Similarities between magnetic and north-finding survey tools

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Borehole surveying is a fundamental part of drilling operations to establish where a hole has actually been drilled. To accomplish this a variety of systems have been developed over more than a century to perform borehole surveys, based on a wide range of physical measurement principles. The key question that is addressed by such tools is how to measure the direction or azimuth of the borehole. In addition to obtaining a survey data set, it is of equal importance to understand with what accuracy a given survey technology has produced the data.

One such class of tools is the well-known magnetic multishot survey system. Tools of this kind are usually cheaper, rugged, and simple to use where natural magnetism of the ground or nearby equipment is low enough to not affect a survey. At the other end of the scale is a range of gyroscopic north-finding tools that have been around in the oil and gas industry for a long time but have gradually made more of an appearance in mining. These tools are among the most expensive; usually they are not magnetically sensitive (apart from those based on fiber-optic gyros).

Given that these two tool types determine the azimuth using different physical measurements, the Earth magnetic field versus the Earth rotation rate, how could there be any interesting similarity between them? It turns out that the physical principle behind the two tool types is actually mathematically identical, and in this article, we will show how the equations for the azimuth in both types of systems are fundamentally the same. From this it follows that some of the basic limitations of magnetic survey tools are also found in gyroscopic north-finding tools.

Introduction

Calculating the borehole path co-ordinates requires three fundamental measurements at a series of points along the borehole. These points are typically called 'stations' and the required data at each station is:

1. **The measured depth along the borehole to the station.** This is usually provided by a counter on the wireline, an optical encoder on the winch for continuous depth read-out, or simply a tally of the number of pipes tripped into or out of the hole.
2. **The inclination or dip angle of the borehole at the station.** This is the angle from vertical that the hole is pointing. This is usually measured using inclinometers that directly measure the direction of Earth gravity with respect to the survey tool.
3. **The azimuth of the borehole at the station.** This is the angle from north that the hole is pointing. The measurement is typically done using various methods including magnetometers, north-finding gyroscopes and inertial measurement gyroscopes, among others.

With these three quantities measured, at a dense-enough series of stations along the borehole, it is possible to use algorithms, such as radius of curvature or minimum curvature (see Long & Mitchell, 1992 and Sawaryn & Thorogood, 2005, given in the References at the end), to calculate the north, east and elevation co-ordinates of the borehole stations. Minimum curvature is today considered to be the industry standard but more advanced methods are known.

It is the measurement of the azimuth that is usually the most challenging information to calculate in any borehole measurement system. Each type of system has its own unique benefits and drawbacks, where measuring azimuth is concerned.

This article is concerned with outlining the parallels in azimuth measurement between magnetic and gyroscopic north-finding tools. Although it might seem that these systems are wildly different in their make-up and performance, they are in fact very similar in their basic measurement principle and limitations due to location and borehole direction.

Magnetic and true-north azimuth equations

Broadly speaking there are two types of each system, depending on the number of sensor axes used. The more general type has three sensor axes, either magnetic or gyroscopic. These are typically mounted in the tool so that one sensor measures on the long axis of the tool, the Z axis, while the other two are perpendicular to the Z axis and each other, creating the X and Y axes. Such a sensor arrangement measures the full three-dimensional Earth magnetic field or Earth rotation rate vector. The second and simpler type uses only the X and Y axis sensors and assumes that the Z axis Earth magnetic field or Earth rotation rate is such that it completes what should be the total value at the survey location.

The second, simpler type originated in earlier days of surveying when sensors had higher power consumption, were larger in size and considerably more expensive and there was therefore an interest in limiting the number of sensors in an instrument. So-called XY-axis tools work best within a limited angle from vertical, but historically this has been an acceptable trade off, since many of these survey technologies originate from oil- and gas-type applications.

The following equations are the most general way of calculating the azimuth for magnetic, AMag, and gyroscopic north-finding tools, ANF, with either XYZ or just XY sensor arrangements (see Williamson 1999 and Torkildsen et al., 2004):

In simpler terms, the gyroscopic north-finding azimuth equations are the same as the magnetic EMS equations if we simply replace the Earth total magnetic field with the Earth's rotation rate and replace the magnetic dip angle with the (negative) latitude of the measurement location.

