NBS

Technical Note 233

SENSITIVITY INDICES FOR HALL GENERATORS

SHERWIN RUBIN AND GEORGE J. ROGERS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications, including assistance to industry, business and consumers in the development and acceptance of commercial standards and simplified trade practice recommendations. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. Research projects are also performed for other government agencies when the work relates to and supplements the basic program of the Bureau or when the Bureau's unique competence is required. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's research are published either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three periodicals available from the Government Printing Office: The Journal of Research, published in four separate sections, presents complete scientific and technical papers; the Technical News Bulletin presents summary and preliminary reports on work in progress; and Central Radio Propagation Laboratory Ionospheric Predictions provides data for determining the best frequencies to use for radio communications throughout the world. There are also seven series of nonperiodical publications: Monographs, Applied Mathematics Series, Handbooks, Miscellaneous Publications, Technical Notes, Commercial Standards, and Simplified Practice Recommendations.

A complete listing of the Bureau's publications can be found in National Bureau of Standards Circular 460, Publications of the National Bureau of Standards, 1901 to June 1947 ($1.25), and the Supplement to National Bureau of Standards Circular 460, July 1947 to June 1957 ($1.50), and Miscellaneous Publication 240, July 1957 to June 1960 (includes Titles of Papers Published in Outside Journals 1950 to 1959) ($2.25); available from the Superintendent of Documents, Government Printing Office, Washington, D.C., 20402.

NATIONAL BUREAU OF STANDARDS

Technical Note 233

ISSUED FEBRUARY 6, 1964

SENSITIVITY INDICES FOR HALL GENERATORS

Sherwin Rubin and George J. Rogers

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402 - Price 20 cents

CONTENTS

SENSITIVITY INDICES FOR HALL GENERATORS[1]

Sherwin Rubin and George J. Rogers

The Hall generator is usually characterized as a product-sensitive device, but product sensitivity (the ratio of the Hall voltage to the product of control current and magnetic induction) is unsatisfactory as a figure of merit for many applications. For this reason, two additional sensitivity indices, one a measure of the effect of magnetic induction on output voltage and the other a measure of the effect of control current on output voltage, are proposed, defined, and illustrated by an example.

1. INTRODUCTION

The sensitivity of any device may be defined as the ratio of output response to a specified change in the input variable. Since the output of Hall generators is proportional to the product of two inputs, magnetic induction and control current, the product sensitivity (the ratio of Hall voltage to the product of control current and magnetic induction) has long been used to characterize the sensitivity of these devices. Product sensitivity is useful when the application depends upon the product relationship between the two inputs, for example when the Hall generator is used to measure power or for analog multiplication and division. Hall generators are also used to measure magnetic induction, however, and in other applications in which one of the two

---

[1]This work was supported by the Navy Department, Bureau of Naval Weapons, and is part of a project to develop standard terminology and measuring methods for galvanomagnetic devices.

input variables is held constant. In these cases indices are needed which express the sensitivity of the Hall generator output to either control current or magnetic induction independently of the other.

When the Hall generator is used as a magnetic induction meter, for example, the control current is held constant, while the magnetic induction varies. Product sensitivity can be very misleading when used to predict performance in such applications. What is really needed is the magnetic sensitivity, or the ratio of the output voltage to magnetic induction at the specified control current. In other applications, the magnetic induction is held constant and the control current is the input variable, in which case the control-current sensitivity is needed, where control-current sensitivity is defined as the ratio of output voltage to control current at the given magnetic induction. Even when the application is one in which the control-current magnetic-induction product is the input variable, a knowledge of the control-current and magnetic sensitivities may be needed to determine the output requirements for the driving source.

Product sensitivity is defined only in the linear case, i.e., when it is assumed that the Hall generator characteristic can be closely approximated by a straight line through the origin. Small-signal applications do not depend on the linear characteristics of the Hall generator however, and are not confined to the linear region of operation. For these applications, the definitions for control-current and magnetic sensitivity must be extended to include the small-signal case, especially since a small-signal product sensitivity is not now available in a useful form.

