BIOMEDICAL INSTRUMENTS: THEORY AND DESIGN

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Preface

Since 1966, we have offered a one-year course entitled "Theory and Design of Biomedical Instruments" as part of the Rutgers University graduate program in biomedical engineering. Although several fundamental books on biomedical instrumentation are available, most of them are addressed to instrument users such as physicians and hospital technicians rather than to engineers. It was necessary, therefore, to prepare notes for our design course, and this book is based upon these notes. The book is written at the level of a senior or beginning graduate engineering student.

The book aims at (a) presenting a physical explanation for the behavior of various transducers, (b) developing the mathematical theory applicable to these transducers, and (c) discussing the practical design of biomedical instruments. Our hope is that the book will serve as a text for biomedical engineering students who will be engaged in the design of instruments, as a reference book for medical instrument designers, and as a source of ideas for the large numbers of biomedical research workers who, at one time or another, must build a gadget to implement their research. Numerous examples of medical instrument design are presented in order to clarify the mathematical analyses.

Chapter 1 introduces the reader to various concepts involved in physiological measurements and to transducers employed to implement these measurements. Chapter 2 provides background in the various analytical techniques that are utilized throughout the book, and acts as a "refresher course" for readers who are not currently using them. Since the book is organized around transduction mechanisms, Chapters 3–9 indicate how each transduction technique can be used in the design of instruments. Because ultrasonic systems have an ever-increasing application in the medical field, Chapter 5 describes some techniques in ultrasonic system design. Most of the electromechanical transducers described need some electronic signal conditioning; the design of signal conditioning amplifiers is covered in Chapter 11. The remaining chapters cover the important, but specialized, areas of computerized radiographic imaging, closed-feedback-loop instrument design, and biotelemetry.

The theory and design of biomedical instruments draws upon many different scientific disciplines – physiology, system analysis, circuit theory, solid state physics, acoustics, electromagnetic theory, and so forth. Each of these disciplines has evolved its own language and set of symbols. This has made it particularly difficult to generate a list of symbols that bears a close resemblance to those that are typically employed in each separate discipline.

The authors would like to thank their many colleagues for stimulating discussions on medical instrumentation. We are grateful to the students whose classroom questions and comments and examination pitfalls are inevitably reflected in the final product. We are indebted to Mrs. Constance Zylman for typing the manuscript. Finally, we wish to thank the publishers and authors who gave us permission to reproduce many of the figures from the literature.

List of Symbols

a	acceleration
a_n	peak cosine component
a_0	a particular acceleration
b	a constant
b_n	peak sine component
c	a constant
c_n	spectral component
d	diameter
d_B	beam diameter
d_c	coil-form diameter
d_p	piezoelectric constant
d_T	transducer diameter
d_w	wire diameter
e	transducer constant
f	frequency
f_a	parallel resonant frequency
f_{BW}	frequency bandwidth
f_0	resonant frequency
f_r	series resonant frequency
f_R	received frequency
f_T	transmitted frequency
g	magnetostrictive constant
g_p	piezoelectric constant
h	height, thickness, depth
i	magnetic loss factor
j	$(-1)^{1/2}$
k	coefficient of coupling
k_a	voltage gain of amplifier
k_B	Boltzmann's constant
k_c	controller gain
k_d	damping constant
k_f	restoring-force constant
k_g	transducer constant
k_0	proportionality constant, voltage gain of active device
k_p	transducer constant
k_r	spring constant
k_t	restoring torque constant
l	length
l_c	length of core
l_d	dielectric-slab thickness
l_e	effective length
l_F	focal length
l_g	air-gap length
l_{g0}	quiescent air-gap length
l_m	magnetic-path length
l_0	reference-temperature length
l_p	length of primary
l_R	depth resolution
l_s	length of secondary
m	mass
m_l	strain-gage factor
n	an integer
p	pressure
p_c	cardiac pressure
p_g	gage pressure
q	charge
r	radius
r_a	average radius, membrane radius
r_c	core radius
r_i	inner radius
r_o	outer radius, maximum radius
s	$j\omega$
t	time
t_c	period of one cycle
t_d	downstream transit time
t_0	time delay
t_{out}	period of output pulse
t_p	pulse period
t_u	upstream transit time
t_ν	normalized time
u	a variable, function of radius, horizontal component
v	velocity, vertical component
v_a	average velocity
v_f	flow velocity
v_l	velocity at $x = l$
v_0	velocity at $x = 0$

