To
Marianne and Catherine
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Preface to the First Edition

A high quality loudspeaker is required to reproduce sound with sufficient fidelity to satisfy a critical audience when fed from an accurate electrical signal. It is immaterial whether the listeners are numbered in thousands or comprise only a few individuals: loudspeaker systems can be designed to cater for both situations without compromising the basic standard of performance.

There are thus numerous applications for high quality loudspeakers. For example, broadcast and recording engineers rely heavily on monitor loudspeakers in order to critically analyse the quality of the programme they are producing. Other applications range in scope from the rock festival to the concert and opera hall, and in size from a theatre auditorium to an ordinary living room. Reinforcement loudspeakers are commonly used for sound amplification in live performances today, and while specialized systems are employed for instruments such as an electric guitar, other wider range sounds such as voice and woodwind require high performance speakers with a capability to allow the reproduced level to match that of the accompanying brass or a modern drum kit. Theatres and opera houses often use systems for off-stage sound effects, and most of today’s star performers would be unable to reach a large audience without the aid of a microphone and sound reinforcement. Special techniques are, however, required to attain the acoustic outputs necessary to satisfy a large stadium audience, and high efficiency, stacked, horn loaded, directional arrays are commonly employed for this purpose.

The author’s aim is to provide an up-to-date analysis and review of high performance loudspeaker techniques. Although it is not intended to be an exhaustive work, reference has been made in the text to original research material including the most important modern work in the field. Precedence is accorded to the moving coil drive unit, as this is by far the most widely used, although some coverage is also given to other viable if less common devices. In addition to the fundamentals—re relevant acoustic theory, transducer design, enclosures, acoustic loading, etc.—space is also accorded to developments in electronic crossover design and active speaker systems, as well as to the latest measurement techniques and such controversial questions as linear phase. By using the references supplied, the book can be used as the basis for further research, and as such, not only high fidelity enthusiasts should find it of interest, but also students studying such subjects as electronics, electroacoustics, broadcasting and recording. Even the design engineer and technical author may find it a useful appraisal of current techniques and a convenient source of subject references.

Martin Colloms
Preface to the Fifth Edition

For the fifth edition, my title *High Performance Loudspeakers* has joined technical publisher John Wiley. My initial concern about the transfer was replaced by increasing confidence. The Wiley UK team backed my proposals to substantially expand the text as well as bring the format and layout up to date. Finally, through economies of scale it was planned to significantly reduce the cover price, making the work accessible to a far wider readership.

Many revisions have made the book as up to date as possible, while continuing with that vital critical viewpoint when covering new developments and technologies. Every existing chapter has seen revision and expansion.

Building on the previous editions, the first chapter has been expanded adding an overview of modern design trends and practice.

Almost as this edition was released to the typesetters a new loudspeaker development was announced in London under the NXT brand, patents applied for by New Transducers Ltd. Covering non pistonic, vibrating acoustic panels, there is significant theory to match the wide variety of applications. Press attendance at the launch broke all records with the consensus view that this was an important development in the evolution of the loudspeaker. Accordingly a major section has been included on this technology.

A new chapter appears covering ‘Home Theatre Systems’ taking account of their special acoustic requirements, Dolby PRO-LOGIC, THX and the more recent AC-3, DTS and MPEG digital discrete, multi channel systems.

The review of computer aided design has been extended, covering both hardware and software systems and including the new generation of low cost audio instrumentation.

Complementing the necessarily academic nature of the theoretical aspects of speaker engineering, there is also a new section which gives much practical advice for real world speaker system design. It has been dubbed ‘Hot Tips’.

In ‘Systems and Crossovers’ new topics include $2\frac{1}{2}$ way system design; external crossovers; D’Appolito types; a distortion analysis of inductors; digital active loudspeakers and low order system design.

There has been a major expansion of the section on sub-woofers, also with relevance to Home Theatre where subs are almost mandatory. Subjective aspects of bass response are explored together with newly expanded sets of boundary matched low frequency alignments.

Speaker placement techniques, multiple driver and port combinations plus adjustable low frequency design are also covered. In ‘drivers’, there are extensions to include both the metal cone driver and its resonance control.
Design considerations for better dynamic performance are explored, both for overall build and for enclosure construction. On measurement issues there are more data on absolute phase and the effect of phase on energy decay waterfall displays. Aspects of running in, quality control and ageing are all considered, together with the effects of tolerances on system performance. Many new diagrams and illustrations have been included involving an overall 25% expansion for this new edition. The front cover features the Nautilus speaker, designed by Laurence Dickie and has been reproduced with kind permission of B&W Loudspeakers Ltd.

