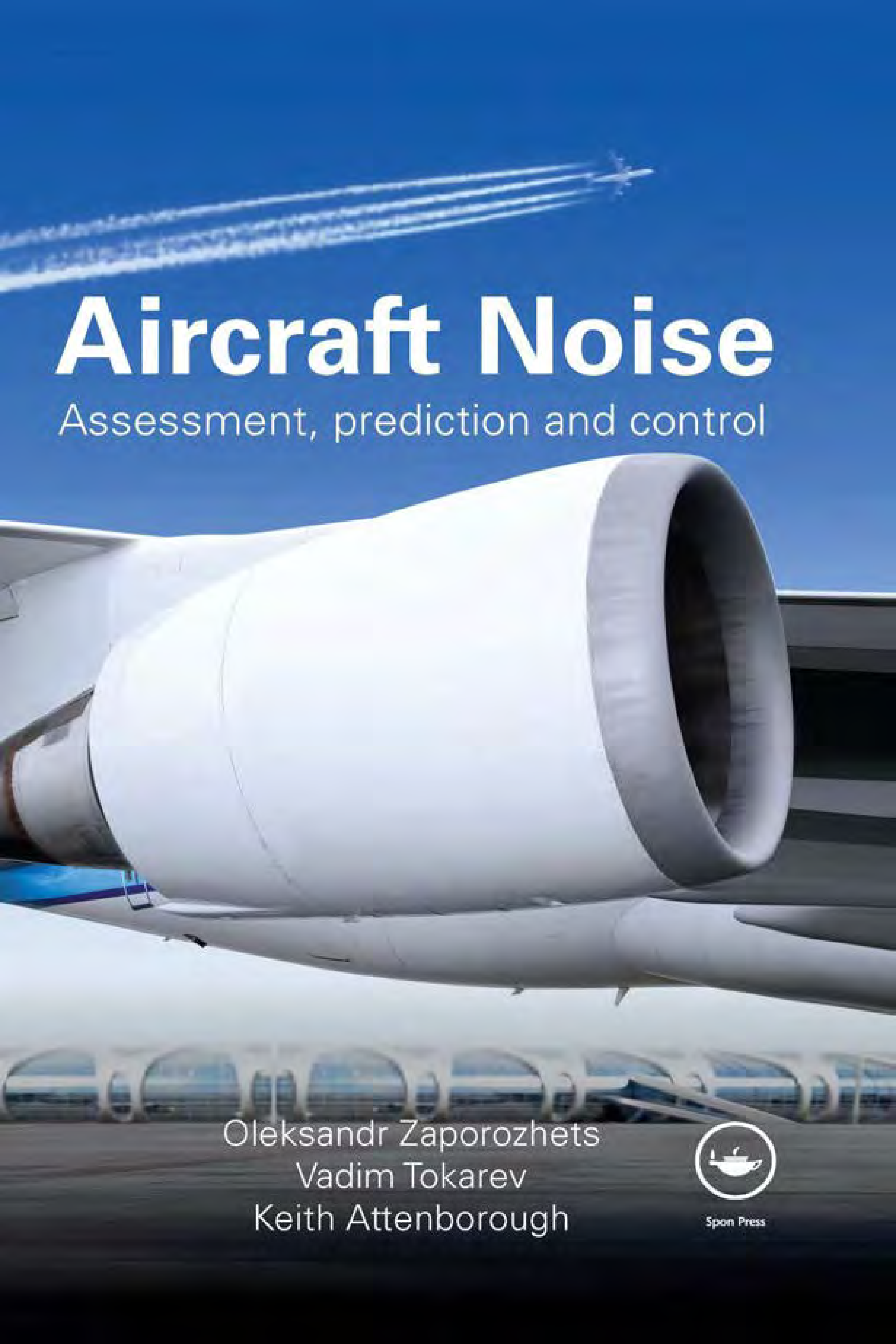

Aircraft Noise

Assessment, prediction and control

Oleksandr Zaporozhets
Vadim Tokarev
Keith Attenborough

Spon Press

Aircraft Noise

Aircraft noise has adverse impacts on passengers, airport staff and people living near airports, it thus limits the capacity of regional and international airports throughout the world. Reducing perceived noise of aircraft involves reduction of noise at source, along the propagation path and at the receiver.

Effective noise control demands highly skilled and knowledgeable engineers. This book is for them. It shows you how accurate and reliable information about aircraft noise levels can be gained by calculations using appropriate generation and propagation models, or by measurements with effective monitoring systems. It also explains how to allow for atmospheric conditions, natural and artificial topography as well as detailing necessary measurement techniques.

Oleksandr Zaporozhets was awarded a D.Sc. for a thesis on the 'Development of models and methods of information provision for environment protection from civil aviation impact' in October 1997 at the Kyiv International University of Civil Aviation and received a Ph.D, for a thesis on 'Optimization of aircraft operational procedures for minimum environment impact' in December 1984 from the Kiev Institute of Civil Aviation Engineers. Jointly with Dr Tokarev, he was awarded a silver medal for achieving successes in the development of the national economy of the USSR in 1987. Currently he is a full Professor at the National Aviation University of the Ukraine.

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Preface

The motivation to write this book arises from over 40 years of investigations by Oleksandr Zaporozhets and Vadim Tokarev into aviation noise sources and into the technical, ecological, economical and social consequences of their impact on environment. The book also reflects these authors' experience over more than 30 years of teaching undergraduate and graduate courses within the framework of the 'Acoustic Ecology' curriculum at the National Aviation University, Ukraine, including modules on the physical factors that impact the environment, methods of biosphere protection and on environmental noise monitoring. The book contains results of research into aircraft noise modeling (including particular issues relating to aircraft noise propagation), assessment of the efficiency of operational methods of aviation noise reduction, flight planning for minimizing aircraft noise and monitoring of environmental conditions in the vicinities of airports.

The experience of these authors in applied aviation acoustics has been the result of collaborations with many scientific organizations including the State Research Center of the Central Aerohydrodynamic Institute (Moscow), the State Scientific Institute of Civil Aviation (Moscow) and the Aviation Design Offices of Tupolev, Il'ushin (Moscow) and Antonov (Kyiv). Consequently, many of the resulting publications are in Russian and in Ukrainian.

First attempts at writing a systematic overview of the subject of aircraft noise in English were made for a special issue of *Applied Acoustics* published in 1998 and for the final report of the NATO project 'Aircraft noise forecasting' (NATO grant EST.CLG.974767). The latter project also provided the impetus for the subsequent collaborations between the authors based in the Ukraine and Keith Attenborough in the UK. Although the scientific collaboration among the three authors has primarily influenced the contents of Chapters 3 and 6, Attenborough has also contributed by intensive editing of the use of English in the other chapters.

The book places equal emphasis on theory and on practical applications. The authors consider that the text differs in scope from the available texts on same topic [e.g. *Aeroacoustics of Flight Vehicles – Theory and Practice. Vol. 1, Noise Sources, Vol. 2, Noise Control* (1995), edited by H.H. Hubbard, Acoustical Society of America, Woodbury, NY, and *Transportation Noise Reference Book* (1987) edited by P.M. Nelson, Butterworths, UK] in that attention is given to operational and maintenance aspects of aircraft noise assessment and noise reduction methodology. The application of low noise operational procedures provides often neglected opportunities for noise reduction around the airports. This text provides the techniques and scientific basis that will allow for successful modeling and analysis of operational methods for aircraft noise reduction as well as the methods of control at source that are more usually considered.

It is also recognized that noise from aircraft is only part of the noise-associated problem around an airport. Mitigation of airport noise must be investigated as a problem of urban or rural soundscape. The methodology advocated in this text for decreasing the impact of aviation noise is based on a complex approach to a problem of noise reduction around the airports, which is considered as a physical process *and* as a phenomenon of social hygiene, sometimes with economic consequences. The approach to aircraft noise management in the vicinity of an airport used in the book corresponds to the balanced approach advocated by the International Civil Aviation Organization.

An important contribution of the book is to demonstrate how optimization of the control of aircraft noise through operational measures can increase the environmental capacity of the airport, particularly in cases where, otherwise, environmental constraints would reduce the operational and economic capacities of the airport. The basic theme of Chapter 1 of the book follows from the results of research on aviation noise in relation to airport noise capacity. The airport noise capacity is represented by the maximum number of aircraft that can be operated during a given period so that total aircraft noise levels do not exceed a prescribed limitation in critical zones around an airport. The capacity of an airport is a function of many different factors and aspects of airport infrastructure, including airfield layout (the number of runways, the extent of taxiways, apron development), the terminals and landsite facilities, air traffic control procedures, ground handling operations and meteorological conditions.

Aircraft are complex noise sources and a variety of noise protection methods can be employed around airports, including organizational, technical, operational and land-use methods. This is explained in Chapter 1 together with a presentation of the information about the basic noise sources on aircraft necessary for an understanding of the mechanisms of aviation noise generation.

Chapter 2 discusses models used to estimate the acoustical characteristics of the jets, fans, turbines, propellers and elements of the airframe. Parametrical investigations into the fundamental sources enable estimates of the influences of constructional and operational parameters on the overall acoustic fields due to aircraft.

Chapter 3 considers the physical phenomena involved in outdoor sound propagation under various operational conditions. These include atmospheric absorption, propagation over flat ground surfaces, over barriers, through trees, refraction by wind and temperature gradients and propagation through turbulence.

Chapter 4 explores methods for aircraft noise calculation, starting from an acoustic model for an aircraft as a whole. A model for predicting noise under the flight path is essential for operational purposes and for determining low-noise flight procedures. Models for predicting noise levels due to aircraft ground operations are important also for determining total airport noise. Some simplifications are introduced for predicting noise in the vicinity of the airport.

Using the models defined in Chapters 3 and 4, Chapter 5 investigates the influences of operational factors on aircraft noise characteristics at receivers on the ground and under the flight path. The optimal operational procedures for reducing noise impact are deduced for specific situations.

Chapter 6 reviews methods of aircraft noise reduction at source, along the sound propagation path and at the receiver, including the efficiency of acoustic screens for reducing noise from airport ground operations. The selection of optimal features of the operation scenario in the vicinity of the airport informs decision-making procedures for airport noise capacity control.

Chapter 7 introduces monitoring of aircraft noise as an essential tool for noise assessment and control around airports. The reasons for aircraft noise monitoring are operational, technical and economic. Current monitoring systems include powerful instrumentation and software, which besides recording noise levels must control the flight tracks, identify the type of noise source from each particular noise event, register noise complaints and measure meteorological parameters. To achieve effective mitigation of the impact of aviation noise on the environment, the interdependencies and trade-offs between noise and other important environmental factors associated with civil aviation, such as engine emission and third party risk, must be taken into account. It is shown that possible solutions may be reached by informational monitoring systems with the support of specifically predefined Aircraft Design Space, Flight Scenario Design Space and an Aviation Environmental Cost–Benefit Tool.

This book should be of interest to all those concerned with aircraft noise problems. After reading this book, the engineer, consultant or airport designer will be able to implement a balanced approach to airport noise management. This will include use of low noise operational procedures and the results of aircraft noise monitoring. The book should also be useful to those responsible for making or responding to decisions about the requirements for environmental control at airports. Although the book could be used as a reference text, it should be noted that the references listed at the end of the book are far from being exhaustive. Essentially, they contain only the references used in writing the book and reflect the particular questions considered by the authors. Nevertheless, by bringing together their many new scientific and practical results, the authors hope that the book's modern approach to aviation noise assessment and reduction will prove a useful addition to the literature.

Oleksandr Zaporozhets
Vadim Tokarev
Keith Attenborough

1 A review of the aircraft noise problem

1.1 Environmental impacts of airports

Aviation in the twenty-first century contributes to climate change, noise and air pollution. Together with various social and economic problems, environmental issues have the potential to constrain the operation and growth of airports. Constraints on airport capacity affect the capacity of the air navigation system as a whole. Many international airports are operating at their maximum, and some have already reached their operating limits including those resulting from environmental impact. This situation is expected to become more widespread as air traffic continues to increase. Already aircraft noise is a limiting factor for the capacity of regional and international airports throughout the world.

There are many definitions of airport capacity with regard to various issues: operational, flight safety, economic and environmental. The relative importance of each issue depends on the local, regional and national circumstances of each airport (see Fig. 1.1). Environmental capacity is the extent to which the environment is able to receive, tolerate, assimilate or process the outputs of aviation activity. Local environmental airport capacity can be expressed in terms of the maximum numbers of aircraft, passengers and freight accommodated during a given period under a particular environmental limitation and consistent with flight safety.[1,2] For example, the airport noise capacity is the maximum numbers of aircraft that can be operated during a given period so that total aircraft noise levels do not exceed a prescribed limitation in critical zones around an airport.

Aircraft noise is noise associated with the operation and growth of airports that impact upon local communities, in particular the nature and extent of noise exposure arising from aircraft operations. It is the single most significant contemporary environmental constraint, and is likely to become more severe in the future.

Local air quality is a capacity issue at some European airports, and is likely to become more widespread in the short to medium term. After aircraft noise, local air quality seems to be the next most significant environmental factor with the potential to constrain airport growth.

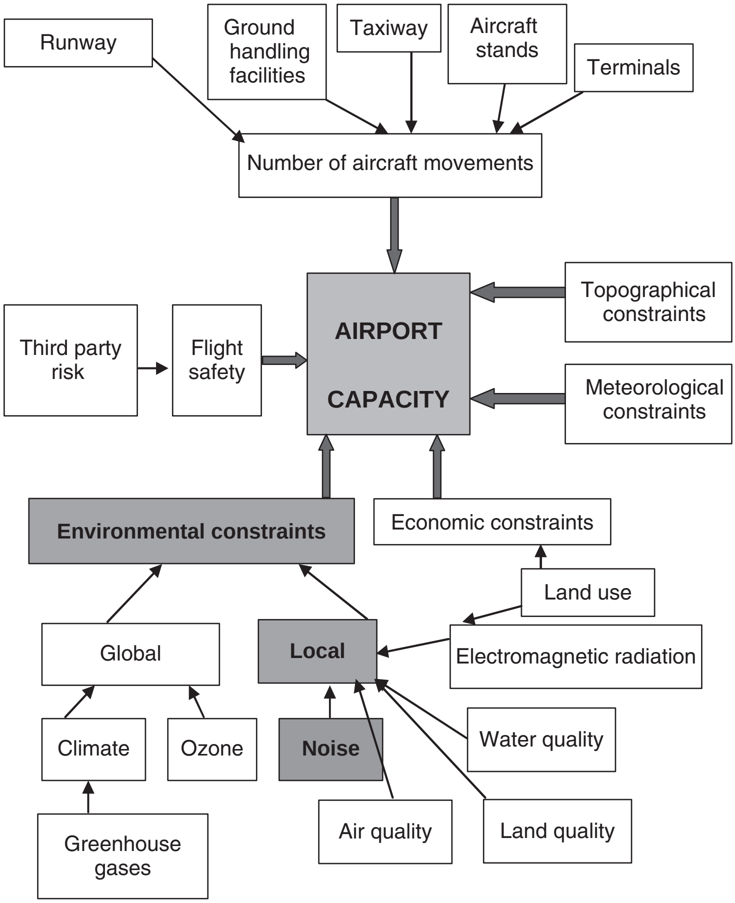

Figure 1.1 Environmental influences on airport capacity.

Third party risk is a potential future constraint for certain larger airports located close to built-up areas. The communities surrounding such airports are exposed to the small risk of an aircraft crash.

Water usage/pollution is both an existing and a potential constraint at certain European airports.

Surrounding land use and habitat value are both existing and potential constraints at a number of European airports.

Greenhouse gas emissions pose a potential constraint in the long term.

The capacity of an airport is a function of many different factors and the airport infrastructure, including the airfield layout (the number of runways, the extent of the taxiway, apron development), the terminals and landsite facilities, air traffic control procedures, ground handling operations and meteorological conditions. An individual airport capacity depends on the time between an aircraft landing and its leaving the airport, the ability of the airport to accept aircraft within a specified delay, the airport air traffic control system and its runway approach facilities.

In 2001, the International Civil Aviation Organization (ICAO) developed a balanced approach to noise management at airports. The balanced approach includes four elements: reduction at source, land-use planning and management, operational procedures for noise abatement and aircraft operational restrictions. The balanced approach has been applied to European airports by means of EU Directive 2002/30/EC concerning rules and procedures for introducing noise-related practices at airports. The noise mitigation measures should take into account specific features of the particular airport and the maximum achievable efficiency of suggested methods.

The potential to reduce noise at source is limited and land-use measures are difficult to implement in densely populated zones. Operational procedures which depend on pilot behavior may lead to a reduction in the level of flight safety. The growth of air traffic is faster than developments in new technologies and methods of noise reduction.

At present, only 2 per cent of the population is exposed to aircraft noise. This proportion should be compared with, for example, the 45 per cent of the population exposed to noise of road traffic and the 30 per cent to industrial noise. Nevertheless, ICAO analysis has suggested that there will be a 42 per cent increase in the number of people affected by aircraft noise in Europe by the year 2020.[3]

The noise produced by aircraft during operations in the areas around airports represents a serious social, ecological, technical and economic problem. Substantial levels of noise emission can bring about worsening of people's health, lowering their quality of life and lessening their productivity at work, through speech interference for example. In the areas around airports, aircraft noise has adverse influences on ground, maintenance and flight operations personnel, on passengers and on the local residential population. In abating aircraft noise, it is necessary to consider several criteria: ecological, technical, economic and social.

Methods of reducing aircraft noise have to take into account many requirements as follows:

1 Noise sources must be placed as far away as possible from built up areas.
2 Noise should be reduced to the lowest level achievable in a given case.
3 Noise abatement of aircraft involves several acoustic sources: jet exhaust stream, engine fan, turbine, combustion chamber, propellers (including the number of rotors and the tail rotor on a helicopter) and the airframe.
4 Since there are different types of aircraft in operation at an airport, the aircraft noise in the vicinity of the airport depends on the type of aircraft

in service, the number of flights by each type, the times of day and the meteorological conditions.

5 Propagation of sound from aircraft to a receiver involves direct transmission through air, reflection, diffraction and scattering from the surface of the Earth, screens and buildings, and through a turbulent and inhomogeneous atmosphere.
6 Apart from dwellings, there might be particularly noise sensitive receiver locations such as in laboratories, schools and hospitals. In developing measures for reducing noise around airports, it is necessary to take into account the short- and long-term forecasts of airport development.
7 There is a need for a balanced approach to engineering noise abatement practice from complex sources taking account not only noise levels but also the spectral characteristics at the receiver.
8 Noise abatement on aircraft can be realized at various stages including their design, manufacture, operation and repair. During operation, noise-reducing activities include reduction at the source, along the propagation path and at the receiver. The most cost-effective is to reduce noise at the source or at the design stage.[4]
9 Noise abatement requires identification of the noise sources, assessment of their contributions to the overall acoustic field and acquaintance with the accumulated knowledge of the effectiveness of available noise abatement methods.
10 The full costs associated with noise pollution (monitoring, management, lowering levels and supervision) should be met by those responsible for the noise.

Although aircraft are not the only sources of environmental noise around airports, they are the main ones. The working cycle of aircraft can be subdivided into starting engine operation, preflight engine run, taxiing to lineup, acceleration on the runway with full or reduced throttle, takeoff and roll-on, flight path, landing, run-on operation and engine run-up. The maximum noise levels are made during the acceleration on the runway, takeoff and roll-on. But these stages are of relatively short duration. Other periods of aircraft noise generation around an airport occur during engine testing, maintenance work, temporary repair and engine replacement after the end of their service life. Maintenance operations and engine run-ups have a long duration and take place at comparatively short distances in relation to surrounding residential zones, passengers and technical staff. So, although they involve lower levels than those from moving aircraft, noise from these ground operations must be considered.