v_p peak sinusoidal velocity
v_r radial component of velocity
v_s velocity of sound
v_x x component of velocity
v_y y component of velocity
v_z z component of velocity
v_θ angular component of velocity
w width
x distance
x_0 quiescent input, horizontal shift
x_p horizontal width
x_ν normalized distance
y distance
y_0 quiescent output, vertical shift
y_p vertical width
z distance
z_k an X-ray density

A area
A_g air-gap cross-sectional area
A_m magnet cross-sectional area
A_p area of primary coil
A_s area of secondary coil
B magnetic flux density
B_A flux density at point A
B_m flux density of magnet
B_r residual flux density
B_x x component of flux density
B_y y component of flux density
B_z z component of flux density
C capacitance
C_d capacitance of dielectric slab
C_f feedback capacitance
C_g air-gap capacitance
C_L load capacitance
C_0 quiescent capacitance, a particular capacitance
C_s capacitance across secondary
C_v inverting source capacitance
D electric flux density
D_x x component of flux density
D_y y component of flux density
D_z z component of flux density
E electric field intensity
E_x x component of electric field
E_y y component of electric field
E_z z component of electric field
F force
F_l force at $x = l$
F_0 force at $x = 0$
F_p peak sinusoidal force
$F(\omega)$ Fourier transform

G conductance
G_c compensating conductance
H magnetic field intensity
H_c coercive force
I current
I_p power density
J current density
J_n Bessel function of the first kind
K dielectric constant
K_0 quiescent dielectric constant
L inductance
L_c inductance of core section
L_0 quiescent inductance, a particular inductance
L_p inductance of primary
L_s inductance of secondary
M magnetomotive force
M_m magnetomotive force of magnet
$M(\omega)$ magnitude response
N number of turns
N_n Bessel function of the second kind
N_p primary turns
N_s secondary turns
N_T primary/secondary turns ratio
P power
P_E electric polarization
Q quality factor
Q_V flow volume
R resistance
R_c compensating resistance
R_f feedback resistance
R_i input resistance of active device
R_{inn} input resistance seen by noninverting generator
R_{inv} input resistance seen by inverting generator
R_L load resistance
R_n resistance of noninverting source
R_o resistance at reference temperature, output resistance of active device
R_p potentiometer resistance, parallel resistance
R_r reflected resistance
$R(r)$ a function of radius
R_s series resistance
R_T thermistor resistance
R_{Th} Thevenin source resistance
R_v resistance of inverting source
$\mathscr{R}$ magnetic reluctance
$\mathscr{R}_g$ air-gap reluctance
$\mathscr{R}_m$ magnetic-path reluctance
$\mathscr{R}_U$ reluctance of U-shaped path