Many thanks to all of those who have continued to provide constructive criticism and support for High Performance Loudspeakers.

Martin Colloms
Preface to the Sixth Edition

With my enthusiasm for all aspects of loudspeaker engineering and design undiminished since the publication of the fifth edition, I have found that this still burgeoning industry has provided a wealth of material, which has made the preparation of this sixth edition well worthwhile.

This time, I have been joined by contributing author Dr Paul Darlington, who was inspired to create a radically new approach to explaining and modelling of the fundamentals of sound radiation. This ground-breaking thinking is presented in a new chapter that supersedes the older material; this was based on Beranek, which is still classic source material but undeniably half a century old. Paul’s approach leads to an elegant equivalent, elegantly leading to the familiar electrical circuit analogues still so useful for low-frequency system analysis. He has also contributed an excellent glossary.

Since the last edition, the PC has played an increasingly important role at the loudspeaker engineer’s workstation—indeed, in some labs, they are one and the same.

The variety, maturity and often moderate cost of sophisticated design analysis software forms one-half of a PC partnership, while effective acoustic measuring systems provide the other. The latter may frequently be enabled by means of a book-sized signal conditioning interface to a PC database or, in some cases, by simply employing an on-board soundcard in conjunction with suitable control software.

It has never been so easy to acquire such sophisticated design and measurement tools, and a number of them are introduced and discussed.

Additional highlights include the commercial introduction of pure diamond tweeters, as well as numerous developments in the field of digital loudspeakers for the extension of Home Theatre coverage, the latter including multi-channel music reproduction as well as 5.1 and 7.1 Theatre systems. Over 300 new source references in the loudspeaker field have been assessed and, where relevant, their significant content has been accounted for in this new edition. Fortuitous timing allowed the inclusion of a new theoretical development in the field of non-diffuse, coherent bending wave speakers, dubbed BMR or Balanced-mode Radiator. This technology employs a fascinating blend of pistonic and practical bending diaphragm behaviour, leading to full bandwidth, wide directivity devices, rectangular and circular.

The listening environment is studied further, in particular, the interactions of different types of speakers, including the low-frequency cardioid, as well as new findings on ideal room proportions.

Likewise, for loudspeaker enclosures, the discussion of diffraction behaviour has been expanded while important developments in the analysis of pipe and line loading are
included. Developments in directivity control are noted, including LaCarruba’s acoustic lens, while a number of research findings concerning perception and psycho-acoustics have been employed to update the text. There is barely a single page of the previous edition that has not benefited from the incorporation of new material for the sixth edition.

Many thanks to all those who have supported and advised us in the making of the past and the present editions. I hope the industry will find the sixth edition every bit as useful and informative as its predecessors.

Martin Colloms
Notation

$A_g$  Magnet gap area
$A_m$  Magnet area
$a$  Piston radius
$a_g$  Magnet gap radius
$B$, $B_g$  Magnetic flux density in the coil and air gap (analogous to current)
$c$, $c_1$  Velocity of sound (345 m/s in air), $c_1$ longitudinal
$C_{AB}$  Acoustic compliance of enclosure volume
$C_{AS}$  Acoustic compliance of suspension
$C_{AT}$  Total acoustic compliance of driver and enclosure
$C_{MEC}$  Electrical capacitance equivalent of moving mass
  
  \[ \left( = \frac{M_{AC} S_D^2}{B^2 l^2} \right) \]
$C_{MS}$  Total suspension compliance of driver
$E_g$  Generator (amplifier) voltage
$F$  Force
$f$  Frequency in Hz
$f_B$  Helmholtz resonance of vented box
$f_c$  System resonance, driver in closed box
$f_o$ or $f_s$  Free air resonance of driver
$f_3$  $-3$ dB cutoff frequency
$g$  Gravitational acceleration (981 m/s$^2$)
$G(S)$  Response function
$H$  Coercive force, magnetic flux (analogous to voltage)
$h$  System tuning ratio \( ( = f_B / f_s ) \)
$I$  Current in coil
$k$  Wave number \( = 2\pi / \lambda \)
$K_B$, $k_H$  Magnetic loss factors
$k_n$  Reference band efficiency factor
$k_p$  Power rating constant
$l$  Length of motor coil wire immersed in magnetic gap field
$L_c$  Inductance of motor coil
$L_{CEB}$  Electrical inductance equivalent of box volume compliance
$L_{CES}$  Electrical inductance equivalent of driver suspension compliance
$L_{CET}$  Electrical inductance equivalent of system compliance
  
  \[ \left( = \frac{C_{AT} B^2 l^2}{S_D^2} \right) \]
Notation

\( M_c \)  
Mass of motor coil

\( M_{EC} \) or \( (M_{MS}) \)  
Acoustic mass of driver diaphragm assembly including air load

