

Design of electromagnetic hazard protection of civil aircraft

Part 1. Guide to theory and threats

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Foreword

BS G 257 : Parts 1 to 3, which have been prepared by Technical Committee ACE/66, constitute a design guide providing information to engineers involved at all levels in the hardening of civil aircraft and their systems against electromagnetic hazards (EMHs).

The design guide will be published in three Parts as follows:

Part 1. *Guide to electromagnetic theory and the electromagnetic threats posed to aircraft*

Part 2. *Guide to protection*

Part 3. *Guide to clearance and testing*

This Part of BS G 257 provides background material on electromagnetic (EM) theory and the threats posed by EMH to aircraft and their systems. A detailed account of EM theory is not given, but enough of an insight is provided in order to understand the threats posed to the aircraft system, resulting effects and avoidance techniques described. This material is covered in the form of a qualitative description of electric, magnetic and EM fields, and the ways in which these interact with conducting bodies. In addition, the section contains discussion of the types and classification of signals which can occur, and the way in which they relate to each other. In particular, it discusses the concepts of broadband and narrowband signals, balanced and unbalanced transmission, common- and differential-mode signal configuration, and the basic concepts of bandwidth and amplitude limitation. The following Parts focus on the description of protection techniques and clearance and testing.

Finally, this Part discusses all the threats and their interactions with the aircraft including continuous wave radio frequency (RF) fields, lightning and static electricity.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 48, an inside back cover and a back cover.

1 Scope

This Part of BS G 257 has been written to assist engineers working at all levels within companies involved in the aircraft industry. The guide does not contain mandatory requirements, but rather advice to assist in the solution of design problems. In order to meet the EMH protection needs of the customer's specification, it is strongly recommended that engineers consider the features discussed and use the suggestions made or provide an alternative solution for any problem.

This guide does not discuss the following:

- a) the protection of the airframe against the structurally damaging, direct effects of lightning;
- b) the design of communication systems in order to produce interference-free operation, since these aspects of RF systems design are covered in adequate detail in other documents; however, the problems of interaction between radio receivers and transmitters remain an important class of electromagnetic compatibility (EMC) problem.

2 Informative references

This Part of BS G 257 refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover, but reference should be made to the latest editions.

3 Definition

For the purposes of this Part of BS G 257, the following definition applies.

electromagnetic compatibility (EMC)

Situation in which an assembly of equipments or systems co-exist without mutual interference or damage and/or upset by the EM environment in which they are immersed.

4 Background

4.1 The design of EMH protection for an electronic system should aim to ensure that the EM environment in which the system is immersed does not affect the normal operation of the system. In addition, the design should reduce the emissions of conducted or radiated EM energy from the system to a level which will not upset or damage the normal operation of other systems. Thus, the overall target of EMH protection should be to achieve EMC.

4.2 It was not until the early 1970s that aircraft made extensive use of electronic systems and thus EMH protection became a concern. In particular, systems affecting flight safety had become dependent on the reliable operation of an electronic system (e.g. fly-by-wire systems).

Such widespread use of electronics necessitated the deliberate design of systems for EMC because the probability of interference had increased enormously, and the difficulty and expense of curing the likely problems was prohibitive. In addition, electronic technology had developed towards very compact, low-power, solid-state components utilizing low-level signalling and thus the susceptibility to electromagnetic interference (EMI) was increased.

4.3 From the early 1980s onwards, the extensive use of carbon fibre composite (CFC) in the airframe has significantly decreased the protection provided by the airframe to the electronic system from external EM threats of frequency content below 100 MHz. This has produced further design needs: the electrical design of the airframe should be considered in order to provide the system with sufficient protection against the external EM environment and there should be minimum intersystem EM coupling.

4.4 Ensuring sufficient protection against EMHs for the complete aircraft has become a deliberate and complex design activity which should include the electrical design of the airframe, the system installation and the design of the electronic equipment. A balanced protection strategy should ensure that the overall EMH protection needs of the aircraft are met within weight, volume and cost targets.

4.5 Achieving the EMC of aircraft systems is fraught with a number of problems, which include the high levels of EM threats, particularly the induced effects of lightning in the airframe, the proximity of the onboard transmitters (particularly the high-frequency (HF) transmitter) and the high cross-coupling between systems as a result of the unavoidable proximity of systems. These EM threats have to be countered within the usual aerospace constraints of weight and volume. In addition, due regard should be taken of the extreme climatic and vibrational environment.

4.6 It is essential that designing for protection against EMHs should be considered from the very earliest stages of the airframe and system installation design. In order to achieve some control of the EMH protection design strategy throughout the aircraft design, development and production, a management strategy should be laid down at the very beginning. The document describing this strategy is often called the EMC control plan. The control plan should highlight a visible design process for the design of the airframe and a complementary system installation design, which will result in only acceptable interference voltages and currents arriving at the equipment connectors. The procurement of equipment with the required protection against EMH should be part of this plan and should be controlled via suitable specifications.

4.7 The safety of the aircraft is of paramount importance and those aspects of protection against EMH that could affect safety should rank equal with all the other design issues. The required performance of the aircraft will inevitably take precedence over the EMH considerations, providing the EMH problem does not seriously affect that performance. It should be noted that consideration of the EMH protection design from the earliest concepts, and in conjunction with other aspects of design, is the only way to achieve optimum solutions in terms of weight, volume and cost.

5 Basic principles of EMH protection design

NOTE. In 5.1 to 5.8, consideration is given to some of the more pertinent points of basic electromagnetics prior to discussing the subjects of intentional and unintentional EM radiation and the interaction of EM waves with conducting bodies.

5.1 EM theory

The behaviour of EM fields is predictable and in broad terms, Maxwell's equations and the basic laws of force field and flow, which will be described later, encompass the complete description of their behaviour.

5.2 The electric field

5.2.1 The mechanical force between two charges q_1 and q_2 is proportional to the product of the charges and inversely proportional to the square of the distance between them, and acts along a line joining them. The force between charges or charged bodies leads to the concept of an electric field. This field produces a force on charges placed in it. If the charges are of the same polarity then the force is one of repulsion. Conversely, if the polarity of the charges is different then attraction occurs. Forces of this nature are encountered in many situations, such as the deflection of the electron beam by the field between the electrode plates in a cathode-ray tube, or the initial movement of free charges in a conductor on application of an electric field.

5.2.2 The magnitude of the electric field intensity E (in V/m) at a distance r (in m) from a charge q (in C) is given by Coulomb's law:

$$E = \frac{q}{4\pi\epsilon_0\epsilon_r r^2} \quad (1)$$

where

ϵ_0 is the permittivity of free space
(8.85×10^{-12} F/m);

ϵ_r is the relative permittivity of the medium in which the charges are placed (dimensionless).