2. THE HALL EFFECT

When a charged particle moves, it generates a magnetic field. When a charged particle moves in an external magnetic field, the interaction between the magnetic field of the particle and the external magnetic field in which it moves causes the particle to be deflected from its initial path in a direction perpendicular to the direction of the magnetic induction. The charge distribution resulting from the deflection of charged particles moving through a conductor or semiconductor causes a difference of potential to be set up across the conductor or semiconductor in a direction mutually perpendicular to both the direction of current flow and the direction of magnetic induction. This phenomenon is called the Hall effect, and the voltage is called the Hall voltage.

A slab or plate designed to generate a Hall voltage when it carries an electric current (control current) in an external magnetic field is called a Hall plate. The Hall plate, together with its leads or pins, encapsulation, heat sink, and other appurtenances attached during the manufacturing process, is called a Hall generator. For a Hall generator with a Hall plate (fig. 1) of thickness d, and with a control current I_c perpendicular to a magnetic induction, B, the Hall voltage is:[2]

$$V_H = (R_H/d) I_c B, \qquad (1)$$

where V_H is the open circuit Hall voltage in volts,

I_c is the control current in amperes,

B is the magnetic induction in teslas (webers/m^2),

d is the thickness in meters, and

R_H is the Hall coefficient in meters^3/coulomb (volt-meter/ampere-tesla).

The Hall coefficient, R_H, is a characteristic of the material of which the Hall plate is made[3] and the thickness, d, is determined in manufacture. For a given Hall generator, therefore, the output voltage is proportional to the product of the control current and the magnetic induction.

3. SENSITIVITY INDICES

The product sensitivity index, V_H/I_cB, is identified in the literature by the symbol K_H, K_o, or S. In this paper it will be designated C_H to avoid the use of the symbol preferred by any particular person or group. Although it would appear from equation (1) that product sensitivity is equal to R_H/d, in a practical device C_H may be less than R_H/d because of

---

[2] See Appendix II for the development of this equation.

[3] See Appendix II, equation II.4.

the finite area of the Hall electrodes and because of the end effects caused by the control current electrodes. The product sensitivity index is usually determined empirically, therefore, rather than by correcting R_H/d to account for the physical configuration of the Hall plate.[4]

The performance of a Hall generator may be characterized by families of curves which define Hall voltage as a function of magnetic induction or control current for particular values of load and source impedance, as illustrated in figure 2. In figure 2(a), the curves are obtained by setting the control current to a constant value and measuring the Hall output voltage as the magnetic induction is varied, and in figure 2(b) by setting the magnetic induction to a constant value and varying the control current. Although these curves have been idealized by drawing them as straight lines passing through the origin, they are very close approximations to the output characteristics of Hall generators within the normal operating region.

The slope of any of the curves of Hall voltage versus magnetic induction in figure 2(a) is the magnetic sensitivity,

---

[4] If the length-to-width ratio is greater than 3, no correction is ordinarily required; for a length-to-width ratio of 1, C_H is about 70% of R_H/d. In this context, length always refers to the dimension which forms the path of the control current, and width to the dimension across which the Hall voltage is developed, so that the length-to-width ratio may be less than unity.

γ_B, at the specified value of control current.[5] Since the magnetic sensitivity of each curve is different, the value of the control current for which the sensitivity was measured must be stated. Similarly, the slope of any curve of figure 2(b) is the control-current sensitivity, γ_I, at the corresponding magnetic induction.

The magnetic and control-current sensitivities could be given by plotting the magnetic sensitivity against control current and the control-current sensitivity against magnetic induction, as shown in figure 3. If the Hall voltage is a linear function of both magnetic induction and control current each of these curves will also be a straight line passing through the origin. It will be noted that both these curves have slopes equal to V_H/I_cB, so that the slope of either curve is the product sensitivity index, C_H, previously defined.