\( M_D \)  
Total driver moving mass (excluding air load)

\( M_T \)  
Total driver moving mass, \( M_D + M_A \)

\( M_{AC} \)  
Acoustic mass of driver and adjacent air load (including baffle effect)

\( M_{AS} \)  
Acoustic mass of driver and air load

\( n \)  
Number of turns

\( P \)  
Sound pressure

\( P_{\text{ref}} \)  
Reference sound level (minimum audible at 1 kHz = \( 2 \times 10^{-5} \) N m\(^2\) or \( 10^{-12} \) W m\(^2\))

\( Q \)  
Ratio of reactance to resistance (series circuit) or resistance to reactance (parallel circuit) (or alternatively the directivity factor)

\( Q_B \)  
Driver \( Q \) at \( f_B \)

\( Q_T \)  
Driver total \( Q \)

\( Q_E \)  
Electrical \( Q \) of driver

\( Q_M \)  
Mechanical \( Q \) of driver

\( Q_{TC} \)  
Working \( Q \) of system of driver and enclosure

\( Q_{TS} \)  
Driver \( Q \) at \( f_s \)

\( R \)  
Resistance (electrical)

\( R_{EC} = \frac{B^2l^2}{(R_{AB} + R_{AS})S_D^2} \)  
electrical equivalent of mechanical losses

\( R_{AB} \)  
Enclosure loss acoustic resistance

\( R_C \)  
Resistance of motor coil

\( R_{MA} \)  
Resistive component of air load radiation impedance

\( R_{ME} \)  
Driver electromagnetic damping factor \( (B^2l^2/R_E) \)

\( R_{MS} \)  
Suspension mechanical resistance

\( r \)  
Reverberation time

\( r \)  
Distance from source

\( S_D \)  
Effective projected diaphragm area

\( s.p.l. \)  
Sound pressure level

\( U_C \)  
Diaphragm or coil axial velocity

\( V_{AS} \)  
Equivalent closed air volume of driver compliance, \( C_{MS} \)

\( V_B \)  
Box or enclosure volume

\( W \)  
Sound power

\( X_{MA} \)  
Reactive mass component of air load radiation impedance

\( Z_{MA} \)  
Air load radiation impedance; \( R_{MA} + jX_{MA} \)

\( \alpha \)  
Compliance ratio \( (= C_{AS}/C_{AB} \) or \( V_{AS}/V_B) \)

\( \eta_0 \)  
System reference efficiency (power in/power out for \( 2\pi \) field) in level range

\( \eta_{\text{ref}} \)  
Reference power available efficiency

\( \theta \)  
Angle from source axis

\( \mu \)  
Magnetic permeability (analogous to conductivity)

\( \rho_0 \)  
Density of air (1.2 kg m\(^{-3}\))

\( \omega \)  
Angular frequency \( = 2\pi f \)

\( \lambda \)  
Wavelength, m
Glossary

**Acoustic**  (from Greek, *akuo*, to hear) lit. *of, or pertaining to, hearing*. Now expanded to include all phenomena of mechanical dynamics, electro-mechanical dynamics and fluid dynamics associated with oscillatory behaviour (e.g. vibration, transduction, etc).

**Acoustic Impedance**  Ratio of pressure to volume velocity.

**Angular Velocity**  Frequency multiplied by $2\pi$, usually denoted by Greek character $\omega$. Arises from use of radian measure in trigonometric and exponential functions.

**Anti-Node**  Point of maximum value of a mode shape ($qv$), defining a position at which the amplitude of motion in that mode will be greatest.

**Audio**  (From Latin, *audire*, to hear) lit. ‘relating to hearing’ (as acoustic ($qv$)). Now used specifically in hearing science (as in audiology) and in electronics and electro-acoustics, where it names those aspects of the applied sciences associated with the manipulation and generation of sound for communication and entertainment.

**Audio Frequency**  Frequency within the bandwidth ($qv$) of normal young adult hearing (ca. 20–20 000 Hz).

**Baffle**  Acoustical component of a loudspeaker system, which can range from a small frame around the loudspeaker, through a vented or sealed box (the enclosure, $qv$), through a large planar surface (such as a ceiling) in which the loudspeaker is mounted.

**Bandwidth**  Range of frequency.

**Bending**  Deformation of an object or structure from equilibrium ($qv$) in which the deformation is caused by a combination of tension ($qv$) and compression ($qv$) on either side of a ‘neutral axis’ ($qv$). Bending generates internal forces, arising from the combination of compression and tension, which oppose the deformation.