	$\mathrm{Tan}[A_{Mag}]$		$\mathrm{Tan}[A_{NF}]$
XYZ:	$\dfrac{B_x\cos[H]-B_y\sin[H]}{\cos[I](B_x\sin[H]+B_y\cos[H])+B_z\sin[I]}$	$\leftrightarrow$	$\dfrac{\Omega_x\cos[H]-\Omega_y\sin[H]}{\cos[I](\Omega_x\sin[H]+\Omega_y\cos[H])+\Omega_z\sin[I]}$
XY:	$\dfrac{B_x\cos[H]-B_y\sin[H]}{\frac{1}{\cos[I]}(B_x\sin[H]+B_y\cos[H]+B\sin[D_m]\sin[I])}$	$\leftrightarrow$	$\dfrac{\Omega_x\cos[H]-\Omega_y\sin[H]}{\frac{1}{\cos[I]}(\Omega_x\sin[H]+\Omega_y\cos[H]+\Omega\sin[-\varphi]\sin[I])}$

Equations for survey station azimuth for the different types and configurations of magnetic multishot (AMag) and gyroscopic north-finding (ANF) survey tools.

Magnetic EMS			North-finding gyroscope	
Magnetic field X	B_x	$\leftrightarrow$	Earth rate X	Ω_x
Magnetic field Y	B_y	$\leftrightarrow$	Earth rate Y	Ω_y
Magnetic field Z	B_z	$\leftrightarrow$	Earth rate Z	Ω_z
Magnetic field total	B	$\leftrightarrow$	Earth rate total	Ω
Magnetic dip	D_m	$\leftrightarrow$	Latitude	$-\varphi$
Inclination from vertical	I	$\leftrightarrow$	Inclination from vertical	I
Highside	H	$\leftrightarrow$	Highside	H

Table 1 – Correspondences between magnetic and gyroscopic north-finding parameters

The highside and inclination angles are obtained using inclinometers while the components of Earth magnetic field and Earth rotation rate axis are measured using magnetometers and gyros. There are variations of the formulas stated above, for instance in the case of near vertical boreholes where highside and azimuth are not well defined, one would instead look at the toolface angle. In addition, different manufacturers have different practical implementations of the azimuth formulas. However, the equations shown here represent the fundamental information used in calculating the azimuth.

Azimuth accuracy depends on drilling location

The fact that this correspondence exists between two very different tools is not surprising. Both systems work by measuring the inclination and azimuth angles using two reference directions (vectors). For magnetic systems, it is the direction of the Earth's gravity and the Earth's magnetic field. For north-finding systems, it is the directions of the Earth's gravity and the Earth's rotation axis.

The best measurement will always be achieved when the two reference directions are perpendicular, since these are then completely independent and provide maximum information. Conversely, it is impossible to compute the azimuth when the two reference directions are parallel, as these then provide the same reference direction and the calculation becomes meaningless. For cases in-between, where the two reference directions become increasingly parallel, the survey system will lose accuracy accordingly.

A consequence of the fundamental mathematics is that a magnetic survey system will have reduced accuracy for borehole locations with high Earth magnetic dip angle (locations where the Earth's magnetic field is closer to vertical). In the same way a gyroscopic north-finding tool will work best close to the equator but will lose accuracy with increasing latitude until it fails completely at the North or South poles.

Azimuth accuracy depends on borehole direction

One other fact that becomes clear in comparing magnetic tools to gyroscopic north-finders is that the accuracy of the azimuth measurement also depends on the azimuth itself. No matter which type of sensors are being used, the method of using two reference directions to determine the current heading of an instrument is such that the best results are obtained when the instrument is directed close to north or south. When the instrument heading is directed east or west the azimuth calculation is more sensitive to sensor errors. Simply put, both systems work best when measuring a borehole directed along a north or south direction, and the azimuth accuracy gets significantly worse as the borehole turns east or west.

This is in contrast to relative measurement systems, such as inertial gyroscopes or those measuring the bend of the tool as it conforms to the curvature of the borehole. These relative systems have an azimuth accuracy which is entirely independent of the borehole location and direction.

Error modeling

In the oil and gas industry these factors, along with many other survey and instrument error sources, are taken into account using wellbore position error modeling as part of efforts to estimate the accuracy of surveys and to prevent well collisions. Tool manufacturers can create so-called IPM files that describe the performance of their tools and can be loaded into well-planning software. This system for instrument performance models follows a standard maintained by the International Steering Committee on Wellbore Survey Accuracy (www.iscwsa.net), which is a committee affiliated with the Society of Petroleum Engineers. When a borehole is planned or surveyed the results are loaded into the software and, given knowledge of what type of survey tool was used, the accuracy of the wellbore angles and co-ordinates can be estimated within statistical confidence limits (see Jamieson et al., 2012). It is important to underline that the ISCWSA provides a standard and method for error modeling, but it is the responsibility of each survey tool manufacturer to supply and verify performance models for their own instruments.

