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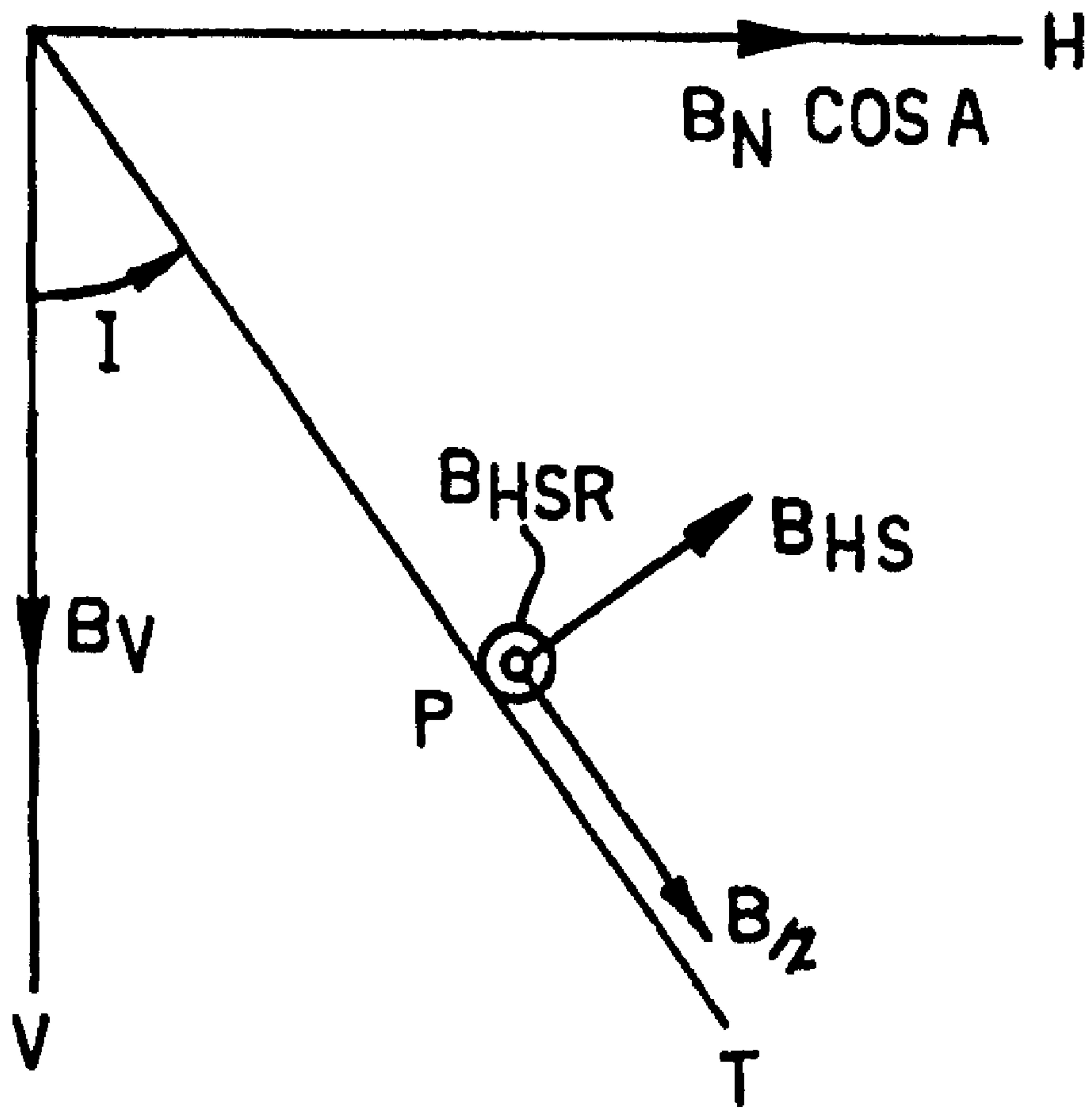
(54) Titre : PROCEDE DE DETERMINATION DE L'AZIMUT D'UN TROU DE FORAGE
(54) Title: METHOD OF DETERMINING AZIMUTH OF A BOREHOLE



(57) Abrégé/Abstract:
A method is provided of determining an azimuth angle of a borehole formed in an earth formation using a magnetometer tool arranged in a drill string extending in the borehole, the magnetometer tool having a selected orientation relative to the drill string.

(57) Abrégé(suite)/Abstract(continued):

The method comprises a) selecting at least two locations along the borehole at which the borehole has selected different borehole inclinations, b) for each selected location, arranging the drill string in the borehole such that the magnetometer tool is positioned at the selected location and operating the magnetometer tool so as to measure a local magnetic field including the earth magnetic field and a drill string magnetisation field having a component in a substantially vertical plane through the longitudinal axis of the drill string at the selected location, c) determining from the measured magnetic field and from the selected borehole inclinations, said component of the drill string magnetisation field, d) correcting the measured magnetic field for said component of the drill string magnetisation field, and e) determining from the corrected magnetic field, the borehole azimuth.