Data for the curves of figures 2 and 3 can be generated from equation (1) if only one of the factors on the right side of the equation is a variable. The actual character-

---

[5] The symbol γ is used to denote sensitivity, with the subscript differentiating between magnetic and control current sensitivities. It has been used without a subscript in the Russian literature to denote magnetic sensitivity. For example, see Yu. A. Vasilevskii, "The Use of Hall Pickups in Magnetic Heads," Avtomatika i Telemekhanika, Vol. 21, No. 9, pp. 402-408, March 1960, or the English translation, Automation and Remote Control, November 1960, pp. 279-282.

istic of a Hall generator is not an absolutely straight line because R_H varies slightly as control current and magnetic induction change. For the present discussion, however, this departure from linearity is assumed to be negligibly small, and, for the particular Hall generator, R_H is considered a constant so that C_H, which is a function of R_H/d is also a constant. Therefore, equation (1) can be written

$$V_H = C_H I_c B. \qquad (2)$$

If the product of control current and magnetic induction is taken as the independent variable, a plot of equation (2) would have the same slope as the curves of figure 3. This slope is the previously defined product sensitivity, since

$$V_H / I_c B = C_H. \qquad (3)$$

On the other hand, if the control current is assumed to be constant and magnetic induction the only variable, control current can be included in the constant term and equation 1 may be written

$$V_H = (C_H I_c) B,$$

which is the equation of the curves of figure 2(a). The slope has been defined as magnetic sensitivity, γ_B, so that

$$\gamma_B = V_H / B = C_H I_c, \qquad (4)$$

where I_c is the magnitude of the control current included in the constant term. Similarly, if B is assumed to be constant and I_c the only variable, the equation is the one plotted in figure 2(b), whose slope is control-current sensitivity, γ_I,

$$\gamma_I = V_H/I_c = C_H B, \qquad (5)$$

where B is the constant value of magnetic induction.

The product sensitivity index, C_H, has the same value for any magnitude of control current and magnetic induction within the linear region, that is, at any point within the normal operating region of the Hall generator. The magnetic sensitivity, γ_B is a constant only for the magnitude of control current at which the measurement was made, however, and the control-current sensitivity, γ_I, is valid only for the magnetic induction at which it was measured. For linear conditions, the sensitivity at any other value of control current or magnetic induction can be obtained by taking a simple proportion.

The magnetic sensitivity carried on the data sheet will be specified at the nominal control current unless otherwise noted. Since nominal control current is defined as the maximum control current at which the specified linearity can be obtained over the specified range of magnetic induction, this magnetic sensitivity is the highest obtainable from the Hall generator with the degree of linearity specified. At smaller control currents, the linearity is better, but the magnetic sensitivity is reduced by the ratio of the desired control current to the nominal control current. At control currents higher than nominal, the magnetic sensitivity will increase but the linearity will be degraded. If poorer linearity can be tolerated, operation is permissible without reducing the magnetic induction provided the control current does not exceed the specified maximum safe operating control current.[6]

Control-current sensitivity will be specified at one decitesla (one kilogauss) unless otherwise noted. Control-current sensitivity at magnetic inductions other than one decitesla can be obtained by multiplying the specified sensitivity index by the ratio of the desired induction to one decitesla. (This is the same as multiplying the control-current sensitivity index by the desired induction expressed in decitesla, or kilogauss.) The specified degree of linearity will be obtained over the range of magnetic induction specified for the particular Hall generator, and operation is permissible at values of magnetic induction higher than the maximum specified in this range if the control current is reduced to keep the dissipation within safe operating limits. (At constant control current, dissipation increases with magnetic induction because of the magneto-resistive effect.)

---

[6] The maximum safe operating control current is the highest control current at which the Hall generator can operate without irreversible changes in the characteristics.

The magnetic and control-current sensitivities are specified in different ways to make the information available in the form in which it is most likely to be needed. When magnetic induction is the input variable, Hall generators are usually picked on the basis of the maximum sensitivity that can be obtained with the specified degree of linearity, since it is relatively easy to obtain whatever magnitude of control current is required. When control current is the input variable, on the other hand, it is likely that the level of magnetic induction will be determined by the sources available, and a comparison of control-current sensitivities at the same induction level is the most meaningful. One decitesla (one kilogauss) was chosen as the induction level at which to make the comparison because it is within the normal operating range of most Hall generators. Under these conditions the control-current sensitivity can also be used as a relative measure of product sensitivity, since product sensitivity and control-current sensitivity are proportional when the Hall generators are compared at the same magnetic induction.