**Bending Wave**  A wave ($qv$) sustained by interaction of potential energy associated with bending ($qv$) and kinetic energy associated with movement of distributed mass. Such a wave is demonstrated in the idealized flexure of a panel form loudspeaker diaphragm.

**BMR: Balanced mode Radiator**  A transducer employing a bending wave diaphragm where modal radiation is balanced.

**Boundary Condition**  In the context of a distributed parameter system ($qv$), the boundary condition specifies the impedance ($qv$) at the periphery of the system. The boundary conditions influence the modes ($qv$) of a distributed system.

**Chassis**  Component of a conventional loudspeaker, forming a frame on which other components are mounted and a mechanical reference with respect to which forces are generated.

**Coincidence**  Equality of bending wavespeed on a panel with the traced speed of sound wavefronts in the adjacent gas or fluid. The lowest frequency at which this equality
occurs is the ‘first coincidence frequency’ or ‘critical frequency’. DM loudspeakers \((qv)\) operate above and below first coincidence.

**Complex Numbers** A mathematical concept, in which the ‘line’ of ordinary numbers (which are called it real numbers) is supplemented by a second orthogonal line of so-called ‘imaginary’ numbers, to form a complex number plane. The unit imaginary number, \(j\), is equal to the square root of minus one: \(j = \sqrt{-1}\). The concept is used, for example, in the complex exponential notation used in Fourier \((qv)\) methods for describing for example, frequency response \((qv)\) functions.

**Compliance** Reciprocal of stiffness.

**Compression** Deformation of an object or structure characterized by reduction of length along an axis parallel to the line of application of force(s) causing the deformation. The change of length generates internal forces that oppose the deformation. Compression is accompanied by an induced tension \((qv)\) perpendicular to the compression.

**Conceptual Frequency** Terminology used to describe the lowest (non-zero) natural frequency of a panel along a particular dimension. Such a panel does not have modes whose natural frequencies are a harmonic series (so the term ‘fundamental frequency’ \((qv)\) would be inappropriate).

**Core Shear** Shear \((qv)\) deformation of the core of a composite structure (formed of a pair of skins sandwiching a core). When the core is deformed in shear along planes normal to the skins, core shear results in transverse motion of the skins, which are (substantially) in bending. When the core is deformed in shear along planes parallel to the skins, (substantially) ‘in-plane’ relative motion of the skins results.

**Critical Frequency** See ‘coincidence’.

**Cross-over** Electrical network used to split full bandwidth audio signals into contiguous frequency bands to drive different units in a multi-way loudspeaker system.

**Cysoid** Sinusoid of arbitrary frequency and phase that forms one frequency component \((qv)\) of a general signal.

**Damper** Means to effect damping \((qv)\). Usually, a device to convert kinetic energy to heat.

**Damping** Act of dissipating energy stored within a dynamic system.

**decibel** Logarithmic energy ratio (often confused with sound pressure level \((qv)\)).

**Diaphragm** Moving object within a transducer, which resolves acoustic pressures into forces or *vice versa* (thus effecting mechanical to acoustical transduction). In a loudspeaker, the diaphragm is forced into motion (by the motor \((qv)\)) and this motion is impressed on the adjacent air. The diaphragm may be formed by one of a number of structural elements, namely, plate, membrane, panel and so on, although practical diaphragms act as a combination of two or more such idealized members.

**Dipole** Acoustic source formed when two closely spaced monopoles \((qv)\) operate in anti-phase. Low frequency radiation is poor and mid- and high-frequency radiation is directional. The diaphragm of a conventional loudspeaker operating outside an enclosure \((qv)\) approximates to a dipole.

**Direct Radiating** A direct radiating loudspeaker is horn-less; sound is radiated directly from its diaphragm into the listening space without an acoustic coupling device. ‘Conventional’ loudspeakers are direct radiating electro-dynamic \((qv)\) devices.

**Directionality** Differential radiation (e.g. from a loudspeaker) as a function of angle—usually reported in terms of polar plots of sensitivity \((qv)\).
Directivity  Method of describing the directional response of a loudspeaker that compares the sensitivity ($qv$) in a particular direction to that which an omni-directional ($qv$) source of equal total output power would achieve.

Directivity Index  Logarithmic statement of Directivity ($qv$).

Dispersion  Effect caused by the propagation of frequency components ($qv$) of a complex wave form at different propagation speeds ($qv$) seen, for example, in a bending panel.

Distortion  Component of a sound or signal that is generated by a system that is not linear ($qv$).

Distributed Mode Loudspeaker  A loudspeaker having a bending-wave diaphragm in which the bending parameters are selected so that the available flexural modes on at least two definable axes are intentionally interleaved in frequency.