The product $\epsilon_0\epsilon_r$ (in F/m) is known as the permittivity ϵ of the medium.

The electric field is thought of as having a flow or electric flux density (sometimes called displacement) associated with it, in a similar way to voltage (potential difference) producing a flow of current. In this case, the electric field E (in V/m) and electric flux density D (in C/m²) at a point are related by:

$$D = \epsilon E \quad (2)$$

where

ϵ is the permittivity of the medium (in F/m);

D is the displacement (in C/m²);

E is the field strength (in V/m).

5.3 The magnetic field

5.3.1 A magnetic field may be described in a similar way to an electric field (see 5.2). However, unlike point charges, magnetic poles are not thought to exist as single poles in isolation; they always occur in pairs called magnetic dipoles. The manifestation of a magnetic field is therefore the rotational force or moment experienced by a magnetic dipole (electric fields can be treated analogously with regard to electric dipoles). The source of magnetic fields is electric current (at an atomic level in permanent magnets), and the relationship between the flux density of magnetic field B (in Wb/m² or T) at a point p situated a distance r (in m) from a short, infinitely thin conductor of length dl (in m) carrying a current I (in A) (see figure 1) is given by the Biot-Savart law:

$$B = \frac{\mu_0\mu_r I dl \sin\theta}{4\pi r^2} \quad (3)$$

where

θ is the vector angle (in degrees);

μ_0 is the permeability of free space
($4\pi \times 10^{-7}$ H/m);

μ_r is the relative permeability of the medium (dimensionless).

The product $\mu_0\mu_r$ (in H/m) is known as the permeability μ of the medium. In the case of this relationship, the field is given in terms of the flux density, i.e. flow per unit area.

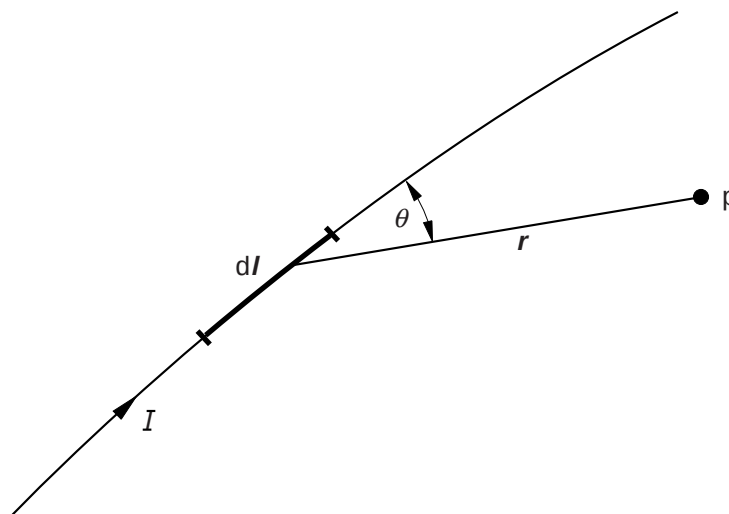


Figure 1. Magnetic field at a point distant from a current element

5.3.2 Once again, an inverse square relationship with distance is shown. However, unlike Coulomb's law, the Biot-Savart law cannot be verified directly because current cannot be made to flow in an isolated length of conductor without causing an accumulation of charge. The verification comes from the study of complete circuits and, therefore, by implication.

5.3.3 In the case of a magnetic field, the relationship between the magnetic field or force field intensity H in and the flux density or flow B is:

$$B = \mu H \quad (4)$$

where μ is the permeability of the medium (in H/m).

5.4 Time-varying electric and magnetic fields

5.4.1 The fundamental laws quoted above give an insight into the nature of the electric and magnetic fields for the time-invariant case. If variations with time are considered, then these laws can be extended to fully predict the magnetic and electric field effects. Magnetic and electric fields are inexorably linked according to Faraday's law of EM induction. This states that in a situation such as that shown in figure 2, the electromotive force (EMF) e (in V) generated in a closed loop is equal to the rate of change of flux Φ (in V·s) with time (in s) which is enclosed by the loop, i.e:

$$e = - \frac{d\Phi}{dt} \quad (5)$$

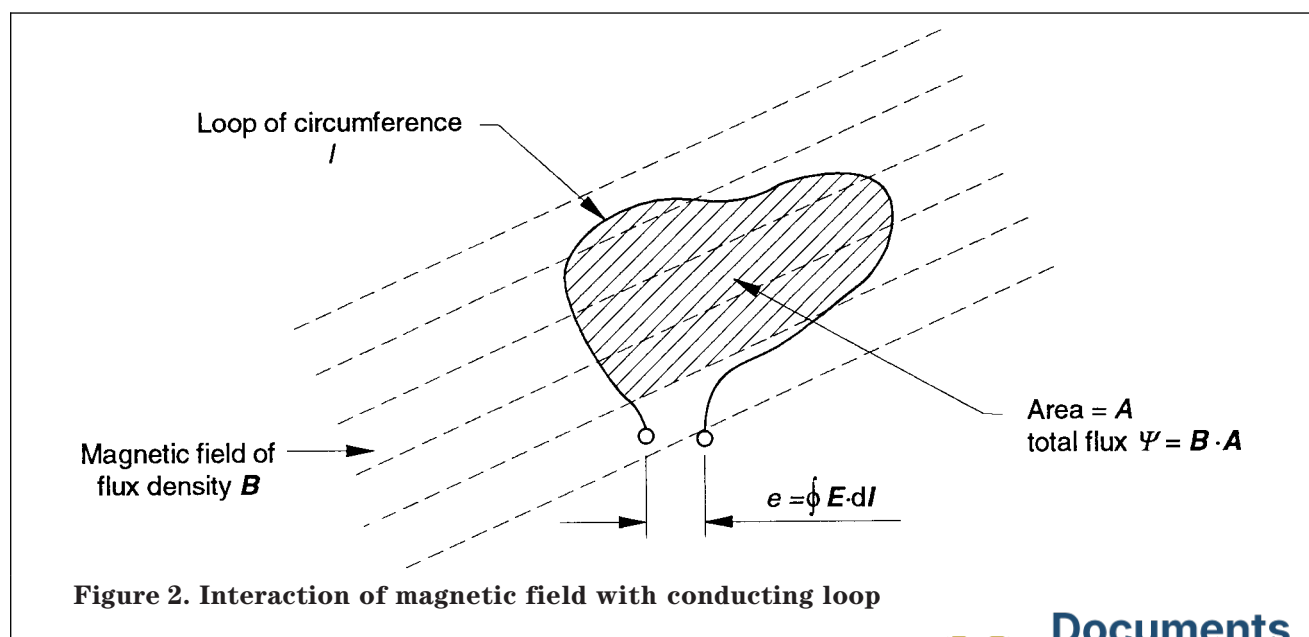


Figure 2. Interaction of magnetic field with conducting loop

5.4.2 If the loop were closed, this EMF would drive current around the loop. The loop can be any shape, but it is the area and orientation to the field which are important. This situation arises in the case of an item of equipment connected by a cable to another item of equipment. If both items of equipment are joined to the ground plane, the incident field will induce current to flow between them. If one or both are isolated then open-circuit voltages may appear.