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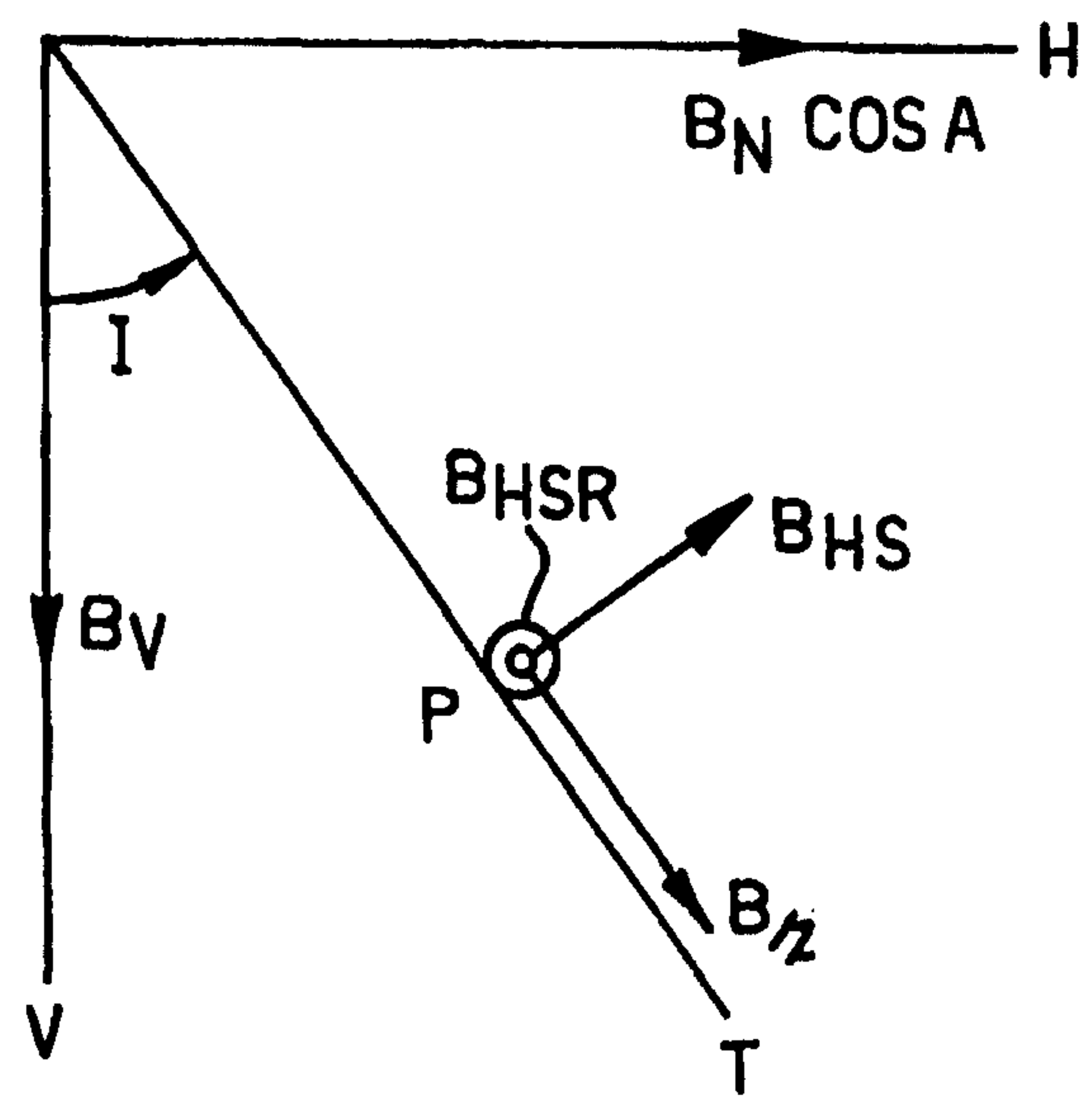
(54) Title: METHOD OF DETERMINING AZIMUTH OF A BOREHOLE

(57) Abstract

A method is provided of determining an azimuth angle of a borehole formed in an earth formation using a magnetometer tool arranged in a drill string extending in the borehole, the magnetometer tool having a selected orientation relative to the drill string. The method comprises a) selecting at least two locations along the borehole at which the borehole has selected different borehole inclinations, b) for each selected location, arranging the drill string in the borehole such that the magnetometer tool is positioned at the selected location and operating the magnetometer tool so as to measure a local magnetic field including the earth magnetic field and a drill string magnetisation field having a component in a substantially vertical plane through the longitudinal axis of the drill string at the selected location, c) determining from the measured magnetic field and from the selected borehole inclinations, said component of the drill string magnetisation field, d) correcting the measured magnetic field for said component of the drill string magnetisation field, and e) determining from the corrected magnetic field, the borehole azimuth.



METHOD OF DETERMINING AZIMUTH OF A BOREHOLE

The present invention relates to a method of determining an azimuth angle of a borehole formed in an earth formation using magnetometer tool arranged in a drill string extending longitudinally in the borehole. During drilling of a borehole in an earth formation it is generally desirable to check the borehole course by measuring the inclination and azimuth of the borehole at regular intervals. The borehole inclination can be determined using accelerometer measurements in the borehole and the Earth gravity field as a reference. The borehole azimuth is determined using a package of magnetometers included in the Bottom Hole Assembly (BHA) of the drill string. The magnetometers are operated to measure the components of the local magnetic field from which the borehole azimuth is determined using the Earth magnetic field as a reference. In many instances however the measured local magnetic field includes, apart from the Earth magnetic field components, components attributable to drill string magnetisation. In order to obtain sufficiently accurate azimuth data it is required that such drill string magnetisation effects are taken into account.

