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Precision EM Instrumentation
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PRODYN APPLICATION NOTE 895
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PRIMER ON ELECTROMAGNETIC FIELD MEASUREMENTS

(WHERE TO FIND WHAT YOU NEED TO KNOW)

I. Preface

Over the years, PRODYN Technologies has received numerous inquiries and requests for information regarding the principles and applications of Electromagnetic field sensors. Many inquiries come from customers who are not EM specialists, but are aware of EM phenomena and are quite properly concerned about EM effects on the systems they are dealing with. A common element in these inquiries is a desire to understand the principles of EM phenomena well enough to assess their effects without having to get a PhD in EM theory. To meet this need, PRODYN publishes Application Notes, the objective of which is to demystify the art and expound the relatively simple principles of EM measurements (the simple stuff which the "in group" has always taken for granted that everyone else already knows).

In the ElectroMagnetic Pulse field alone, there is a voluminous collection of informal "notes", The *index* to which runs nearly 200 pages! The existence of such a vast liturgy is intimidating, and carries a false implication that one must have read and understood it all in order to be able to even think about the effects of EM phenomena.

As the variety and sophistication of EM test instrumentation explodes on the market, we remember the classic tale of the Emperor's New Clothes (Note 1), wherein a weaver and a tailor [EM test equipment manufacturer and salesman] approach the emperor [customer] with a proposal to make for him the finest possible suite of new clothes [set of EM test equipment]. PRODYN Technologies does not offer elaborate systems laboriously synthesized of magic materials, and one need be neither worthy nor competent to appreciate the beauty of our wares. Instead, PRODYN Technologies has chosen to pursue excellence by implementing the profound yet simple *elegance* of the fundamentals of EM phenomena in its products. This article seeks to articulate the elegance of the fundamentals of EM measurements in our literature. It is written for those who have other things on their agenda besides mastery of EM theory, who don't necessarily weep reverently over it's profundity, but who are anxious to benefit from its simplicity.

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II. Introduction:

In this note, we will discuss the topics we have been asked about most. Many have been discussed in other PRODYN Application Notes, which are incorporated as appendices to this note. We will summarize and refer to them in what we hope will be a logical sequence. We will simply present formulary without proof, since rigorous developments are found in the application notes and other references cited. We will discuss ElectroMagnetic radiation itself first, then move on to how radiated EM fields are measured. Parenthetic numbered notes (Note #) are located at the end of the article. They provide further insight and entertainment, but they need not be read to maintain continuity.

III. ElectroMagnetic Radiation

ElectroMagnetic radiation is the transportation of energy through a medium by simultaneous propagation of a time variant electric field and an associated covariant magnetic field. EM radiation can be in the form of a continuous wave (CW) as in radio waves, or a single burst as in an ElectroMagnetic Pulse (EMP). The electric and magnetic fields which occur in a traveling wave or a burst are related to each other, to the power transmitted by the wave or burst and to the properties of the medium (we first consider free space). The relationship is described by the Poynting Vector **S**:

$$\mathbf{S} = \mathbf{E} \times \mathbf{H} = \mathbf{E} \times \mathbf{B} / \mu_o = \mathbf{D} \times \mathbf{B} / \mu_o\epsilon_o = c^2\, \mathbf{D} \times \mathbf{B} \qquad (1)$$

where

- $\mathbf{S}$ = power density being transported in the direction of the vector, w/m^2
- $\mathbf{E}$ = electric field strength (vector), v/m
- ϵ_o = permittivity of free space, 8.85×10^{-12} farad/m or coul/v-m
- $\mathbf{D}$ = electric displacement (vector), $coul/m^2$, (= $\epsilon_o\mathbf{E}$ in free space)
- $\mathbf{H}$ = magnetic field strength (vector), amp/m
- μ_o = permeability of free space, 1.26×10^{-6} h/m or weber/amp-m (1 weber = 1 v-sec and 1 weber/amp = 1 h), or, fundamentally, v-sec/amp-m
- $\mathbf{B}$ = magnetic induction (vector), $weber/m^2$ or $v\text{-}sec/m^2$ (= $\mu_o\mathbf{H}$ in free space) (1 $weber/m^2$ = 1 Tesla = 10^4 Gauss)
- c = speed of light in free space, 3×10^8 m/sec

The Poynting vector and its constituents are described in Appendix A (PAN 192, Electric & Magnetic Field Sensor Application), p 4. The electric and magnetic fields are orthogonal, so the magnitude of the Poynting vector is EH (most commonly written in the form EB/μ_o), and the direction is the direction of propagation. The Poynting vector readily describes how an EM wave or burst transmits power through an area perpendicular to the direction of propagation:

$$P = \int \mathbf{S} \cdot d\mathbf{A} = SA,$$

$$\text{or} \qquad S = P/A = EB/\mu_o \tag{2}$$

The power of the Poynting vector (pun intended) as an analytical tool can hardly be overstated. Some of the high priests of EM theory will go so far as to state that if the Poynting vector can be evaluated, the problem can be solved.