5.4.3 Using vector notation and generalizing the statement of Faraday's law:

$$\oint \mathbf{E} \cdot d\mathbf{l} = - \frac{\delta}{\delta t} \int_s \mathbf{B} \cdot d\mathbf{s} \quad (6)$$

where

- $\mathbf{E}$ is the electric field strength (in V/m);
- $d\mathbf{l}$ is an element of the path along which the integral is calculated (in m);
- $\mathbf{B}$ is the magnetic field intensity (in T);
- $d\mathbf{s}$ is an element of area (in m²);
- δt is an element of time (in s).

If the Biot-Savart law is generalized in a similar way, then Ampère's law is generated:

$$\oint \mathbf{H} \cdot d\mathbf{l} = \int_s \mathbf{J} \cdot d\mathbf{s} \quad (7)$$

where

- $\mathbf{H}$ is the magnetic field strength in (A/m);
- $\mathbf{J}$ is the current density (A/m²).

This equation, in vector notation, is merely stating that the summation of magnetic field around a closed path (any shape) is equal to the total current enclosed by that path.

5.4.4 For an infinitely long wire of circular cross-section, the magnitude of the magnetic field H (A/m) is given by:

$$H = \frac{I}{2\pi r} \quad (8)$$

where

- I is the current (in A);
- r is the radius of the wire (in m).

In the case of Faraday's law, the summing of the electric field (V/m) around the closed path to produce the EMF is effected simply by a loop of wire. In the case of Ampère's law the summation of magnetic field can be effected by a toroidal winding as shown in figure 3.

5.4.5 Maxwell developed the concept of displacement current, an example of which is shown in figure 4. The path of integration of the magnetic field could either be around a conductor, or around the electric field in the capacitor, since it is unreasonable to expect the line integral of the magnetic field to disappear at this point. Maxwell postulated a form of current flow which could exist in insulators and called it displacement current. The extra term he included, to account for current flow in insulators, was derived from Gauss's law and the equation of continuity or conservation of charge. The displacement current can be considered to flow in parallel, and therefore in addition to, the conduction current, although in practice one or other of the currents predominates.

If the Biot-Savart law is modified by the addition of the term for displacement current, then the total current density is expressed and the following is obtained:

$$\oint \mathbf{H} \cdot d\mathbf{l} = \int_s (\mathbf{J} + \mathbf{D}) \cdot d\mathbf{s} \quad (9)$$

where

$$\mathbf{D} \equiv \frac{d\mathbf{D}}{dt}$$

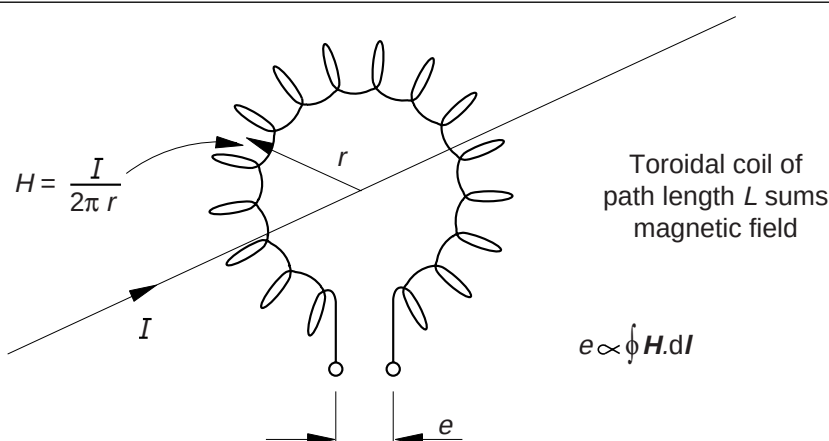
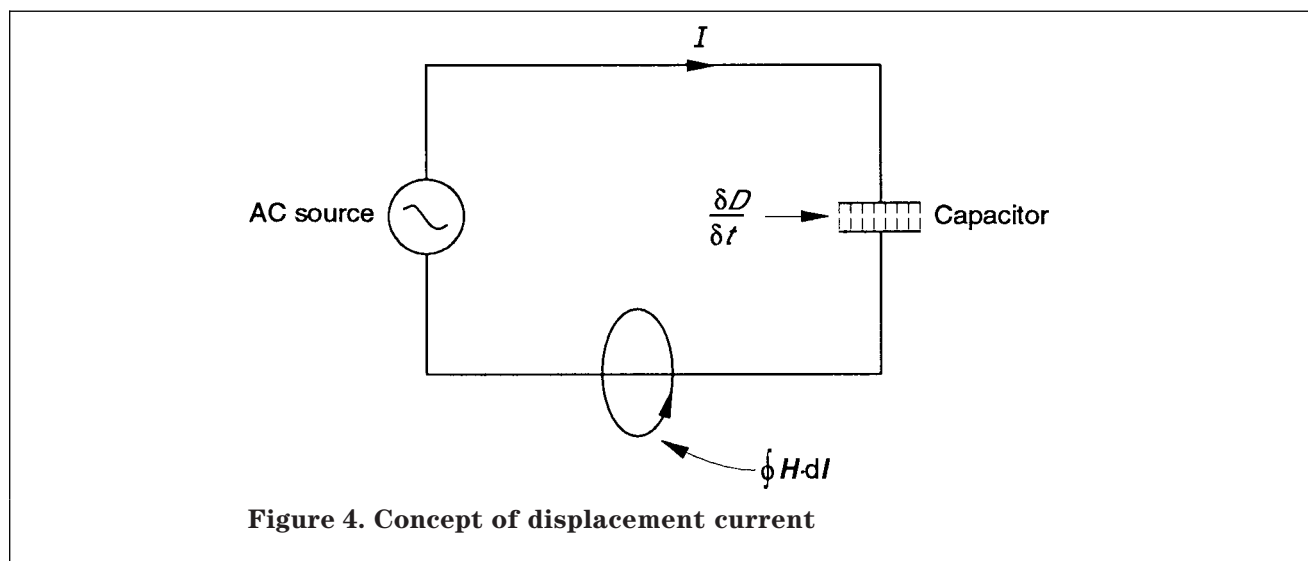