The following definitions of the proposed indices are consistent with the practice used in specifying vacuum tube and transistor characteristics. For a given magnitude of control current, the static magnetic sensitivity, γ_B, is the ratio of Hall voltage to the magnetic induction which produced it,

$$\gamma_B = \frac{V_H}{B}, \; I_c = \text{constant.} \qquad (6)$$

Similarly, for a given magnitude of magnetic induction, the static control-current sensitivity, γ_I, is the ratio of the Hall voltage to the control current which produced it,

$$\gamma_I = \frac{V_H}{I_c}, \; B = \text{constant.} \qquad (7)$$

The upper case subscripts indicate that these are static values, which are compatible with the presently used product sensitivity index.

If the instantaneous values are needed to specify the slope at a point on the curve when the linear approximation will not suffice, a similar pair of indices can be defined in terms of small changes in the independent variables. If, in equation (1), both control current and magnetic induction vary simultaneously, the total differential is

$$dV_H = \frac{\delta V_H}{\delta B} dB + \frac{\delta V_H}{\delta I_c} dI_c \qquad (8)$$

in which $\frac{\delta V_H}{\delta B}$ is easily identified as the small-signal magnetic sensitivity and $\frac{\delta V_H}{\delta I_c}$ as the small-signal control-current sensitivity. Therefore,

$$dV_H = \gamma_b dB + \gamma_i dI_c \qquad (9)$$

where the lower-case subscripts indicate the small-signal magnetic and control-current sensitivities.

Equation (9) is valid even if a simple equation relating Hall voltage, control current, and magnetic induction cannot be written, since the small-signal sensitivities can be determined empirically for any value of control current and magnetic induction. The small-signal control current sensitivity, γ_i, is the ratio of the change in Hall voltage to the corresponding small change in control current about the desired point, and the small-signal magnetic sensitivity, γ_b, is the ratio of the change in Hall voltage to the corresponding small change in magnetic induction.

Equation (9) can be used as a basis for defining the small signal sensitivities. If the control current is held constant, dI_c is zero, and:

$$dV_H = \gamma_b dB, \text{ so that}$$

$$\gamma_b = \frac{dV_H}{dB}, \; I_c = \text{constant}. \qquad (10)$$

If the magnetic sensitivity is held constant, dB is zero, and

$$\gamma_i = \frac{dV_H}{dI_c}, \; B = \text{constant}. \qquad (11)$$

Since the product sensitivity index is usually the only one specified in present Hall generator data sheets, it will often be necessary to derive the magnetic and control current sensitivities from the product sensitivity. This is possible only in the static case. The necessary relationships are given in equations (4) and (5). If it is desired to find the static magnetic sensitivity at a particular value of control current, I'_c,

$$\gamma_{B\,(I_c = I'_c)} = C_H I'_c \tag{12}$$

Similarly, the static control-current sensitivity at a magnetic induction B = B' is:

$$\gamma_{I\,(B = B')} = C_H B'. \tag{13}$$

The advantage of specifying magnetic and control-current sensitivities can be illustrated by an example. Table I lists the pertinent data as it appears in the manufacturer's specification sheets for two Hall generators. The values for the product sensitivity index listed in Table I make it appear that there is only a slight (20%) difference in the sensitivity of the two Hall generators. For many Hall generator applications this would be a reasonable conclusion, but for induction-sensitive applications this first impression would be misleading.