The crowning achievement of Maxwell's field theory is the relationship of the speed of light to the properties of free space (Note 2):

$$c^2 = 1/\mu_o\epsilon_o \tag{3}$$

This relationship (the ultimate example of elegance - profound yet simple), is used to derive the various forms of the Poynting vector in Equation 1. It is also used to define another convenient property:

$$c\,\mu_o = 1/c\epsilon_o = \sqrt{\mu_o/\epsilon_o} = Z_o, \tag{4}$$

the impedance of free space (Note 2).

Another elegant result of describing EM radiation with Maxwell's equations is that the speed of propagation of the wave or burst is given by the ratio of its electric and magnetic components:

$$c = E/B \tag{5}$$

Combining the relationship between propagation speed and field strength (Equation 5) with the definition of the magnitude of the Poynting vector (Equation 2) and the definition of the impedance of free space (Equation 4), we obtain an interesting result:

$$S = P/A = EB/\mu_o = E^2/c\mu_o = E^2/Z_o$$

$$\text{or} \qquad P = E^2A/Z_o \tag{6}$$

E^2A has the units of volts ^{2}, and Z_o has units of ohms. The analogy to Ohms law ($P = V^2/R$) is obvious, irresistible and valid. In fact, the Poynting vector can be applied to a length of wire to calculate the electrical power infused in (or radiated from) it.

The utility of the Poynting vector in EM measurements lies in the ability to measure either or both of the constituent field intensities and calculate the radiated power density, or to calculate either or both of the constituent field intensities from a specified radiated power density. This is discussed in more detail in Appendix A (PAN 192, Electric & Magnetic Field Sensor Application), p 4. The pertinent formulae are:

$$S = P/A = E_p B_p / 2\mu_o \quad (7)$$

or, using $E_p = cB_p$,

$$E_p = \sqrt{2\mu_o\, c\, S} \text{ and } B_p = \sqrt{2\mu_o S/c} \quad (8)$$

The Frequency and Time domains (Bandwidth vs Rise Time)

It is most convenient to consider continuous wave (CW) Electro-Magnetic radiation in the frequency domain, and ElectroMagnetic Pulse (EMP) bursts in the time domain. This leads to expressing the frequency range or bandwidth of a measurement system used for CW measurements, while expressing the rise time of a measurement system (perhaps the same system) used for pulse measurements. It is helpful to remember that CW and EMP radiation are two forms of the same phenomenon, and that both forms can be considered in either domain. In other words, a sine wave has a rise time and a pulse has an equivalent frequency (Note 3). The magnetic field in a CW is $B(t) = B_p \sin 2\pi ft$, where B_p is the amplitude or maximum value, f is the frequency or the reciprocal of the period T and t is the time. The signal induced in a conducing loop of area A, normal to this field, is directly proportional to the time rate of change, or derivative of the magnetic field intensity (Faraday's Law, $V = dB/dt\ A$). The derivative of B is $2\pi f\ B_p \cos 2\pi ft$ so it has the same waveform except for amplitude magnification of $2\pi f$ and a phase shift of $\pi/2$. Note that as frequency increases, the amplitude of the derivative of the field intensity increases, so that at high frequencies, even low field intensities give rise to high rates of change, and induction, which is directly proportional to the rate of change, is high. This is what makes radio feasible, and the higher the frequency (the shorter the wavelength, hence the term "short wave radio"), the lower the power required to induce a given signal in a radio antenna at a given distance from the transmitter.

The fields in an EMP are often best represented by exponential, rather than sinusoidal functions. This is discussed in more detail in Appendix B (PAN 1195, The Exponential Model of ElectroMagnetic Pulse). A typical burst might have a magnetic field intensity component described by a double exponential pulse function of the form

$$B(t) = B_o\ (e^{-at/\tau} - e^{-bt/\tau}) \quad (9)$$

where:

B_o = the initial value of magnetic field source function (not to be confused with B_p, the maximum value of B(t))
a = discharging coefficient
b = charging coefficient, = a+1
τ = time constant of the charging source function.