Figure 3. The summation of magnetic field around a closed loop



5.4.6 If an equation arising from the statement that magnetic fields always form closed loops (equivalent to stating that there is no such thing as an isolated pole) is added to Gauss's law, Ampère's law and Faraday's law, a self-consistent set of equations known as Maxwell's equations is obtained:

$$\oint \mathbf{H} \cdot d\mathbf{l} = \int_s (\mathbf{D} + \mathbf{J}) \cdot d\mathbf{s} \quad (9)$$

$$\oint \mathbf{E} \cdot d\mathbf{l} = - \int_s \mathbf{B} \cdot d\mathbf{s} \quad (10)$$

$$\int_s \mathbf{D} \cdot d\mathbf{s} = \int_v \rho dV \quad (11)$$

$$\int_s \mathbf{B} \cdot d\mathbf{s} = 0 \quad (12)$$

where

V is the enclosing volume (in m^3);

ρ is the volume charge density (in C/m^3).

These are shown in their integral form but, by vector algebra manipulation and using Stokes' theorem and the divergence theorem, the equations can be quoted in their differential form as follows:

$$\nabla \times \mathbf{H} = \dot{\mathbf{D}} + \mathbf{J} \quad (13)$$

$$\nabla \times \mathbf{E} = - \mathbf{B} \quad (14)$$

$$\nabla \cdot \mathbf{D} = \rho \quad (15)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (16)$$

where:

$$\nabla = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j} + \frac{\partial}{\partial z} \mathbf{k}$$

These equations can be summarized as follows.

Equation 9: The magnetomotive force around a closed path is equal to the conduction current plus the rate of change of the electric displacement

(displacement current) with time through any surface bounded by the path.

Equation 10: The EMF around a closed path is equal to the rate of change with time of the magnetic displacement through any surface bounded by the path.

Equation 11: The total electric displacement through the surface enclosing a volume is equal to the total charge within the volume.

Equation 12: The net magnetic flux emerging through any closed surface is zero.

5.4.7 It can be seen from the first of Maxwell's equations that in free space (i.e. $\mathbf{J} = 0$), a time-varying electric field produces a magnetic field, and from the second equation that a time-varying magnetic field produces an electric field. This suggests a self-perpetuating phenomenon, where one field supports the other and vice versa.

Using these two equations to eliminate either electric or magnetic field, a wave equation in either magnetic or electric field can be derived.

$$\nabla^2 \mathbf{E} = \mu\epsilon \ddot{\mathbf{E}} \quad (17)$$

$$\nabla^2 \mathbf{H} = \mu\epsilon \ddot{\mathbf{H}} \quad (18)$$

5.5 Wave phenomena

5.5.1 General

5.5.1.1 Jordan and Balmain [1] define a wave thus: 'If a physical phenomenon that occurs at one place at a given time is reproduced at other places at later times, the time delay being proportional to the space separation from the first location, then the group of phenomena constitutes a wave.'

5.5.1.2 It should be noted that a wave need not be a repetitive phenomenon; the EM field emanating from a lightning strike is a transient EM wave approximating to a double exponential.

5.5.2 Generalized waves

5.5.2.1 From the definition it is possible to summarize mathematically what is meant by wave phenomena. If P is some function of position and time such that:

$$p = f (x - v_0t) \tag{19}$$

5.5.2.2

$$p = f (x + v_0t) \tag{20}$$

where

- v_0 is the velocity of propagation (in m/s);
- x is the displacement (in m);
- t is the time (in s);

then the function P is a wave. A generalized wave is illustrated in figure 5.

In order to keep the function $(x - v_0t)$ constant, a steadily increasing value of x in the positive direction is required, i.e. movement with velocity v_0 . Similarly, $f(x + v_0t)$ is a wave travelling in the negative x direction.

5.5.2.3 Waves can be observed at a fixed point either in space or time. Figure 6 illustrates a wave observed at a fixed point in space as a function of time, while figure 7 illustrates the same wave function observed as a variation in space at a fixed time. It can be seen that the wave function appears as a mirror image in the positive direction. In the case of symmetrical waves there will be no difference.