The historical changes in priorities among the various operational factors during the development of civil aviation are indicated in Table 1.1.[5]

Although flight safety remains paramount in importance, currently the problems of flight operation of aircraft and environmental protection,

Table 1.1 Changes in priorities for civil aviation

1950–1970	*1970–1990*	*1990–2020*
Flight safety	Flight safety	Flight safety
Speed	Economic indexes	Environmental protection (including noise)
Range	Noise around airports	Resources
Economic indices	Regularity of operation	Regularity of operation
Comfort	Comfort	Economic indices
Regularity of operations	Speed	Comfort
Noise around airports	Range	Speed and range

including noise abatement, are combined. Noise abatement by operational measures involves additional pilot workloads for pilots and air traffic control and can result in additional operational costs for the aircraft operator. Aviation safety will always have priority over noise abatement operating measures. The pilot-in-charge will make the decision not to use low-noise flight procedures if it prejudices flight safety. For example, the pilot will ignore the demands of minimum noise impact under any kind of failure or shut-down of an engine, equipment failure or any other apparent loss of performance at any stage of takeoff. Noise abatement procedures in the form of reduced power takeoff should not be required in adverse operational conditions such as when the runway is not clear and dry, when horizontal visibility is less than 1.9 km, when a cross-wind component, including gusts, exceeds 28 km/h, when a tail-wind component, including gusts, exceeds 9 km/h, when wind shear has been reported or forecast or when thunderstorms are expected to affect approach or departure.

1.2 Description of aircraft noise

Aircraft are complex noise sources (see Fig. 1.2). So a variety of noise protection methods are employed around airports; including organizational, technical, operational and zoning methods. The main noise sources on an aircraft in flight are the power unit and the aerodynamic noise. Aerodynamic noise becomes particularly noticeable during the landing approach of heavy jet aircraft, when the engines are at comparatively low thrust.

The scientific basis for abating noise from aircraft relies on advances that have been made in aeroacoustics. Unlike classical acoustics (which is concerned mainly with the sound caused by oscillating surfaces), aeroacoustics investigates aerodynamic noise conditioned by turbulent non-stationary flow. Typically, jet aircraft noise sources include: jet noise, core noise, inlet and aft fan noise, turbine noise and airframe noise. Table 1.2 shows a classification of aircraft noise sources.

Usually third-octave band spectra are used for noise assessment of any type of aircraft in any mode of flight or during maintenance activities in the

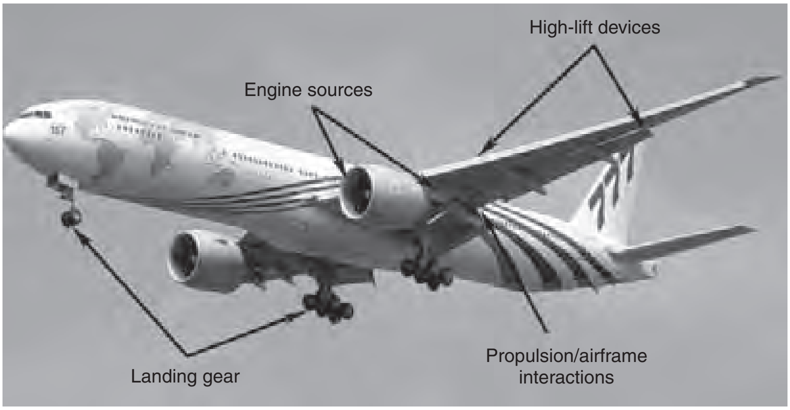

Figure 1.2 Aircraft noise sources.

Table 1.2 A classification of noise sources on aircraft

Aircraft class		*Main sources of noise*	
		Power-unit	*Airframe*
Aircraft – ordinary takeoff and landing	Turbojet	Jet, fan, core noise	Flap and wing trailing edges, flap side edges, slats, gear sources, fuselage and wing turbulent boundary layers
	Turboprop	Propeller, propfan, engine exhaust	
Aircraft – short takeoff and landing	Turbojet	Fan, engine exhaust	Interaction jet with flap
	Turboprop	Propeller	
Supersonic aircraft		Jet	Interaction of flow with frame
Helicopters		Blades of main rotor, engine exhaust	Not important
Aircraft of general aviation	Turbojet	Jet, fan	Not important
	Turboprop	Propeller, engine exhaust	

vicinity of the airport. In this case, the common computational procedure for the prediction of the aircraft noise under the flight path or around the aircraft on a ground (run-ups, taxiing, waiting for the takeoff along the runway) is based on the assumption that sound waves are spreading along the shortest distance between the aircraft and the point of noise control.

From measurement experience it can be argued that the acoustic field produced by an aircraft moving at constant altitude, speed, attitude and engine power setting through a uniform atmosphere represents a stationary random process. The acoustic signal received from a moving aircraft at a fixed microphone location, however, is clearly non-stationary. The characteristics of the spectrum of the received signal change because of the directionality of the source, spherical spreading, atmospheric absorption and refraction, Doppler effect and ground reflection and attenuation. The received acoustic signal can be assumed to be weakly stationary only over some sufficiently small time interval. However, use of too small analysis time intervals results in too few statistical degrees of freedom and poor confidence in the sound pressure level.

Any type of aircraft noise criterion or index is estimated from a set of noise spectra (in third-octave frequency bands from 50 to 10,000 Hz) and sample duration 0.5 s, that vary during the particular noise event or during any kind of noise exposure. Several methods of sound pressure filtering in the frequency domain are used. The most appropriate for aircraft noise analysis are the A-weighting correction, which gives a measure of the loudness, and the perceived noise calculation scheme, which gives a measure of the noisiness.

The jet and the fan are the main noise sources in a jet engine. Bypass engines have inner and outer contours. The bypass ratio (m) represents the ratio of air masses flowing through the outer and inner contours of the engine. On an engine with a high bypass ratio ($m > 3$), used typically for contemporary subsonic heavy aircraft, the fan is the predominant source of noise, spreading forward over the engine inlet and backwards over the fan exhaust system. On engines with a low bypass ratio ($m < 2$), such as those used on first-generation supersonic transport, jet noise is predominant. Increase in the bypass ratio lowers the contribution of jet noise to the total acoustic field of the engine and increases the contributions of fan and turbine noise.

A third-octave frequency band spectrum and an overall sound pressure level (OASPL) for an aircraft with a low bypass engine ($m = 1$) during takeoff engine mode measured at the lateral noise monitoring point 1 (450 m from the runway axis) are shown in Fig. 1.3. Figure 1.4 shows the measured noise characteristics of the same aircraft at the flyover noise monitoring measurement point 2 (6500 m from aircraft gear release on runway during takeoff). The engine mode is nominal. For the same aircraft, Fig. 1.5 shows the landing noise characteristics measured at the approach noise monitoring point 3, located 2000 m before runway edge. The engine mode is around 60 per cent of nominal thrust.

During takeoff (as measured at monitoring points 1, 2) the dominant aircraft engine noise source is the jet. During landing (at monitoring point 3) the dominant engine source is the fan in the high-frequency range and the jet and airframe (noise from flaps, gears, other airframe components) are dominant in the low-frequency range.

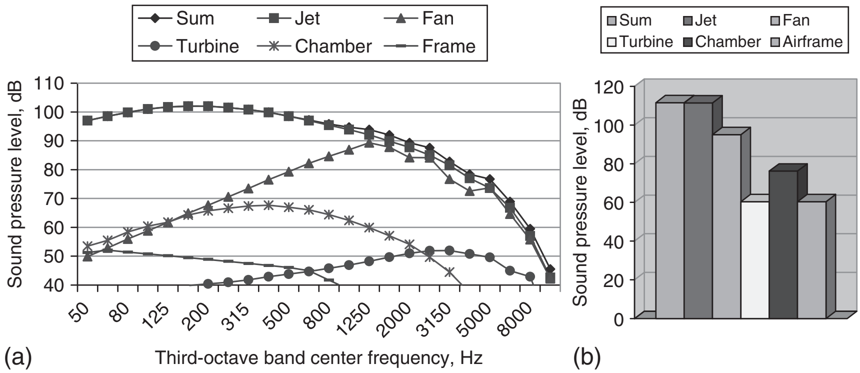

Figure 1.3 Noise source contributions for aircraft with low bypass ratio engines (bypass engine ratio, $m = 1$) at control point No. 1 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, ‘lateral attenuation’ neglected): (a) spectra; (b) overall sound level.

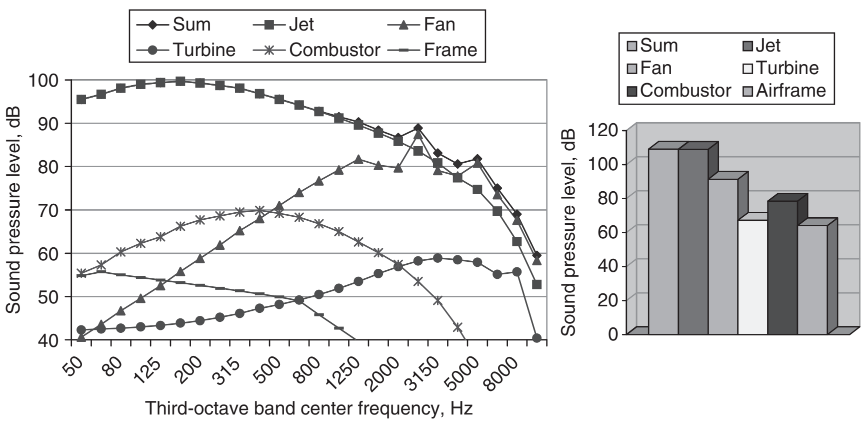

Figure 1.4 Noise source contributions for aircraft with low bypass ratio engines (bypass engine ratio, $m = 1$) at control point No. 2 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, ‘lateral attenuation’ neglected): (a) spectra; (b) overall sound level.

Noise characteristics of an aircraft with middle bypass ratio ($m \sim 2.5$) engines are shown in Figs 1.6–1.8 for noise monitoring points 1, 2 and 3 respectively. At takeoff (points 1, 2; Figs 1.6 and 1.7) the dominant noise sources of the aircraft are the jets (in the low-frequency range) and the fans (in the high-frequency range). During landing (monitoring point 3; Fig. 1.8) the dominant sources are the fans and the airframe.

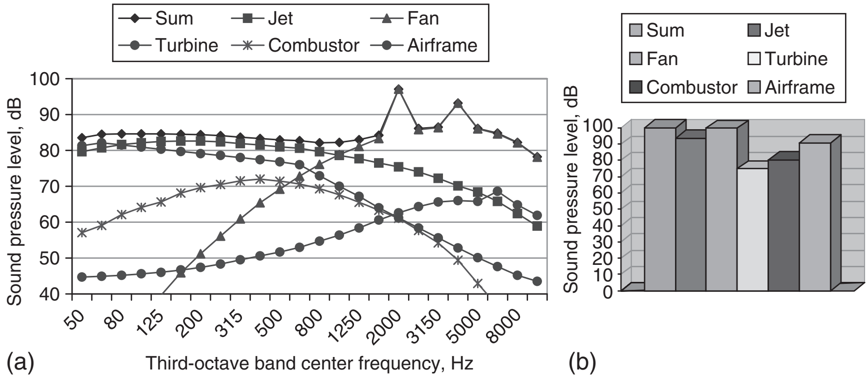

Figure 1.5 Noise source contributions for aircraft with low bypass ratio engines (bypass engine ratio, $m = 1$) at control point No. 3 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

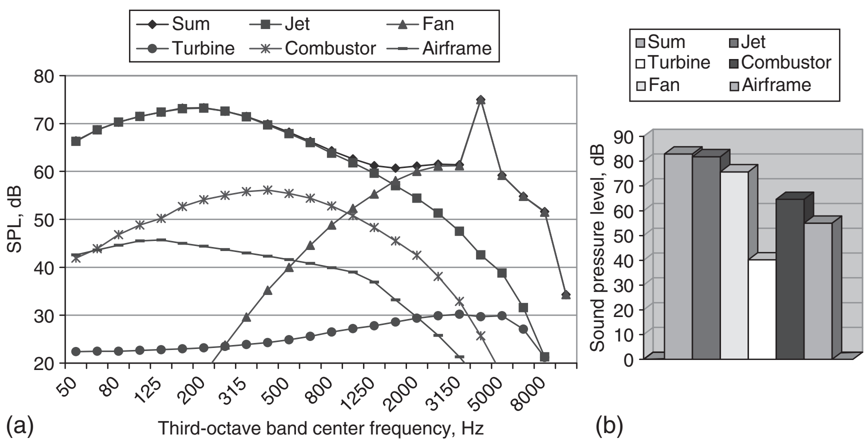

Figure 1.6 Noise source contributions for aircraft with intermediate bypass ratio engines (bypass ratio, $m = 2.5$) at control point No. 1 (take-off mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) Overall sound level

The noise characteristics of the aircraft with high bypass ratio ($m = 6$) engines are shown in Figs 1.9–1.11 for noise monitoring points 1, 2 and 3, respectively. During takeoff (points 1 and 2; Figs 1.9 and 1.10) the dominant noise sources (in the high-frequency range) on the aircraft are the fans, the combustion chambers of the engines and the airframe. During landing (point 3; Fig. 1.11) the dominant sources are the fans (in the high-frequency range), the airframe and the combustion chambers.

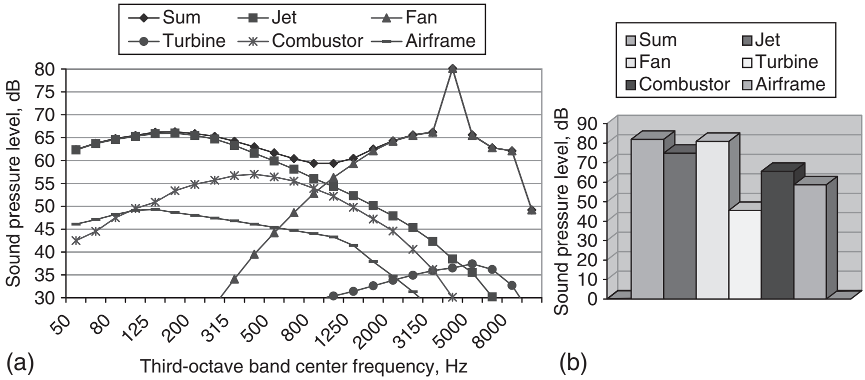

Figure 1.7 Noise source contributions for aircraft with intermediate bypass ratio engines (bypass ratio, $m = 2.5$) at control point No. 2 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

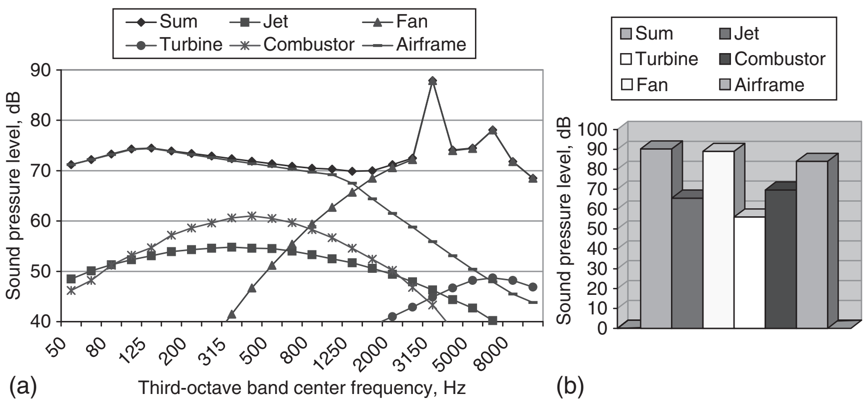

Figure 1.8 Noise source contributions for aircraft with intermediate bypass ratio engines (bypass ratio, $m = 2.5$) at control point No. 3 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

At present, attention is focused mainly on the noise reduction of engines with high bypass ratios ($m \geq 6$), since they are widely used. Consideration is given to possible design methods: optimization of fan, gas-dynamic and operation parameters on the basis of integrated aeroacoustic design and installation of intake and exhaust silencers.

The noise characteristics of an aircraft with turboprop engines are shown in Figs 1.12 and 1.13 corresponding to noise monitoring points 2 (Fig. 1.12) and 3 (Fig. 1.13). The use of third-octave frequency bands means that the

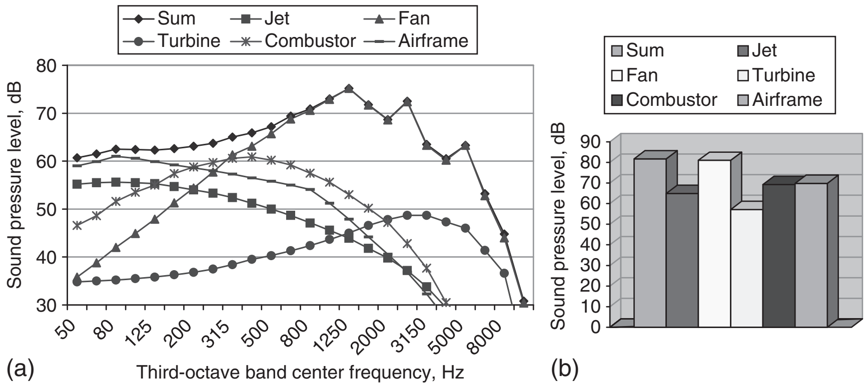

Figure 1.9 Noise source contributions for aircraft with high bypass ratio engines (bypass ratio, $m = 6$) at control point No. 1 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

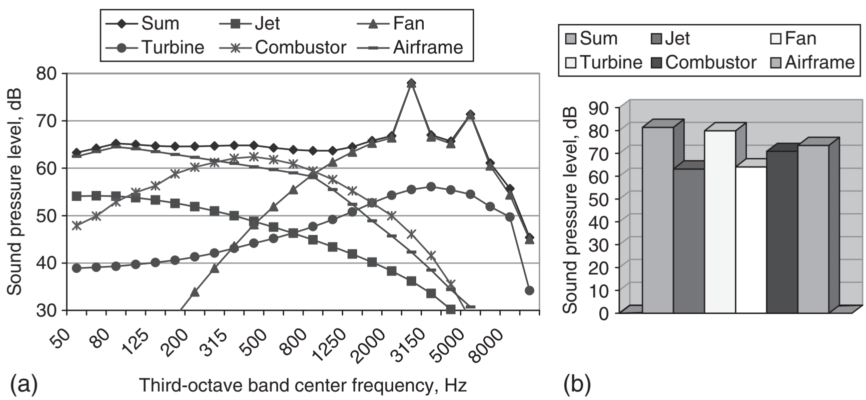

Figure 1.10 Noise source contributions for aircraft with high bypass ratio engines (bypass ratio, $m = 6$) at control point No. 2 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

broad band noise emission masks the discrete harmonics. During takeoff and landing the dominant noise sources on such aircraft are the propellers. Their noise levels exceed those from other sources by more than 10 dB.

Figure 1.14 shows the stages in the procedure for reducing aircraft noise at its source.

Turbulent airflow over the airfoil (corresponding to high speed and Reynolds number) results in radiation of aerodynamic noise. In turbulent flow one can distinguish the disturbances due to vorticity, entropy and

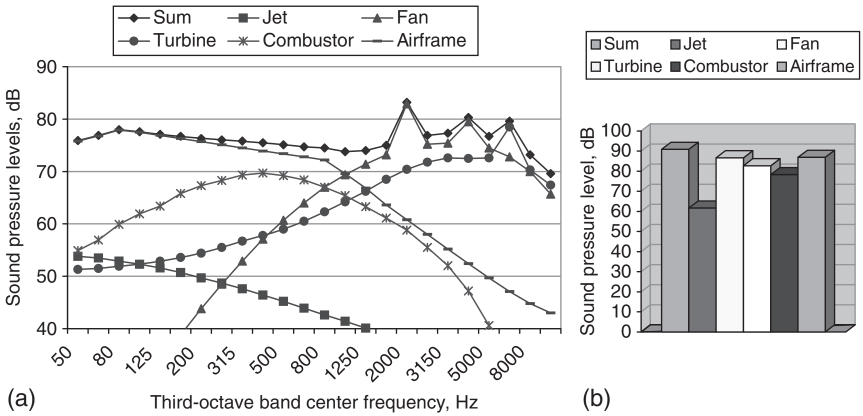

Figure 1.11 Noise source contributions for aircraft with high bypass ratio engines (bypass ratio, $m = 6$) at control point No. 3 (takeoff mass 160 t, distance 450 m, engine mode at maximum thrust, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

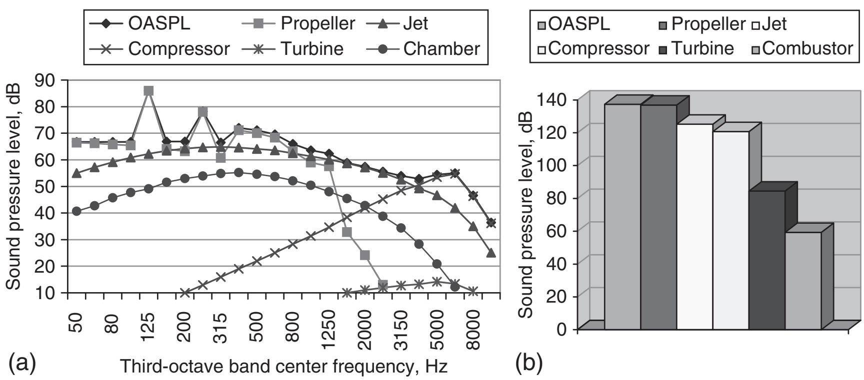

Figure 1.12 Noise source contributions for turboprop aircraft at control point No. 2 (takeoff mass 9.8 t, distance 300 m, engine mode – maximum, 'lateral attenuation' neglected): (a) spectra; (b) overall sound level.

sound. Interaction between these disturbances, described mathematically by non-linear equations, is determined by the turbulent flow structure and the acoustical field characteristics.