This function is the product of a charging function of the form $1 - e^{-t/\tau}$ and a discharging function of the form $B_o e^{-t/a\tau}$. The product has physical meaning in that a source of radiant energy charges the medium at the point under consideration, while the energy radiating away from the point under consideration simultaneously discharges the medium.

The rise time of a pulse is usually taken as the time required for the function to rise from 10 to 90% of its maximum value (more on this later). The peak time t_p or time of maximum value is the time at which B(t) reaches B_p. The width of a pulse is usually taken as the "full width half maximum," the time it takes B(t) to go from $B_p/2$ to B_p to $B_p/2$ again.

The derivative of B is the time rate of change of B:

$$dB/dt = B_o/\tau \; (be^{-bt/\tau} - ae^{-at/\tau}) \tag{10}$$

This function has the same mathematical form as the function from which it was derived, as is the case with CW, but the constants have a significant effect on the shape of the derived function, whereas with CW, the constants affect only the amplitude and the phase, while the shape remains sinusoidal. Another common feature is that the maximum value of the derivative becomes large as the rise time, which is proportional to the time constant, becomes small. Again, with short rise times (high equivalent frequencies), even low field intensities give rise to high rates of change; and induction, which is directly proportional to the rate of change, is high. This is what makes EMP bursts such a threat to electronic systems, and the shorter the rise time, the lower the power required to induce a given spurious signal in a piece of electronic equipment at a given distance from the source.

The literature is full of derivations of the relationship between frequency and rise time. The author's favorite, given in Appendix B (PAN 1195, The Exponential Model of ElectroMagnetic Pulse), equates the initial slope and peak value of an exponential pulse of the form $B(t) = B_o\,(e^{-at/\tau} - e^{-bt/\tau})$ to the initial slope and peak value (amplitude) of a sine wave $B(t) = B_p \sin 2\pi f\, t$, as shown in Figure 1. This results in a useful relationship between the time constant of the pulse and the period of the sine wave:

$$\tau/B_o = T/2\pi B_p \tag{11}$$

A sine wave rises from zero to its maximum value in 1/4 of the period, or .25T = .25/f. If one calculates the time it takes for the pulse to rise from zero to its maximum value (by setting Equation 10 = 0) and then uses Equation 11 to relate to the period of the sine wave, alas! The rise time is .44 T = .44/f. This is because the rate of change of the double exponential pulse decreases exponentially as the value