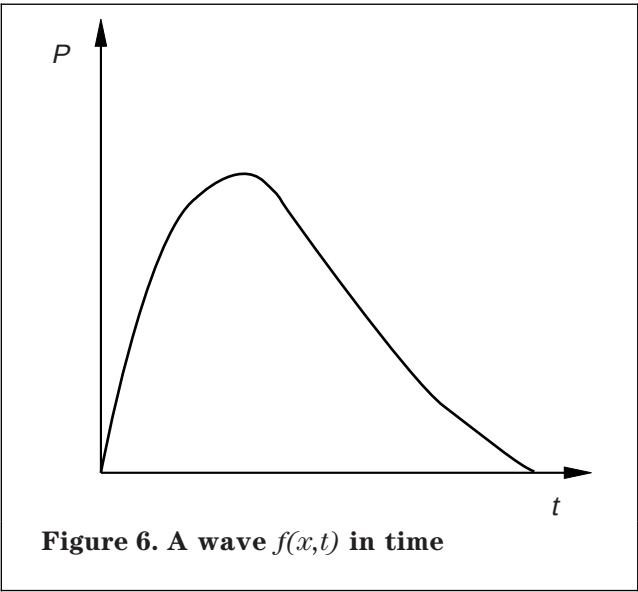


Figure 6. A wave $f(x,t)$ in time

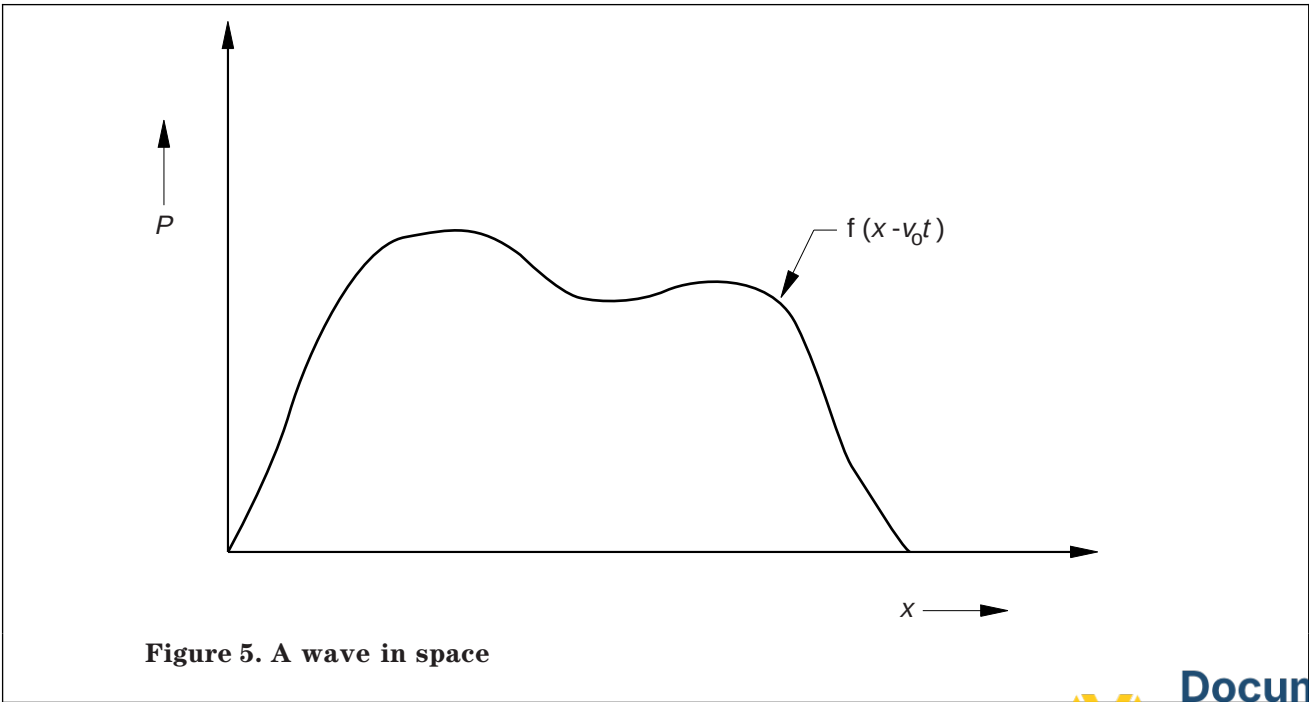
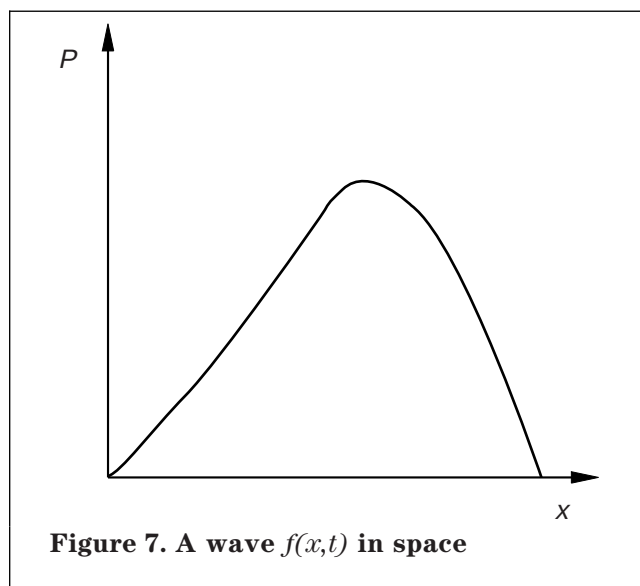


Figure 5. A wave in space



5.5.3 Periodic waves

5.5.3.1 Periodic waves are of particular importance in electromagnetics, i.e. where $f(x - v_0 t)$ is a periodic function. These include, in particular, waves of the form:

$$\mathbf{E} = \mathbf{E}_0 \cos(\omega t - \beta x) \quad (21)$$

where

$$v_0 = \frac{\omega}{\beta} \quad (22)$$

and in this instance

- $\mathbf{E}$ is electric field strength (in V/m) as a function of time and position;
- $\mathbf{E}_0$ is peak field (in V/m);
- β is the phase shift constant or wave number (in rad/m);
- ω is the angular frequency (in rad/s).

5.5.3.2 The sinusoidal, time-varying wave can be illustrated in time and space as shown in figure 8. It can be seen from the spatial plot that β is given by:

$$\beta = \frac{2\pi}{\lambda} \quad (23)$$

where λ is the wavelength (in m).

ω is given by:

$$\omega = 2\pi f \quad (24)$$

where f is the periodic frequency (in Hz).

Thus it can be seen that the frequency f and the wavelength λ are related to each other by the velocity of propagation v_0 by:

$$v_0 = \lambda f \quad (25)$$

It is often convenient to represent a sinusoidal wave as a complex exponential i.e. the cosine wave of equation 21 can be represented as:

$$\mathbf{E} = R_e \mathbf{E}_0 \exp(j\omega t - j\beta x) \quad (26)$$

where R_e is the real part of the expression.

5.5.3.3 In certain situations, the wave may decay in amplitude due to energy dissipation in the medium in which it propagates. Such a wave is shown at a fixed time as a positional variation in figure 9. In such a case an exponential decay term is added:

$$\mathbf{E} = R_e [\mathbf{E}_0 \exp\{j(\omega t - \beta x)\} \exp(-ax)] \quad (27)$$

Separating the space and time exponents gives:

$$\mathbf{E} = R_e [\mathbf{E}_0 \exp(j\omega t) \exp\{-(a + j\beta)x\}] \quad (28)$$

where

- a is the attenuation factor (in Np/m);¹⁾
- β is the phase shift (in rad/m).

This is often written as:

$$\mathbf{E} = R_e \{\mathbf{E}_0 \exp(j\omega t) \exp(-\gamma x)\} \quad (29)$$

where $\gamma = (a + j\beta)$ is the propagation constant.

¹⁾ The neper and the decibel are related by: 1 Np = 8.6 dB.