EP-A-0 193 230 discloses a method of determining azimuth of a borehole formed in an earth formation using a magnetometer package included in a drill string extending into the borehole, wherein the effect of drill string magnetisation is taken into account by first eliminating the effect of cross-axial drill string magnetisation prior to eliminating the influence of axial drill string magnetisation. The cross-axial drill string magnetisation is eliminated by taking so-called rotational shots, i.e. by measuring the local magnetic field at different rotational locations of the magnetometer tool and determining the cross-axial drill string magnetisation from the magnetic field data thus obtained. The axial drill string magnetisation is computed from the measured magnetic field and from the Earth magnetic field. Once the measured magnetic field has been corrected for cross-axial and axial drill string magnetisation, the borehole azimuth is determined from the corrected field and from the Earth magnetic field which is generally known for most places on Earth. The computed azimuth however is very sensitive to inaccuracies in the Earth magnetic field data, especially in case of highly inclined boreholes extending substantially in east or west direction.

It is an object of the invention to provide an improved method of determining azimuth of a borehole, which method is less sensitive to inaccuracies in the Earth magnetic field data even for highly inclined boreholes extending substantially in east or west direction.

In accordance with the invention there is provided a method of determining an azimuth angle of a borehole formed in an earth formation using a magnetometer tool arranged in a drill string extending in the borehole, the magnetometer tool having a selected orientation relative to the drill string, the method comprising: a) selecting at least two locations along the borehole at which the borehole has selected different borehole inclinations; b) for each selected location, arranging the drill string in the borehole such that the magnetometer tool is positioned at the selected location and operating the magnetometer tool so as to measure a component of a local magnetic field along an axis having a selected orientation relative to the magnetometer tool, the local magnetic field including the earth magnetic field and a drill string magnetisation field; c) determining from the measurements and from the selected borehole inclinations, a contribution from the drill string magnetisation field to the measured components; d) correcting the measurements for said contribution from the drill string magnetisation field; and e) determining from the corrected measurements, the borehole azimuth, wherein said component of the local magnetic field is the axial component of the local magnetic field, wherein for a borehole inclination at a first one of said locations being less than 45°, step c) comprises determining the contribution from axial component of the drill string magnetisation from the relationship:

$$C_z\ (\cos I_2 - \cos I_1) = B_{HS}{}^{e}{}_{1} \sin I_1 - B_{z1} \cos I_1 - B_{HS}{}^{e}{}_{2} \sin I_2 + B_{z2} \cos I_2$$

as defined hereinbefore.

The contribution from the Earth magnetic field to each measured component along the axis of selected orientation is different for the different borehole locations because the drill string, and therefore also said axis, is oriented differently relative to the earth magnetic field at the different locations. On the other hand, the contribution from the drill string magnetisation field to the measured component is the same for the different borehole locations because the orientation of said axis relative to the drill string magnetisation field does not change. Since the orientation of said axis is directly related to the orientation of the drill string and therefore to the borehole inclination, the contribution from the drill string magnetisation field to the measured component can be determined from the difference between the measured components at the different locations and from the different borehole inclinations at the different locations. An example of such determination is presented in the detailed description below.

Preferably said component of the local magnetic field is the axial component of the local magnetic field, which is the component in axial direction of the drill string. It is to be understood that the contribution from the drill string magnetisation field to the cross-axial component (if any at all) of magnetic field generally is an order of magnitude smaller than the axial contribution. Therefore, for most applications it is sufficiently accurate to disregard such cross-axial contribution. Alternatively, the measured magnetic field can be corrected for a cross-axial contribution from the drill string magnetisation field prior to step c).

The method can suitably be applied for a borehole of which the longitudinal axis at the selected locations is substantially located in a vertical plane.

For most applications it is sufficient to select two said locations of different borehole inclination.

For enhanced accuracy in applying the method of the invention, the borehole inclinations at at least two of said locations differ from each other by an angle of at least 40°.

If furthermore the drill string magnetisation at the first location is different than at a second one of the locations, e.g. due to different Bottom Hole Assemblies, the borehole inclination angle at the second location is suitably between 80°-100°.

In the case where the wellbore inclination at the first location exceeds 45° it is preferred to determine the contribution to the axial components attributable to drill string magnetisation from the horizontal component of the Earth magnetic field. If furthermore the drill string magnetisation at the first location is different than at the second location, the borehole inclination angle at the second location is suitably between 0° and +10°.

The invention will be described further in more detail and by way of example with reference to the accompanying drawings in which

Fig. 1 shows a horizontal plane of the (N,E,V) coordinate system;

Fig. 2 shows a vertical plane through line H of the coordinate system of Fig. 1;

Fig. 3 shows a borehole-fixed coordinate system (HS, HSR, z) and a tool-fixed coordinate system (x,y,z).

In Fig. 1 is shown the horizontal N-E plane of the North (N), East (E), Vertical (V) coordinate system, wherein line H is a projection in the N-E plane of the longitudinal axis of a borehole 10 (Fig. 3) and angle A indicates the borehole azimuth. It is to be understood that angle A may vary along the length of the borehole. B_N represents the horizontal vector component of the earth magnetic field.