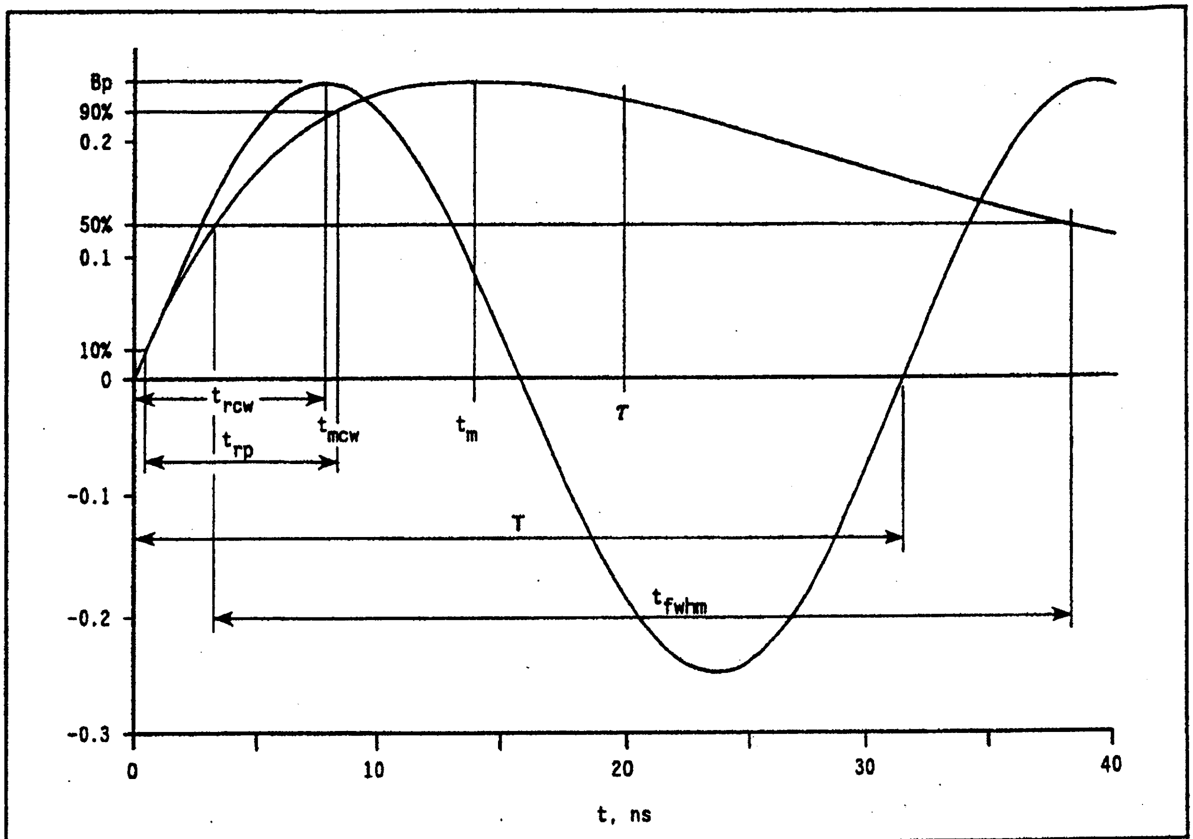


Figure 1. Relationship between exponential pulse and sine wave.

increases, which means that the last 10% of the rise takes 40% of the rise time, while the first 10% only takes only 4%. Early in the history of EMP engineering, some bright young star made the practical observation that if we define the rise time of a pulse as the time it takes to get from 10% to 90% of the maximum, then the pulse rise time is 100% - 40%- 4% = 56% of .44 T, which, lo and behold, is .25 T! Regardless of the validity of the premise, and regardless of the fact that the "10 to 90%" rise time of a sine wave is only .16 T, the paradigm was enshrined:

$$t_r = .25\ T = .25/f_o$$

or $$f_o = 1/T = .25/t_r \qquad (12)$$

where:
f_o = equivalent frequency of the pulse = frequency of the sine wave
T = period of the sine wave
t_r = 100% rise time of the sine wave and 10 to 90% rise time of the pulse

This result is used in Appendix C (PAN 890, I vs I-Dot), pp 7-8 to derive the more commonly used expression

$$f_3 = 1/T = .35/t_r \qquad (13)$$

where f_3 is the 3 dB equivalent frequency of the pulse, the frequency of the sine wave whose amplitude is 3 dB down from the sine wave of frequency f_o due to frequency response limitations (Note 4, dB defined).

IV. EM Field Measurements

Electric ("D-dot") and magnetic ("B-dot") field sensors which were developed to measure Electro-Magnetic Pulse (EMP) phenomena are now being used to measure lightning and other EM phenomena. These new applications typically do not employ the same jargon the EMP practitioners use, so many potential users are having difficulty using the sensor "transfer function" to pick the appropriate size sensor.

The field sensor transfer function is a statement of the sensitivity of the sensor, giving the current or voltage output as a function of the flux of the electric or magnetic field through the sensor and the size (equivalent area) of the sensor. The sensitivity of the sensor is in fact its equivalent area. The term "sensor" is used to distinguish this class of instruments, which measure without transforming energy, from "transducers", which measure by transforming energy from one form to another (eg, mechanical to electrical as in a strain gage). The sensor is not encumbered by an energy transformation mechanism (electrical phenomena are sensed electrically), whereas the transducer depends on some transformation mechanism which usually has some nonlinearity and variability over time. These deviations from ideal performance make it necessary to calibrate transducers periodically. The equivalent area of a sensor is not subject to change, so the sensor needs only verification of its equivalent area. Once the equivalent area of a given model is established, the variance between units of that model is insignificant, so periodic calibration is unnecessary.