TABLE I

Typical Hall Generator Specifications

Characteristic	Type A	Type B
I_c nominal[7]	150 mA	400 mA
B nominal[7]	1 Tesla (10 kilogauss)	1 Tesla (10 kilogauss)
V_H for B and I_c nominal	95 mV	300 mV
C_H	0.063 mV/mA-decitesla	0.075 mV/mA - decitesla
Linearity error percent of maximum	1%	1%

[7] For practical purposes the nominal values of control current and magnetic induction are the highest at which the Hall generator will operate with the degree of linearity specified. To some extent one of these limits can be reduced to compensate for increases in the other, but both cannot be exceeded simultaneously without degrading the linearity.

When the magnetic and control-current sensitivities are needed, it is necessary to calculate them from the product sensitivity, using the nominal value of control current and a magnetic induction of one decitesla. For generator A,

$$\gamma_B = C_H I_{c(nominal)} = 0.063\ (150)$$

$$= 9.45\ \text{mV/decitesla},\ I_c = 150\ \text{mA},$$

and

$$\gamma_I = C_H B_{(1\ decitesla)} = 0.063\ (1)$$

$$= 0.063\ \text{mV/mA},\ B = 1\ \text{decitesla}.$$

For generator B,

$$\gamma_B = C_H I_{c(nominal)} = 0.075\ (400)$$

$$= 30\ \text{mV/decitesla},\ I_c = 400\ \text{mA},$$

and

$$\gamma_I = C_H B_{(1\ decitesla)} = 0.075\ (1)$$

$$= 0.075\ \text{mV/mA},\ B = 1\ \text{decitesla}.$$

Thus it is seen that while there is no significant difference between the product sensitivity indices of the two Hall generators, their static magnetic sensitivities differ by a factor of three to one. As expected, the control-current sensitivities are proportional to the product sensitivities.

In this example the magnetic and control-current sensitivities were easily calculated because the value of the nominal control current was available from the specifications. It is common practice in the literature, however, to use product sensitivity to specify the sensitivity of magnetic induction meters, often without stating the control current at which the meter operates. Without information about control current, it is impossible to compare two such devices. This situation would not occur if the magnetic sensitivity of the device was given, rather than the product sensitivity.

4. CONCLUSIONS

The use of product sensitivity alone to specify the sensitivity of Hall generators is inadequate for two reasons. First, it is not specific enough when the application is one in which either magnetic induction or control current is the input variable, and second, it cannot furnish small-signal information for applications in which the static sensitivity is not a satisfactory index. The two proposed indices, magnetic and control-current sensitivity, have been defined for both the static and small-signal case to provide the necessary information. In addition, the control-current sensitivity is specified in such a way that it can be used as a substitute for product sensitivity.

APPENDIX I

Proposed specifications for the magnetic and control current sensitivities of Hall generators

Control current sensitivity: The control current sensitivity is a measure of the effect of control current on Hall voltage for a given magnitude of magnetic induction under given temperature conditions. The static control-current sensitivity, γ_I, is the ratio of Hall voltage to control current at any point on the curve of Hall voltage versus control current for a constant magnetic induction. The small-signal control current sensitivity, γ_i, is the ratio of a change in Hall voltage to the corresponding small change[8] in control current about the desired point on the curve.

Magnetic sensitivity: Magnetic sensitivity is a measure of the effect of magnetic induction on Hall voltage for a given magnitude of control current under given temperature conditions. The static magnetic sensitivity, γ_B, is the ratio of Hall voltage to magnetic induction at any point on the curve of Hall voltage versus magnetic induction for a constant control current. The small-signal magnetic sensitivity, γ_b, is the ratio of a change in Hall voltage to the corresponding small change[8] in magnetic induction about the desired point on the curve.

[8] The change is considered small if doubling its magnitude does not produce a change in the sensitivity that is greater than the specified accuracy of the measurement.

Conditions of measurement: Unless otherwise stated, these sensitivities shall be measured at nominal control current[9] and at a magnetic induction of one decitesla (one kilogauss). The Hall generator shall be suspended by standard size leads in still air at 25°C when the measurements are made. Both the decrease in sensitivity for optimum linear loading, and the limiting range of magnetic induction to insure a given maximum percentage non-linearity shall be stated.

---

[9] For a specified range of magnetic induction, nominal control current is that magnitude of control current which, if exceeded, would cause the linearity error of the device to exceed the rated magnitude under optimum drive and/or load conditions.