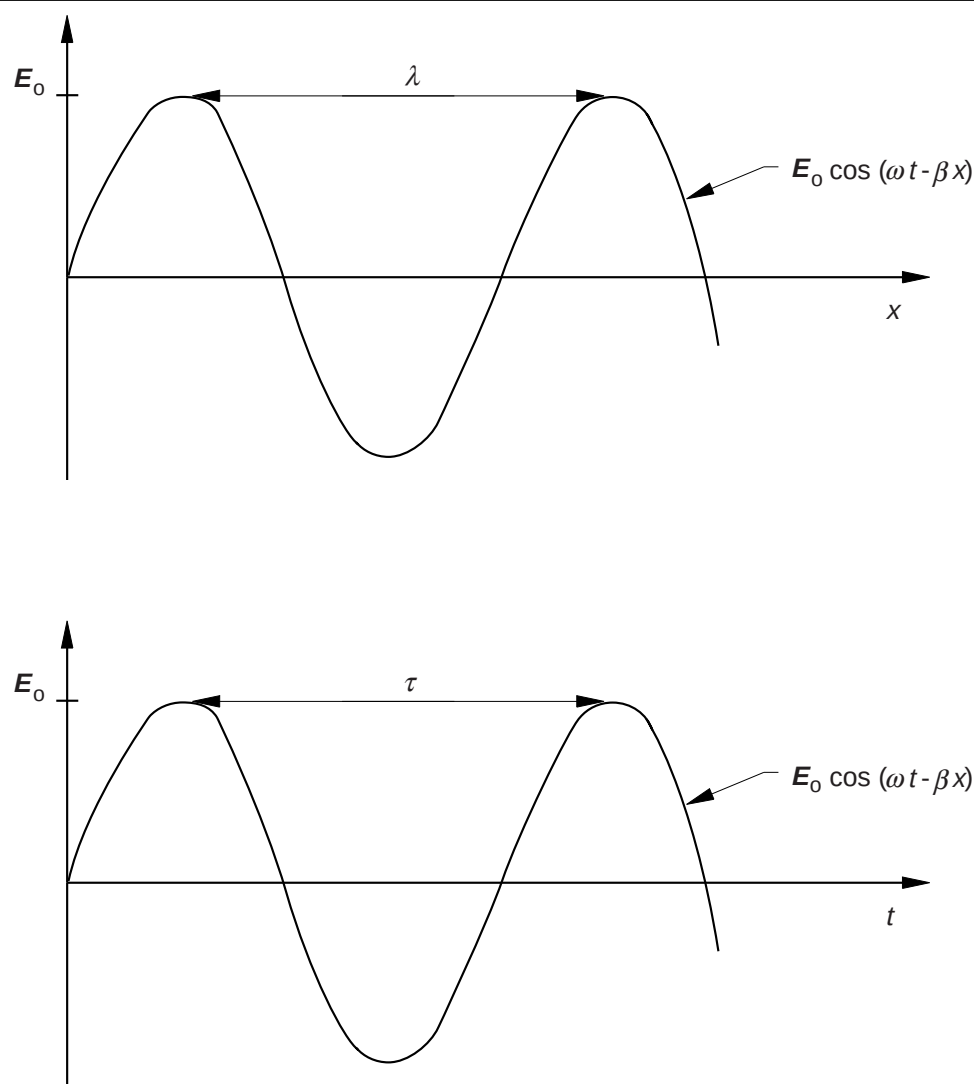


Figure 8. A sinusoidally periodic wave

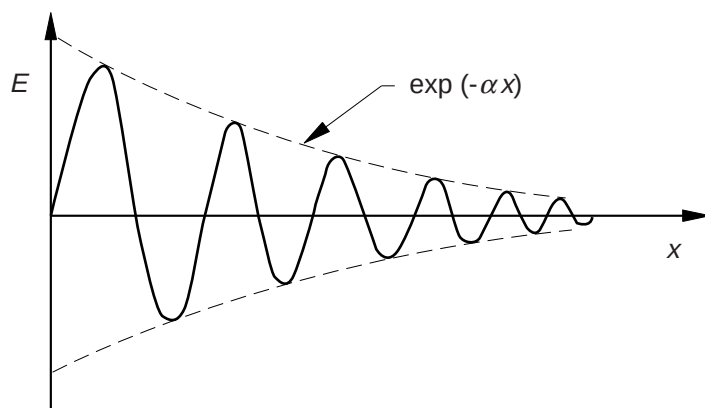


Figure 9. Exponential decay of signal with position

5.5.4 The superposition of periodic waves

5.5.4.1 If the medium through which the waves are propagating is linear, then the instantaneous amplitude of one or more waves can be added together to give the total instantaneous amplitude.

5.5.4.2 Consider two one-dimensional waves of the same frequency propagating in the positive (+) x -direction, the first originating at the origin and the second originating at $x = -d$ with a time-phase shift of φ relative to the first wave. Then:

$$E_1 = E_{10} \exp[j(\omega t - \beta x)] \quad (30)$$

and

$$E_2 = E_{20} \exp[j\{(\omega t + \varphi) - \beta(x + d)\}] \quad (31)$$

The total wave amplitude is:

$$E_r = (E_{10} + E_{20}) \exp[j(\varphi - \beta d)] \exp[j(\omega t - \beta x)] \quad (32)$$

5.5.4.3 The wave term in (32) indicates that this is still a wave of the same frequency and direction of propagation as the two component waves; the superposition is shown in figure 10. The complex amplitude in (5-32) gives the peak amplitude of the wave. This term is a constant and does not vary with x or t . Note that if $E_{10} = E_{20}$ and $(\varphi - \beta d) = \pi$, then the amplitude is zero, i.e. the two waves cancel. The modulus of the complex amplitude is the peak amplitude of the composite wave. The instantaneous amplitude at any value of x and t is given by the real part of equation 32.

5.5.4.4 The summation of two waves of equal frequency and amplitude that are travelling in opposite directions gives a standing wave. The net energy transfer is zero. It can be shown that the resulting standing wave is described mathematically as:

$$E_r = 2E_0 \exp(j\omega t) \cos(\beta x) \quad (33)$$

This is now a wave with a fixed spatial distribution of amplitude with a sinusoidal time variation of $E_e \exp(j\omega t)$.