Radiation of the sound usually results from non-stationary flows, and separated flows associated with elements of the aircraft with imperfect aerodynamics. These destabilize the flow and a large part of the kinetic energy of the flow turns into energy of acoustic radiation. Table 1.3 lists some values of the acoustic efficiency η_a, which is the ratio of acoustic power

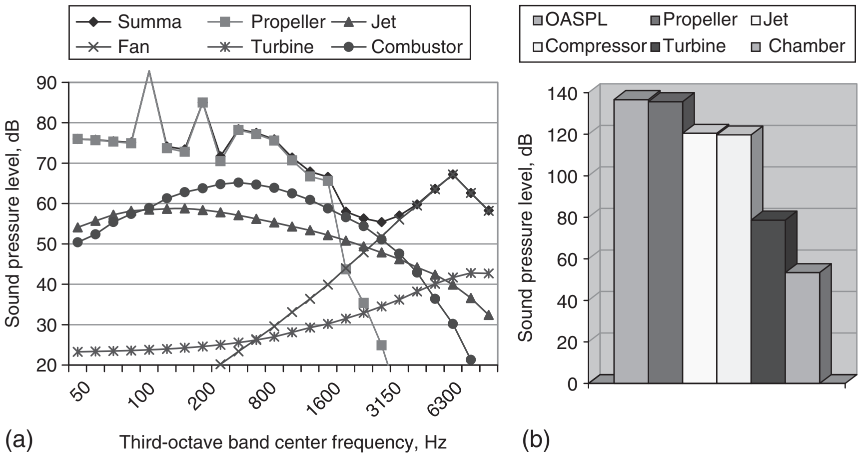

Figure 1.13 Noise source contributions for turboprop aircraft at control point No. 3 (landing mass 9.8 t, distance 100 m, engine mode – 0.6 nominal, 'lateral attenuation' neglected).

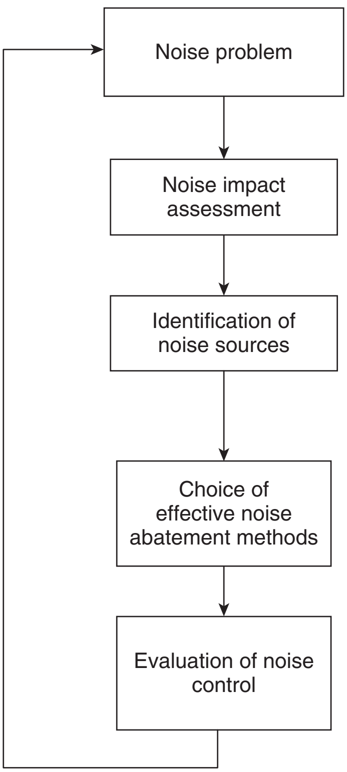

Figure 1.14 An algorithm for noise management.

Table 1.3 A comparison of acoustic efficiency coefficient (η_a) values

Source type	*Coefficient* η_a
Human voice	5×10^{-4}
Noise of jet aircraft engine	$5 \times 10^{-4} M^5$ for $M \leq 0.7$
	$10^{-4} M^5$ for $0.7 \leq M \leq 1.6$
	2×10^{-3} for $M \geq 2$
Separated flow in regulator of airborne air-conditioning system	10^{-3} for $M \leq 1.3$
Siren	0.5

to the strength of the flow for particular sources. The flow Mach number M is the ratio of typical flow velocity V and ambient sound velocity a_0, $M = V/a_0$.

The transformation of kinetic energy of the flux into acoustic power can be described using three types of noise sources: the monopole (representing a volume source of gas mass changing in time), the dipole (representing two monopole sources at a small distance from one another in comparison with sound wave length and pulsating in opposite phase) and the quadrupole (representing the superposition of four equal monopole sources in phase opposition to each other in pairs and at small distances from one another in comparison with sound wavelength). The acoustic efficiency diminishes from monopole to dipole and then to quadrupole.

In turbulent flow, a typical eddy length scale L is used. For a sound wave, a typical scale is the wavelength, λ. If the source distribution for subsonic flows ($M = V/a_0 < 1$) is assumed to be compact and proportional to V/L, then the wavelength is given by $\lambda = LM^{-1}$. If M $<< 1$, the wavelength is larger than the scale of the turbulent flow: $\lambda >> L$. The noise of turbulent flow has a multipole nature. Table 1.4 gives the parameters of density fluctuation $\rho'(x,t)$(relative to ambient density) and acoustic power $W(W = 4\pi\,|x|^2 a_0^3 \rho_0^{-1} < \rho'^2 >)$ for monopole, dipole and quadrupole in compact and non-compact sources. The symbol $<>$ indicates the mean square average of the density fluctuation.

The effective transformation mechanical energy of flow into acoustical energy for compact sound sources of monopole, dipole and quadrupole nature are proportional to M, M^3 and M^5, respectively. The decrease of the efficiency with increase in multipole order ($M < 1$) is the result of partial suppression of radiation sources, located at a small distance (in comparison with λ) from one another. With increasing Mach number of flow (for example, in the case of supersonic flow), sound sources become non-compact. For these non-compact sound sources, the radiation of separate sources is prevalent, and the dependence on the multipole structure of acoustical sources is insignificant.

Table 1.4 The characteristics of compact and non-compact acoustic radiators

Acoustic radiator	*Compact sources of sound*		*Non-compact sources of sound*	
	$\rho'(x,t)$	W	$\rho'(x,t)$	W
Monopole	$\rho_0 \frac{L}{\lvert x\rvert} M^2$	$\rho_0 V^2 L^2 M$		
Dipole	$\rho_0 \frac{L}{\lvert x\rvert} M^3$	$\rho_0 V^2 L^2 M^3$	$\rho_0 \frac{L}{\lvert x\rvert} M$	$\rho_0 V^3 L^2 M^{-1}$
Quadrupole	$\rho_0 \frac{L}{\lvert x\rvert} M^4$	$\rho_0 V^3 L^2 M^5$		

The analysis of acoustic sources given above is based on qualitative investigations of the radiation. Only solutions of the basic continuum equations will allow descriptive relationships between the parameters of noise radiation and turbulent flow to be obtained.

1.3 Basic equations

The propagation of acoustic waves in a medium depends on its properties. If the airflow is homogeneous and in thermodynamic equilibrium, the airflow and sound field are described by differential equations, which are based on conservation of flow mass, momentum and energy.

$$\begin{aligned}
&\frac{\partial \rho}{\partial t} + \frac{\partial \rho v_j}{\partial x_j} = 0 \\
&\frac{\partial \rho v_i}{\partial t} + \frac{\partial \rho v_i v_j}{\partial x_j} = -\delta_{ij}\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} \\
&\rho\left(\frac{\partial s}{\partial t} + v_j \frac{\partial s}{\partial x_j}\right) = U,
\end{aligned} \tag{1.1}$$

where x_i are Cartesian coordinates, p is pressure, ρ is density, v_i are the velocity vector components, $U = \frac{\partial}{\partial x_j}\left(\frac{Q_j}{T}\right) + \frac{\rho q_0}{T} + \sigma$, T is the temperature, $Q_j = \chi \frac{\partial T}{\partial x_j}$, $\chi$is the thermal conductivity, $\tau_{ij} = \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial v_l}{\partial x_l}\right) + \varsigma_B \delta_{ij}\frac{\partial v_l}{\partial x_l}$ is the viscous stress tensor, $\sigma = T^{-2}\chi\delta_{ij}\frac{\partial T}{\partial x_i}\frac{\partial T}{\partial x_j} + \frac{\mu}{2T}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial v_l}{\partial x_l}\right)^2 + \varsigma_B T^{-1}\frac{\partial v_i}{\partial x_i}\frac{\partial v_j}{\partial x_j}$, μ, ς_B are the coefficients of dynamic and bulk viscosity, respectively, s is the specific entropy, $i, j, l = 1, 2, 3$, $\delta_{ij} = 0$ if $i \neq j$, $\delta_{ij} = 1$, if $i = j$, q_0 is amount of heat. Repeated indices imply summation.

In general, the entropy change for finite volume of gas is described by

$$\frac{dS}{dt} = \frac{d_eS}{dt} + \frac{d_iS}{dt}. \tag{1.2}$$

The first item in (1.2) is an entropy flux which determines the entropy change due to interaction with ambient medium (this change can have any sign). The second component of the equation (1.2) represents the production of the entropy and determines the entropy flux for irreversible processes $\left(\frac{d_iS}{dt} \geq 0\right)$. Making use of some continuous function $F(s)$, one can rewrite the third equation of the system (1.1) in the form

$$\rho\left(\frac{\partial F}{\partial t} + v_j\frac{\partial F}{\partial x_j}\right) = F_sU, \tag{1.3}$$

where $F_s = dF/ds$. After multiplying the first equation of system (1.1) by Fv_i, the second by F and equation (1.3) by v_i, and summing the results, the following result is obtained:

$$\frac{\partial(\rho F v_i)}{\partial t} + \frac{\partial(\rho F v_i v_j)}{\partial x_j} = -\delta_{ij}F\frac{\partial p}{\partial xi} + F\frac{\partial \tau_{ij}}{\partial x_j} + F_s v_i U. \tag{1.4}$$

From the first equation of the system (1.1) and equation (1.3)

$$\frac{\partial(\rho F)}{\partial t} + \frac{\partial(\rho F v_j)}{\partial t} = F_sU. \tag{1.5}$$

After transformations of the equations (1.4) and (1.5) and adding the expression

$$-\frac{\partial}{\partial x_i}a^2\frac{\partial(\rho F)}{\partial x_i}$$

to both parts of equation, it is found that

$$\frac{\partial^2 \rho F}{\partial t^2} - \frac{\partial}{\partial x_i}a^2\frac{\partial \rho F}{\partial x_i} = \frac{\partial^2 \rho F v_i v_j}{\partial x_i \partial x_j} + \Phi, \tag{1.6}$$

where $a^2 = (\partial p/\partial \rho)_s$, a is the speed of sound and

$$\Phi = \frac{\partial UF}{\partial t} - \frac{\partial}{\partial x_i}\left(F\frac{\partial \tau_{ij}}{\partial x_j} + v_iF_sU\right).$$

The parameters of the gas are connected by the equation of state

$$\rho F(s)A(p) = constant \tag{1.7}$$

For an ideal gas ($\frac{d_e S}{dt} = 0$), $F(s) = \exp(s/c_p)$ and $A(p) = p^{-\frac{1}{\gamma}}$, therefore equation (1.6) can be written as

$$\frac{\partial^2 p^{\frac{1}{\gamma}}}{\partial t^2} - \frac{\partial}{\partial x_i} a^2 \frac{\partial p^{\frac{1}{\gamma}}}{\partial x_i} = \frac{\partial^2 (p^{\frac{1}{\gamma}} v_i v_j)}{\partial x_i \partial x_j} + \Phi, \tag{1.8}$$

where γ is the specific heat ratio and c_p is the specific heat of the gas at constant pressure. Equation (1.8) has the form of a wave equation. The terms on the right-hand side are determined by the aerodynamic noise sources connected with speed, entropy and viscous stress. Equation (1.8) is an exact consequence of conservation of mass, momentum and energy of flow, since it is derived from equations (1.1). It is necessary to make supplementary hypotheses for practical application of equation (1.8).

Suppose that the entropy per unit of mass of any given flow particle remains constant, then equation (1.7) yields

$$\frac{p}{\rho^\gamma} = constant \quad \text{or} \quad \frac{p^{\frac{1}{\gamma}}}{\rho} = constant$$

In this case, equation (1.8) is transformed to

$$\frac{\partial^2 \rho}{\partial t^2} - \frac{\partial}{\partial x_i} a^2 \frac{\partial \rho}{\partial x_i} = \frac{\partial^2 (\rho v_i v_j)}{\partial x_i \partial x_j} + \Phi. \tag{1.9}$$

At flow with high Reynolds number the viscous contribution terms in equation (1.9) can be neglected, and if there are no heat transfer effects, then

$$\frac{\partial^2 \rho}{\partial t^2} - \frac{\partial}{\partial x_i} a^2 \frac{\partial \rho}{\partial x_i} = \frac{\partial^2 (\rho v_i v_j)}{\partial x_i \partial x_j} + \frac{\partial}{\partial x_i} (a^2 - a_0^2) \frac{\partial \rho}{\partial x_i}. \tag{1.10}$$

In orthogonal curvilinear coordinates q_i, equation (1.10) (for which the viscous contribution was neglected) becomes

$$\frac{\partial^2 \rho'}{\partial t^2} - \frac{a_0^2}{h_1 h_2 h_3} \frac{\partial}{\partial q_i} \frac{h_1 h_2 h_3}{h_i^2} \frac{\partial \rho'}{\partial q_i} = \frac{1}{h_1 h_2 h_3} \frac{\partial}{\partial q_i} \frac{1}{h_i} \frac{\partial}{\partial q_j} \frac{(\rho v_i v_j h_1 h_2 h_3)}{h_j} + \frac{1}{h_1 h_2 h_3} \frac{\partial}{\partial q_i} (a^2 - a_0^2) \frac{h_1 h_2 h_3}{h_i^2} \frac{\partial \rho'}{\partial q_i}, \tag{1.11}$$

where h_1, h_2, h_3 are Lame's coefficients.

Sound is a consequence of fluctuations of the variables that describe the flow with typical wavelength λ and time scale $T = 1/f$ at the oscillation frequency f. The total values of variables are the sum of the variable values for the ambient medium and their fluctuations. The fluctuations are represented by primes on the symbols: $v' = v - V_0$ (velocity), $\rho' = \rho - \rho_0$ (density), $p' = p - p_0$ (pressure), $a'^2 = a^2 - a_0^2$ (square of the adiabatic sound speed – $s = const$). The perturbation terms due to a sound wave are small ($\varepsilon << 1$):

$$\frac{v'}{< V_0 >} = O(\varepsilon)$$

$$\frac{\rho'}{< \rho_0 >} = O(\varepsilon)$$

$$\frac{p'}{< p_0 >} = O(\varepsilon). \tag{1.12}$$

If it is assumed that there are no heat transfer effects in the flow and that entropy is homogeneous throughout the ambient medium, then from equation (1.9) one obtains Lighthill's equation for sound generated by free turbulence.[6,7]

$$\frac{\partial^2 \rho'}{\partial t^2} - a_0^2 \frac{\partial^2 \rho'}{\partial x_i^2} = A(\vec{x}, t) = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}, \tag{1.13}$$

where $T_{ij} = \rho v_i v_j - \tau_{ij} + p\delta_{ij} - a_0^2 \rho \delta_{ij}$.

Equation (1.13) can be rewritten as an integro-differential equation for the fluctuation in density:

$$\rho' = \frac{1}{4\pi a_0^2} \int\limits_{V(\vec{y})} A(\vec{y}, \tau) \frac{dV(\vec{y})}{r}, \tag{1.14}$$

where $V(\vec{y})$ is the domain of turbulent flow, $r = |\vec{x} - \vec{y}|$, $\vec{y}, \vec{x}$ are coordinates, respectively, of the sources in domain of turbulent flow and the observation point, $\tau = t - \frac{r}{a_0}$ is a retarded time.

If the velocity due to the noise sources is denoted by $\vec{V}$, use of the new variable $\vec{\eta} = \vec{y} - a_0 \vec{M} \tau$, enables the solution of Lighthill's equation (1.13) to be written

$$\rho'(\vec{x}, t) = \frac{1}{4\pi a_0^2} \iiint \frac{A(\vec{\eta}, \tau)}{|\vec{x} - \vec{y}| - \vec{M}(\vec{x} - \vec{y})} dV(\vec{\eta}), \tag{1.15}$$

where $\vec{M} = \frac{\vec{V}}{a_0}$, $\tau = t - \frac{|\vec{x} - \vec{y}|}{a_0}$. Suppose also that the function $A(\vec{y}, \tau)$ decreases sufficiently rapidly and the receiver is sufficiently far from source. In the far field, the density perturbation is approximately given by

$$\rho'(\vec{x},t) \approx \frac{1}{4\pi a_0^4 |\vec{x}|} \iiint \frac{\partial^2 T_0(\vec{y},\tau)}{\partial \tau^2} dV(\vec{y}), \tag{1.16}$$

where $T_0 = \frac{x_i x_j}{|\vec{x}|^2} T_{ij}$.

For a subsonic turbulent jet ($0.3 \leq M \leq 1$), the equation (1.16) yields an expression for sound power

$$W_j = \frac{K \rho_j^2 S_j V_j^8}{\rho_0 a_0^5}, \tag{1.17}$$

where $K \approx 10^{-5}$ is an empirical constant and ρ_j, V_j, S_j, are respectively the density, velocity and area of the jet nozzle. The ratio of the sound power to the mechanical power of the jet is given by $\frac{W_a}{W_j} = K \left(\frac{\rho_j}{\rho_0}\right) \left(\frac{V_j}{a_0}\right)^5$. For subsonic flow, only a small part of the mechanical power of the jet is transformed into acoustic energy. On the other hand, the turbulent structure of the jet produces a powerful sound.

Neglecting the viscous contribution and supposing $v_i = 0$, then equation (1.10) becomes a homogeneous wave equation

$$\frac{\partial^2 \rho'}{\partial t^2} - a_0^2 \Delta \rho' = 0, \tag{1.18}$$

where Δ is the Laplacian.

The acoustic equation is determined neglecting the second and higher-order terms in the non-linear equations of continuum mechanics and retaining only the first order terms. Taking into account (1.12), then, after neglecting the quadratic and higher-order terms in the expansion of the second equation in (1.1), one obtains

$$\rho_0 \frac{\partial v_i'}{\partial t} + \frac{\partial p'}{\partial x_i} = 0. \tag{1.19}$$

Integrating equation (1.19) over time yields

$$v_i' = -\frac{1}{\rho_0} \frac{\partial}{\partial x_i} \int p' dt. \tag{1.20}$$

So, the acoustical field is irrotational and can be described in terms of a velocity potential φ, given by

$$\varphi = -\frac{1}{\rho_0} \int p' dt. \tag{1.21}$$

The perturbations in pressure, density and velocity in the sound wave are

$$p' = -\rho_0 \frac{\partial \varphi}{\partial t}, \quad \rho' = \frac{p'}{a_0^2}, \quad v_i' = \frac{\partial \varphi}{\partial x_i}. \tag{1.22}$$

From equations (1.22) and (1.18), it follows that the perturbations of pressure, density and velocity potential satisfy homogeneous wave equations:

$$\begin{aligned} &\frac{\partial^2 \rho'}{\partial t^2} - a_0^2 \Delta \rho' = 0 \\ &\frac{\partial^2 p'}{\partial t^2} - a_0^2 \Delta p' = 0 \\ &\frac{\partial^2 \varphi}{\partial t^2} - a_0^2 \Delta \varphi = 0. \end{aligned} \tag{1.23}$$

If we consider harmonic time dependence $\exp(-i\omega t)$ for the pressure perturbation

$$p'(\vec{x}, t) = p(\vec{x}) \exp(-i\omega t), \tag{1.24}$$

where ω is the angular frequency ($\omega = 2\pi f$) and $p(\vec{x})$ is the amplitude of the complex sound pressure, then the acoustic equation in (1.23) reduces to the Helmholtz equation

$$\Delta p + k^2 p = 0, \tag{1.25}$$

where $k = \omega / a_0$ is wave number ($k = 2\pi/\lambda$), $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ is the Laplacian, and $x = x_1$, $y = x_2$, $z = x_3$ are Cartesian coordinates.