In Fig. 2 is shown a vertical plane through line H. Line T represents the longitudinal axis of the borehole and angle I the borehole inclination which varies along the length of the borehole. B_V represents the vertical vector component of the earth magnetic field and B_n.cos A is the projection of the horizontal component of the earth magnetic field on line H.

In Fig. 3 is shown a cross-sectional view of the borehole 10, a co-ordinate system (HS, HSR, z) fixed to the borehole 10 and a co-ordinate system (x, y, z) fixed to a magnetometer tool (not shown) for measuring the components of a local magnetic field $\underline{B}$ in the (x, y, z) co-ordinate system. The magnetometer tool is fixedly arranged in a drill string (not shown) extending through the borehole, therefore the (x, y, z) co-ordinate system can be thought of as being fixed to the drill string. The HS-, HSR-, x-, and y-axes extend in the transverse plane of the borehole at point P whereby the x-, y-axes are rotated relative to the HS-, HSR-axes about an angle α which is referred to as the tool-face angle. The z-axis extends in longitudinal direction of the borehole 10. The drill string is furthermore provided with an accelerometer tool (not shown) for measuring the components of the earth gravity field $\underline{G}$ in the (x, y, z) co-ordinate system.

During normal operation the magnetometer tool measures the components B_x, B_y, B_z of the local magnetic field vector $\underline{B}$ and the accelerometer tool measures the components G_x, G_y, G_z of the gravity field vector $\underline{G}$ while the drill string is kept stationary. The tool-face angle α and the inclination angle I are determined from the equations:

$$G_{HS} = G_x \cos \alpha - G_y \sin \alpha \qquad (1)$$

$$G_V = G_z \cos I - G_{HS} \sin I \qquad (2)$$

$$G_z \sin I + G_{HS} \cos I = o \qquad (3)$$

wherein

G_{HS} is the component of $\underline{G}$ in HS-direction;

G_V is the (known) component of $\underline{G}$ in V-direction.

From the measured magnitudes of B_x, B_y, B_z and from the tool face angle α, the components of $\underline{B}$ in the (HS, HSR, z) co-ordinate system are determined thus yielding the local magnetic field vector (B_{HS}, B_{HSR}, B_z). These components include contributions from the earth magnetic field and from drill string magnetisation. Denoting the earth magnetic field vector by ($B_{HS}{}^e$, $B_{HSR}{}^e$, $B_z{}^e$) and the drill string magnetisation vector by (C_{HS}, C_{HSR}, C_z) the local magnetic field vector is

$$(B_{HS}, B_{HSR}, B_z) = (B_{HS}^e, B_{HSR}^e, B_z^e) + (C_{HS}, C_{HSR}, C_z) \quad (4)$$

The cross-axial contributions from drill string magnetisation are then determined and eliminated from the magnetic field vector, for example by means of a "rotational shot" whereby a number of surveys are taken at various rotational angles of the magnetometer tool in the borehole as described in EP-A-0 193 230. After such elimination the local magnetic field vector is

$$(B_{HS}, B_{HSR}, B_z) = (B_{HS}^e, B_{HSR}^e, B_z^e + C_z) \quad (5)$$

The sum of the vertical components of B_{HS}^e and B_z^e is equal to the vertical component B_v of the magnetic field (B_{HSR}^e has no vertical component), thus yielding

$$B_v = -B_{HS}^e \sin I + B_z^e \cos I$$

and from eq. (5)

$$B_v = -B_{HS}^e \sin I + (B_z - C_z) \cos I \quad (6)$$

By operating the magnetometer tool at two borehole locations with different inclinations I_1 and I_2 two local magnetic field vectors (B_{HS1}, B_{HSR1}, B_{z1}) and (B_{HS2}, B_{HSR2}, B_{z2}) are obtained, and from eq. (6) it follows

$$B_v = -B_{HS}^e{}_1 \sin I_1 + (B_{z1} - C_{z1}) \cos I_1 \quad (7)$$

$$B_v = -B_{HS}^e{}_2 \sin I_2 + (B_{z2} - C_{z2}) \cos I_2 \quad (8)$$

Axial drill string magnetisation depends primarily on the magnetic properties of the BHA, not on borehole inclination. Therefore it is considered that at least as long as the BHA is not changed:

$$C_{z1} = C_{z2} = C_z \quad (9)$$

Equations (7), (8), (9) contain the unknowns B_v, C_{z1} and C_{z2}. The inclinations I_1 and I_2 are known from measurements using one or more accelerometer meters included in the drill string. It is found that

$$C_z(\cos I_2 - \cos I_1) = B_{HS}{}^{e}{}_1 \sin I_1 - B_{z1} \cos I_1 - B_{HS}{}^{e}{}_2 \sin I_2 + B_{z2} \cos I_2 \quad (10)$$

from which C_z is determined.

The local magnetic field at each point can now be corrected for axial drill string magnetisation.

The above approach is preferred for low borehole inclinations, i.e. inclinations less than 45°, because C_z then is relatively insensitive to variations in borehole inclination.

For borehole inclinations beyond 45° the following approach is preferred.