S	strain
T	temperature
T_0	reference temperature
U	volume
V	voltage
V_a	amplifier output voltage
V_C	capacitor voltage
V_G	gyrator voltage
V_{inn}	voltage of noninverting source
V_{inv}	voltage of inverting source
V_n	voltage at noninverting terminal
V_N	rms noise voltage
V_{Nf}	feedback resistor noise voltage
V_{Nk}	noise voltage of active device
V_{Nn}	noninverting-source noise voltage
V_{Nv}	inverting-source noise voltage
V_p	voltage of primary
V_R	received voltage
V_s	voltage of secondary
V_T	transmitted voltage
V_{Th}	Thevenin source voltage
V_v	voltage at inverting terminal
V_ν	normalized voltage
W	work, energy
X	reactance
X_L	inductive reactance
X_{Lp}	inductive reactance of primary
X_{Ls}	inductive reactance of secondary
X_m	mutual inductive reactance
X_s	reactance of secondary
Y_m	mechanical admittance
Y_0	Young's modulus of elasticity
Y_p	maximum tensile stress
Z	impedance
Z_f	feedback impedance
Z_k	coil impedance
Z_L	load impedance
Z_0	characteristic impedance
Z_{Th}	Thevenin source impedance
Z_v	impedance of inverting source
α	a constant, attenuation constant
α_E	temperature coefficient of expansion
α_{ES}	temperature coefficient of expansion of structure
α_{EW}	temperature coefficient of expansion of wire
α_R	temperature coefficient of resistivity
α_{R_c}	temperature coefficient of compensating resistance
β	a constant
γ	conductivity
δ	deflection
ϵ	$2.718 \cdots$
ϵ_0	permittivity of vacuum
ζ	elastic constant
η	small displacement
θ	an angle
θ_{BW}	angular length bandwidth
θ_0	angular length at resonance
λ	viscosity
μ	magnetic permeability
μ_i	incremental permeability
μ_{ir}	incremental relative permeability
μ_m	permeability of magnet
μ_0	permeability of vacuum
μ_r	relative permeability
ν	inverse of permeability
ν_i	inverse of incremental permeability
ξ	susceptibility constant
π	$3.141 \cdots$
π_{ijkl}	piezoresistive constant
ρ	resistivity
ρ_D	mass density
ρ_0	resistivity at reference temperature
ρ_q	charge density
σ	Poisson's ratio
τ	time constant
τ_f	$2\pi\tau$
ϕ	an angle, magnetic flux
ϕ_c	flux of core section
ϕ_d	downstream phase shift
ϕ_u	upstream phase shift
ψ	electric flux
ω	radian frequency
ω_a	parallel resonant radian frequency
ω_0	resonant radian frequency
ω_r	series resonant radian frequency
ω_x	horizontal component of spatial radian frequency
ω_y	vertical component of spatial radian frequency
ω_ν	normalized radian frequency
Γ	reflection coefficient
Δ	a small change
Λ	inverse of temperature
Λ_0	inverse of reference temperature
Σ	a complicated algebraic sum
Υ	stress
Υ_R	radial stress
Υ_z	length stress
Υ_θ	hoop stress

Contents

1

Some Physiological Specifications

When one considers the design of instruments for physiological measurements it should be stressed that the same basic constraints that apply to other fields, such as instruments for industrial measurements or instruments for oceanography, also apply to this field. However, additional considerations such as anatomy, physiological function, and medical safety must also be taken into account in the design of these special instruments.

The particular emphasis of this book is on transducers, particularly electromechanical transducers. Some consideration will also be given to electrothermal devices and to electronic and systems concepts. The transducers being considered are all electrical output devices. Such devices can operate most readily with a variety of metering output instruments, recording equipment, and computers. Matching of transducers to output systems requires extensive consideration of sensitivity, signal to noise concepts, and signal conditioning circuitry. As mathematical techniques are applied more extensively in physiology and medicine, it is necessary that accurate data be supplied for these analyses. This requires that the basic measurements be accurate, and therefore that the measuring instruments be accurate. Crude instrument design has no place in the medical field.

A problem particular to medical instrument design is the anatomy of the system being measured. The geometry of many organs is complex and a choice must therefore be made between designing a transducer compatible with the geometry or attempting to make the measurement from outside the body. The measurement of heart sounds is a good example of this choice. One can carry out sound measurements from the chest wall and attempt to distinguish between the original signal and the distortions produced by transmission through the chest cavity. Alternatively, one can design a microphone small enough to fit through the blood vessels and heart valves so that measurements can be made inside the heart chambers. The anatomy of the blood vessels places difficult constraints upon this approach.

The physiological function also determines many of the design criteria. Considering again the problem of measuring heart sounds, one finds that the sound levels inside the heart have a magnitude of approximately 60 dB referred to 1 dyne/cm^2. The chest surface sound level is approximately 40 dB referred to 1 dyne/cm^2. The frequency range of the sounds is about 5–2000 Hz. In either case the design must be of a device of sufficient sensitivity to have a reasonable output voltage and of appropriate frequency response.

Of special import in the medical field are the questions of safety and reliability. The intracardiac microphone mentioned must be compatible with the blood chemistry. Its mechanical configuration must be such that it does not damage the blood vessels or heart valves during insertion. It in turn must be rugged enough so that it is not damaged either during insertion or during measurement. Any voltage-carrying leads must be adequately insulated from the body. In addition, care must be taken in design so that even under damage conditions, unsafe voltages are not presented to the body. In fact, for any instrument with electrical measurement characteristics care must be taken to eliminate the possibility of unsafe voltages being applied to the body.