The boundary conditions for the acoustic field equation are determined by the situation to be modelled. When modelling the radiation, reflection and diffraction sound in flow without viscosity and with thermal conduction at the surfaces, it is usual to specify:

(a) the normal component of acoustic velocity on surface S (for harmonic waves)

$$V_S = \left(\frac{\partial \varphi}{\partial n} \right)_S = f_1(S), \tag{1.26}$$

where n is the normal vector pointing out of the surface into the flow;

(b) the sound pressure on surface S is (for harmonic waves)

$$(\varphi)_S = f_2(S); \tag{1.27}$$

(c) a mixed boundary condition on the surface (for example, for a velocity potential)

$$\frac{1}{a_0}\frac{\partial \varphi}{\partial t} - \frac{1}{\beta}\frac{\partial \varphi}{\partial z} = 0, \tag{1.28}$$

where β is the normalized admittance of surface and z is the coordinate pointing out to normal to surface into the flow.

For $f_1(S) = 0$, the boundary value problem (1.26) represents sound reflection on an absolutely hard surface. If $f_2(S) = 0$, (1.27) represents sound reflection on an absolutely soft surface. The relation (1.28) represents sound reflection from an impedance boundary. In reflection problems, usually the total acoustic field $\varphi_t = \varphi_i + \varphi$ is the sum of an incident field φ_i and a scattered field φ. The remaining condition is Sommerfeld's radiation condition for outgoing waves. For a three-dimensional pressure perturbation, this is written as:

$$|rp| < C,$$
$$r\left(\frac{\partial p}{\partial r} + ikp\right) \to 0$$

uniformly with respect to direction as $r \to \infty$, where C is some finite constant.

For medium that is at rest, then equations (1.23) of linear acoustics yield the principle of superposition of acoustic waves. In a linear ambient medium, free waves propagate irrespective of other waves, and a sound field is a sum of separate free waves. For scalar variables (for example, pressure), the summation is algebraic. For vector variables (for example, velocities), the summation is vectorial.

Consider some domain V, enclosed by surface S. In terms of the velocity potential φ and its normal derivative $\partial\varphi/\partial n$ on the surface, Kirchhoff's solution yields

$$\varphi(R) = \frac{1}{4\pi}\iint_S \left\{\frac{\partial \varphi}{\partial n}\frac{\exp(ikr)}{r} - \varphi\frac{\partial}{\partial n}\left[\frac{\exp(ikr)}{r}\right]\right\} dS, \tag{1.29}$$

where R is the radial vector of the observer, r is the radial vector between the observer point and radiation point in domain V and n is the vector normal pointing into the surface. The form of the solution (1.29) represents the sound field as the sum of spherical and dipole sources on the surface.

Sound radiation by a flat surface is given by Huygen's formulas. The first Huygen's formula gives the field over a perfectly hard surface as

$$\varphi(R) = \frac{1}{2\pi} \iint_S \frac{\partial \varphi}{\partial n} \frac{\exp(ikr)}{r} dS. \tag{1.30}$$

The acoustical field over a perfectly soft surface is determined by the second Huygen's formula as

$$\varphi(R) = -\frac{1}{2\pi} \iint_S \varphi \frac{\partial}{\partial n} \left[\frac{\exp(ikr)}{r} \right] dS. \tag{1.31}$$

For the inhomogeneous Helmholtz equation (1.23), the solution for pressure can also be represented as the sum of an incident pressure and a secondary pressure

$$p_t = \frac{1}{(2\pi)^{\frac{3}{2}}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d\beta_x d\beta_y \int_{-\infty}^{\infty} \frac{\Gamma(\beta_x, \beta_y, \beta_z) \exp[-i(\beta_x x + \beta_y y + \beta_z z)]}{k^2 - \beta_x^2 - \beta_y^2 - \beta_z^2} d\beta_z$$
$$+ \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(\alpha, \delta) \exp(-\gamma z - i\alpha x - i\delta y) d\alpha d\delta, \tag{1.32}$$

where $\gamma = \sqrt{\alpha^2 + \delta^2 - k^2}$, function $\Gamma(\beta_x, \beta_y, \beta_z)$ is a Fourier transformation of the multipole source term $\Gamma(x, y, z)$, $\alpha, \delta, \beta_x, \beta_y, \beta_z$ are complex variables, k is the wave number and $A(\alpha, \beta)$ is an unknown function defined by the solution of a boundary value problem.

Many acoustical models have been developed following the classical work of Lighthill on 'sound-generated aerodynamically'.[6–15] Lighthill's theory provides the basic theory of free jet noise. The sound generated by free turbulence is given by equation (1.13). According to Lighthill's acoustic analogy, equation (1.13) describes the generation of sound waves by quadrupole sources. In Lighthill's acoustic analogy, the sound sources are in the domain of turbulent flow and embedded in a medium at rest (with density and sound velocity, respectively, ρ_0, a_0). If there are no heat transfer and viscosity effects, then Lighthill's stress tensor reduces to $T_{ij} \approx \rho_0 v_i v_j$ (neglecting also the fluctuations of density at source, i.e. $\rho \approx \rho_0$).

A circular turbulent jet may be subdivided into the initial mixing region (extending about four diameters from the jet exit), the intermediate downstream region and the main extensive mixing region (reaching to between 16 and 18 diameters from the jet exit). The initial region includes a mixing layer with ambient and potential core. The initial mixing region and the extensive mixing region have a self-preserving structure. In the

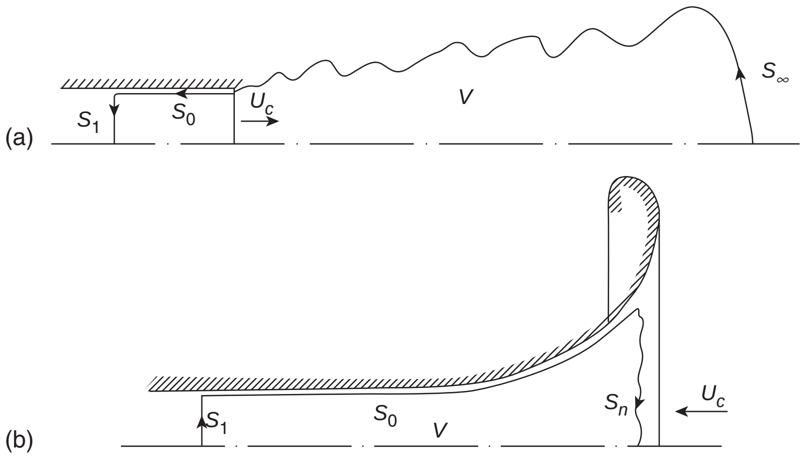

Figure 1.15 Schematics of an air stream: (à) a free jet; (b) jet suction.

intermediate region, the turbulent structure transforms from the self-preserving structure of the initial mixing region to the new structure of the extensive mixing region. The end of the initial mixing region and the intermediate region generate the most acoustic power. The turbulent mixing region of a circular jet separates from the ambient irrotational flow, which is the inflow into the jet. The thickness of the separation zone is small in comparison with the typical turbulence scale. Therefore, the separation zone is considered as a geometrically random surface, distorted by the instability of the vortex sheet (see Fig. 1.15a).

At the separation surface, there is a jump in vorticity because outside the turbulent volume V, the flow is potential (the gas velocity of inflow into the jet over the separation is continuous).

We suppose that a subsonic jet contains compact noise sources. To calculate the parameters of turbulent flow, we introduce non-dimensional inner variables

$$\overline{x}_i = \frac{x_i}{L}, \overline{v}_i = \frac{v_i}{V_j}, \overline{\tau} = \frac{tV_j}{L}, \overline{a} = \frac{a}{a_0},$$

where L, V_j define jet turbulence length and velocity scales, respectively. Equation (1.10) can be rewritten in non-dimensional inner variables

$$M^2 \frac{\partial^2 h}{\partial \overline{\tau}^2} - \Delta h = M^2 \frac{\partial^2 h \overline{v}_i \overline{v}_j}{\partial \overline{x}_i \partial \overline{x}_j} + \frac{\partial}{\partial \overline{x}_i} (\overline{a}^2 - 1) \frac{\partial h}{\partial \overline{x}_i}, \tag{1.33}$$

where $h = \rho/\rho_0$. The asymptotic expansion of the inner solution is

$$h(\overline{x}, \overline{\tau}, M) = 1 + \delta_1(M)\sigma_1(\overline{x}, \overline{\tau}) + \delta_2(M)\sigma_2(\overline{x}, \overline{\tau}) + \ldots,$$
$$\overline{a}^2 = 1 + \delta_1(M)\overline{a}_1^2(\overline{x}, \overline{\tau}) + \ldots,$$
$$\overline{v}_i = \overline{v}_i^{(0)}(\overline{x}, \overline{\tau}) + \delta_1(M)\overline{v}_i^{(1)} \ldots,$$

where for $M \to 0$, the variables $\overline{x}, \overline{\tau}$ are fixed. The solution for $\sigma_i(\overline{x}, \overline{\tau})$ satisfies the equations

$$\delta_1(M) = M^2;\ \Delta\sigma_1 = -\frac{\partial^2 \overline{v}_i^{(0)} \overline{v}_j^{(0)}}{\partial \overline{x}_i \partial \overline{x}_j}; \tag{1.34}$$
$$\delta_2(M) = M^4;$$
$$\Delta\sigma_2 = \frac{\partial^2 \sigma_1}{\partial \overline{\tau}^2} - \frac{\partial^2}{\partial \overline{x}_i \partial \overline{x}_j}\left(\overline{v}_i^{(1)}\overline{v}_j^{(0)} + \overline{v}_i^{(0)}\overline{v}_j^{(1)} + \sigma_1 \overline{v}_i^{(0)}\overline{v}_j^{(0)}\right) - 2\frac{\partial}{\partial \overline{x}_i}\overline{a}_1^2 \frac{\partial \sigma_1}{\partial \overline{x}_i}.$$

The solution of the first equation (1.34) is

$$\sigma_1(\overline{x}, \overline{\tau}) = \frac{1}{4\pi}\int_V \frac{\partial^2 \overline{v}_i^{(0)} \overline{v}_j^{(0)}}{\partial \xi_i \partial \xi_j} \frac{d\xi}{|\overline{x} - \overline{\xi}|}$$
$$+ \frac{1}{4\pi}\int_S \left[\frac{1}{|\overline{x} - \overline{\xi}|}\frac{\partial \sigma_1(\xi)}{\partial n} - \sigma_1(\xi)\frac{\partial}{\partial n}\frac{1}{|\overline{x} - \overline{\xi}|}\right] dS, \tag{1.35}$$

where integration has been performed on the volume of turbulent flow $V(\xi)$, and over bounding surfaces $S = S_1 + S_0 + S_\infty$ (Fig. 1.15a): S_1 is the surface on the nozzle to a distance on the order of typical sound wavelength, S_0 is determined by the jet nozzle surface, S_∞ is the part of the surface sufficiently far from jet exit and separation surface.

The integral along the surface S in equation (1.35) relates to noise sources along surfaces S_0, S_1. Some noise sources exist outside the separation surface in the surrounding non-turbulent ambient medium. The solution of the first equation (1.34) is determined by integrating over $V(\xi)$. Using the result from differentiation of $f(\xi)$,

$$\frac{1}{|\overline{x} - \xi|}\frac{\partial^2 f}{\partial \xi_i \partial \xi_j} = \frac{\partial^2}{\partial \overline{x}_i \partial \overline{x}_j}\frac{f}{|\overline{x} - \xi|} + \frac{\partial^2}{\partial \overline{x}_i \partial \xi_j}\frac{f}{|\overline{x} - \xi|} + \frac{\partial}{\partial \xi_i}\frac{\frac{\partial f}{\partial \xi_j}}{|\overline{x} - \xi|},$$

in equation (1.35),

$$\sigma_1(\overline{x},\overline{\tau}) = \frac{1}{4\pi}\left\{\frac{\partial^2}{\partial\overline{x}_i\partial\overline{x}_j}\int\limits_V \frac{\overline{v}_i^{(0)}\overline{v}_j^{(0)}}{|\overline{x}-\xi|}d\xi + \frac{\partial}{\partial\overline{x}_i}\int\limits_V \frac{\partial}{\partial\xi_j}\frac{\overline{v}_i^{(0)}\overline{v}_j^{(0)}}{|\overline{x}-\xi|}d\xi\right.$$
$$\left. + \int\limits_V \frac{\partial}{\partial\xi_j}\frac{\frac{\partial\overline{v}_i^{(0)}\overline{v}_j^{(0)}}{\partial\xi_j}}{|\overline{x}-\xi|}d\xi + \int\limits_S\left[\frac{1}{|\overline{x}-\xi|}\frac{\partial}{\partial n} - \sigma_1(\xi)\frac{\partial}{\partial n}\frac{1}{|\overline{x}-\xi|}\right]\right\} dS. \tag{1.36}$$

After some transformations in equation (1.36) one obtains

$$\sigma_1(\overline{x},\overline{\tau}) = \frac{1}{4\pi}\left\{\frac{\partial^2}{\partial\overline{x}_i\partial\overline{x}_j}\int\limits_V \frac{\overline{v}_i^{(0)}\overline{v}_j^{(0)}}{|\overline{x}-\xi|}d\xi + \frac{\partial}{\partial\overline{x}_i}\int\limits_S l_j\frac{\overline{v}_i^{(0)}\overline{v}_j^{(0)} + \sigma_1(\xi)\delta_{ij}}{|\overline{x}-\xi|}dS\right. \tag{1.37}$$
$$\left. + \int\limits_S l_i\frac{1}{|\overline{x}-\xi|}\frac{\partial}{\partial\xi_j}\left[\overline{v}_i^{(0)}\overline{v}_j^{(0)} + \sigma_1(\xi)\delta_{ij}\right]dS\right\}.$$

The equation of conservation of momentum (1.1) in the approach considered has the form

$$\frac{\partial\overline{v}_i^{(0)}}{\partial\overline{\tau}} + \frac{\partial}{\partial\xi_j}[\overline{v}_i^{(0)}\overline{v}_j^{(0)} + \sigma_1(\xi)] = 0. \tag{1.38}$$

Therefore, after taking into consideration equation (1.35), equation (1.37) becomes

$$\sigma_1(\overline{x},\overline{\tau}) = \frac{1}{4\pi}\left[\frac{\partial^2}{\partial\overline{x}_i\partial\overline{x}_j}\int\limits_V \frac{\overline{v}_i^{(0)}\overline{v}_j^{(0)}}{|\overline{x}-\xi|}d\xi + \frac{\partial}{\partial\overline{x}_i}\int\limits_S l_j\frac{\overline{v}_i^{(0)}\overline{v}_j^{(0)} + \sigma_1(\xi)\delta_{ij}}{|\overline{x}-\xi|}dS\right.$$
$$\left. - \frac{\partial}{\partial\overline{\tau}}\int\limits_S l_i\frac{\overline{v}_i^{(0)}}{|\overline{x}-\xi|}dS\right]. \tag{1.39}$$

For a subsonic jet, ($M = \frac{V_j}{a_0} < 1$) and if the source distribution is assumed compact, then $L = M\lambda$ and we can introduce non-dimensional outer variables

$$\tilde{x}_i = \frac{x_i}{\lambda},\ \tilde{v}_i = \frac{v_i}{a_0},\ \tilde{\tau} = \overline{\tau} = \frac{tc_0}{\lambda},\ \tilde{a} = \frac{a}{a_0},\ M < 1.$$

Equation (1.10) can be rewritten in non-dimensional outer variables

$$\frac{\partial^2 h}{\partial \tilde{\tau}^2} - \Delta h = \frac{\partial^2 h \tilde{v}_i^{(0)} \tilde{v}_j^{(0)}}{\partial \tilde{x}_i \partial \tilde{x}_j} + \frac{\partial}{\partial \tilde{x}_i} (\tilde{a}^2 - 1) \frac{\partial h}{\partial \tilde{x}_i}. \tag{1.41}$$

The asymptotic expansion of the outer solution is

$$\begin{aligned} h(\tilde{x}, \tilde{\tau}, M) &= 1 + \Delta_1(M) h_1(\tilde{x}, \tilde{\tau}) + \Delta_2(M) h_2(\tilde{x}, \tilde{\tau}) + \ldots, \\ \tilde{v}_i(\tilde{x}, \tilde{\tau}, M) &= \Delta_1(M) \tilde{v}_i^{(1)} + \Delta_2(M) \tilde{v}_i^{(2)} + \ldots, \\ \tilde{a}^2(\tilde{x}, \tilde{\tau}, M) &= 1 + \Delta_1(M) \tilde{a}_1^2 + \ldots, \end{aligned} \tag{1.42}$$

where, for $M \to 0$, variables $\tilde{x}, \tilde{\tau}$ are fixed. The function $h_1(\overline{x}, \overline{\tau})$ satisfies the homogeneous wave equation

$$\frac{\partial^2 h_1}{\partial \tilde{\tau}^2} - \Delta h_1 = 0.$$

In general, the solution of homogeneous wave equation in far field ($|\tilde{x}| >> 1$) is a spherical symmetric wave spreading out from the source in the ambient medium

$$h_1(\tilde{x}, \tilde{\tau}) = \frac{1}{4\pi |\tilde{x}|} H(\tilde{\tau} - |\tilde{x}|), \tag{1.43}$$

where $H(\tilde{\tau} - |\tilde{x}|)$ is any twice differentiable function.

To carry out matching of inner and outer expansions, we rewrite the first term of the inner expansion (1.39) in outer variables ($\tilde{x} = M\overline{x}$)

$$\begin{aligned} M^2 \sigma_1(\tilde{x}, \tilde{\tau}) = \frac{M^2}{4\pi} \Bigg[& M^2 \frac{\partial^2}{\partial \tilde{x}_i \partial \tilde{x}_j} \int_V \frac{\overline{v}_i^{(0)} \overline{v}_j^{(0)}}{|\tilde{x} M^{-1} - \xi|} d\xi \\ & + M \frac{\partial}{\partial \tilde{x}_i} \int_S l_j \frac{\overline{v}_i^{(0)} \overline{v}_j^{(0)}}{|\tilde{x} M^{-1} - \xi|} dS - \frac{\partial}{\partial \tilde{\tau}} \int_S \frac{l_i \overline{v}_i^{(0)}}{|\tilde{x} M^{-1} - \xi|} dS \Bigg]. \end{aligned} \tag{1.44}$$

For $M < 1$ equation (1.44) simplifies to

$$\begin{aligned} M^2 \sigma_1(\tilde{x}, \tilde{\tau}) = \frac{1}{4\pi} \Bigg[& M^5 \frac{\partial^2}{\partial \tilde{x}_i \partial \tilde{x}_j} \frac{1}{|\tilde{x}|} \int_V \overline{v}_i^{(0)} \overline{v}_j^{(0)} d\xi - M^4 \frac{\partial}{\partial \tilde{x}_i} \frac{1}{|\tilde{x}|} \frac{\partial}{\partial \tilde{\tau}} \int_S \overline{v}_i^{(0)} dS \\ & - \frac{M^3}{|\tilde{x}|} \frac{\partial}{\partial \tilde{\tau}} \int_S l_i \overline{v}_i^{(0)} dS \Bigg]. \end{aligned} \tag{1.45}$$

Matching three terms of the inner expansion [orders M^3, M^4, M^5in equation (1.45)] with the outer solution [equation (1.43)] gives

$$\Delta_1(M)h_1(\tilde{x},\tilde{\tau}) = \frac{M^5}{4\pi}H^{(1)} + \frac{M^4}{4\pi}H^{(2)} + \frac{M^3}{4\pi}H^{(3)}, \tag{1.46}$$

where

$$H^{(1)} = \frac{\partial^2}{\partial\tilde{x}_i\partial\tilde{x}_j}\frac{1}{|\tilde{x}|}\int\limits_V [\overline{v}_i^{(0)}\overline{v}_j^{(0)}]_\bullet d\xi,$$

$$H^{(2)} = \frac{\partial}{\partial\tilde{x}_i}\frac{1}{|\tilde{x}|}\int\limits_S l_j[\overline{v}_i^{(0)}\overline{v}_j^{(0)}]_\bullet dS,$$

$$H^{(3)} = -\frac{1}{|\tilde{x}|}\frac{\partial}{\partial\tilde{\tau}}\int\limits_S l_i[\overline{v}_i^{(0)}]_\bullet dS,$$

The symbol '$[\ \ ]_\bullet$' signifies retarded time. In dimensional variables, the solution is

$$\frac{\rho-\rho_0}{\rho_0} = \frac{1}{4\pi a_0^2}\left\{\frac{\partial^2}{\partial x_i\partial x_j}\frac{1}{|x|}\int\limits_V\left[v_i^{(0)}v_j^{(0)}\right]_\bullet d\xi + \frac{\partial}{\partial x_i}\frac{1}{|x|}\int\limits_S l_j\left[v_i^{(0)}v_j^{(0)}\right]_\bullet dS\right.$$
$$\left. - \frac{1}{|x|}\frac{\partial}{\partial t}\int\limits_S l_i\left[v_i^{(0)}\right]_\bullet dS\right\} \tag{1.47}$$

In the far field, equation (1.47) simplifies to

$$\frac{\rho-\rho_0}{\rho_0} \approx \frac{1}{4\pi a_0^4}\frac{x_ix_j}{|x|^3}\int\limits_V\frac{\partial^2 v_i^{(0)}v_j^{(0)}}{\partial\tau^2}d\xi + \frac{1}{4\pi a_0^3}\frac{x_i}{|x|^2}\int\limits_S l_j\frac{\partial}{\partial\tau}\left(v_i^{(0)}v_j^{(0)} + \sigma_1\delta_{ij}\right)dS$$
$$- \frac{1}{4\pi a_0^2|x|}\int\limits_S l_i\frac{\partial v_i^{(0)}}{\partial\tau}dS. \tag{1.48}$$

In expression (1.48), the first term of the asymptotic expansion represents a quadrupole source term. The second and third terms represent the effects of interaction of the jet with the external medium including elements of the jet nozzle surface and elements of any jet noise suppression devices.