The sum of the components of $B_{HS}{}^{e}$ and $B_z{}^{e}$ in direction H is equal to the component of the earth magnetic field in direction H, thus yielding

$$B_n \cos A = B_{HS}{}^{e} \cos I + B_z{}^{e} \sin I \quad (11)$$

or

$$B_n \cos A = B_{HS}{}^{e} \cos I + (B_z - C_z) \sin I \quad (12)$$

For two points with respective inclinations I_1, I_2 and azimuth A_1, A_2 it follows that

$$B_n \cos A_1 = B_{HS}{}^{e}{}_1 \cos I_1 + (B_{z1} - C_{z1}) \sin I_1 \quad (13)$$

$$B_n \cos A_2 = B_{HS}{}^{e}{}_2 \cos I_2 + (B_{z2} - C_{z2}) \sin I_2 \quad (14)$$

The HSR components of the local magnetic field, corrected for cross-axial drill string magnetisation as described above, for the two points are

$$B_{HSR}{}^{e}{}_1 = -B_n \sin A_1 \quad (15)$$

$$B_{HSR}{}^{e}{}_2 = -B_n \sin A_2 \quad (16)$$

From eqs. (13) - (16), and with $C_{z1} = C_{z2} = C_z$ (e.g. for unchanged BHA), it follows that

$$(B_{HSR}{}^{e}{}_1)^2 + (B_{HS}{}^{e}{}_1 \cos I_1 + (B_{z1} - C_z) \sin I_1))^2 - (B_{HSR}{}^{e}{}_2)^2 + (B_{HS}{}^{e}{}_2 \cos I_2 + (B_{z2} -$$

$C_z) \sin I_2))^2 = 0$ (17)

Eq. (17) is a quadratic expression in C_z with generally two solutions for C_z. The solution which gives a horizontal magnetic field component closest to the expected horizontal magnetic field component is to be selected from the two. The local magnetic field at each point can then be corrected for axial drill string magnetisation.

If different BHA's are used during the measurements at the different survey points C_{z1} is generally not equal to C_{z2}. Therefore it is preferred that for the low inclination mode, i.e. when using eq. (10), at least one survey point is at a borehole inclination between 80°-100°, preferably about 90°, because then one of the components $C_{z1} \cos I_1$ or $C_{z2} \cos I_2$ in eqs. (7), (8) substantially vanishes.

Similarly, it is preferred that for the high inclination mode, i.e. when using eq. (17), at least one survey point is at a borehole inclination between 0° and +10°, preferably about 0°, because then either $C_{z1} \sin I_1$ or $C_{z2} \sin I_2$ in eq. (17) substantially vanishes.

Instead of using two survey points as described above, more than two survey points can be used to correct for axial drill string magnetisation.

CLAIMS:

1. A method of determining an azimuth angle of a borehole formed in an earth formation using a magnetometer tool arranged in a drill string extending in the borehole, the magnetometer tool having a selected orientation relative to the drill string, the method comprising:

a) selecting at least two locations along the borehole at which the borehole has selected different borehole inclinations;

b) for each selected location, arranging the drill string in the borehole such that the magnetometer tool is positioned at the selected location and operating the magnetometer tool so as to measure a component of a local magnetic field along an axis having a selected orientation relative to the magnetometer tool, the local magnetic field including the earth magnetic field and a drill string magnetisation field;

c) determining from the measurements and from the selected borehole inclinations, a contribution from the drill string magnetisation field to the measured components;

d) correcting the measurements for said contribution from the drill string magnetisation field; and

e) determining from the corrected measurements, the borehole azimuth, wherein said component of the local magnetic field is the axial component of the local magnetic field, wherein for a borehole inclination at a first one of said locations being less than 45°, step c) comprises determining the contribution from axial component of the drill string magnetisation from the relationship:

$C_z (\cos I_2 - \cos I_1) = B_{HS}{}^e{}_1 \sin I_1 - B_{z1} \cos I_1 - B_{HS}{}^e{}_2 \sin I_2 + B_{z2} \cos I_2$

as defined hereinbefore.

2. The method of claim 1, wherein the longitudinal axis of the borehole at the selected locations is substantially located in a vertical plane.

3. The method of claim 1 or 2, wherein the borehole inclinations at at least two of said locations differ from each other by an angle of at least 40°.

4. The method of claim 1, wherein the drill string magnetisation for the magnetometer tool at the first location is different than for the magnetometer tool at the second location, and wherein the borehole inclination angle at the second location is between 80°-100°.

5. The method of claim 1, wherein, for a borehole inclination angle at the first one of said locations exceeding 45°, step c) comprises determining the axial component of the drill string magnetisation from the relationship:

$(B_{HSR}{}^e{}_1)^2 + (B_{HS}{}^e{}_1 \cos I_1 + (B_{z1} - C_{z1}) \sin I_1))^2 - (B_{HSR}{}^e{}_2)^2 + (B_{HS}{}^e{}_2 \cos I_2 + (B_{z2} - C_{z2}) \sin I_2))^2 = 0$

as defined hereinbefore.

6. The method of claim 5, wherein the drill string magnetisation for the magnetometer tool at the first location is different than for the magnetometer tool at the second location, and wherein the borehole inclination angle at the second location is between 0° and +10°.