The development of the transfer functions of these sensors is given in resplendent detail in Appendix A (PAN 192, Electric & Magnetic Field Sensor Application) pp 1-3, wherein Maxwell's equations are applied to simple sensing elements to derive relationships between the field strength and the area of the element. Gauss's Law is applied to a conductive disk in a ground plane to derive the transfer function for D-dot sensors:

$$V_o = R\, A_{eq}\, dD/dt \qquad (14)$$

Faraday's Law is applied to a conductive loop in a plane normal to a magnetic field to derive the transfer function for B-dot sensors:

$$V_o = A_{eq}\, dB/dt \qquad (15)$$

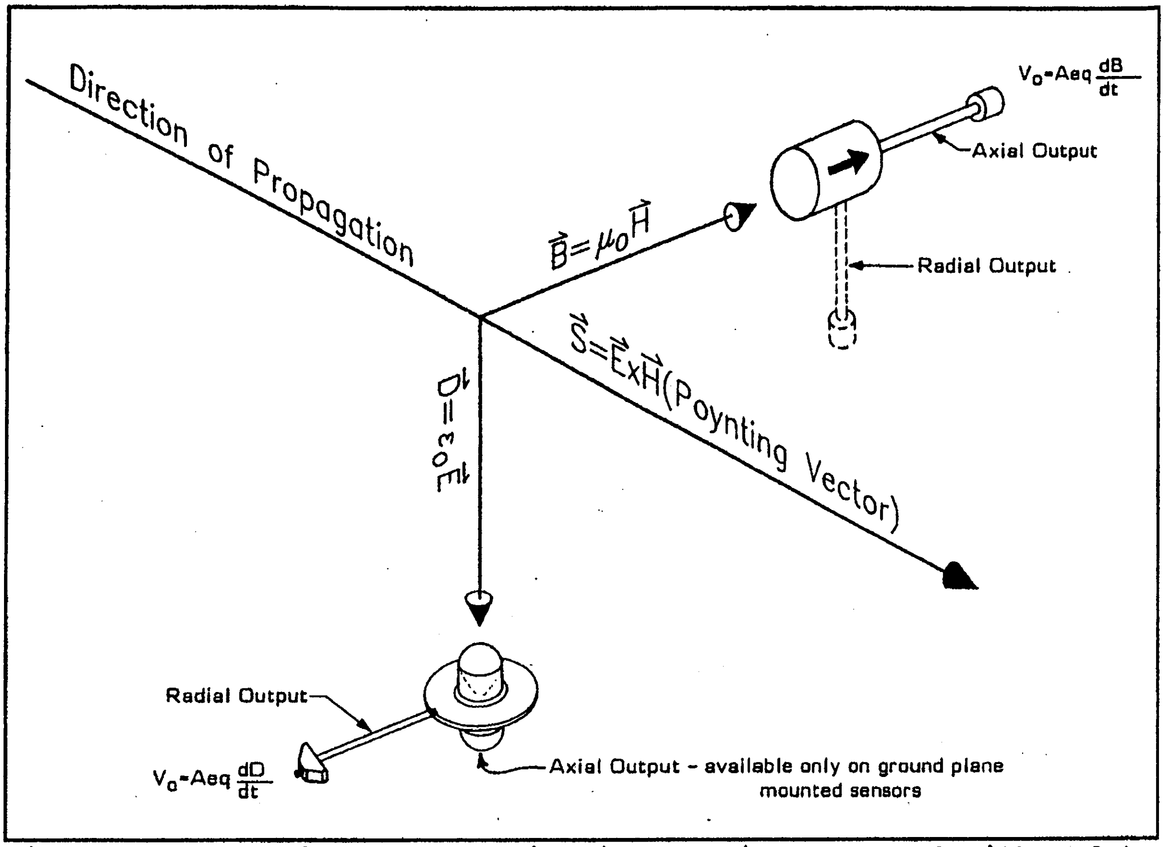


Figure 2. Electric and magnetic fields being measured with D-dot and B-dot sensors.

The Poynting vector and its constituent electric and magnetic vectors are shown in Figure 2, with a D-dot sensor and a B-dot sensor positioned so as to measure the electric and magnetic field strengths. The equivalent areas of PRODYN sensors are physically shown as vectors on the sensor. One simply aligns the vector shown on the sensor with the vector of the field to be measured.

It is often necessary to measure currents induced in various cables, structural members, aircraft components, etc. Current measurements are really just measurements of the magnetic field associated with the current being measured. Thus an I-dot sensor may be thought of as a set of B-dot sensors assembled into a toroid. This could be implemented by installing six or eight small B-dot sensors around the girth of a missile body to measure the total current flowing through the missile. This topic is discussed in Appendix C (PAN 890, I vs I-Dot), p 1.