5.5.5 The wave equation

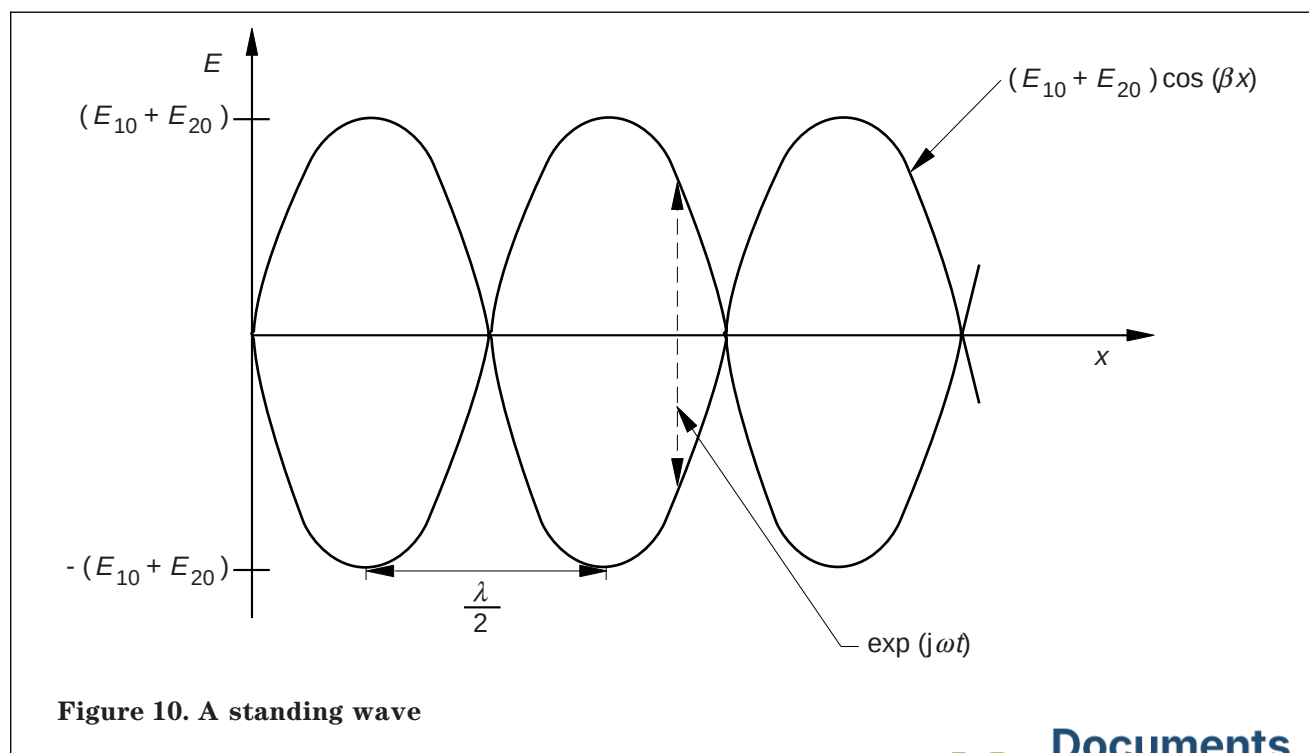
5.5.5.1 It can be shown that equations 19 and 20 are both solutions of the wave equations 17 and 18. If the wave equation for a uniform plane wave stated in terms of the electric field is considered, it can be shown that the solution is:

$$E_z(x, t) = E_{z0} \sin\{(\omega t - \beta x)\mathbf{a}_z\} \quad (34)$$

where $\mathbf{a}_z$ is the unit vector in the z direction.

5.5.5.2 It should be remembered that associated with this electric field component wave is a magnetic field component wave (see 5.4.7). The magnetic field wave is in phase with it, but the field vectors of the two waves are orthogonal (see figure 11). The ratio of the magnitudes of the two fields in the EM wave is the wave impedance η , whose value for a uniform plane wave in free space is always 377Ω . The power flow in the EM wave is given by the cross product of the electric and magnetic field vectors. This is known as the Poynting vector $\mathbf{P}$ (in W/m^2) and is given by:

$$\mathbf{P} = \mathbf{E}_z \times \mathbf{H}_y \quad (35)$$



5.5.5.3 The Poynting vector represents the total power flow through one square metre of space as a result of the wave propagating through that area of space. The Poynting vector is parallel to the direction of propagation of the wave and therefore orthogonal to the plane in which the $\mathbf{E}$ and $\mathbf{H}$ vectors lie.

From the solution of Maxwell's equations, it can be shown that the velocity of propagation v_0 is given by:

$$v_0 = \frac{1}{\sqrt{\epsilon\mu}} = f\lambda \quad (36)$$

In free space, this gives a value of 3×10^8 m/s. In a medium with either a higher permittivity or permeability, the velocity of propagation will be reduced and accordingly from equation 36, the wavelength will be reduced.

5.5.6 Wave polarization

5.5.6.1 The polarization of an EM wave is conventionally understood to mean the orientation of the electric field vector to the Earth's surface. Thus vertical, horizontal and slant polarizations fully describe the polarization of an EM wave. Such polarizations are termed linear because the polarization angle relative to Earth remains constant with space and time. The waves emitted by test objects in, say, an EMC test laboratory are unlikely to be so conveniently orientated and will require resolving into two convenient orthogonal components. In general, these will not be in time phase and the resulting wave is said to be elliptically polarized (see figure 12). The two components into which the wave can be resolved are given by:

$$\mathbf{E}_x(z, t) = \mathbf{E}_{x0} \sin(\omega t - \beta z) \quad (37)$$

$$\mathbf{E}_y(z, t) = \mathbf{E}_{y0} \sin(\omega t - \beta z + \phi) \quad (38)$$

