bending occurs when the wavelength of the sound is comparable to the dimensions of the obstacle.

Since the wavelength of audible sound varies from about one centimeter to several meters, the wavelength has always the same order of magnitude as the usual objects. For this reason, diffraction effects must be taken into account, even for sound of shorter wavelength.

In order to explain the bending of sound rays, one uses the method of wavefront construction according to the *principle of Huygens*.

As sketched in Figure 1.3-1, Huygens theory states that every vibrating point on a wavefront becomes the origin of a new disturbance. The secondary waves, traveling with the speed of sound, are enveloped by a surface identical in its properties with the wavefront from which the secondary disturban-

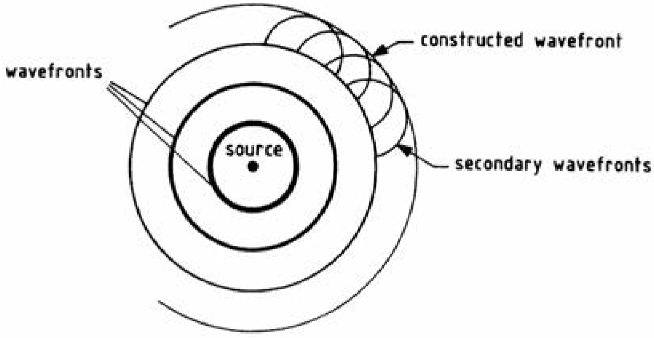


Figure 1.3-1. Huygen's construction of wavefront

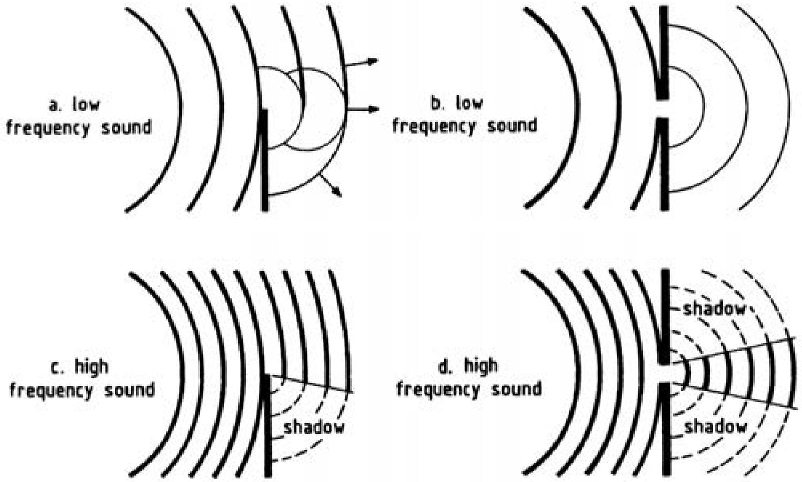


Figure 1.3-2. Effects of diffraction

ces start and this surface forms a new overall wavefront. This implies that each next position of a wavefront can be established from a preceding.

In the case that a solid barrier is placed in the sound field, as in Figure 1.3-2a, we see that secondary waves also provide for a spreading of the sound energy into the space behind the barrier.

Clearly, the sound pressures at a point in the shadow zone are less than they would have been, if the object had been not present.

Figure 1.3-2b indicates what happens when the sound meets a wall with an opening in it. Now the hole acts as were it a new source, radiating spherical sound waves, but with lower sound pressures.

Naturally, the amount of bending, i.e., the distance into the shadow region for which the diffraction produces noticeable effects, depends on the dimensions of the object relative to the wavelength (the frequency) of the sound. Low frequency sound diffuses completely round edges and through holes, whereas high frequency sound forms a more intensive shadow beyond a barrier (Figures 1.3-2c and 1.3-2d).

1.4 REFRACTION

Bending of the sound also occurs when there are *temperature* and *wind gradients* in the atmosphere. According to Equation (1.2-7), the speed of sound depends on the temperature of the air. In an isothermal atmosphere the