Composite expansions can be obtained by using standard methods of matching the inner and outer expansions.[16]

In accordance with equation (1.10) for an unbounded flow (neglecting the effects of heat conductivity, viscosity and solid boundaries on S), the noise of an isothermal jet source is quadrupole. If $\frac{\partial^2 v_i^{(0)} v_j^{(0)}}{\partial \bar{x}_i \partial \bar{x}_j} = 0$ from equation (1.11), it follows that aerodynamic acoustical sources in the turbulent domain $V(\xi)$ will be less effective radiators of sound than acoustic sources defined by the term $M^2\sigma_1$. The aerodynamic acoustical source is multipole, the effectiveness of which diminishes with source-order growth. Besides the trivial solution, $\bar{v}_i^{(0)} = 0$, there are several aerodynamic fields with the following properties in Cartesian coordinates (x, y, z):

1 $v_x^{(0)}(t), v_y^{(0)}(x,t), v_z^{(0)}(x,y,t)$;
2 $v_x^{(0)}(t), v_y^{(0)}(x,z,t), v_z^{(0)}(x,t)$;
3 $v_x^{(0)}(y,z,t), v_y^{(0)}(t), v_z^{(0)}(x,y,t)$;
4 $v_x^{(0)}(y,t), v_y^{(0)}(t), v_z^{(0)}(x,y,t)$;
5 $v_x^{(0)}(z,t), v_y^{(0)}(x,z,t), v_z^{(0)}(t)$;
6 $v_x^{(0)}(y,z,t), v_y^{(0)}(z,t), v_z^{(0)}(t)$.

Cylindrical polar coordinates (r, φ, z):

7 $v_r^{(0)} = 0, v_\varphi^{(0)}(r,t), v_z^{(0)}(r,\varphi,t)$;
8 $v_r^{(0)} = 0, v_\varphi^{(0)}(r,z,t), v_z^{(0)}(r,t)$.

Toroidal coordinates $\{x = r\sin(\theta),\ y = [l + r\cos(\theta)]\cos(\psi),\ z = [l + r\cos(\theta)]\sin(\psi)\}$:

9 $v_r^{(0)} = v_\theta^{(0)} = 0, v_\psi^{(0)}(r,\theta,t)$.

Paraboloidal coordinates $\{x = sp\cos(\varphi), y = sp\sin(\varphi), z = \frac{1}{2}(s^2 - p^2)\}$:

10 $v_s^{(0)} = v_p^{(0)} = 0, v_\varphi^{(0)}(s,p,t)$.

Prolate spheroidal coordinates: $x = \alpha\cos(s)sh(p)\cos(\varphi),\ y = \alpha\cos(s)sh(p)\sin(\varphi),\ z = \alpha\sin(s)ch(p)$.

11 $v_s^{(0)} = v_p^{(0)} = 0, v_\varphi^{(0)}(s,p,t)$.

Oblate spheroidal coordinates: $x = \alpha\sin(s)sh(p)\cos(\varphi),\ y = \alpha\sin(s)ch(p)\sin(\varphi),\ z = \alpha\cos(s)sh(p)$.

12 $v_s^{(0)} = v_p^{(0)} = 0, v_\varphi^{(0)}(s,p,t)$.

The flows forming such types of jet enable lowering of acoustic radiation of free jet by modification of the shape of the nozzle exit, for example, with corrugated nozzles and screw jets.

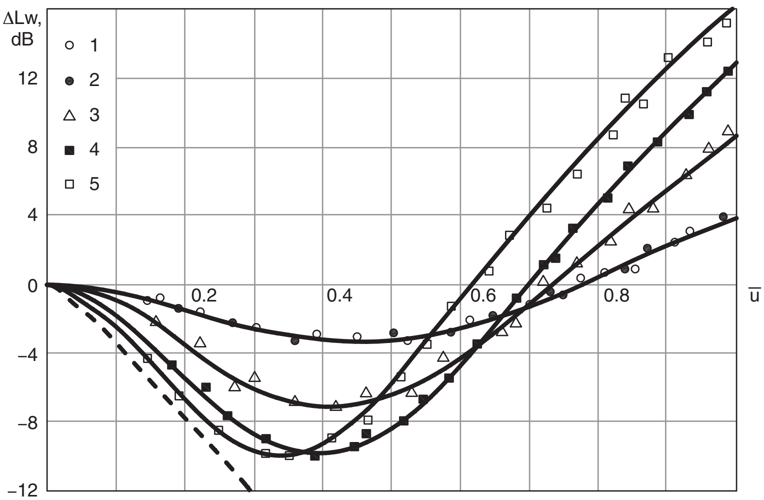

Figure 1.16 Dependence of surplus noise output of a coaxial jet (in comparison with that of a single jet) on relative velocity $\overline{u}$. The coaxial jet is specified by the primary diameter d_1 and the secondary diameter d_2: 1 – $d_1 =$ 30 mm, $d_2 =$ 50 mm; 2 – $d_1 =$ 18 mm, $d_2 =$ 30 mm; 3 – $d_1 =$ 18 mm, $d_2 =$ 50 mm; 4 – $d_1 =$ 12 mm, $d_2 =$ 50 mm; 5 – $d_1 =$ 8 mm, $d_2 =$ 50 mm. The broken line represents 80lg(1 – $\overline{u}$).

Jet noise reduction techniques are based on reducing noise emission with minimal loss of jet thrust (less than between 3 and 5 per cent). Corrugated nozzles have been used on many civil aircraft flying between 1955 and 1980. Derivatives of such nozzles are used on modern aircraft.[12] Substantial noise reduction could be obtained with the coaxial airstream (used in bypass jets and in the turbofan engine).

The application of coaxial jets changes the flow structure of the jets, slows down the jet velocity and reduces the velocity gradient, which results in a decrease in jet noise. Figure 1.16 shows the dependence of the ratio of the noise power level of coaxial jets (W_{cj}) and the power of the jet (W_1) on the dimensionless parameters ($\overline{d} = d_2/d_1, \overline{u} = u_2/u_1$)

$$\Delta L_W = 10\,\mathrm{lg}\,\frac{W_{cj}}{W_1}.$$

The noise power W_{cj} for $\overline{u}$=1 is given by equation (1.17) (the sources are quadrupoles). The acoustical radiation of the coaxial jets for $\overline{d} \geq 4$ and $\overline{u} \leq 0.3$ is determined by the interaction between the primary and secondary jet. The dashed line in Fig. 1.16 is determined by the formula $\Delta L_W = 80\,\mathrm{lg}(1 - \overline{u})$. Substantial noise reduction of 10 dB is achieved for $\overline{d} \approx 5$ and $\overline{u} = 0.3$ to 0.4.

Table 1.5 Value of approximating coefficients a_{ij}

j	*i*					
	0	*1*	*2*	*3*	*4*	*5*
0	0.1667	−13.416	246.8	−673.0	648.213	−214.3
1	−0.1638	13.052	−234.69	590.416	−516.959	154.714
2	0.016	−1.5114	19.774	−39.586	24.837	−3.995

The sound power level (L_{Wcj}) of cold coaxial jets can be defined as

$$L_{Wcj} = L_{W_1} + \Delta L_{Wcj},\ \Delta L_{Wcj} = \sum_{i=0}^{i=5}\sum_{j=0}^{j=2} a_{ij}\overline{u}^i\overline{d}^j,$$

where L_{W_1} is the sound power level of the primary jet and a_{ij} are coefficients (see Table 1.5); $0 \le \overline{u} \le 1$; $1.7 \le \overline{d} \le 6.3$.

To investigate the effect of a suction jet, we have used various nozzle shapes on a model in an anechoic chamber (Fig. 1.15b). The sound power level due to air nozzle suction can be determined from

$$W_s = K_s(1 - M_s)^2 u_s^6 S_1 \rho c^{-3},$$

where u_s, M_s are respectively the velocity and Mach number in the most narrow cross-section of the nozzle, $(1 - M_s)^2$ is a factor taking into account the sound convection effect in the axial direction, S_1 is the area of the suction nozzle in its most narrow cross-section (d_s is the diameter of the cross-section) and $K_s = 1.8958 \times 10^{-5}$. The sound power level spectra are determined from

$$L_W(f) = 10\lg W_s + \Delta L_W(f) + 120,$$

where $\Delta L_W(f)$ is a spectrum amendment defined in Fig. 1.17 (the abscissa of which uses a parameter $Sh \cdot M = fd_s/c$, where Sh is the Strouhal number).

The sound of supersonic jets is generated by different mechanisms: vortex–vortex interaction, interaction of the vortex with the shock wave and instability waves. The noise spectrum of a supersonic jet may include both broadband and discrete components. For an imperfectly expanded supersonic jet, the essential characteristic is noise emission from the shock cell structure. In this case screech tones are observed. For a perfectly expanded jet, the screech tone disappears and broadband noise is generated by turbulent mixing of air within the jet. At high Strouhal numbers, the broadband noise is due the interaction of disturbances in the jet with shock waves. In experiments on supersonic jets at low to moderate Reynolds numbers, the large coherent structures in the flows were found to influence the emitted sound.

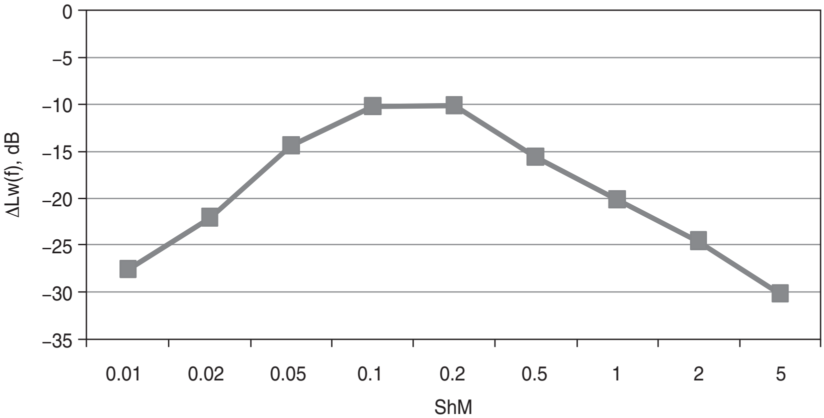

Figure 1.17 Sound power level spectrum of jet suction.

For predicting propeller noise, propfan noise, rotor noise, turbomachinery noise and airframe noise, the Ffowcs-Williams and Hawkings equation for a moving surfaces can be used.[17]

$$\frac{1}{a^2}\frac{\partial^2 p}{\partial t^2} - \Delta p = \frac{\partial}{\partial t}[\rho_0 v_n \delta(f)] - \frac{\partial}{\partial x_i}[l_i \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j}[T_{ij} H(f)], \tag{1.49}$$

where $\delta(f)$ is the Dirac delta function, $f = 0$ gives the equation of the moving surface, l_i is the ith component of the surface force and T_{ij} is Lighthill's stress tensor. The right side of equation (1.49) contains the following source terms: the first is the thickness source (monopole), the second is the loading source (dipole) and the third is the quadrupole source. The integral formulation equation (1.49) for subsonic motion can be represented as in Farassat's formula (neglecting the quadrupole contribution).[18]

$$\begin{aligned} 4\pi p = {} & \frac{1}{a}\int\limits_{f=0}\left[\frac{\dot{l}_i r_i}{r(1-M_r)^2}\right]_{\bullet} dS + \int\limits_{f=0}\left[\frac{l_r - l_i M_i}{r^2(1-M_r)^2}\right]_{\bullet} dS \\ & + \frac{1}{a}\int\limits_{f=0}\left[\frac{l_r(r\dot{M}_i r_i + aM_r - aM^2)}{r^2(1-M_r)^3}\right]_{\bullet} dS \\ & + \int\limits_{f=0}\left[\frac{\rho_0 v_n(r\dot{M}_i r_i + aM_r - aM^2)}{r^2(1-M_r)^3}\right]_{\bullet} dS, \end{aligned} \tag{1.50}$$

where dots on the Mach number $M_i = \frac{v_i}{a}$ and l_i denote derivatives with respect to source time, v_i is the local velocity of moving surface and M_r is the Mach number of the source in the direction of the observer.

The propeller is the main noise source on a turboprop engine. Propeller noise arises as a result of the periodic displacement of the air by the volume of a passing blade (thickness noise). The pressure fluctuation due to lift and draft disturbance gives the loading noise of the propeller. The propeller noise spectrum contains broadband and harmonic noise. The harmonic noise has frequencies given by $f_k = nzk$, where $k = 1, 2, \ldots, n$ is rotational speed and z is the number of blades. If the propeller has a small number of blades, then for subsonic blade section speeds, the noise is determined in the main by the first two harmonics. For such a propeller, the level of broadband noise is 10 dB less than that of the first harmonic. Because the propeller blade tip speed is one of the important parameters, reducing the tip speed results in lowering of the noise. Increasing the number of blades also reduces propeller noise for small blade rotation speeds (less than 240 m/s). On a propeller, a small thickness of blades reduces thickness noise, a large diameter with many blades diminishes loading noise and a large blade sweep reduces quadrupole noise. Increasing the propeller diameter for a given thrust combined with a relatively small tip speed reduces loading noise. On an aircraft with few propellers, noise levels in the aircraft cabin can be decreased by anti-phasing the rotation of the propellers on opposite sides of the fuselage (so-called synchrophasing). In this case, use is being made of noise cancellation through the opposite phases of waves.

On a helicopter, the main noise sources are aerodynamic and mechanical (see Fig. 1.18). The aerodynamic noise sources include the main rotor, tail rotor and the gas turbine of the engine. The mechanical noise sources include the gearbox and transmission. The mechanical noise sources radiate high-frequency sound, which is more rapidly attenuated by the atmosphere. The main rotor is a source of impulsive noise.

The acoustic spectrum of a helicopter (for example, with a single main rotor) includes discrete and broadband noise. The main rotor and tail rotor form a discrete frequency rotational noise spectrum. Broadband noise originates from the interaction of the blades with atmosphere turbulence

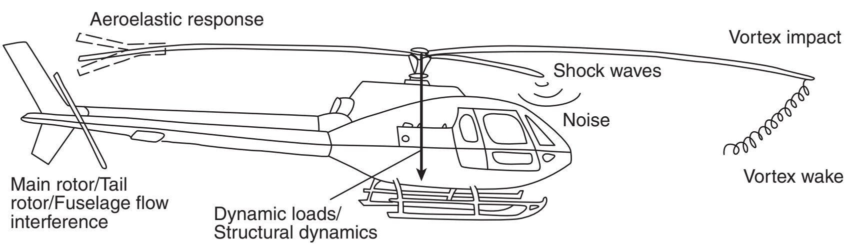

Figure 1.18 Helicopter noise sources.

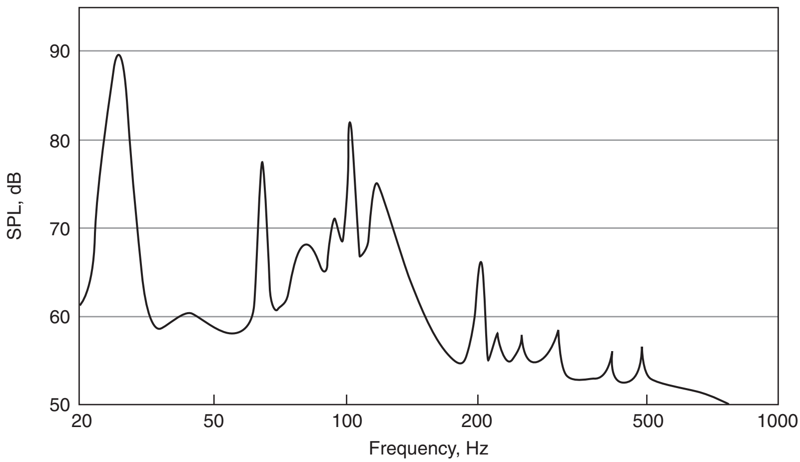

Figure 1.19 Typical form of helicopter noise spectrum.

and the vortex following the blade itself. The typical spectrum of helicopter noise is shown schematically in Fig. 1.19.

The main parameter determining helicopter rotor noise is the blade tip speed. To reduce noise emission, tip speeds can be reduced. In helicopters with a single main rotor, a reduction in the intensity of impulsive noise at subsonic speeds of the main rotor can be achieved by adding special blade tips (thinned, tapered or swept). Reduction in the noise of the tail rotor for a single main rotor can be achieved by increasing the number of blades, tapering the tip of the rotor and placing the tail rotor in an annulus.

1.4 Criteria and methods of aircraft noise assessment

To evaluate the effectiveness of aircraft noise abatement during airport operations, several different criteria may be employed:[19–24]

- the number of people within specified noise contours;
- the physical extent of specified noise contours;
- the number of noise complaints received;
- the amount of time communities are exposed to noise above a predetermined level;
- the number of noise events above a predetermined level to which communities are exposed.

Minimization of aircraft noise impact involves a systems approach and assessment of various technical, ecological, economic and social factors. The 'minimum noise impact' vector of criteria is large but the determination of its structure is an important task. For example, certain optimization criteria determine the parameters for low noise flight procedures.

The effects of aircraft noise include speech and sleep interference, and physiological, psychological and social problems. Annoyance from aircraft noise depends on both acoustical and non-acoustical factors. The latter include fear of aircraft crashing, potential benefits, housing availability, possibilities for compensation, sensitivity to noise and so on.

For aircraft noise impact assessment, in addition to choosing the relevant aircraft noise index, it is necessary to consider aircraft noise source descriptions, the flight procedures, details of population affected by noise and the airport staff and passengers' reaction to aircraft noise. Important roles are played by the requirements of health norms, flight safety, economic efficiency of aircraft operation and maintenance.

Aircraft noise annoyance is determined by several factors including the intensity, frequency content, duration and repetition, individual noise sensitivity and time of the day. The various criteria for aircraft noise assessment differ in the extent to which they account for these factors, and also in their mathematical structure. At present several criteria are used in the assessment of aircraft noise. Table 1.6 lists the most frequently used aircraft noise indices.

Models and methods used for assessing environmental noise problems must be based on the noise exposure ratings used by the relevant national and international noise control regulations and standards. These vary greatly one from one another both in their structure, and in the basic approaches used for their definitions (see Table 1.7).

According to ICAO, the effective perceived noise level (EPNL) should be used for evaluating the acoustical performance of aircraft. On the other hand, it is well known that L_{Aeq} correlates well with the effects of noise on any kind of human activity. Moreover, the percentage of highly noise-annoyed people p living in zones of significant aircraft noise impact is one of the best descriptors of total noise impact. This criterion is used as the regulatory basis in some countries and is based on the well-known relationship by Shultz.[5] The latter approach is convenient for the efficient comparison of alternative approaches to the noise problem in particular cases. For example, the value of the unit cost of noise protection for a population (UCNPP) rises with growth in noise levels in the protection zone.