Thus far the discussion has been of transducers in general, without any specific types detailed. This book includes the following transducers that are in common use in instruments:

1. variable resistance,
2. piezoelectric,
3. electrodynamic,
4. variable inductance,
5. differential transformer,
6. magnetostrictive,
7. variable capacitance.

In the area of electrothermal tranducers, variable resistance devices are discussed in detail. In particular, the design of thermistor instruments is considered. While most of the design discussion is restricted to simple transducers, the design of force balance instruments is also covered in detail. Such instruments, with only a slight increase in complexity, yield greatly increased accuracy and environmental insensitivity.

The point of view being taken here is quite a bit different from some other approaches to medical instrumentation. The emphasis is on the transduction technique rather than on the measurement being made, such as pressure. It is believed that there is much more similarity between different measurement instruments (for example, pressure gage and accelerometer) using the same transduction technique than between instruments making the same measurement with different transduction techniques (for example, strain gage versus differential transformer pressure instruments). Certain analytical methods (analogies, transfer function techniques) are common to all electromechanical transducers and can be discussed as a unified topic. Similarly, pressure-coupling characteristics are a common problem and will be discussed without regard to specific transducers.

Since the ultimate aim of this textbook on medical instrumentation is to teach instrument design, many examples of such designs are discussed in detail. These include:

1. respiratory-flow transducer,
2. catheter tip blood pressure gage,
3. electronic thermometer,
4. intracardiac catheter microphone,
5. piezoelectric ventricular-assist device,
6. ultrasonic blood flowmeter,
7. electrodynamic ventricular-assist driving system,
8. electrodynamic blood flowmeter,
9. variable-capacitance microphone,
10. force balance blood pressure gage,
11. biotelemetry units.

Before considering details of analysis, transducer design, and instrument design it is important to consider the nature of some of the measurements that one would like to make on biological systems. Figure 1-1 schematically represents typical physiological measurements made on man and displays some of the waveforms that can be recorded. In addition to direct electrical measurements such as the electrocardiogram, electroencephalogram, and electromyogram, which can be recorded by use of appropriate electrodes and signal conditioning amplifiers, there are a number of measurements that require the use of medical instrument transducers. These include blood flow, blood pressure, temperature, breathing flow and rate, and heart sounds. The characteristics of these measurements determine the requirements for the applicable transducers, as considered in the sections that follow.

1-1 Blood Flow

In this instance one would like to measure flow in an elastic vessel with a variety of nonuniform characteristics. Because the flow is pulsatile, it is desirable to measure frequencies from 0 to 100 Hz. The flow amplitude depends upon the