One of the most frustrating problems in EM field measurements is the issue of units. The most intense confusion seems to be centered in magnetic units. The units needed for EM field measurements are discussed in Appendix A (PAN 192, Electric & Magnetic Field Sensor Application) p 1. The bewildering array of magnetic units (8 units of magnetic field intensity?) is addressed in the same note, p 6. The best advice we can give is to convert derived units (webers, gauss, farads, henries, etc) to more fundamental units (charge, mass, length, time, and voltage and current). For example, prefer units of volt-seconds to Webers, ohm-seconds to henries, coluombs/volt to farads, and even volts/amp to ohms. The D-dot sensor transfer function works directly with D-dot expressed in amps/meter^2 , and R expressed in volts/amp. The B-dot sensor transfer function works directly with B-dot expressed in volts/meter^2.

The theoretical development of the transfer functions of D-dot and B-dot sensors is summarized in Appendix A (PAN 192, Electric & Magnetic Field Sensor Application) pp 8-10. A differential equation representing the current or voltage in an equivalent circuit including the sensing element and a capacitance (for D-dot sensors) or an inductance (for B-dot sensors) is written in the time domain and then transformed into the frequency domain by Laplace Transforms, where it is solved for the output. In both cases, the output is represented as a quotient whose numerator is a field flux · area product and whose denominator contains two terms, one being dependent on the temporal characteristics (the time constant) of the sensor and the other being unity.

$$i_o(s) \text{ or } V_o(s) = A_{eq}\, s\Phi(s)/(s\tau_s + 1) \qquad (16)$$

where

$i_o(s)$ or $V_o(s)$ = sensor output as a function of frequency
$s = j\omega$. $j^2 = -1$ and $|j\omega| = |s| = \omega$. $\omega = 2\pi f$. s replaces t in the Laplace transform, $\mathcal{L}[F(t)] = F(s)$ and $\mathcal{L}[dF/dt] = sF(s)$.
A_{eq} = The equivalent area of the sensor, m^2
$s\Phi(s)$ = Laplace transform of first time derivative of Field flux (D for D-dot sensor, B for B-dot sensor). See Appendix A, p 9.
τ_s = time constant of the sensor (RC for D-dot sensors, L/R for B-dot sensors)

The transfer functions are obtained by neglecting the frequency dependent term and are only valid when the signal frequency is low enough that the frequency dependent term is small with respect to unity, ie, $|s\tau_s| = \omega\tau_s <<$
1. When this condition is met,

$$i_o(s) \text{ or } V_o(s) = A_{eq}\, s\Phi(s)$$

or, transforming back to the time domain,

$$i_o(t) \text{ or } V_o(t) = A_{eq}\, d\Phi(t)/dt = A_{eq}\, \Phi\text{-dot} \qquad (17)$$

The sensor is said to be operating in the "differentiating mode", ie, the output is proportional to the first time derivative of the field intensity, hence the suffix "-dot" (Note 5). The differentiating mode of operation is depicted in Figure 3a. PRODYN's D-dot and B-dot sensors are designed with very small time constants such that $s\tau_s$ is small compared to unity in the high megahertz to low gigahertz frequency range.

When the signal frequency is very high, the frequency dependent terms become large with respect to unity and the high frequency transfer function becomes valid. When this condition prevails, ie, $|s\tau_s| = \omega\tau_s >> 1$,