The total cost for any probable type of noise protection CNP is given by:

$$CNP = \sum_k UCNPP_k(L_{Aeq})p(L_{Aeq})P_kS_k, \tag{1.51}$$

where P_k is the number of people living in the kth zone of noise control with area S_k and the boundaries of the zones are defined by values of the noise control criterion, for example, by values of L_{Aeq}.

Table 1.6 Aircraft noise criteria

Criterion symbol	*Name*	*Basic unit*	*Tone corrections*	*Duration factor*	*Event repetition factor*	*Duration and/or time periods*
L_A	A-frequency weighted level	dBA				
PNL	Perceived noise level	PNdB				
PNLT	Tone corrected perceived noise level	TPNdB	•			
EPNL	Effective perceived noise level	EPNdB	•	•		Aircraft pass by
$L_{Aeq,24h}$	A-weighted average sound level	dBA		•	$10\lg N$	24 hours
DNL	Day–night sound level	dBA		•	$10\lg N$	2 periods
NEF	Noise exposure forecast	PNdB	•	•	$10\lg N$	2 periods
NNI	Noise and number index	PNdB			$15\lg N$	Depends on aim
WECPNL	Weighted equivalent continuous perceived noise level	EPNdB	•	•	$10\lg N$	2 periods
CNR	Composite noise rating	PNdB			$10\lg N$	2 periods
CNEL	Community noise equivalent level	dBA		•	$10\lg N$	3 periods
B	Noise load in Kosten units	dBA			$20\lg N$	Aircraft pass by
DENL	European reporting data noise exposure	dB		•	$10\lg N$	3 periods
$L_{eqnight}$	Overall night-time noise exposure	dB		•	$10\lg N$	8- hour night-time

Table 1.7 Noise ratings used for aircraft noise impact assessment

Aircraft noise index	*Loudness scale approach A-weighted noise descriptors*	*Nuisance approach perceived noise descriptors*
Maximum value of time-varying levels	L_{Amax}	PNL_{max} *(PNLTM)*
Effective levels	LAX, SEL	EPNL
Equivalent levels	L_{Aeq}	ECPNL
Time-of-day weighted levels	*DNL*	WECPNL
Noise exposure indices	TNI, NII	NEF, NNI
Number or percentage of population annoyed by noise	p[%]-relationship by Shultz	π-function of ICAO

In addition, the area of noise contour S defined by a noise level of particular significance (for example, that specified by the national regulations) is given by

$$S = \sum_k S_k, \; k = 1, N$$

EPNL values of 100 or 90 EPNdB are used for noise contour analysis in current research and they are correlated with L_{Aeq} values of 75 and 65 dBA, respectively. The correlation between the values of noise contour areas S and the values of EPNL at the noise monitoring points are also good.

CAEP/5 suggests use of Day–Night Sound Level to forecast the population annoyed in the area with the prescribed value of noise level L_{dn}. Two thresholds are specified: 'significant' exposure is defined by $L_{dn} = 55$ dB or higher and 'high' exposure is defined by $L_{dn} = 65$ dB or higher.

Harmonization of noise indicators (*NI*) is an essential component of European strategy to reduce noise. The Commission of the European Communities has suggested use of the following criteria for *NI*:[1,5]

- validity (relationship with effects);
- practical applicability (easy to calculate using available data, or to measure using available equipment);
- transparency (easy to explain, the relationship with physical units);
- enforceability (use of indicator in assessing changes or when set limits are exceeded);
- consistency.

Since the purpose of *NI* is to reduce a large volume of information to a single noise metric value, information about the individual contributions of noise sources can be lost. Five steps are considered when designing a method for estimating reaction to noise. The first step is to reduce the frequency spectrum to a single number (using A-, B-, C-, D-weightings, PNdB or Zwicker/Stevens phons). The second step produces a single value per event by means of energetic summation (for example, L_{AX}) or the maximum level per event ($L_{A\max}$). In the third step, the number of events per day (day, evening, night) is incorporated by means of energetic summation over the period T of interest (for example, $L_{Aeq,T}$). The fourth step summation with a specified weighting factor for different periods. In the simplest form of the fourth step, the day, evening or night periods are summed to give a 24-hour value. In some cases either evening/night corrections are used. Finally, as the fifth step, a long-term value is obtained by means of energetic summation and averaging.

The following types of indices or rating schemes result:[23]

- noise exposure levels, which take into account human noise response (for example, overall levels in A-, B-, C-, D-weighted decibel, *PNL*);
- effective noise levels, which take into account noise exposure levels and the duration of the event (for example, EPNL);
- noise indices, which take into account the variation of noise levels with time and the number of flights per specified time period (for example, $L_{Aeq}, L_{DN}, NEF, NNI, N, CNEL, WECPNL$);
- noise criteria, which indicate simultaneously the change of noise levels over time, the number of flights per specified time period and population reaction to aircraft noise (for example, number or percentage of the population annoyed by noise).

Another method is to use noise impact scaling as shown in Fig. 1.20. On an axis corresponding to a particular noise index or rating, it is necessary to decide upon the border (O indicates the border point) between unacceptable and acceptable levels of annoyance. Such scaling allows a balanced approach in aircraft noise abatement.

Some tasks, for example, the allocation of the aircraft fleet in the vicinity of an airport to minimize aircraft noise can be turned into two optimization tasks by the method of decomposition. In the first stage, it is necessary to determine a low noise takeoff and approach flight procedure for each separate aircraft using, for example, EPNL. The second optimization task involves a higher-level criterion (for example, the area restricted by a given noise contour EPNL = *constant*).

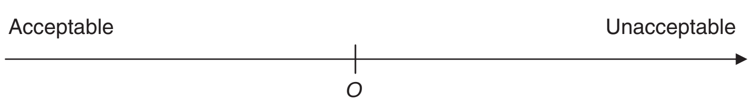

Figure 1.20 Structure for one-dimensional scaling of annoyance.

1.5 Control of noise impact

The aircraft noise problem can be addressed in several ways: by government policy through aircraft noise control legislation; by the aircraft industry through the creation of low noise aeronautical equipment; by regional zoning for noise; and by local application of low noise flight procedures around an airport. The flight procedures for noise abatement are developed by the airline in consultation with the aircraft manufacturer. The authority for approving the introduction of any noise abatement operating procedure may be the national Civil Aviation Authority and/or the national authority for civil aviation safety. Low noise flight procedures for any particular flight must conform to the requirements of the state or country in which the airport is located.[16] Consequently, aviation noise reduction through operating procedures depends on communication between airlines, airports and the Civil Aviation Authority.

The abatement of aircraft noise involves limiting the noise at the source, noise control along the sound transmission path, low noise takeoff and approach flight procedures, optimal distribution of aircraft between the arrival and departure routes and land-use planning. Methods of noise abatement can be realized at all stages of the 'life cycle' of aircraft, from designing to aircraft phase-out.

Increasing stringency of the noise certification limits for subsonic airplanes, the phasing out of Chapter 2 aircraft, noise-based operational restrictions, reduction of noise at source, land-use planning and low noise operational procedures are all elements of the ICAO program on noise reduction. International organizations, for example, the ICAO and the European Civil Aviation Conference (ECAC), and the aviation industry, work together to formulate and implement environmental regulations.

According to the World Health Organization (WHO) data, recent years have seen an uncontrolled increase in environmental noise. The European Union (EU) has a strategic goal – to prevent an increase in the number of people affected by noise within the next few years. Indeed, the aim of the long-term EU program inside the VIth Action Plan on Environment Protection is to decrease the number of people exposed to high noise levels.

In Europe, for example, programs X-NOISE, SILENCE(R), the Fifth EU Framework Program has an objective to reduce noise impact by 10 EPNdB within 10 years. The 'critical technology' for source noise reduction embraces the engine (fan, compressor, turbine, core, jet noise reduction, progress in nacelle design), the airframe and the use of favourable installation effects. Large-scale integration programs for reduction of aircraft noise impact include source noise reduction and low noise operational procedures.

Aircraft noise management includes noise exposure simulation, environmental regulations, land-use planning, noise monitoring and air traffic control. This approach to the noise problem includes the following steps:

- reduction of aircraft noise at source by means of new technologies to mitigate noise impacts (propulsion system noise reduction using higher bypass ratios and turbomachinery noise reduction);
- special operational measures (for example, throttling back the engine on takeoff, low-power low-drag approaches, continuous descent approaches, and delayed flap and landing-gear extension);
- rational distribution of aircraft in the zone of the airport (preferred runway operation and flight tracks/corridors, use of less noisy aircraft, particularly at night, and fewer night flights);
- restricted building in high noise-level zones around airports and the introduction of noise-mitigation measures;
- noise monitoring systems in the vicinity of the airport and effective policing of them.

The essential elements of air traffic noise management are airport noise prediction and forecasting; noise exposure simulation; elaboration of noise-reducing strategies; noise certification of aircraft, accounting for noise propagation under various operational conditions; local environmental adjustments at the airport and the monitoring of aircraft noise. Airport noise forecasting needs information about the traffic pattern, the structure of the aircraft fleet, aircraft noise characteristics, aircraft weight and flight path, the number of aircraft operating on the flight path, their schedule and operational measures, the atmospheric parameters, sound propagation in atmosphere and the ground surfaces and topography in the vicinity of airport.

Environmental adjustments at an airport include some restrictions: the limitation of number of operations; bans on the operation of noisy aircraft; special operational measures and the rational distribution of aircraft in the zone of the airport. Table 1.8 summarizes aircraft noise abatement measures.

It is important to distinguish between the notions of imission and emission with regard to noise abatement. Imission is the influence of noise received by a receiver in a noise source action zone. Emission describes the radiation of noise from the source. Permissible emission is related to standardized imissions after taking into account the noise propagation from source to receiver. International and national experience allows the derivation of normative requirements on noise in the working zone, to define noise control methods and to establish normative noise levels for individual acoustic sources. There are several groups of normative documents on noise. The first group determines the terms, system of units and the permissible noise level norms (for example, in dwellings and public buildings in the vicinity of the airport). The second group determines methods for measuring noise in the working zone. The third group of normative documents establishes methods for measuring the noise of the sources (for example, of engines and equipment). The fourth group of normative documents establishes procedures for verifying the effectiveness of noise suppressors (for example,

Table 1.8 A classification of noise abatement methods

Noise abatement measures	*Procedure*	*Aircraft and equipment operation*						
		Taxiing	*Takeoff*	*Landing*	*Roll-on*	*Training flight*	*Run-up*	*Ground equipment*
Aircraft noise emissions	Standard and recommended practices of ICAO, Annex 16, volume 1, National standards		•	•				
Aircraft noise transmission and imissions	National imission standards, noise monitoring	•	•	•	•		•	•
Planning of airport	Change of direction runway, length of runway	•	•	•	•	•		
	Displacement of runway threshold			•		•		
	Building of high speed taxiway	•			•			
	Reconstruction of terminal building	•					•	•
	Use of noise mufflers or screens for isolation of zones run-up of engines	•					•	•
Rational use of a zone of the airport and airspace near to airport	Preferred runway operations	•	•	•	•	•		
	Preferred on noise flight tracks operations or change of flight procedures of takeoff and landing		•	•	•	•		
	Restriction of aircraft taxing	•						
	Restriction of run-up of the engine						•	•
	Restriction of intensity aircraft operation of separate types	•	•	•	•	•	•	•

Table 1.8 Cont'd

Noise abatement measures	*Procedure*	*Aircraft and equipment operation*						
		Taxiing	*Takeoff*	*Landing*	*Roll-on*	*Training flight*	*Run-up*	*Ground equipment*
	Ban of noisy aircraft, limiting night flights	•	•	•	•	•	•	•
	Augmentation of inclination of glidepath or entrance height in glidepath			•		•		
	Descent of aircraft in configuration with low drag			•		•		
Operation of aircraft	Engine, flaps deployment and flight speed control		•	•		•		
	Reverse thrust limitation				•			
Land-use planing	Alienation of land-use in the vicinity of the airport	•	•	•	•	•	•	•
	Purposeful airport development	•	•	•	•	•	•	•
	Zoning territory in the vicinity of the airport	•	•	•	•	•	•	•
	Observance of national building norms and sound insolating of dwelling	•	•	•	•	•	•	•
Development of noise abatement programs	Landing charge with noise factor calculation	•	•	•	•	•		
	Research of population complaints on noise	•	•	•	•	•	•	•
	Inculcation of automation noise monitoring systems	•	•	•	•	•	•	•

mufflers and screens). The fifth group establishes the requirements on the performance of noise suppressors and sound-proofing materials.

Normative documents are made by the International Organization on Standardization (ISO), the International Electrotechnical Commission (IEC), ICAO, the WHO and other organizations. The approaches to noise normalization can be categorized as sanitary or technical. Sanitary noise normalization establishes the limitations on noise under conditions of insignificant harmful influence on man. Technical noise normalization establishes the maximum noise levels with regard to technically achievable methods of noise reduction for given acoustic sources. The sanitary norms determine the necessary noise attenuation and the technical norms specify the attainable noise levels of the equipment.

The government policy on the control, abatement and mitigation of aircraft noise involves a balance between the needs of an efficient aviation industry and the need to minimize the impact of noise around airports. An important improvement in aircraft certification noise levels has been achieved over the past 25 years. It is necessary to take into account ICAO long-term strategy on the stringency of noise standards. In January 2001, the Committee on Aviation Environmental Protection (CAEP-5) recommended new, stricter noise certification standards, which was forwarded to the ICAO Council for a final decision. The new standards that the sum of noise levels measured at three measurement points (under the takeoff, under the arrival, and along the side of the runway) is 10 EPNdB lower than current Chapter 3 standards for noise reduction. At the federal level, noise control tools can include general environmental legislation, a noise quota system and quota limits, optimization of flight procedures, land-use planning, legislation to avoid construction of noise sensitive buildings and a noise monitoring system.

At the regional level, tools for noise control can include noise limits for aircraft flying over a region, noise emission limits, restrictions on the number of inhabitants within certain noise contours and an environmental audit.

In the vicinity of an airport, the noise control tools can include zoning and land use with respect to aircraft noise, limitations on the number of night movements, noise charges, noise minimization operations through optimization of airplane movements, layout of parking areas, construction of acoustic screens for reducing aircraft noise impact, construction of engine test places and actions to take care of ecological aspects around the airport.

Noise abatement tools for the airline can include the process of aircraft fleet formation and training the flight crew on low noise operational procedures.

1.6 Regulations and standards for aircraft noise

Since noise is the main source of environmental disturbance caused by air transport, the dominant environmental issue for air transport and a major constraint to growth, noise issues have received more regulatory and technological attention than any other aviation environmental problem. The most important effect in terms of the number of affected people is so-called *annoyance*, which can be determined from structured field surveys. Noise annoyance is strongly connected with specific effects, such as the necessity to close windows in order to enable sleep, disturbance or interference with communication, listening to the TV, the radio or music. Additionally, a number of serious medical effects may arise, such as high blood pressure, mental stress, heart attacks and hearing damage, although the latter concerns a smaller part of the population. Furthermore, there are negative effects on the learning capabilities of children. It is evident that people reporting noise-induced annoyance experience a reduced quality of life. This is a reality for at least 25 per cent of the EU population who are exposed to A-weighted transportation noise levels exceeding 65 dB, which many countries consider to be unacceptable. Between 5 and 15 per cent of the EU population suffers serious noise-induced sleep disturbance.[20] Even though the uncertainty of these estimates is very large, there is no doubt about the high prevalence of noise annoyance in the EU.

Aircraft, road traffic and railways are the most important sources of environmental noise in Europe.[21,22] However, locally, the noise situation can be dominated by other types of sources, for example, by noise from industrial sources or from residential and leisure areas. Important environmental noise effects are perceived in the domestic environment – in and near the home, in public parks, in schools. Current economic estimates of the annual damage in the EU due to environmental noise range from EUR 13 billion to 38 billion.[25] Elements that contribute are a reduction of housing prices, medical costs, reduced possibilities of land use and cost of lost labor days. In spite of some uncertainties, it seems likely that the costs of noise involve tens of billions of euros per year.

Public concern about exposure to noise pollution remains high, for example, in the EU, in spite of existing legislation. Noise emission from products is covered by Council Directive 86/188/EEC of 12 May 1986 on the protection of workers from risk related to exposure to noise at work, as amended by Directive 98/24/EC, and noise insulation between dwellings is converted by Council Directive 89/106/EEC of 21 December 1988 through regulations and administrative provisions of the Member States relating to construction products, as amended by Directive 93/68/EEC.

Legislation on environmental noise is divided into two major categories namely, legislation on noise emission by products (cars, trucks, aircraft and industrial equipment) and on allowable noise levels in the domestic environment. Emission standards consist of emission limit values applicable to individual sources and included in type approval procedures to ensure that new products comply with the noise limits at the time of manufacture. Emission standards must be grounded on the best available technology, that is, the technology that minimizes noise emissions for a given source. However, because the technology is sometimes too expensive for the industry to adopt without operating at a loss (considering civil aviation, for example), a determination is made of best practicable technology, which means taking socio-economic, as well as engineering factors into account. The regulations may be stricter for new sources than for existing ones. The aircraft noise norms and certification procedures declared by ICAO Annex 16,[26] are good examples of this approach.

Immission standards are based on noise quality criteria or guideline values for noise exposure[24,27] to be applied to specific locations and are generally built into planning procedures. Noise is associated with several negative feelings: annoyance, disturbance, bother and intrusion. In discussing noise annoyance, Langdon[28] considers the noise itself, its source, meaning, perception and the degree of interference as external factors. Except at higher sound levels, increases in annoyance are not always related to increases in sound, but some degree of relatedness remains.

Where sound pressure levels vary quite substantially and rapidly, such as during a low-level jet aircraft pass by, one might also want to consider the rate of change of sound pressure levels (the onset rate, for example). At the same time, the frequency content of each noise will also determine its effect on people, as will the number of events when there are relatively small numbers of discrete noisy events. Combinations of these characteristics determine how each type of environmental noise affects people.

Noise limits have been fixed for aircraft noise to ensure that rules are followed when building new dwellings and other noise sensitive installations close to existing airports and are taken into consideration for airport capacity expansion. Zones are generally designed to separate land uses. This is done by mapping noise contours and relating permissible land use to ambient noise levels.

The EU Green Paper on Future Noise Policy[21] and underlying studies analyzed the characteristics and impact of the EU and Member State approaches. It concluded that, to date, the total effect is unsatisfactory.

Directive 92/14/EEC, which came into force in April 1995, is the latest in a series of legislative measures in the EU begun in 1979 (Directives 80/51/EEC and 89/629/EEC) aimed at limitation of aircraft noise emission. These directives, like broadly similar legislation in other 'noise restrictive states' (most of non-EU Europe, Japan, Australia and New Zealand and the USA), use the benchmark standards specified by the ICAO in the Environmental Protection Annex 16, Volume I,[26] to the Chicago Convention, to which most countries in the world adhere. The limit values for individual aircraft types during takeoff and landing are specified in the terms of EPNL in EPN dB, and depend on the aircraft weight and number of engines. The oldest, noisier jet transport aircraft are 'non-noise certificated' (NNC), the second generation's characteristics are reflected in Chapter 2 of Annex 16 and the most modern, quieter aircraft meet the standards in Chapter 4.

Air transport was among the first of the world's transport industries to meet internationally accepted noise regulations. People living around airports often feel that air transport is a heavy strain on the local environment particularly with regard to noise. Their complaints cause airport authorities to introduce their own noise rules, restricting airline operations. In turn, the airlines look to manufacturers for quieter aircraft.

Quieter aircraft have significantly reduced the number of people affected by aircraft noise. Environmental performance of the product is only one of many considerations taken into account in the design process. The aeroplane manufacturer must carefully weigh and re-weigh each objective against all others to establish a design eventually that meets all regulatory and market requirements for the product. Noise reduction as a design metric must be balanced with respect to other customer needs. Anyway, the aircraft noise reduction that has been achieved is quite impressive. For example, on takeoff, a Boeing 727 (a 1960s aircraft) created an intrusive noise 'footprint' (defined as the area bounded by a contour specified by a normative value of noise index, for example, in terms of L_{Amax}, EPNL or DNL), which covered an area exceeding 14 km^2. In contrast, a modern commercial jet of similar capacity, but with greater takeoff power, such as the Airbus A-320, creates a 'noise footprint' covering only 1.5 km^2. This represents an area reduction by nearly a factor of 9 (Fig. 1.21). In the turboprop segment, the takeoff noise footprint area of the Fokker 50 (1987) compared to the Fokker F27 MK500 (1968) shows a reduction of the 80 dB contour from 3.77 km^2 to 0.84 km^2, that is, an area reduction factor of 4.5.