Distributed Parameter System  A system in which those parameters pertinent to its dynamics are distributed over space, rather than localized. Such systems are described by partial differential equations and are capable of sustaining wave effects.

Dividing Network  Alternative name for Crossover ($qv$).

DM Loudspeaker  Distributed Mode Loudspeaker ($qv$).

Doublet  Dipole ($qv$).

Dynamic  (i) Characterized by motion (i.e. not static). (ii) abbrev. Electro-dynamic ($qv$).

Efficiency  Ratio of input to output power.

Elastic  A deformation or strain of an object or structure is elastic if the object or structure returns to equilibrium after the forces causing the deformation are released. A deformation of such magnitude that the object or structure suffers permanent deformation after the release of external forces has exceeded the ‘elastic limit’. Deformations below the elastic limit give rise to internally generated forces that exhibit simple relationship between the deformation and the resultant internally generated opposing force.

Electro-acoustics  Transduction science and applied science of energy and information conversion between electrical and acoustical representations (and vice versa).

Electro-dynamic  Electro-mechanical transduction principle by which forces are generated by passing a current through a coil located in a magnetic field. Often abbreviated to ‘dynamic’.

Electrical Impedance  Ratio of voltage to current.

Electro-static  Electro-mechanical transduction method exploiting forces generated between charged electrodes.

Enclosure  Box (or part-box) in which a loudspeaker is mounted. The loudspeaker is generally mounted on a wall of the box. The enclosure performs more than a mounting function—the inside and outside of the enclosure influence the acoustics of the loudspeaker (see also baffle).

Equilibrium  Stable (minimum energy) state of a system at which all forces are balanced.

Far Field  Region distant from a complex source, wherein pressures are associated only with the wave-borne passage of acoustic energy away from the source (distinct from the near field ($qv$)).

Flat (response)  A system has a flat response if the ratio of output to input energy is (approximately) independent of frequency.

Force Factor  Relationship between force and current (BI) in an electro-dynamic transducer.
**Forced Response**  Response of a dynamic system to a steady, externally applied forcing input. The forced response is composed of a combination of the allowed modes \((qv)\) of the system in such a ratio so as to be consistent with the applied forcing input.

**Former**  Component of an electro-dynamic \((qv)\) loudspeaker motor \((qv)\) that carries the voice coil and communicates motor forces to the diaphragm.

**Fourier**  J.J-B. Fourier. French diplomat and mathematician who devised a method by which differential equations can be reduced to algebraic equivalents (through ‘Fourier Transformation’) for solution. The method can be used to perform frequency analysis \((qv)\).

**Frequency**  The number of occurrences in an interval of time—in the context of sound and vibration, the number of repetitions of a repeating pattern in one second. Measured in units of Hertz \((qv)\).

**Frequency Analysis**  Decomposition of the energy contained in a sound or signal into individual frequency components \((qv)\).

**Frequency Component**  Fraction of the total energy in a sound or signal carried by a cysoid \((qv)\) of specified frequency.

**Frequency Response**  Ratio of output signal to input signal, reported as a function of frequency. The ratio is generally complex to account for phase differences between input and output. The frequency response function is also known as the transfer function \((qv)\), of which it is one component.

**Fundamental Frequency**  The number of repetitions of a complex periodic signal or sound in one second (or number of approximate repetitions of a quasi-periodic signal in one second). Such a periodic signal is formed of a harmonic series \((qv)\) of frequency components \((qv)\), the lowest (non-zero) frequency of which is called the fundamental frequency. The fundamental frequency of a sound is strongly correlated with the perceived pitch \((qv)\) associated with that sound.

**Gain**  Ratio of output to input signal level (often reported at one frequency, such that it corresponds to the magnitude of the frequency response \((qv)\) function.

**Harmonic Series**  (i) Series of numbers in sequence 0, \(x\), 2\(x\), 3\(x\), 4\(x\) ... (ii) \((misuse)\) Series of frequency components lying at frequencies that themselves form a harmonic series.

**Hz**  Unit of frequency (abbreviation of Hertz).

**Impedance**  Ratio of potential to flow variables within a dynamic system.

**Loudspeaker**  Electro-acoustic transducer intended to generate sound that is substantially correlated with an applied electrical signal (as distinct from a sounder, which generates an arbitrary sound in response to the application of electrical energy).