$$i_o(s) \text{ or } V_o(s) = A_{eq}\, \Phi(s)/\tau_s$$

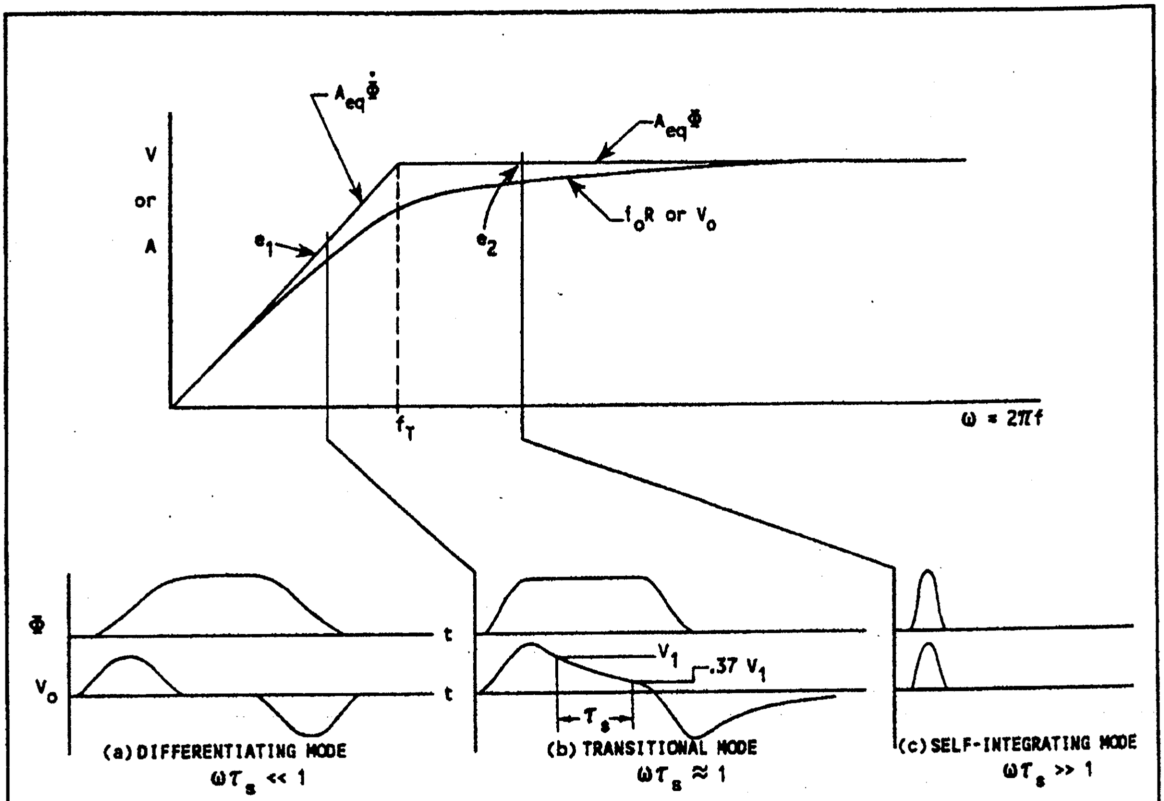
or, transforming back to the time domain,

$$i_o(t) \text{ or } V_o(t) = A_{eq}\, \Phi(t)/\tau_s \qquad (18)$$

The sensor is said to be operating in the "self integrating" mode, ie, the output is proportional to the integral of the derivative of the field intensity (the field intensity itself). The self integrating mode of operation is depicted in Figure 3c. Current probes are designed with large time constants such that $s\tau_s$ is large compared to unity. The current probe cannot properly be called a current sensor because it does not respond to direct current (for which I-dot and the associated B-dot = 0). It is designed to sense and integrate the first time derivative of the current, or, more precisely, the magnetic field associated with the current being measured. The integration process depends physically on the time constant of the probe, which depends on the properties of the medium in the working volume of the probe, which depend on the frequency of the current being measured. In short, the current probe is a transducer, and as such requires calibration.

When the signal frequency is high enough that the low frequency transfer function is not valid, but not high enough to validate the high frequency transfer function, the sensor is said to be operating in the "transitional mode" (see Figure 3b). In this mode, the full transfer function must be used without benefit of the simplifications which apply to the low and high frequency modes. The transition frequency is defined as that frequency for which the frequency dependent term equals unity. The complete transfer functions are represented by the graph in Figure 3, which shows that the actual transfer function approaches the low and high frequency transfer functions asymptotically. A more complete discussion of the frequency response of differentiating sensors is given in Appendix C (PAN 890, I vs I-dot), pp 2-7, wherein the error factors given in Figure 3 are derived.

It is often necessary to transform a specified cw power rating to the maximum pulse frequency a current probe can handle. Appendix C (PAN 890, I vs I-dot), p 8 compares the energy in one cycle of a sine wave of frequency f_r to the energy in a pulse in a series of



Errors for various values of $a = f/f_T$:

a	1/10	1/7	1/4	1/3	1/2	1	2	3	4	7	10
e_1	.005	.01	.03	.05	.106	.293					
e_2						.293	.106	.05	.03	.01	.005

Figure 3. Operating modes of field sensors.

pulses with repetition rate f_r. The result is

$$f_r = P_{cw}R \,/\, V_p^2 \; t_H \,, \tag{19}$$

where

P_{cw} = power in the continuous wave, watts
R = sensor output impedance (usually 50 or 100 ohms)
V_p = peak sensor output voltage for the pulse, volts
t_H = full width half maximum amplitude of the sensor output pulse, sec.