As a result, in the United States and Europe, the number of people directly affected by aircraft noise is now only about 5 per cent of what it was with 1970s technology aircraft. The 19 million inhabitants of the USA and Europe affected by aircraft noise in 1970s have been reduced to only 0.8 millions in 1990s owing to improvements in engine and

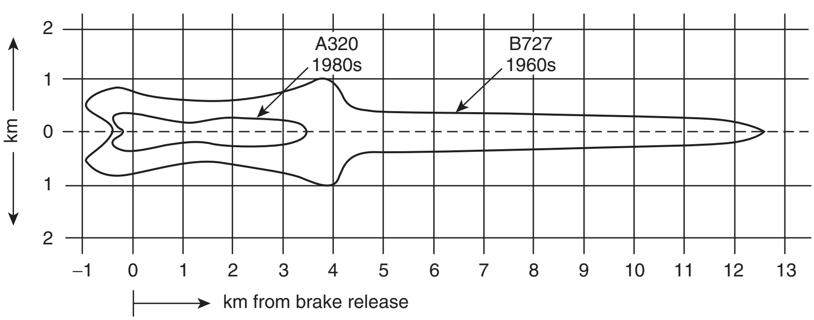

Figure 1.21 Noise impact at takeoff [noise contour for 85 dBA]: A320–200 with CFM-56-5 engines and TO weight 67.5 t (noise footprint = 1.55 km^2); B727–200 with JT8D-15 engines and TO weight 76.5 t (noise footprint = 14.25 km^2).

aircraft technologies. These data are derived from the Nationwide Airport Noise Impact Model developed for the Federal Aviation Administration (FAA) Nationwide Airport Noise Impact Model (NANIM, 1993). NANIM calculated the regional and national totals of the number of people, the land area and the number of housing units exposed to a *DNL* of 65 dB or higher.

The MAGENTA (Model for Assessing Global Exposure form Noise of Transport Airplanes) study[29] of the ICAO has been used to help in the identification of noise problems around airports and assess the relevance of the noise certification scheme to these problems.

Based on the initial success of the FAA activity, the fourth meeting of CAEP (CAEP-4) recommended that a task group be formed to complete the development of the same tool for CAEP analysis. The model calculates noise contours for major airports and overlays them on population maps. Global noise exposure calculations were made for a number of ‘snapshot’ years between 1998 and 2020, taking account of increases in traffic. The airline fleets, aircraft noise and performance characteristics and airport operations by type were defined by CAEP.

From the 1998 starting point to 2002, noise exposure (levels of *DNL* 55 and *DNL* 65 were taken as the thresholds of significant and high noise impact, respectively) generally falls as a result of the ongoing phase-out of Chapter 2 aircraft. Beyond 2002, airport capacity is a key factor. The extent to which global noise exposure goes up or down will depend very much on how airport operators accommodate the forecasted doubling of passenger traffic over the next 20 years. Around 25 million inhabitants, living in the vicinity of the airports, are likely to be impacted significantly worldwide.[29]

Many of the adverse environmental effects of civil aviation activity can be reduced by the application of integrated measures embracing technological improvements, appropriate operating procedures, proper organization of air traffic and the appropriate use of airport planning and land-use control mechanisms. States and international organizations recognize the leading role of ICAO in dealing with the problems of aircraft noise and they keep the Council informed of their policies and programs to alleviate the problem of aircraft noise in international civil aviation.

The ICAO is becoming involved in activities relating to environmental policies affecting air transport and it strives to achieve a balance between the benefit accruing to the world community through civil aviation and the harm caused to the environment. The ICAO Assembly considers that improvements in the noise climate achieved at many airports by the introduction or revision of aircraft-related measures (for example, the phase-out of Chapter 2 aircraft) should be safeguarded by taking into account the sustainability of future growth and should not be eroded by incompatible urban encroachment in areas where reductions in noise levels have been achieved.

Guidance on the Balanced Approach to Aircraft Noise Management was published by ICAO in 2004. The Balanced Approach encompasses four principal elements: reduction of noise at source, land-use planning and management, operational procedures for noise abatement and operating restrictions on aircraft. The process of implementing the Balanced Approach would typically consist of an assessment of the noise situation at an individual airport, definition of the objective, provision for consultation, identification of measures available to reduce the noise impact, evaluation of the relative cost-effectiveness of the measures, selection of measures, adequate public notification of intended actions, implementation of measures and a provision for dispute resolution available to stakeholders.

Under the Balanced Approach, reduction of noise at source is limited to noise reduction through the adoption and implementation of noise certification standards set by ICAO and is not within the control of individual airports. The prime purpose of noise certification is to ensure that the latest available noise reduction technology is incorporated into aircraft design demonstrated by procedures which are relevant to day-to-day operations, to ensure that noise reduction offered by technology is reflected in reductions around airports.

Standards for aircraft noise were first adopted by the Council of ICAO on 2 April 1971 pursuant to the provisions of Article 37 of the Convention and designated as Annex 16 to the Convention. All of the standards and recommended practice for aircraft noise are included in Volume 1 of the Annex 16 'Aircraft noise', and all the questions concerning engine emissions are in Volume 2 – 'Aircraft engine emission'. Part II of the Volume 1 contains standards and guidelines for noise certification applicable to the classification of aircraft specified in individual chapters of this part. Chapter 2 contains the oldest version of the standards for the most popular types of the subsonic jet aircraft that have not been in production since the 1980s. More stringent standards were implemented and applied to new airplane designs in the late 1970s. These new standards were included in Chapter 3, Annex 16 of Volume 1 to the ICAO Convention and applied to new jet aircraft types starting on 6 October 1977. ICAO has recently confirmed the Chapter 4 noise certification standards. Effectiveness and reliability of certification schemes from the viewpoint of technical feasibility, economic reasonableness and environmental benefit need to be achieved in all the standards.

Several steps are involved in developing a noise reduction concept, beginning with the initial idea, evaluating the feasibility of the idea, evaluating the merits of the idea and establishing and executing a development plan to carry the idea through to a practical, useful concept.

Two types of cost assessments were made before introduction of the new Chapter 4 noise certification standards.[30]

(1) First, it was used to determine the amount of noise reduction for each noise certification reference condition required to enable each current or near-term production aircraft type10 to meet the noise stringency options under study, in this case Chapter 3 limits minus 8, 11 and 14 EPNdB. The incremental operating and capital costs associated with the required insertion of noise reduction technology for aircraft failing each of the proposed noise stringency levels was also determined in this step.

(2) For the noise policy options that included phasing out the noise non-compliant aircraft among the in-service fleet, the Aircraft Noise Design Effects Study (ANDES) model was used to estimate the combined incremental capital and operating costs resulting from the insertion of the required noise reduction technology that would bring into compliance aircraft that did not meet the proposed noise stringency levels (Fig. 1.22). It was also used as a screening tool to determine which in-service aircraft could be potential candidates for re-certification (that is, modification of the airplane with retrofit noise reduction technology packages).

Noise reduction features can be divided into three classes:

- features that attack those sources which need reduction to meet requirements;
- features with a higher technology readiness level in order to minimize risk of failure and the need for a redesign; and
- features offering the required benefit at the minimum cost.

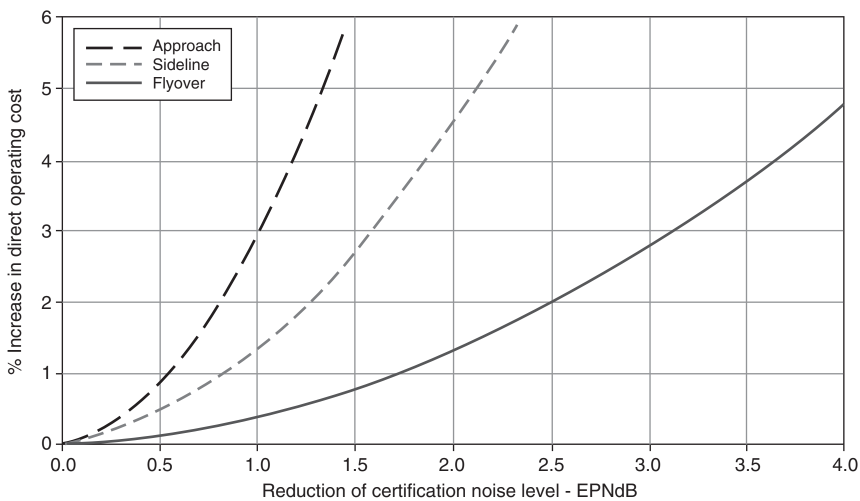

Figure 1.22 Combined incremental capital and operating costs resulting from the application of the required noise reduction technology.

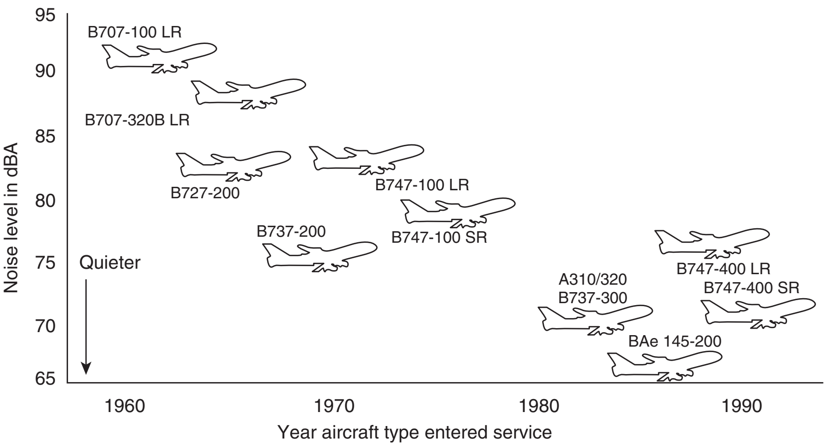

Figure 1.23 Progress in aircraft noise reduction due to aircraft and engine development.

Since the 1970s, the limits set by legislation and certification have been tightened and distributed over the whole spectrum of possible airplane types. Reduction in engine noise has contributed most to the dramatic reduction of the overall aircraft noise. Figure 1.23 gives an overview of the progress in aircraft noise reduction since 1960.

CAEP-5 has defined Chapter 4 limits as giving rise to a cumulative 10 dB below the Chapter 3 standards. However, there is no requirement for a minimum improvement at each of the three reference noise measurement points. Given that aircraft noise affects communities on either side of airports as well as under the approach and departure routes, Chapter 4 does not ensure that ICAO's goal to limit or reduce the number of people affected by noise will be met, as it does not guarantee an improvement at all of the reference noise measurement points.

When Chapter 4 was decided in 2001, the cumulative decrease of 10 dB was already being met by virtually all aircraft in production. This means that aircraft certificated after the commencement date of 2006 are not required to perform better than the majority of aircraft already in production in 2001. A substantial reduction in the noise impact around airports is therefore not expected from the Chapter 4 standard.

Table 1.9 illustrates some of the major parameters that are currently considered in the course of an aircraft 'design-to-noise-objectives' process. The table shows the trend of each parameter's potential impact on certification noise levels. The sign indicates the direction of change required for the parameter to achieve a noise reduction (+, increase; –, decrease; = no direct influence). Many of these parameters result from general trade-off studies

Table 1.9 Useful parameters for an aircraft 'design-to-noise-objectives' process

Design parameters	*Sideline*	*Takeoff flyover*	*Approach*
Aircraft performance			
Weight	−	−	−
Thrust rating	−	+	=
Wing L/D	+	+	+
Engine			
Bypass ratio	+	+	+
Fan pressure ratio	−	−	−
Nacelle			
Intake liner efficiency	+	+	+
Fan duct liner efficiency	+	+	+
Intake and/or fan duct length	+	+	+
Airframe			
Low noise high lift devices	+	+	+
Low noise landing gear	=	=	+

leading to the detailed design of the aircraft and are not fully independent of each other.

Their individual impact on other aircraft requirements can also be significant. Nevertheless, it shows that, with the exception of engine thrust rating that can have an opposite effect on the takeoff, flyover and sideline certification points (see later), any variation causing a noise reduction at one point will cause either no change or a corresponding noise reduction at any other point. Whether this remains true of all design parameters has to be evaluated on a case-by-case basis. The consequence is that designing to a 'cumulative' noise objective most likely results in improving preferentially one or two out of the three certification points, without significantly negatively impacting the third one, but possibly minimizing the impact on other aircraft requirements. On the other hand, designing to one challenging individual noise level could lead to a detrimental impact on non-noise aircraft design requirements, could potentially yield limited benefit to the other two noise point levels, and result in poor cumulative performance.

For example, for subsonic transport category large airplanes and subsonic turbojet-powered airplanes, compliance with the requirements of the Chapter 2 must be shown with noise levels measured and evaluated as prescribed in this chapter and demonstrated at the measuring points and in accordance with the flight test conditions prescribed under this chapter.

Compliance with the noise level standards must be shown at the three measuring points:

(a) For takeoff, at a point 6500 m from the start of the takeoff roll on the extended centerline of the runway.
(b) For approach, at a point 2000 m from the threshold on the extended centerline of the runway.
(c) For the sideline, at the point, on a line parallel to and 450 m from the extended centerline of the runway, where the noise level after liftoff is greatest.

It must be shown by a flight test that the noise levels of the airplane, at these three monitoring points, do not exceed the following limits (with appropriate interpolation between weights):

(1) Stage 2 noise limits for airplanes, regardless of the number of engines, are as follows:

 (i) For takeoff: 108 EPNdB for maximum weights of 272 t or more, reduced by 5 EPNdB per halving of the 272 t maximum weight down to 93 EPNdB for maximum weights of 34 t and less.
 (ii) For sideline and approach: 108 EPNdB for maximum weights of 272 t or more, reduced by 2 EPNdB per halving of the 272 t maximum weight down to 102 EPNdB for maximum weights of 34 t and less.

(2) Stage 3 noise limits are as follows:

 (i) For takeoff:

  (A) For airplanes with more than three engines: 106 EPNdB for maximum weights of 385 t or more, reduced by 4 EPNdB per halving of the 385 t maximum weight down to 89 EPNdB after which the limit is constant (under maximum weight of 20.2 t).
  (B) For airplanes with three engines: 104 EPNdB for maximum weights of 385 t or more, reduced by 4 EPNdB per halving of the 385 t maximum weight down to 89 EPNdB after which the limit is constant (under a maximum weight of 28.6 t).
  (C) For airplanes with fewer than three engines: 101 EPNdB for maximum weights of 385 t or more, reducing by 4 EPNdB per halving of the 385 t maximum weight down to 89 EPNdB after which the limit is constant (under a maximum weight of 48.1 t).

 The various noise limits as a function of takeoff weight are shown in Fig. 1.24.

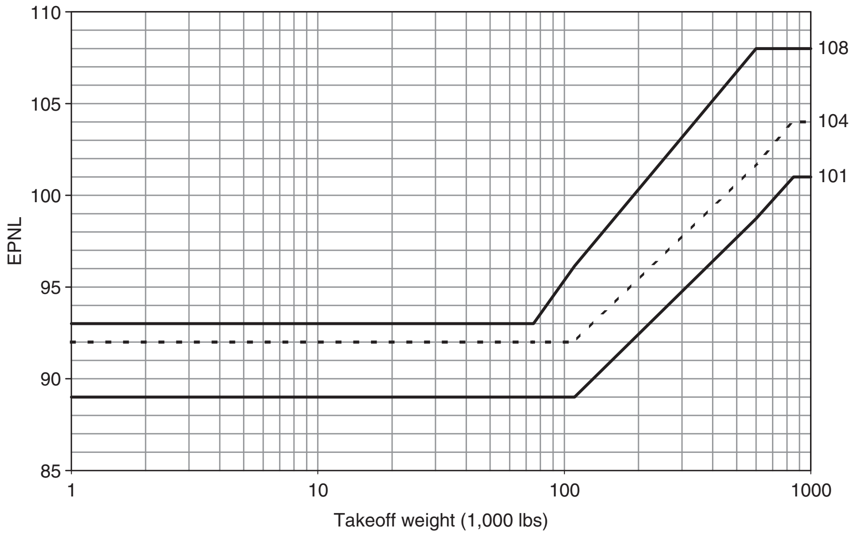

Figure 1.24 Stage 3 aircraft noise limits.

(ii) For the sideline, regardless of the number of engines: 103 EPNdB for maximum weights of 400 t or more, reduced by 2.56 EPNdB per halving of the 400 t maximum weight down to 94 EPNdB after which the limit is constant (under the maximum weights of 35 t).

(iii) For the approach, regardless of the number of engines: 105 EPNdB for maximum weights of 280 t or more, reduced by 2.33 EPNdB per halving of the 280 t weight down to 98 EPNdB after which the limit is constant (under maximum weights of 35 t).

All of the limits can be calculated from equations of noise levels as a function of takeoff mass M (t). They are shown in Tables 1.10–1.14 for the particular types of airplanes considered in Annex 16.

Table 1.10 Noise and mass relationships for Chapter 2 aircraft requirements (before 6 October 1977)

Maximum takeoff mass, M (t)	0	34	272
Lateral noise level (EPNdB)	102	$91.83 + 6.64 \lg M$	108
Approach noise level (EPNdB)	102	$91.83 + 6.64 \lg M$	108
Flyover noise level (EPNdB)	93	$67.56 + 16.61 \lg M$	108

Table 1.11 Noise and mass relationships for Chapter 2 aircraft requirements (after 26 October 1981)

Maximum takeoff mass M (t)	0	34	35	48.3	66.7	133.45	280	325	400
Lateral noise level (EPNdB)	97		$83.87 + 8.51 \lg M$						106
Approach noise level (EPNdB)	101		$89.03 + 7.75 \lg M$				108		
Flyover noise level, 2 engines (EPNdB)	93			$70.62 + 13.29 \lg M$				104	
Flyover noise level, 3 engines (EPNdB)	93	$67.56 + 16.61 \lg M$			$73.62 + 13.29 \lg M$			107	
Flyover noise level, 4 engines (EPNdB)	93	$67.56 + 16.61 \lg M$				$74.62 + 13.29 \lg M$		108	

Table 1.12 Noise and mass relationships for Chapter 3 aircraft requirements

Maximum takeoff mass M (t)	0	20.2	28.6	35	48.1	280	385	400
Lateral noise level (EPNdB)	94			$80.87 + 8.51 \lg M$				103
Approach noise level (EPNdB)	98			$86.03 + 7.75 \lg M$		105		
Flyover noise level, 2 engines (EPNdB)	89				$66.65 + 13.29 \lg M$		101	
Flyover noise level, 3 engines (EPNdB)	89	$69.65 + 13.29 \lg M$					104	
Flyover noise level, 4 engines (EPNdB)	89	$69.65 + 13.29 \lg M$					108	

Table 1.13 Noise and mass relationships for Chapter 5 aircraft requirements

Maximum takeoff mass M (t)	0	34	358.9	384.7
Lateral noise level (EPNdB)	96	$85.83 + 6.64 \lg M$		103
Approach noise level (EPNdB)	98	$87.83 + 6.64 \lg M$		105
Flyover noise level (EPNdB)	89	$63.56 + 16.61 \lg M$	106	

Table 1.14 Noise and mass relationships for Chapter 8 aircraft requirements

Maximum takeoff mass M (t)	0	0.788	80
Lateral noise level (EPNdB)	86	$87.03 + 9.97 \lg M$	106
Approach noise level (EPNdB)	87	$88.03 + 9.97 \lg M$	107
Flyover noise level (EPNdB)	85	$86.03 + 9.97 \lg M$	105

Tests for compliance with the required noise limits must be conducted under the following conditions:

(a) Takeoff power or thrust must be used from the start of takeoff roll to at least the specified altitude above the runway:

   (1) ICAO Annex 16: for Stage 2 airplanes (and in accordance with FAR-36 for Stage 1 airplanes and for Stage 2 airplanes that do not have turbojet engines with a bypass ratio of 2 or more), the following apply:

      (i) For all types of the airplanes: an altitude of 210 m.
      (ii) For airplanes with more than three turbojet engines: an altitude of 214 m.
      (iii) For all other airplanes: an altitude of 305 m.