7. The method of any one of claims 1-6, wherein the magnetometer tool determines the components of the local

magnetic field in a co-ordinate-system having a primary axis substantially in axial direction of the borehole, a secondary axis substantially in high-side direction of the borehole, and a tertiary axis substantially in high-side right direction of the borehole.

8. The method of any one of claims 1-7, wherein two said locations are selected along the borehole.

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PATENT AGENTS

Fig.1.

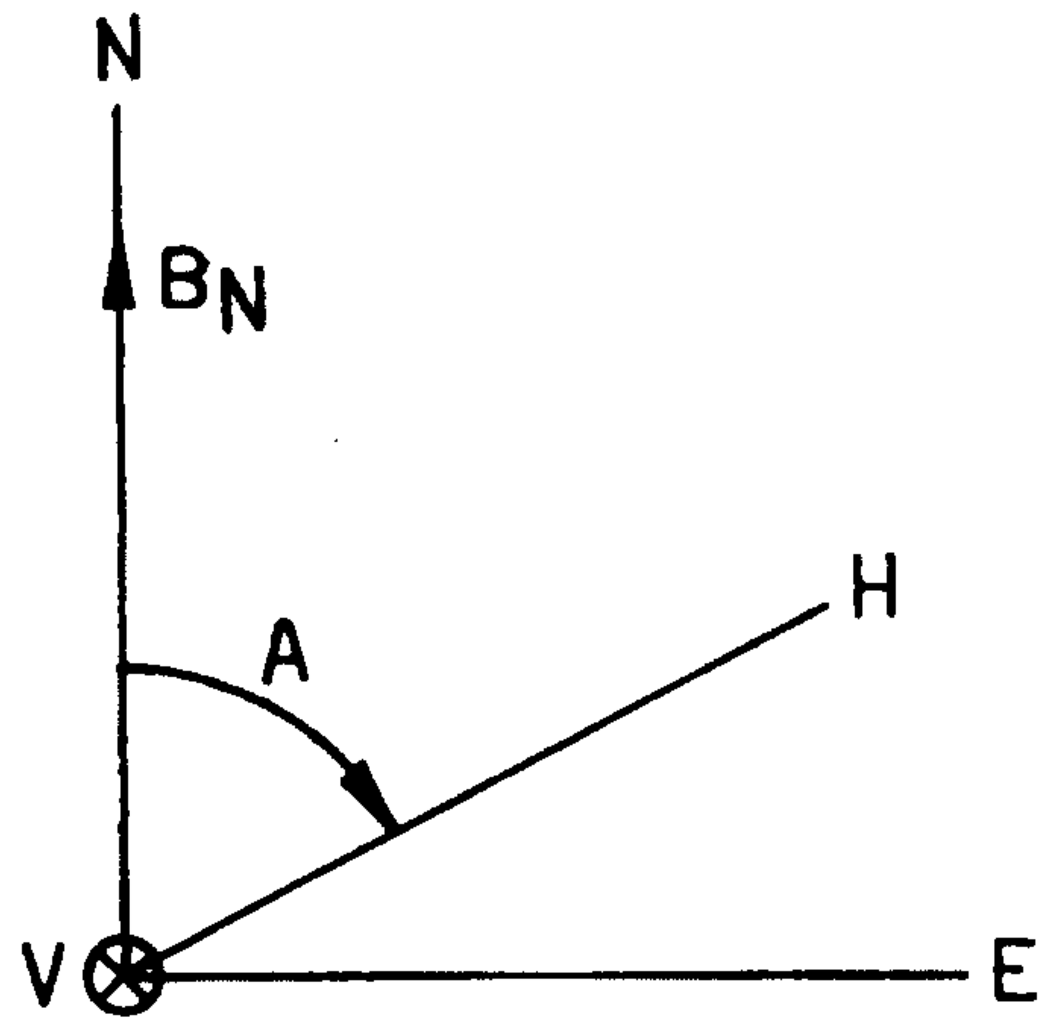


Fig.2.