Examples of the directional effect are shown in Figs. 1, 2 and 3. To create these plots, standard error models for magnetic and gyroscopic instruments were applied to a large series of trajectories corresponding to a straight hole of length 1000 m with constant inclination and constant azimuth and surveyed with 3 m stations. The vertical axis represents a hole drilled toward north, while the horizontal axis is a hole drilled toward east. An increasing radius represents holes increasing from an inclination of 0°

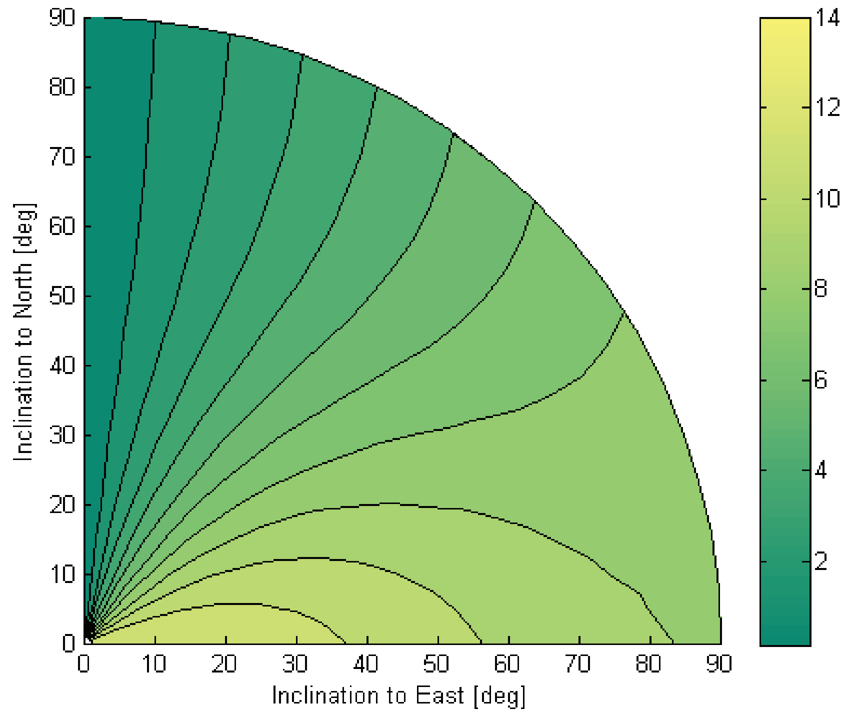

Figure 1 – End-of-hole position error for a typical magnetic multishot survey tool, as meters / 1000 meters. The position error worsens as the borehole heads towards the east or west. The results for inclination towards south and west are the same as for towards north and east.