   (2) For Stage 2 airplanes that have turbojet engines with a bypass ratio of 2 or more (FAR-36) and for Stage 3 airplane (FAR-36 and ICAO Annex 16), the following altitudes apply:

      (i) for airplanes with more than three turbojet engines: 210 m.
      (ii) for airplanes with three turbojet engines: 260 m.
      (iii) for airplanes with fewer than three turbojet engines: 300 m.
      (iv) for airplanes not powered by turbojet engines (only in accordance with FAR-36): 305 m.

(b) Upon reaching the altitude specified in paragraph (a) of this section, the power or thrust may not be reduced below that needed to maintain level flight with one engine inoperative, or to maintain a 4 per cent climb gradient, whichever power or thrust is greater.
(c) A constant takeoff configuration, selected by the applicant, must be maintained throughout the takeoff noise test, except that the landing gear may be retracted.
(d) For applications made for subsonic airplanes after September 17, 1971, and for Concorde airplanes, the following requirements on speeds apply:

   (1) For subsonic airplanes, the test day speeds and the acoustic day reference speed must be the minimum approved value of $V_2 +$ 19 km/h (V_2 is takeoff safety speed), or the all-engines-operating speed at 35 feet (for turbine engine powered airplanes) or 50 feet (for reciprocating engine-powered airplanes), whichever speed is greater as determined under the regulations constituting the type certification basis of the airplane. These tests must be conducted at the test day speeds ± 3 knots. Noise values measured at the test day speeds must be corrected to the acoustic day reference speed.

In all cases, compliance must be tested against the defined noise limits for approach.

(a) The airplane's configuration must be that used in showing compliance with the landing requirements in the airworthiness regulations constituting the type certification basis of the airplane. In accordance with ICAO Annex 16 Chapter 2, the configuration shall be with the maximum allowable landing flap setting. In accordance with FAR-36 and ICAO Annex 16 Chapter 3, if more than one configuration is used in showing compliance with the landing requirements in the airworthiness regulations constituting the type certification basis of the airplane, the configuration that is most critical from a noise standpoint must be used.
(b) The approaches must be conducted with a steady glide angle of 3 degrees +0.5 degrees and must be continued to a normal touchdown with no airframe configuration change.
(c) All engines must be operating at approximately the same power or thrust (FAR-36 requirement).
(d) For applications made for subsonic airplanes after September 17, 1971, and for Concorde aircraft, the following apply:

    (1) For subsonic airplanes, a steady approach speed, that is, either $1.30V_s$ + 19 km/h ($1.30V_s$+ 10 knots; V_s is stall speed) or the speed used in establishing the approved landing distance under the airworthiness regulations constituting the type certification basis of the airplane, whichever speed is greater, must be established and maintained over the approach measuring point.
    (2) In accordance with FAR-36 for Concorde aircraft, a steady approach speed, that is, either the landing reference speed +10 knots or the speed used in establishing the approved landing distance under the airworthiness regulations constituting the type certification basis of the airplane, whichever speed is greater, must be established and maintained over the approach measuring point.
    (3) A tolerance of +3 knots may be used throughout the approach noise testing.

Besides the requirements for jet aircraft, the ICAO Annex 16 includes the standards for noise levels of propeller-driven aircraft (Chapter 5 for weights over 5700 kg, Table 1.13;[26] Chapter 6 for weights not exceeding 5700 kg), propeller-driven STOL aircraft (Attachment C to Annex 16, which is only a guideline, not an enforceable standard), helicopters (Chapter 8 and Chapter 11; see Table 1.14). Noise limits and guidelines are also defined for auxiliary power units that are installed on board the aircraft (Attachment D to Annex 16). Some standards use indices such as L_{Amax} or *SEL* for the limits that differ greatly from EPNL. As a rule, test circumstances are different for these sources too. Nevertheless, the aircraft noise emission limits take into account not only the acoustical properties of the engines as a main contributor to the total noise levels under the flight path aside the aircraft, but also their installation effects, the aerodynamic properties of the airplanes, possibilities for effective flight procedures and so on. That is why the noise limits must be considered as a complex measure for acoustic efficiency of the particular type of airplane as a whole.

Chapter 2 aircraft have not been in production since the late 1980s and the retirement of noisier aircraft has been underway for many years. Manufacturers estimate that, as of the year-end 1991, nearly 2000 jet aircraft had been permanently retired. The peak of retirements, which occurred in the early 1980s, coincided with an economic recession and mainly involved the noisiest aircraft banned by noise regulations. Further retirements are now taking place and there will be a substantial need to replace large numbers of aircraft with newer models. Currently, the standards are used only for new designs of aircraft and not applied to aircraft in operation. In resolution A29-12 (1995), the 29th ICAO Assembly proposed in resolution A29-12 to phase out from operation the oldest, noisiest jet transport aircraft – those that are 'non-noise certificated' and have second-generation characteristics (reflected in Chapter 2 of Annex 16). The recommendations of the ICAO were reflected, for example, in USA FAR-91 and EU Directive 92/14. By 2002, aircraft which do not meet the latest ICAO noise certification standards – the so-called Chapter 2 aircraft – have to be phased out of commercial airline operations in most countries, or modified to meet these standards.

Subsonic non-noise certificated aircraft have been excluded from airports for several years and, under the terms of Directive 92/14 Chapter 2, aircraft over 25 years old have been banned from European Community airports since April 1995 unless granted exemptions designed to avoid unreasonable economic hardship to the airlines of developing nations, for instance. Chapter 2 aircraft were systematically phased out over the 1995–2002 period, and as of 1 April 2002, only Chapter 3 aircraft were allowed to use Community airports. FAR-91 considers more stringent terms, from 1995 up to 2000 only. Meanwhile, increased stringency is being considered by ICAO's Committee on Aviation Environmental Protection (CAEP) and the European Civil Aviation Conference (ECAC).

Aircraft manufacturers estimate that over the next 20 years, the world's airlines are expected to take delivery of up to 12,000 aircraft, worth an estimated US$ 857 billion (1992 dollars). While the three major aircraft manufacturers differ in their forecasts of the size and total number of the future aircraft fleet, all predict delivery of around 600 new planes a year for the next 15 years. In addition to significant enhancements in performance, these new aircraft will also bring major improvements in airline utilization, thereby reducing emissions and aircraft noise. So, wherever possible, airlines are:

- buying or leasing aircraft that satisfy the strictest international environmental requirements;
- replacing aircraft that do not meet these requirements as soon as operations and economics allow; and
- actively encouraging manufacturers to develop new, quieter, cleaner and more energy-efficient aircraft.

These developments, coupled with the high growth in the past and projected high growth for the future, may mean that only short to medium term benefit will be gained from the phase out of Chapter 2 aircraft and that after 2002, the overall noise emissions and consequently, the overall noise footprints may not be contained within the reduced boundaries expected to be achieved by that date. Further improvements in the noise impact around airports will require a combination of measures, including changes in operating procedures and better land-use planning.

Land-use planning procedures to ensure separation of dwellings and other noise sensitive buildings from noise sources are one of the means of putting immissions regulations into practice and are a key tool for noise abatement. It is a principal element of the Balanced Approach. The airport authority should work closely with local and regional authorities responsible for land-use management aiming to implement all noise-control measures around airports with regard to the noise impact of aviation operations. It is a planning, mitigating and financial instrument at the same time.

Airport planning must be recognized as an integral part of an area-wide comprehensive planning program. The location, size and configuration of the airport need to be coordinated with patterns of residential, industrial, commercial, agricultural and other land uses of the area, taking into account the effects of the airport on people, flora, fauna, the atmosphere, water courses, air quality, soil pollution and other facets of the environment. The social and economic impact, together with the environmental effects of the airport, can then be evaluated.

The need for some public control of land in the vicinity of an airport was recognized in the early history of civil aviation. In general, these early actions were usually concerned with height control of possible hazards or obstacles to flight into or out of airports. The compatibility of land use with noise exposure in the vicinity of airports did not become a major consideration until the early 1960s, a few years after the widespread introduction of commercial turbojet aircraft operations, although litigation regarding aircraft noise was not infrequent before that time.

Today, aircraft noise is probably the most significant influence on land-use planning in the vicinity of airports. Over the long-term it is one of the most efficient ways of reducing noise impact, as it can be used to prevent new problems occurring. In particular, noise abatement through land-use planning can include:[31] restricting the use of land that is already subject to high levels of noise, restricting the siting of new noise generators, such as traffic routes or industrial installations, in order to protect existing developments and encouraging noise-generating activities to cluster together in order to preserve other low noise areas. Noise is one of the considerations to be dealt with in environmental statements for developments requiring an environmental impact assessment.

The first noise limit of 112 PNdB for the new family of jet-powered aircraft, the Boeing 707 and McDonnell–Douglas DC-8 was set in 1959 at New York airport. This placed them in the same noise bracket as the quietest 75 per cent of propeller-driven airplanes. The first national noise standards for commercial aircraft were implemented in the United States in 1969. Now, all of the existing aircraft noise standards are included in US Federal Aviation Rules FAR-36 and they are equivalent to the ICAO Annex 16 standards due to the practice of worldwide harmonization of all rules that have an influence on civil aviation. The technical standards mentioned are examples of emission standards and relate to technological possibilities of the manufacturer to design a quiet aircraft.

Noise limits around the airports are considered to be ecological immission standards that must mitigate the noise impact on the population in the vicinity of the airports due to the environmental requirements and the possibilities of fulfilling these requirements by technical and financial efforts. Immision standards are included in special rules, for example, in the USA in the FAR-150 'Airport Noise Compatibility Programs'.

As a rule, noise immision standards are very specific for a particular nation. Work done under the ICAO coordination or in the EU community for their harmonization is only at a very early stage. Two basic approaches are generally followed. One uses the L_{Aeq} as for road and rail, the other uses indices that consider the number of aircraft movements and the peak noise level of each movement, with weightings for different periods of the day. In view of the diversity of the indices, it is difficult to compare immission limits.

In the USA, the Aviation Safety and Noise Abatement Act of 1979 directed the FAA to:

- establish a single system of measuring noise for which there is a highly reliable relationship between projected noise exposure and surveyed reactions of people to noise, to be uniformly applied in measuring the noise at airports and the areas surrounding airports;
- establish a single system for determining the exposure of individuals to noise that results from airport operations, which includes consideration of the noise intensity, duration, number of occurrences and time of occurrence;
- identify land uses that are normally compatible with various exposures of individuals to noise;

- establish a program for airport operators voluntarily to develop and submit to the FAA (1) noise exposure maps showing present and future non-compatible land uses around an airport, and (2) a noise compatibility program setting forth measures to reduce existing incompatible land uses and to prevent the introduction of additional incompatible land uses around an airport; and
- make Federal funding available for preparing a noise compatibility program and for projects to carry out a noise compatibility program.

The FAA implemented the Aviation Safety and Noise Abatement Act through the issuance of Part 150 of the Federal Aviation Regulations (FAR 150 or Part 150) (DOT, FAA 1989)[36]. Part 150 prescribes the procedures, standards and methodology governing the development, submission and review of airport noise exposure maps and airport noise compatibility programs, including the process for evaluating and approving or disapproving of those programs. It prescribes single systems for: (a) measuring noise at airports and surrounding areas that generally provide a highly reliable relationship between projected noise exposure and surveyed reaction of people to noise; and (b) determining exposure of individuals to noise, which results from operations.

In Part 150, the FAA designated *DNL* as the noise metric to be used, and required noise exposure maps to include *DNL* contours of 65 dB, 70 dB, 75 dB. The FAA has received noise exposure maps that include the *DNL* 60 dB contour and the *DNL* 55 dB contour. Part 150 includes the 1980 FICUN land-use compatibility criteria. These criteria are guidelines only, and Part 150 specifically allows local discretion in using the criteria. The FAA has received noise exposure maps and noise compatibility programs that include variations to these criteria, usually identifying land uses as incompatible at levels lower than *DNL* 65 dB.

An airport operator that undertakes airport noise compatibility planning under Part 150 is required to: develop present and future noise exposure maps; examine the airport's current and forecast future noise problems based on these maps; consider ways to reduce the exposure of noise sensitive land uses to levels of aircraft noise that are not compatible with those land uses; recommend noise reduction/land-use compatibility measures to be implemented; and submit its maps and recommended program to the FAA.

The Act directs the FAA to approve an airport operator's noise compatibility program if it meets specified standards. These standards require the program to:

- provide for reduction of existing incompatible land uses and prevention of the establishment of additional incompatible land uses;
- impose no undue burden on interstate or foreign commerce;
- not unjustly discriminate among users;

- not result in derogation of safety or adversely affect the safe and efficient use of airspace;
- meet both the local needs and the needs of the national air transportation system, to the extent practicable, considering trade-offs between economic benefits derived from the airport and the noise impact;
- be capable of implementation in a manner consistent with all of the powers and duties of the FAA Administrator; and
- provide for program revision, if necessary.

A large degree of international consensus has emerged over the years as to what constitutes unacceptable levels of noise exposure and what should be the maximum levels of exposure for certain specific situations. At the international level, the WHO together with the Organization for Economic Cooperation and Development (OECD) are the main bodies that have collected data and developed their own assessments on the effects of exposure to environmental noise. On the basis of these assessments, guideline values for different time periods and situations have been suggested.

In the mid-1980s the OECD[32] reported the thresholds for noise nuisance as follows (in day-time L_{Aeq}):

- at 55–60 dBA noise creates annoyance;
- at 60–65 dBA annoyance increases considerably;
- above 65 dBA constrained behavior patterns, symptomatic of serious damage caused by noise arise.

The World Health Organization (WHO)[33] has suggested a standard guideline value for average outdoor noise levels of 55 dBA, applied during normal daytime in order to prevent significant interference with the normal activities of local communities. Additional guideline values suggested for specific environments (WHO, all figures are in L_{Aeq}) are shown in Table 1.15.

The Fifth Environmental Action Program established a number of broad targets on which to base action up to the year 2000 for night time (L_{Aeq}):

- to phase out average exposure above 65 dBA;
- to ensure that at no point in time a level of 85 dBA should be exceeded coupled with the aim of ensuring that the proportions of the population exposed to average levels between 55 and 65 dBA should not increase; and
- exposure in quiet areas should not increase beyond 55 dBA.

A survey of the situation in Community countries has shown that most Member States have adopted legislation or recommendations aiming for immission limits in noise sensitive areas similar to these guideline values.[25] The national regulations were initially developed in the 1970s and

Table 1.15 World Health Organization guideline values (L_{Aeq} dB) for specific environments

	Day		*Night*	
	Inside	*Outside*	*Inside*	*Outside*
Residential	50	55		
Bedroom			30	45
			45	
Schools	35	55		
Hospitals	35		35	45 (for L_{Amax})
	30		30	40 (for L_{Amax})
Concert halls	100 for a 4-hour period		100 for a 4-hour period	
Disco	90 for a 4-hour period		90 for a 4-hour period	

1980s in the northern Member States and somewhat later in the southern Member States. Generally, these immission limits are more detailed and specific about the noise sources, the current noise situation and the kind of living area than the WHO guideline values.

Increasingly, these regulations are being integrated into national abatement laws and are used in land-use plans. Noise immission standards for new developments are normally set by local authorities as part of planning policy and are used as a reference in environmental impact assessments. They serve as a means of ensuring that appropriate measures are taken to minimize the noise impact of a site. Where an acceptable level of noise cannot be achieved, planning permission may be refused or action may be required to improve insulation from the noise sources.

Noise limits have been fixed for aircraft noise to ensure that rules are followed when building new dwellings and other noise sensitive installations close to existing airports and to be taken into consideration for airport capacity expansion. Zones, designed to separate land uses, are established by mapping noise contours and relating permissible land use to ambient noise levels.

In addition to certification limits and land-use planning, it is possible to reduce the effects of noise by acoustical barriers. Acoustical barriers can include wide-ranging measures such as the use of ear protectors for people subjected to high-intensity noise, to soundproofing of buildings and methods for screening the sound source. Specific attention should given to the proper location of ground aircraft engine run-up sites and the orientation of buildings at the airport. A good protection against ground run-up noise might be expected from properly planted trees, as indicated by a study in Japan of the sound-insulating characteristics of wooded areas. The sound attenuation through 100 m of evergreen trees can be 25–30 dB. But the screening efficiency of the trees may suffer from the seasonal changes because their sound-insulating characteristics (at higher frequency) are determined primarily by foliage density (see Chapter 3). Important consideration should be given to selecting species that do not generate a bird hazard for flights.

Noise insulation can lower interior noise levels for residential structures that cannot reasonably be removed from noise-exposed areas. Noise insulation is particularly effective for commercial buildings, including offices and hotels. The degree of insulation required varies from country to country. In some countries there are legal limits for internal noise. For effective noise insulation, it is necessary to have a closed-window condition, which may not be desirable to home-owners in all seasons and which may impose the additional ongoing costs of climate-control systems.

Earth berms or manmade barriers must be both structured and positioned accurately on the ground, to be located between sources of loud ground-level noise on the airport and very close in noise sensitive receptors. They do not mitigate in-flight noise. People appear to hear less noise if they do not see the aircraft on the ground or the maintenance facility that is the source of the noise. A proper positioning of airport buildings can also function as a noise screen for adjacent communities against certain airport activities.

Operational procedures are an important element of the Balanced Approach to noise control around the airports. They include: flight noise abatement procedures at takeoff and landing; preferential runway use; takeoff and/or landing displacement on runways; noise abatement flight tracks/corridors; reverse thrust limitations; flight scheduling and so on. For example, noise abatement flight tracks or corridors effectively concentrate aircraft noise over a small area. This can be very effective if the underlying area is not populated. Reverse thrust limitations may involve the use of the minimum reverse thrust necessary for the safe operation of the aircraft. This is generally interpreted as reverse thrust no greater than reverse idle.

The selection of an appropriate procedure with regard to airport-specific environmental constraints requires the quantification and analysis of the available operational solutions for each runway and departure corridor in terms of noise and/or gaseous emissions. The environmental effects of the procedures depend on the type of aircraft and operating conditions. The assessment of noise effects as part of procedure should therefore be based on actual information regarding the airport fleet mix and geographical position of the airport and its runway(s) with regard to noise sensitive areas.

The ICAO (in PANS-OPS,[34] Part V, Chapter 3) provides recommendations regarding the conditions in which noise abatement procedures can be safely used and the envelope within which main flight parameters defining the procedure can be safely adapted for airport noise mitigation. One procedure called NADP1 is used to mitigate noise at relatively shorter distances and another procedure, called NADP2, to reduce noise at relatively greater distances from the brake release point. Examples of such flight parameters are the height at which engine thrust is reduced and the height at which acceleration and flap/slat retraction are initiated.

Environmental principles may be arranged into a hierarchical set to be applied in developing or analyzing noise abatement operating procedures. The most important is the avoidance of residential areas. In all cases, aviation safety, including system safety through simplified operating arrangements, will be given priority over noise abatement considerations. However, assuming safety conditions have been satisfied, the sole test for moving to a lower level standard is that the higher standard is not operationally practicable.

In some regions of the world, for example, in Europe, there is growing pressure to impose operating restrictions on night flights and hence a curfew, which is an 'easy and ready to use' instrument. A curfew can be either global or partial in nature. It is global when it bans all flights during an identified time period. It is partial when it prohibits the operation of specific types of aircraft, or prevents the use of specific runways, or only affects arrivals (landing) or departures (takeoff). The 'phase-out' of Chapter 2 aircraft from the operation before the 1998 (when 'phase-out' began to be implemented in international flights) has been considered as a curfew, realized in many airports of the world. Even now this curfew exists, for example, in the form of domestic flight restrictions, because 'phase-out' deals with international flights mostly.

In fact the duration and the timing of the curfew depend on parameters such as airport configuration, noise contours/levels, number of people living around the airport, types of aircraft and the nature of night activities at the airport concerned. In addition, cultural considerations and the traditions and lifestyle of people living around the airport could also be taken into account.

There are more than 600 types of curfew implemented worldwide.[35] At present, nine airports in the UK impose a unique type of curfew in the form of Quota Count systems. These are based on a count of aircraft movements against a noise quota according to aircraft noise classification, distinguishing between arrivals and departures. Their effect is to discourage the operation of the noisiest aircraft at these airports, especially for departures, while allowing flexibility in the mix of aircraft.