**Linear**  A system is linear if each frequency component \((qv)\) of its input is also present at the output, scaled by a constant complex factor. The set of all such constant factors is the transfer function \((qv)\) A system that is not linear will generate distortion \((qv)\). \((Occasionally, incorrectly, applied to a flat frequency response).\)

**Lumped Parameter System**  A system in which those parameters pertinent to its dynamics are localized, rather than distributed, at discrete points in space. Such systems are described by ordinary differential equations and are not capable of sustaining true wave effects. The simplest lumped parameter system capable of demonstrating the oscillatory dynamics of acoustics (and, hence, resonance \((qv)\)) is of second differential order,
comprising of a mass element and a stiffness element (such as the diaphragm and suspension of an idealized loudspeaker).

**Mechanical Impedance**  Ratio of force to velocity.

**Membrane**  Member extending transverse of its thickness with negligible bending stiffness. Membranes can sustain wave motion if they are placed in tension at equilibrium (as in the skin of a drum).

**Modal Density**  The number of modes in a unit bandwidth \((qv)\). In a bounded distributed parameter system, the modal density increases with increasing frequency. The rate of such increase is greater in the context of a fourth-order system (such as a panel in bending) than in a second-order system (such as transverse waves on a membrane).

At low frequencies of low modal density, the transfer function \((qv)\) of the system has discrete resonant peaks. Once the modal density reaches a certain value, the transfer function becomes smooth as the discrete modes ‘blur’ together.

**Mode**  An allowed pattern of motion, corresponding to a spatial and temporal solution of the characteristic equation of a dynamic system. A distributed parameter system \((qv)\) must be finite and bounded by specified boundary conditions \((qv)\) before modes are present.

**Mode Shape**  Spatial component of a solution to the characteristic equation of a distributed parameter system \((qv)\) that describes the pattern of motion associated with a particular mode \((qv)\).

**Monopole**  Simplest possible acoustic source, sometimes called a point source, which radiates sound equally in all directions. The monopole might be visualized as an infinitely small sphere, with modulating radius.

**Motor**  Device for generating forces to move the diaphragm \((qv)\) of a loudspeaker, thus effecting electrical to mechanical transduction. This may exploit, for example, electro-dynamic \((qv)\) or electro-static \((qv)\) means.

**Moving coil**  Electro-mechanical transduction means in which a current is passed through a coil suspended in a magnetic field: Electro-dynamic \((qv)\)

**Natural Response**  Behaviour by which a closed dynamic system dissipates excess energy (above equilibrium). The natural response will always consist of motion in one or more modes \((qv)\) allowing dissipation of the excess energy through damping \((qv)\).

**Near Field**  Region close to a complex radiating object, the extent of which is determined by frequency and the size/shape of the source, in which pressures are associated both with energy storage in the air around the source and with energy propagation into the far field \((qv)\)

**Neutral Axis**  Line or plane through an object or structure that experiences no length change during bending \((qv)\).

**Node**  Zero of a mode shape \((qv)\) defining a point at which motion in that mode will always be zero.

**Octave**  Frequency ratio of 2:1 (derived from the musical interval of an octave, which has 2:1 ratio of fundamental frequencies).