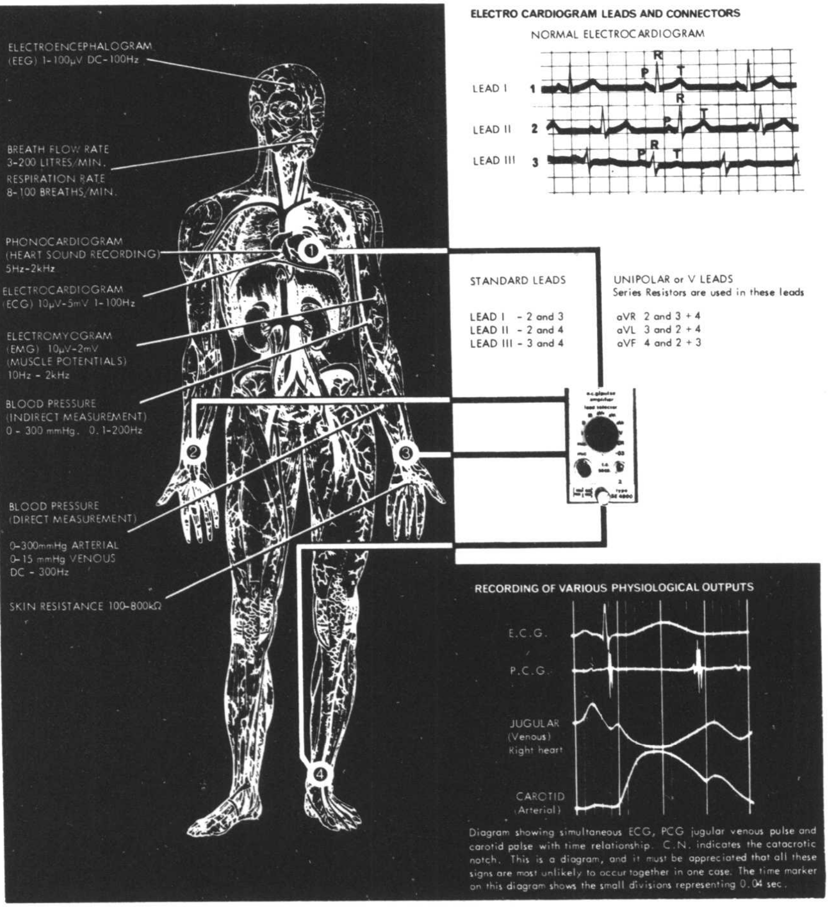

Fig. 1-1 Typical physiological measurements and ranges. (Reprinted by permission from SE Labs (EMI) Ltd.)

vessel being studied, but the maximum instantaneous velocity is less than 1 m/sec. Ideally, one would like to make this measurement without inserting anything into the body, and some ultrasonic instruments attempt this. More commonly, the measurement is made from outside the blood vessel with the objective of not interfering with the normal flow while making the measurement. Vessel sizes are small, ranging from a maximum diameter of a few centimeters down to a fraction of a millimeter.

If the transducer is inserted into the body it must be compatible with the body chemistry. An implantable device is advantageous.

1-2 Blood Pressure

It is desirable in this case, too, to make the measurement from outside the body – and to some degree this is commonly done. By the indirect occluding-cuff technique the maximum and minimum values (systolic and diastolic) of the pressure waveform are measured externally. Often, however, a complete pulsatile waveform is needed. This measurement requires a frequency response of the instrument of approximately 0–300 Hz. If this measurement is made at various locations inside the heart or in the blood vessels, the instrument must not interfere with the normal function. The pressure amplitude ranges from 0 to 15 mm Hg in the veinous system and from 0 to a maximum of 300 mm Hg in the arterial system. If an external technique of measurement is used, it must be suitable for monitoring over an extended period of time.

1-3 Body Temperature

For diagnosis it is desirable to measure temperature inside the body, and when this is required it is customary to make an oral or rectal measurement. Other locations for core temperature have been investigated but none has widespread acceptance. In evaluating vascular difficulties it is sometimes desirable to measure temperature at the ends of the fingers and toes. Temperature sensors should be small so that their response time is short and the measurement is automatically localized. Normally, great accuracy is required (0.1–0.2°F). The required range for monitoring core temperatures is about 95–110°F (35–44°C) and for peripheral temperatures about 80–100°F (26–38°C). As a control device during hypothermia, an instrument with a measurement range from 60 to 110°F (15–44°C) is needed.

1-4 Breathing Flow and Rate

In order to make accurate flow measurements of respired air, the transducer must surround the total inspired or expired breath. The breath is generally moist so that the transducer must be operable in a high humidity environment. The number of breaths per minute can range from about 8 to perhaps 100. The flow rate has an even wider dynamic range – from 3 to 200 liters/min. The former is characteristic of very shallow breathing, while the latter occurs during coughs. Since respiration is very sensitive to oral pressure, the breathing instrument must produce very low back pressure during normal flow. Thus it must carry out its function with a very low flow impedance. It must have a frequency response of about 0–20 Hz to reproduce the flow waveforms adequately.

1-5 Heart Sounds

As implied in the course of this introductory chapter, appropriate measurements of heart sounds require a microphone that generates 1 mV, with a frequency response from 5 to 2000 Hz. This calls for a sensitivity of at least -120 dB referred to 1 $V/dyne/cm^2$ for internal heart sound measurement (or -100 dB referred to 1 $V/dyne/cm^2$ for external measurements). The mechanical design must be appropriate to the anatomy. It should always be kept in mind when designing an external cardiac microphone with electronic displays that there exists a very simple instrument – the stethoscope – with a long history of satisfactory performance.