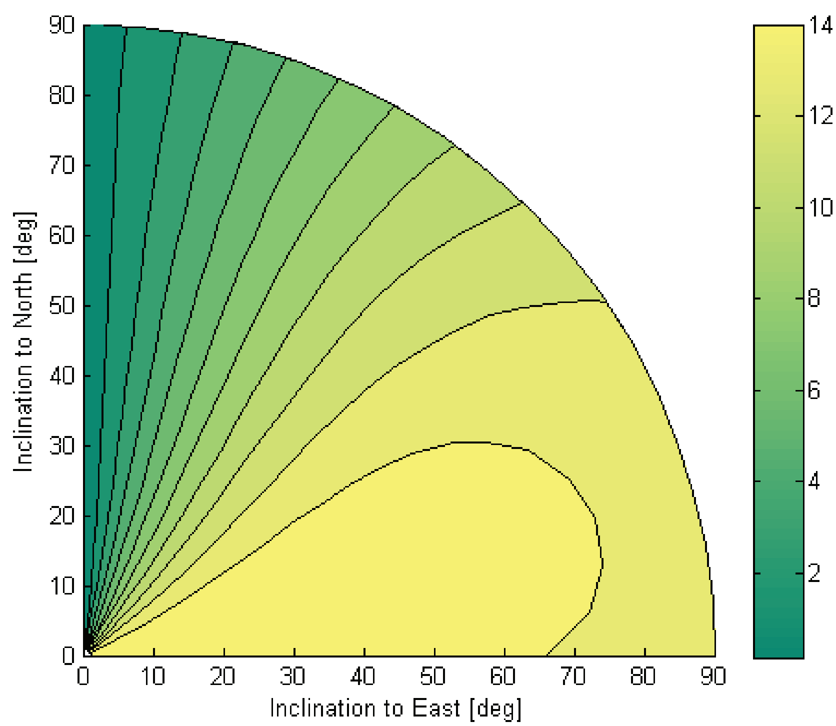

Figure 2 – End-of-hole position error for a typical gyroscopic north-finding survey tool, as meters / 1000 meters. The position error worsens as the borehole heads towards the east or west. The results for inclination towards south and west are the same as for towards north and east.

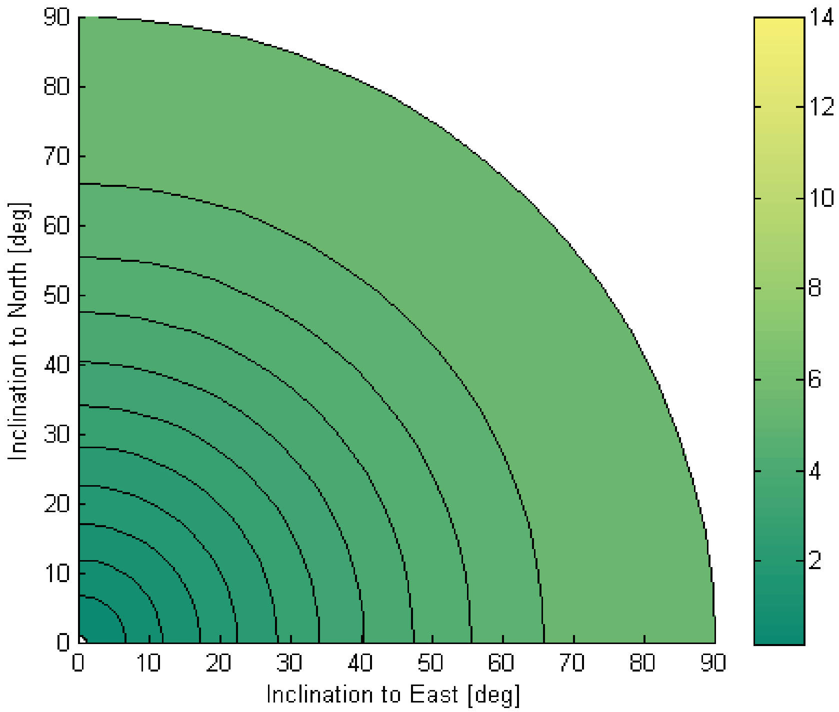

Figure 3 – End-of-hole position error for a typical relative survey tool, as meters / 1000 meters. The position error is independent of borehole direction.
The results for inclination towards south and west are the same as for towards north and east.

(vertical) to 90° (horizontal). Each point in a plot represents the estimated end-of-hole position error in meters / 1000 meters.

The location for these examples has been chosen to correspond to Conroe, Texas, with a latitude of 30.36°. The Earth magnetic total field is 47 236 nT and the magnetic dip angle 59.27°. The figures have been calculated using typical good-performance parameters for each tool type. The results represent a 95 % statistic confidence level in the end-of-hole errors.

As can be seen, the magnetic and gyroscopic north-finding tools perform best in north or south borehole directions, but show noticeably worse accuracy for an east or west borehole direction, where they are out-performed by a standard reference gyroscope.

It should also be pointed out that the model used for the gyro compass errors in Fig. 2 is based on the performance of a three-axis fiber-optic gyro from KVH. The corresponding errors for a common XY-axis gyroscopic north-finding survey tool are highly sensitive to inclination errors, and instruments based on such gyros will not work above an inclination limit.

Conclusion

Magnetic multishot and gyroscopic north-finding survey tools operate on two seemingly different measurement principles, the former measures the Earth's magnetic field while the latter measure the Earth's rotation rate. However, physically and mathematically they are very similar in performance and accuracy when it comes to the effects of latitude or magnetic dip and borehole direction. In contrast, relative survey tools have a constant error behavior regardless of the direction of the borehole or location on Earth. All of these technologies have now existed for many years and have their benefits and drawbacks. In this article we have detailed how tool users should be aware that different technologies have different error behaviors depending on where, and in which direction, a borehole is drilled.

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