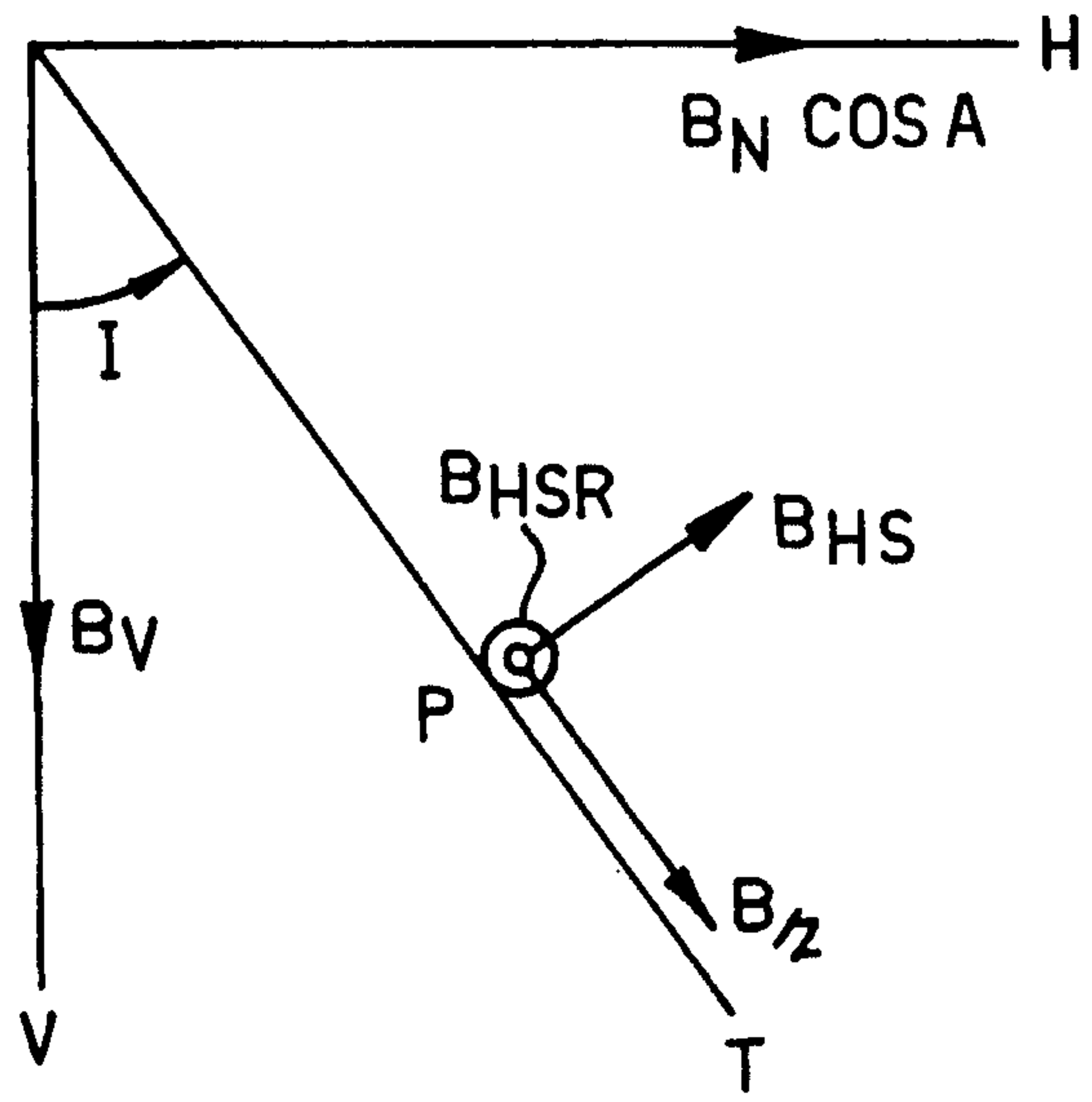
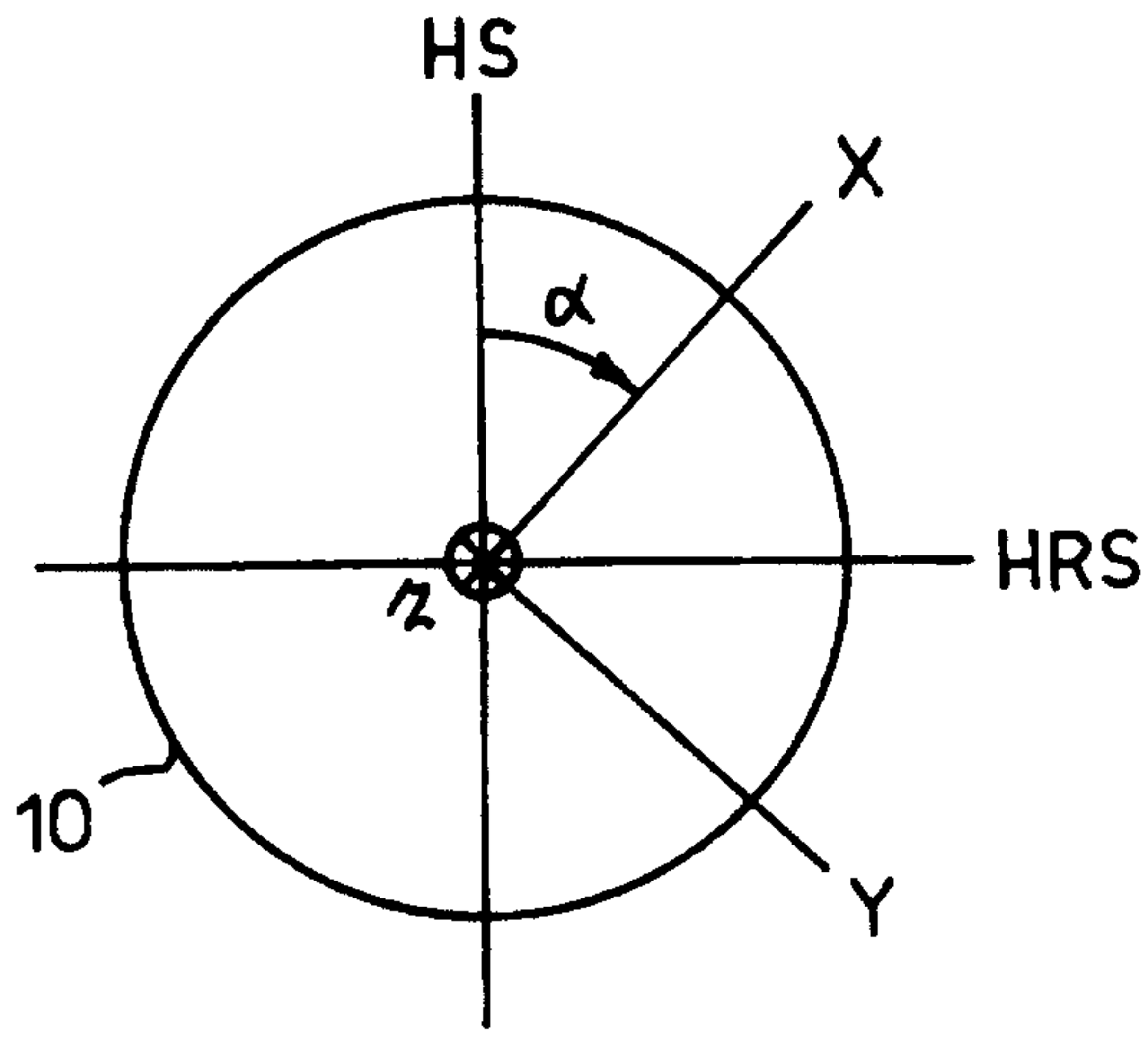
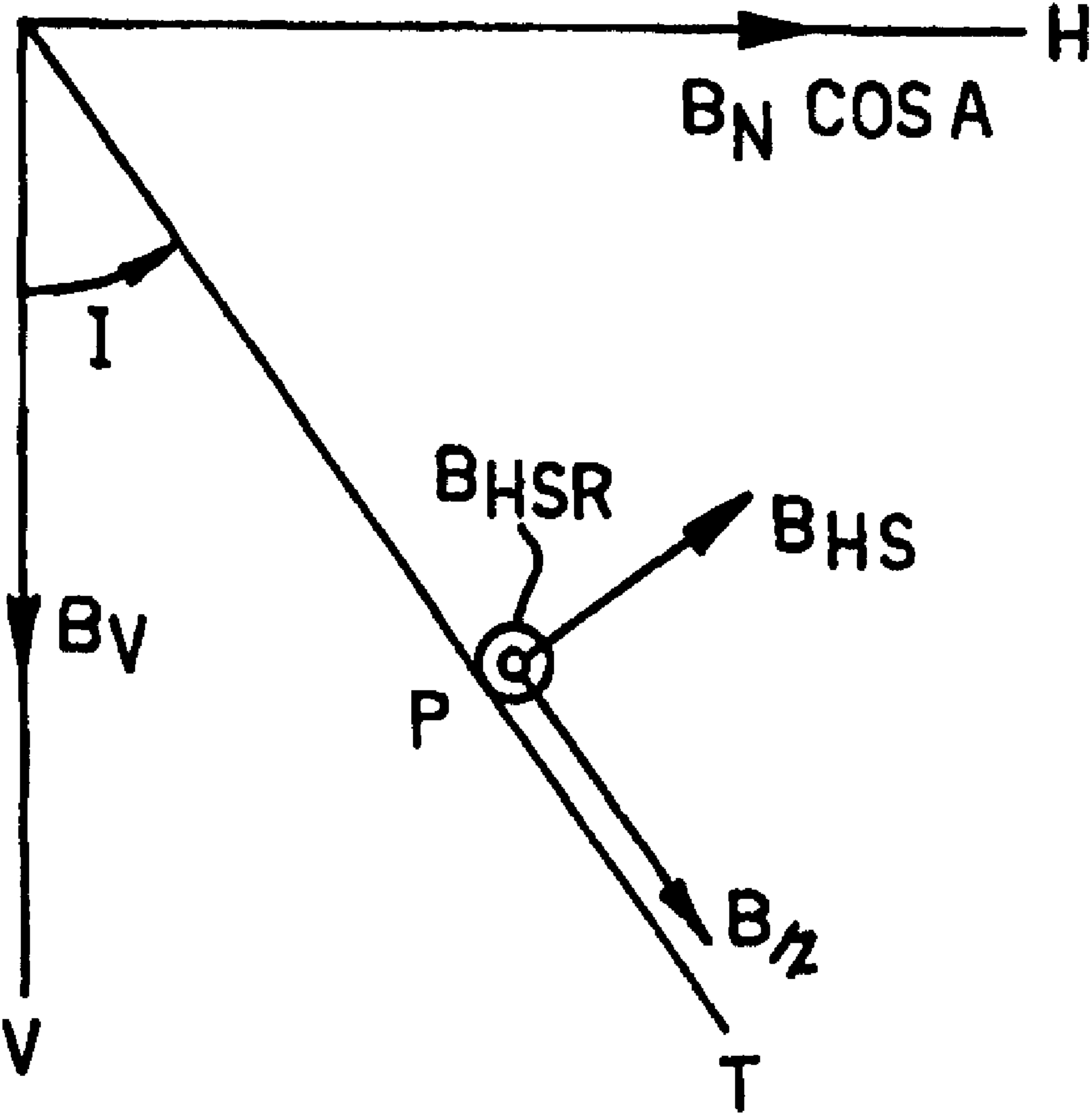


Fig.3.

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B_N COS A
I
B_{HSR}
B_{HS}
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P
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