APPENDIX II

HALL VOLTAGE DERIVATION

A standard derivation for the equations relating Hall voltage to control current and magnetic induction follows:

If a Hall plate, oriented along cartesian coordinates x, y, and z, as shown in figure 1 has a current flowing in the x direction and is acted on by a magnetic induction in the y direction, there will be an electric field set up in the z direction. This field is caused by the action of the magnetic field on the moving charges, which action concentrates the charges along the xy edge of the plate.

There are two forces acting in the z direction. The Lorentz force due to the magnetic induction B acting on the charges, e, which move in the x direction with a velocity, v_x, is

$$F = ev_xB_y. \qquad \text{(II.1)}$$

The force due to the electric field, E_z, caused by the concentration of charges along the edge of the plate is

$$F = eE_z. \qquad \text{(II.2)}$$

At equilibrium these two forces are equal, and

$$eE_z = ev_xB_y,$$

so that

$$e_z = v_xB_y. \qquad \text{(II.3)}$$

Since the charge velocity $v_x = \mu E_x$, where μ, the charge mobility, is equal to the drift velocity per unit field, and field strength $E_x = J_x/\sigma$, where σ is the conductivity of the material of the Hall plate in mhos per unit length and J_x is the current density,

$$v_x = \mu(J_x/\sigma),$$

and

$$E_z = \mu(J_x/\sigma)\, B_y. \qquad \text{(II.4)}$$

Charge mobility and conductivity are properties of the Hall plate material, and their ratio, μ/σ is a constant of the material called the Hall coefficient, R_H, so that equation II.4 can be written

$$E_z = R_H J_x B_y. \qquad \text{(II.5)}$$

Equation II.5 shows that the field strength set up by the Hall effect is a function of the Hall coefficient of the plate material, the control current density, and the magnetic induction, and is independent of the dimensions of the Hall plate. In a practical device, however, it is preferable to replace field strength and current density by their equivalents, volts per unit distance and current per unit cross section area. It is conventional in describing Hall effect devices to define length, l, as the dimension which forms the path of the control current, width, w, as the dimension across which the Hall voltage is developed, and thickness, d, as the dimension parallel to the magnetic induction. Using this convention, $E_z = V_z/w$, and

$J_x = I_x/wd$. Furthermore, V_z is the Hall voltage, V_H, and I_x is the control current, I_c; the magnetic induction is usually written without a subscript. Making these substitutions,

$$V_H = R_H J_x (w) B \tag{II.6}$$

$$= (R_H/d) I_c B \tag{II.7}$$

R_H and d are grouped together because they are a characteristic of the Hall plate, while I_c and B are independent variables.