This is a continuous power dissipation rating. If the concern is for a single pulse, sustained heat dissipation is unnecessary, and he peak voltage is limited by the maximum output voltage of the sensor.

NOTES:

1. The weaver and the tailor describe the proposed suit in glowing terms, concluding by mentioning a peculiar characteristic of the material: it is so fine and pure that only those worthy and competent to hold their positions can see it - It is invisible to any who are not. The emperor agrees to the proposition, whereupon the consummate clothiers set up a loom in the court and begin weaving the fabric, describing it eloquently, and receiving the approval of all in the court. Someone in the court, in order to demonstrate his worthiness and competence, suggests that such an elegant suit should be shown to the whole empire at a grand parade. Not to be suspected of unworthiness or incompetence, everyone quickly agrees. After a long series of enhancements, [scope increases] suggested by the weaver and the tailor, the suite is ready, and the parade begins. The people manifest ecstatic approbation, except for one child, who, not having learned of the peculiar characteristic of the fabric, innocently exclaims, "he has nothing on but his underwear!"

2. Free space is often called a void, but for purposes of EM theory, it is really a medium with ultimately small yet finite properties, permeability (μ_o, 1.26×10^{-6} v-sec/amp-m) and permittivity (ϵ_o, 8.85×10^{-12} amp-sec/v-m). These properties determine the speed of light in free space:

$$c = 1/\sqrt{\mu_o \epsilon_o} = 3\times10^8 \text{ m/sec}$$

The serious student will plug the values into the equation (including units, please) and verify this fundamental truth. This exercise will prepare the student for the following stimulating, if tangential, exercise:

If we could modify a medium so as to decrease μ_o or ϵ_o or both so that $\mu_o' < \mu_o$ and/or $\epsilon_o' < \epsilon_o$, then

$$c' > c,$$

and speeds faster than light would be possible. If we could decrease either property to zero, the speed of light in that medium would be infinite.

3. Periodic functions can be expanded into Forier Series of the form

$$f(t) = a_o/2 + a_1 \cos 2\pi ft + a_2 \cos 4\pi ft \ldots + a_n \cos 2n\pi ft + \ldots$$
$$+ b_1 \sin 2\pi ft + b_2 \sin 4\pi ft \ldots + b_n \sin 2n\pi ft + \ldots$$

By choosing the appropriate periodic function, shifting it so that it is symmetrical about $t = 0$ and performing a half range expansion for $t > 0$, virtually any function can be synthesized from Forier series terms. A pulse can thus be synthesized by combining appropriate sine and cosine functions of various frequencies and amplitudes. The lowest frequency component required (f) is the equivalent frequency.

4. Decibels (dB) are units of the logarithmic ratio between two related quantities such as the input and output of a device. The Decibel is defined as 10 times a logarithmic power ratio, but it has been adapted to describe voltage or current ratios. The defining relation $G_{dB} = 10 \text{ Log } (P_2/P_1)$ can be used with Equation 6 to illustrate:

$$G_{dB} = 10 \text{ Log } (P_2/P_1) = 10 \text{ Log } [(E_2{}^2A/Z_o)/(E_1{}^2A/Z_o)] = 10 \text{ Log } [E_2/E_1]^2$$

$$G_{dB} = 20 \text{ Log } (E_2/E_1)$$

The exponential form of this relation is

$$E_2/E_1 = 10^{G_{dB}/20}$$

Some numerical examples of this relation are given here:

E_2/E_1	100	10	1	.707	.5	.1	.01	.001	.0001
(10^n)	10^2	10^1	10^0	$10^{-.15}$	$10^{-.3}$	10^{-1}	10^{-2}	10^{-3}	10^{-4}
G_{dB}	40	20	0dB	-3	-6	-20	-40	-60	-80

A device that increases a signal by a factor of 100 has a gain of 40dB. A device that decreases a signal by a factor .5 has a loss (negative gain) of -6dB.

5. The notation dB/dt is equivalent to the term "B-dot", which expresses the mathematical notation

$$\dot{B} = dB/dt = \text{first time derivative of } B(t) = \text{"B-dot"}$$

"B-dot" has only two syllables and is much easier to say than "dB/dt" which has four, and it is much faster to write by hand. Most engineers are verbally and scriptorally lazy, so the term "B-dot" stuck.

APPENDICES

The Appendices to this article are PRODYN Application Notes (PANs) which were written independently and stand alone as aids to users of Electromagnetic test equipment. They are bound into and incorporated in this article, but are paginated independently.