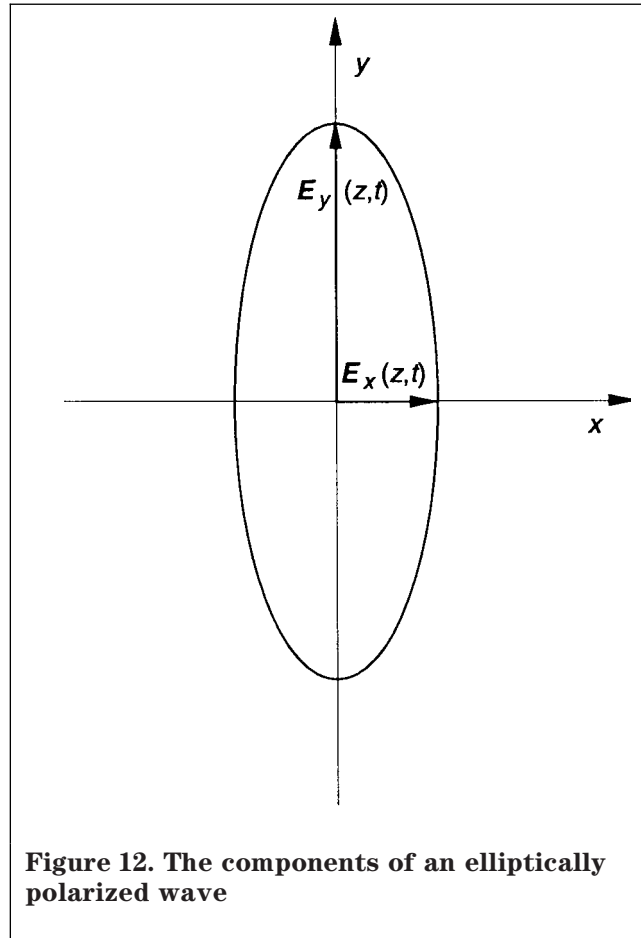


Figure 12. The components of an elliptically polarized wave

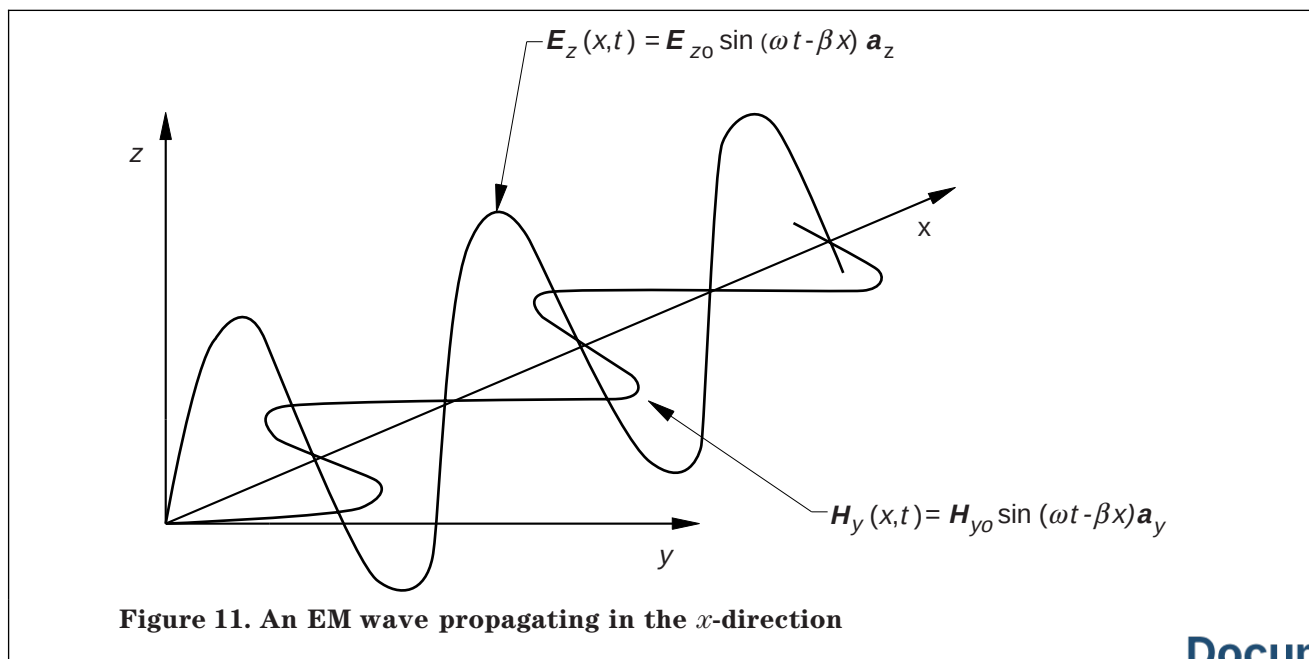


Figure 11. An EM wave propagating in the x -direction

5.5.6.2 The resulting polarization of a wave composed of two components of differing phase rotates about the axis along which the wave propagates. The magnitude of the wave in general describes an ellipse. A special case of interest occurs when $\varphi = 90^\circ (= \pi/2 \text{ rad})$ and $E_{x_0} = E_{y_0}$. This is a commonly used form of polarization in communications, the E -field vector describing a circle and being called circular polarization.

5.6 Sources of EM radiation

NOTE. The intention of 5.6.1 to 5.6.2 is to provide a basic outline of the behaviour of antennas (intentional or unintentional) in order to understand the techniques of EMC testing, the EM radiation from equipment and the reasons for susceptibility to an EM environment.

5.6.1 Antennas as sources of EM waves

5.6.1.1 Two of Maxwell's equations (9 and 10) indicate that if an oscillating magnetic field is produced then an associated oscillating electric field exists, and if an oscillating electric field is produced then an associated oscillating magnetic field exists. In short, if sinusoidally varying current is passed around the loop, this will generate an EM wave, as will an oscillating dipole of charge.

5.6.1.2 It can be shown [2] that the fields near an electrically very small oscillating dipole are:

$$H_\phi = \frac{I_0 h}{4\pi} \{\exp(-j\beta r)\} \left(\frac{j\beta}{r} + \frac{1}{r^2} \right) \sin \theta \quad (39)$$

$$E_r = \frac{I_0 h}{4\pi} \{\exp(-j\beta r)\} \left(\frac{2\eta}{r^2} + \frac{2}{j\omega\epsilon r^3} \right) \cos \theta \quad (40)$$

$$E_\theta = \frac{I_0 h}{4\pi} \{\exp(-j\beta r)\} \left(\frac{j\omega\mu}{r} + \frac{1}{j\omega\epsilon r^3} + \frac{\eta}{r^2} \right) \sin \theta \quad (41)$$

where

- I_0 is the current on the dipole (in A);
- h is the length of the dipole (in m);
- β is the wave number ($2\pi/\lambda$);
- r is the distance of observation (in m);
- η is the impedance of free space (377Ω);
- μ is the permeability of free space;
- ϵ is the permittivity of free space.

and the orientation of the dipoles and fields are as shown in figure 13.

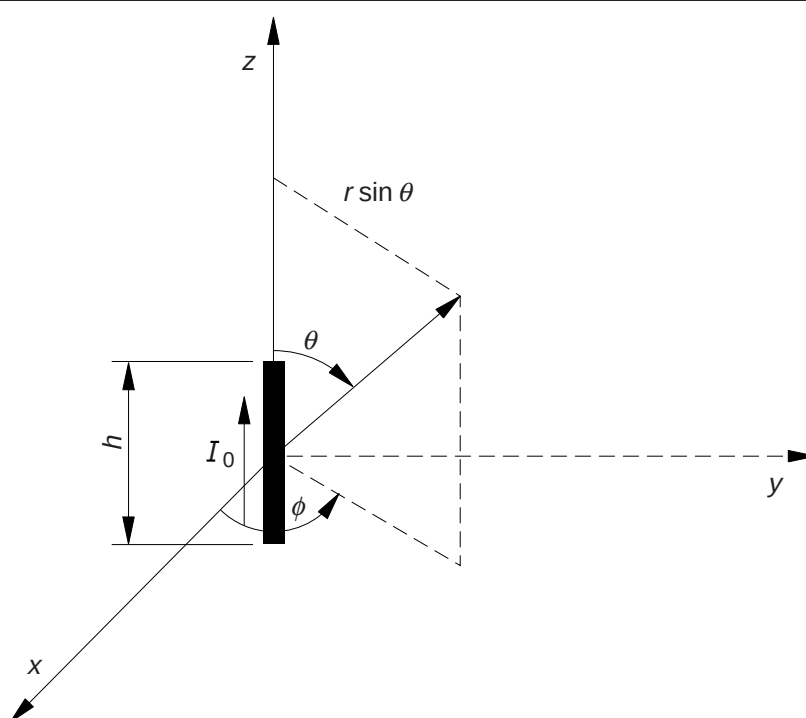


Figure 13. A short dipole in cartesian co-ordinates