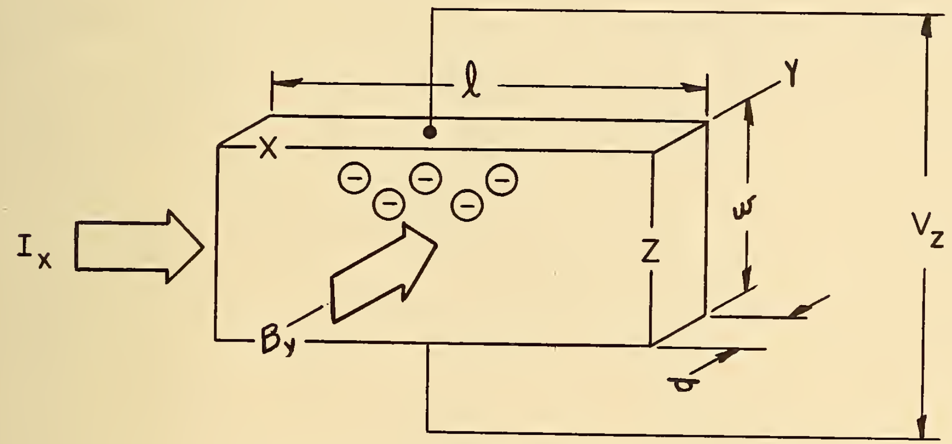
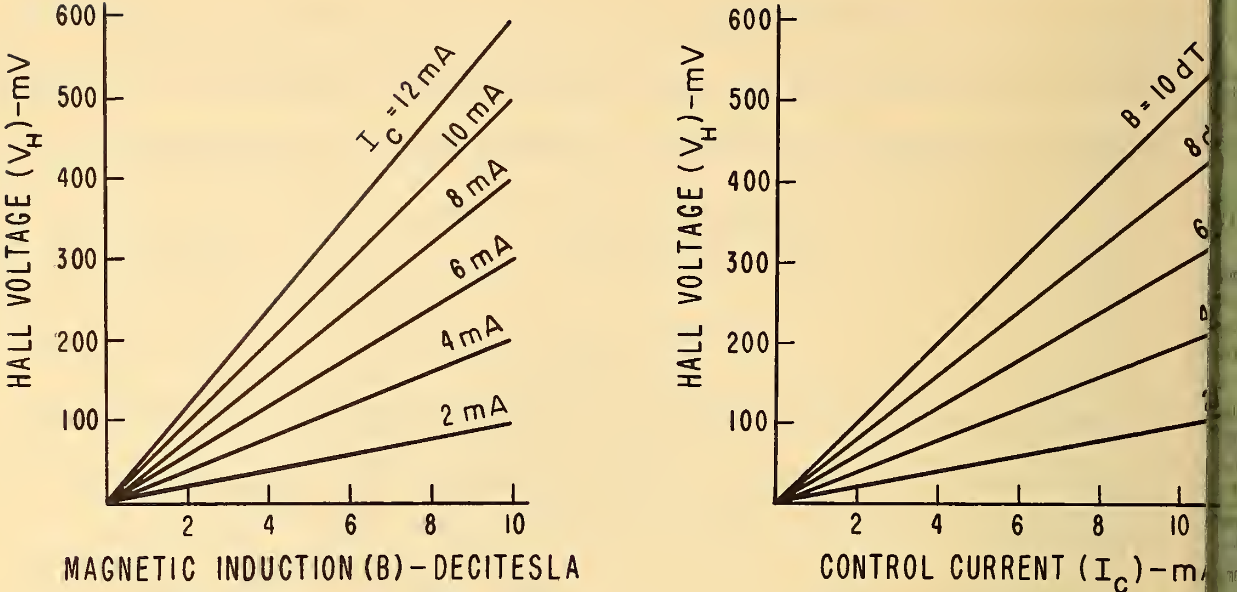


Figure 1. A Hall plate carrying control current, I_x, in a magnetic induction, B_y, producing a Hall voltage, V_z.