**Omni-directional**  Radiating (or receiving) equally in all directions.

**On-axis**  Loudspeakers (particularly those with obvious symmetries) have geometric and acoustic reference axes, on which (or with respect to which) it is useful and convenient to specify response. On-axis measurements are made on such reference axes.
Orthogonal  Two functions are orthogonal if their averaged product is zero. The Modes (qv) of a dynamic system are orthogonal (both over time and over space).
Panel  Member extending transverse of its thickness which has sufficient rigidity to be self-supporting (thus differentiating it from a membrane) and sufficient flexibility to allow bending and shear deformation (thus differentiating it from a plate).
Period  Inverse of frequency.
Periodic  Description of a sound or signal that cyclically repeats itself. Such a sound can elicit a pitch (qv) response from a listener (if the fundamental frequency (qv) of its periodicity is less than approximately 5000 Hz).
Phase  Time shift between cycloidal frequency components (qv), forming (with the gain (qv)) the frequency response (qv).
Phase Speed  Speed of propagation of a single frequency component (qv) in a medium that displays dispersion (qv).
Piston  Plate (qv) element, usually circular, often used as first-order model of a loudspeaker diaphragm.
Pistonic Motion  Intended ‘piston-like’ rigid body translation of a conventional loudspeaker.
Pitch  Human auditory percept, which allows the comparison of two quasi-periodic sounds on a basis most strongly correlated with fundamental frequency (qv).
Plate  Member extending transverse of its thickness, which is so rigid as to be capable of only whole-body motion (translation and rotation).
Propagation Speed  Speed at which points of equal phase move through or across a medium during the passage of a single frequency wave. The propagation speed may be a function of frequency (see ‘dispersion’) but will always be related to the wavelength (qv), since propagation speed is the product of wavelength and frequency.
Q factor  (abbreviation: Quality Factor—often further abbreviated as Q). Property of a mode of a resonant dynamic system controlled by the amount of damping (qv) present. Lower damping will result in high Q factors, typified by strong peaks in the transfer function (qv) of a system near resonant frequencies and by the slow decay of the modes in the natural response (qv).
Quasi-periodic  Description of a sound or signal, which is approximately periodic (especially from the perspective of the human auditory system).
Reflex  Type of loudspeaker enclosure (qv) in which rear radiation from the diaphragm is phase-inverted by an acoustic network (e.g. a ‘vent’ or ‘port’) to support low-frequency response. Also called Bass reflex and Phase inverter.
Resonance  Phenomenon of a lumped parameter system (qv) or of a bounded distributed parameter system (qv) of second (or higher) differential order associated with one of a set of allowed patterns of motion—one ‘mode’ (qv). Resonance is associated with one frequency—the ‘resonant frequency’ and (in the case of coupled or distributed systems) one spatial pattern—the ‘mode shape’ (qv). The natural response (qv) and the forced response (qv) of a dynamic system are comprised of a combination of all the resonant modes in ratio appropriate to the initial conditions or forcing function respectively.
Sensitivity  (Generally incomplete or imprecise) statement of the efficiency (qv) of a loudspeaker made by reporting pressures generated in a standard radiating condition in response to the application of a specified electrical input (e.g. x dB/W at 1 m)
Shear  Deformation of an object or structure characterized by the lateral relative displacement of adjacent parallel planes of section through the object or structure, the displacement occurring along an axis parallel to the line of application of the net force causing the deformation, (a resolved component of) which is parallel to the planes of section. The relative movement of the planes of section within the object or structure generates forces that oppose the deformation.

Signal  Electrical, acoustical or mechanical representation of time-varying information (speech, music, etc.).

Sound Pressure Level  Ratio between an acoustic pressure and the reference acoustic pressure (20 micro pascals), expressed in logarithmic form (so as to improve correlation with the human auditory percept of loudness).

Sound Wave  Compression wave in an elastic medium (most significantly in air).

Specific Acoustic Impedance  Ratio of pressure to particle velocity.

Suspension  Component(s) by which moving elements of a loudspeaker (especially the diaphragm (qv)) are fixed to the chassis (qv) or other mechanical reference. The suspension can be designed to allow relative motion and/or to introduce a means of damping (qv). The suspension forms a boundary condition (qv) for the diaphragm

Tension  Deformation of an object or structure characterized by increase of length along an axis parallel to the line of application of force(s) causing the deformation. The change of length generates internal forces that oppose the deformation. Tension is accompanied by an induced compression (qv) perpendicular to the compression

Transducer  Device to convert energy and information between two different representations (as in the loudspeaker; an electro-acoustic transducer).

Transfer Function  (Also termed ‘frequency Response Function’). Complex function of frequency, describing the ratio between the frequency components (qv) of the output and the input of a linear (qv) system.

TwoPort  (From analogy with method of electrical network analysis). System or sub-system having two ‘ports’, across each of which a potential (such as a voltage) can be developed and into each of which a flow (such as a current) can be induced. TwoPorts can be used to model electrical, mechanical, acoustical and other linear dynamic systems as well as transducers.

Voice Coil  Component of the motor (qv) of an electro-dynamic (qv) loudspeaker. The voice coil is a coil of wire through which the operating current is passed. The coil is located in a magnetic field, usually supplied by a permanent magnet. The coil is glued to a cylindrical component called the ‘former’ (qv), which is, in turn, is fixed to the diaphragm. Force generated on the coil is communicated through the former to the diaphragm, which accelerates the diaphragm into motion.

Volume Velocity  Particle velocity multiplied by a radiating area, giving a statement of volume flow (units: m³/s)

Wave  Phenomenon of a distributed parameter system (qv) in which energy is transported by the orderly local exchange of potential and kinetic energy. The wave is characterized by a propagation speed (qv) and a wavelength (qv).

Wavelength  Minimum distance between points of equal phase in the propagation of a single frequency wave.

Wavenumber  Normalized frequency, defined as angular velocity divided by the speed of sound (T/c = 2Bf/c)
Speech and music is noise with meaning. The recording and reproducing of sound is imperfect, the process reduces meaning and adds noise.

It is the art of the loudspeaker designer to use science to help increase meaning in reproduced sound. An understanding of music in all its forms is a vital criteria for the reasoned application of acoustical engineering to loudspeaker design.

It is now 80 years since the loudspeaker as we know it was first developed—an electrodynamic transducer of respectable loudness, of satisfactory and uniform amplitude versus frequency, reliable in use and with the potential for economic manufacture. Before this, there were only earphones of various kinds. Earlier, moving coil and cone speakers had been made; even Ernst Werner Siemens’ US patent of 1874 was one of these. Ironically, at that time, no electrical audio signals were available to drive it. The familiar moving-coil cone loudspeaker, whose principle is so effective that its key elements have remained essentially unchanged to this day, came with ‘the New Hornless Loudspeaker’ of 1925 by Rice and Kellogg of GE (US), which set the stage for the mass controlled, low-resonant frequency form we know so well, a driver where at least part of the frequency response is fundamentally uniform with frequency and may be predictably acoustically loaded at lower frequencies.

To create the motor of such a transducer, take an affordable magnet and add a simple arrangement of magnetically permeable ‘soft’ iron to help concentrate much of the available magnetic flux into a narrow radial gap formed with a cylindrical pole. A small light coil or solenoid is wound onto thin card or a similar low mass former and is suspended freely in the magnetic gap, allowing an overall axial motion of half a centimetre or so. Following Maxwell’s electromagnetic equations, an axial force is generated on the coil when a current flows through it. This force is the product of $B$, the magnetic field strength, $l$ the length of the wire immersed in that flux field and $I$, the current flowing. The force relationship is fundamentally linear and there is no perceptible distortion, for the moment ignoring effects at high amplitudes of motion where the precision of the coil and flux field and of the suspension may ultimately affect performance. There is no lower resolution limit for a moving-coil transducer. An infinitely small electrical input will produce an equivalent and essentially infinitely small sound output. Another excellent feature of
the moving-coil transducer, generally taken for granted, is that despite its operation as a moving mechanical device it is essentially noiseless. It does not grate, or scrape or whirr.

Apply a sub-audible 5 Hz sine-wave current and you can see the coil move, but silently. It is these fundamental strengths that make the moving-coil principle so effective, and so justly popular. Over 99% of all loudspeakers ever made are moving coil. The principle may be used over a very wide range, from low-power speech reproducers of just 2.5 octave bandwidth and a modest 75 dB of sound pressure output and built on a frame just 20 mm in diameter, up to low-frequency monsters of 600 mm diameter, capable of generating 20 Hz sound waves at body shattering 110 dB pressure levels. Used alone, the moving coil itself generates almost zero sound output as radiated sound level is proportional to the area of air load driven by the transducer element, and for the coil alone, this is merely a thin ring.

To couple the moving element to the air load, a rigid, light diaphragm is attached to the coil. Typically, larger diaphragms have their own flexible surround suspension, coupled to an outer, skeletal, non-reflective support frame or chassis, providing centration of the moving system.

Paper as a flat sheet is stiff in tension but is very weak in bending. However, curl it up to form a cone and this structure exhibits an extraordinary axial stiffness for its mass, a marvellous means of coupling a large area of air load to the moving-coil motor. The latter is bonded to the cone apex.

Acting as an impedance transformer, the cone matches the lower acoustical impedance of the air load to the higher driving force impedance of the coil, maximizing the energy transfer in the path from electrical input to mechanical force, leading to useful radiated sound pressure, highly effective in practice even if the actual conversion efficiency is quite low.

Specialized smaller drivers intended for higher frequencies may have the cone replaced by a light dome formed from a variety of materials, paper, moulded plastic foil, resin doped fabric, metal foil or even vacuum-deposited pure diamond. In sizes down to 19 mm effective radiating diameter, the frequency response may extend to beyond audibility, up to 80 kHz. By apportioning the audible frequency range, appropriate combinations of moving-coil driver sizes may cover a frequency range of 10 Hz to 80 kHz, a ratio of no less than 8000:1 in acoustic wavelength, 34 m to just 4.25 mm.

Loudspeaker systems with such a wide range have been designed for costly high fidelity installations; the near 12 octave span may be achieved with typically four, size and frequency-dedicated moving-coil drivers. Such systems can cost as much as a luxury car, and yet the humblest moving-coil speaker driver for modest speech use only may cost tens of cents in typical trade order quantities.

When the diaphragm of a moving-coil driver is appropriately horn loaded, the horn may additionally improve the matching efficiency between air load and transducer. It is then possible to reach an efficiency of almost 50% compared with the typical 1% efficiency of a direct radiating high fidelity speaker. With horn designs, a fairly easily obtained 40 electrical watts will result in a seriously loud 20 acoustic watts, sufficient to effectively address large audiences at realistic volume levels.

Moving-coil drivers have proved to be remarkably durable with many examples of these operating for 50 years and longer. Alternatives have been proposed, but like the wheel, it reigns supreme.