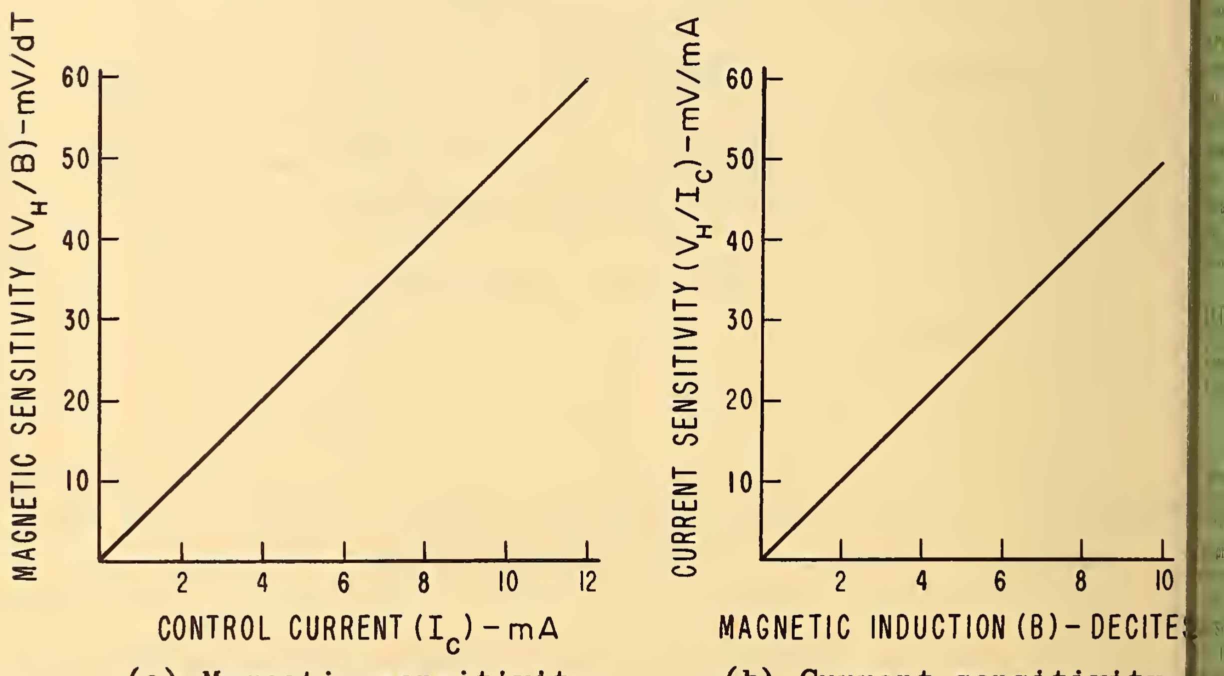
The plate is assumed to be of n-type material with conduction predominantly by electrons. If p-type material were used, conduction would be primarily by holes, and the polarity of the Hall voltage would be reversed.



(a) Hall voltage versus magnetic induction.

(b) Hall voltage versus control current

Figure 2. Typical Hall generator performance curves



(a) Magnetic sensitivity versus control current.

(b) Current sensitivity versus magnetic induction

Figure 3. Hall generator sensitivity.
The slope of either curve is 5 millivolts per decitesla.

* U.S. GOVERNMENT PRINTING OFFICE : 1964 O—718-54

THE NATIONAL BUREAU OF STANDARDS

he scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and oulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. general, each section carries out specialized research, development, and engineering in the field indicated by title. A brief description of the activities, and of the resultant publications, appears on the inside of the nt cover.

ASHINGTON, D. C.

lectricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. ielectrics. High Voltage. Absolute Electrical Measurements.

trology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. ss and Volume.

eat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

adiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. cleonic Instrumentation. Neutron Physics.

nalytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Refer- ce Materials. Applied Analytical Research. Crystal Chemistry.

chanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion ntrols.

lymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Charac- ization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

tallurgy. Engineering Metallurgy. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

rganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. ystallography.

ilding Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. des and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

plied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Op- tions Research.

ta Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. gineering Applications. Systems Analysis.

mic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron ysics. Atomic Physics. Plasma Spectroscopy.

trumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instru- nts. Basic Instrumentation.

ysical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Ele- tary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

fice of Weights and Measures.

ULDER, COLO.

ogenic Engineering Laboratory. Cryogenic Processes. Cryogenic Properties of Solids. Cryogenic Technical vices. Properties of Cryogenic Fluids.

CENTRAL RADIO PROPAGATION LABORATORY

nosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Re- rch. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical ndings Research.

oposphere and Space Telecommunications. Data Reduction Instrumentation. Radio Noise. Tropospheric surements. Tropospheric Analysis. Spectrum Utilization Research. Radio-Meteorology. Lower Atmosphere sics.

io Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Fre- ncy Utilization. Modulation Research. Antenna Research. Radiodetermination.

per Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere ysics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

dio Standards Physics. Frequency and Time Disseminations. Radio and Microwave Materials. Atomic Fre- ency and Time-Interval Standards. Radio Plasma. Microwave Physics.

dio Standards Engineering. High Frequency Electrical Standards. High Frequency Calibration Services. High quency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency libration Services.

NBS LABORATORY ASTROPHYSICS GROUP

(Joint Institute for Laboratory Astrophysics at Univ. of Colo.)

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS