3.2.1 Introduction

In the oil industry directional drilling refers to the drilling of wells where, apart from vertical sections, sections with a curved axis can also be found. In general, the latter have a radius with a constant curvature where the inclination with regard to the vertical varies evenly until it reaches angles between 30° and 60°, but also greater angles (even 90°), if necessary; the curved sections are followed by straight sections whose inclination is kept constant. Directional drilling is, therefore, a technique that makes it possible to reach deep mining targets even at a considerable horizontal distance from the location of the surface rig.

There are numerous types of directional wells each having configurations that can be very different and complex (Fig. 1): from the standard slant and S-shaped holes, to slanted holes that are drilled starting from facilities which are also slanted, to the different types of horizontal, single and multiple, wells. Besides the inclination, even the direction in which wells can be drilled may vary; consequently, a directional well can have several shapes. Each of these shapes meets specific operational demands. Moreover, during the drilling process, on the basis of the information as and when it is relayed to the drilling engineer, both the inclination and the direction can still be modified; therefore it is possible, and indeed quite accurate, to

Fig. 1. Main configurations of a directional or horizontal well.
talk about navigational drilling. In other words, with the state-of-the-art technologies available nowadays, the hole may take highly complex, even three-dimensional shapes, and it is possible to ‘navigate’ through the subsurface in the way deemed most appropriate.

Applications of directional drilling

Directional drilling is used in a number of operational situations, the most recurrent of which are listed below.

Multi-well drilling from a single position. This solution is applied both offshore and onshore. In the former case, where it has been systematically used for very many years, the main reason for applying such a solution is the need to minimize a field’s drilling and exploitation costs. This is due to the fact that, from a single platform (Fig. 2 A), it is possible to drill a great number of wells (even more than thirty), whereas, if the vertical well option had been chosen, it would be necessary to drill them one by one with dedicated rigs and then connect each of them to the same production platform.

In the case of onshore wells, besides the need to reduce the drilling and production costs of the field, the main reason for using a single cluster is the need to reduce the environmental impact of the operations, especially when working in areas such as parks, natural reserves and habitats of certain protected animal and plant species. Onshore directional drilling has been adopted more recently than offshore directional drilling. In particular it spread after the introduction of horizontal drilling due to the undeniable advantages that it also brings in terms of increased well productivity.

Inaccessible places. Resorting to the drilling of deviated and horizontal wells is unavoidable when the target is located in mountains regions or below or rivers (Fig. 2 C), or in any circumstance where it is difficult or costly to set up the drilling rig directly over the vertical of the target.

Drilling in salt domes or in particular geological formations. In order to reach a target located below formations difficult to drill (e.g., salt domes, extensive faults), it is sometimes preferable to start drilling the well laterally with respect to the structure and then deviate around the ‘cap’ of the salt dome (Fig. 2 E), or perpendicularly to the fault plane to minimize the natural tendency of the hole to deflect (Fig. 2 B) which could cause great problems in maintaining the inclination and the direction.

Sidetracking. When a section of hole becomes unworkable due to pipe sticking or failure, or when the target is changed once the drilling has already started, a new hole is drilled starting from the maximum depth where the well proves to be free (Fig. 2 D) to later take up drilling again in a direction which is compatible with the newly planned well path.

Relief wells. These directional wells are drilled to intercept a formation from which a well is blowing out with the main purpose to ‘kill’ it (Fig. 3).

Horizontal wells

As mentioned earlier, the drilling of directional wells is a technological option that has been employed for a long time by the oil industry and which makes it
possible to reach all targets. In contrast, horizontal wells have been introduced more recently and have permitted an increase in the productivity of single wells and a decrease, at the same time, in both the operating costs of the development of a particular field and its environmental impact. A horizontal well, in fact, may cost from 20% to 2-3 times as much as a vertical or deviated well but permits a productivity 2 to 10 times greater, and therefore a smaller number of wells is necessary to develop a field, with positive effects both on the global costs and on the environment. This does not mean that a directional well, or even more so a horizontal one, is the best solution in all circumstances (the positive aspects are always to be compared to the disadvantages, especially in terms of wellbore stability, penetration rate, limits of productivity, etc.) but, undoubtedly, the technologies available nowadays tend to impose the choice of directional and horizontal wells over vertical ones as a priority, particularly when drilling development wells in a field. Vertical wells still remain the most common in drilling exploratory wells.

The first efforts at drilling horizontal wells date back to the beginning of the twentieth century. However, it was necessary to wait until the 1980s for the drilling of horizontal wells to spread. After a few isolated attempts carried out in North America and in Europe (the former Soviet Union, France, the North Sea), the drilling of horizontal wells became so common in subsequent years as to be considered a ‘routine’ technology and to be applied whenever the circumstances allow it.

A horizontal well, apart from greater drilling costs, has the following advantages compared to both a vertical and a directional well: a) wells may have problems related to gas coning; or water coning; a long section of horizontal well increases the exposure of the producing zone, thus making it possible to obtain greater productivity and a smaller difference between bottomhole and wellhead pressures during production without a high risk of attracting gas or water back into the well as it can navigate far enough from both the gas cap and the water table; b) fractured reservoirs; there is a greater chance to intersect the fractures from which the well produces; c) reservoirs difficult to access; it is possible to reach reservoirs located in particular areas, such as below inhabited areas, lakes, rivers, on inaccessible land in more severe conditions and at greater distances compared to those that may be resolved by drilling a well which is simply deviated; d) application of enhanced oil recovery techniques; horizontal wells ensure a better injection and effectiveness of oil displacement from the mineralized areas; e) more effective reservoir exploitation; in the case of layers which have already been drained and which had previously gone into production by the use of vertical wells, the drilling of a subsequent horizontal well may make it possible to drain even the remotest areas of the field, which would not otherwise be exploited.

3.2.2 Characteristics, configurations and planning of a directional or horizontal well

Directional drilling and spontaneous deviation

Before describing in full detail the engineering aspects connected to directional and horizontal drilling, it is necessary to consider some of the

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Fig. 3. Drilling of a relief well (right) to ‘kill’ a blowout well visible on the left (courtesy of D. Giacca).
problems which may arise and that must be resolved when making a hole follow a pre-established path, even if such a hole is several thousands of metres long. In fact, it is especially when drilling a directional or horizontal well and when monitoring the inclination and the direction, that it becomes clear how difficult it is, from a practical viewpoint, to constrain the drill bit to go along a path that accurately follows the design trend. This is due to the fact that the drill bit in the well is subject to a number of mechanical interactions with the formations to be drilled. These interactions are difficult to predict and quantify and their main effect is to deflect the hole away from the design path. The above is also true of vertical wells: there exists no such thing as a truly vertical well but, on the contrary, there will always be a deviation from the vertical. Such deviations may be more or less pronounced and have to be kept within pre-established limits in order to reach the target at the planned depth. The design of a well, be it vertical or directional, therefore establishes the ideal trajectory of reference which must be constantly followed by applying all the solutions that modern technology puts at our disposal.

Before relating in detail the characteristics and problems of directional and horizontal drilling, it is necessary to discuss, on the one hand, the causes of the spontaneous deviation of the well and, on the other hand, the effects brought about by the drill string on the hole trajectory as these elements are also very important in planning a directional well.

The conceptual difference between directional drilling and spontaneous deviation is that, in the former case, the deviation is a desired effect and the course of the hole is calculated, whereas, in the latter case, the trajectory the well follows is random and is determined by changing lithological and geostuctural conditions that arise during the drilling phase as well as by the interactions between the drill string and the rock formations. The trajectory that drilling would spontaneously follow thus differs from the one designed. In operating practice, consequently, perfectly vertical or deviated holes are never identical to the programmed ones as the deviation forces in action cannot entirely be compensated for. It is, however, necessary to limit the deviation from the pre-established well path as it can cause some serious operating problems if it becomes excessive. For instance, these problems may consist of a drill pipe failure due to fatigue, formation of ‘keys’ (recesses created in the wall of the hole due to rotation of the drill string), variations in inclination and direction that are too abrupt (dog legs) where the drill string can become stuck, problems in the stability of the rocks that may even result in collapse and, in the most serious cases, in the need for well sidetracking, a difficulty in lowering the casings and the tools into the well to record the electric logs, the failure to reach the target and, in short, a huge waste of economic resources.

It is not possible to control certain factors which determine the spontaneous tendency of the well to deflect. Such factors are, for example, the lithological features of the formations, as well as their pressure gradients, sequence, thickness and density. In contrast, other factors such as the features of the drill string (diameter, number and position of the drill collars and the stabilizers, etc.), the drilling parameters applied (in particular, the weight on the bit), and the annulus between the hole and the string, can be chosen at the design and execution stages of the well.

**Configurations of a directional well**

Directional and horizontal wells are drilled on the basis of a design that follows precise technical criteria in order to obtain a regular and ‘practicable’ hole both at the drilling stage and during all of its subsequent productive life.

Broadly speaking, the drilling of a directional or horizontal well has the following operating stages:

- **Beginning of the drilling.** The first step is the drilling of the vertical section until the point where the deviation begins (the Kick-Off Point, KOP) is reached with a drill string that is normally stabilized (Fig. 4). The vertical section may be more or less long depending on the final depth of the well, the number and location of the mining targets, the configuration – more or less complex – that the well will have to take (wells having a shallow or deep KOP).
In addition, there exist a few particular cases of rigs having a tower whose inclination may vary from the vertical to an angle of 35° (tilted or slant rig). For this reason the hole already appears to be deviated from the very beginning and keeps a constant angle until the target is reached. This solution is applied when the targets to be reached are located at very superficial levels and there is not enough space to put the deviation in place. Sometimes the terminal section of the hole may be horizontal in order to reach superficial targets that are located at a considerable distance away from the drilling rig.

During this first stage, the control of the well course is generally carried out by means of deviation measurements that are not very frequent except in the case of wells starting from the same cluster where, instead, the control of the inclination and of the direction must be as precise and accurate as possible to avoid the risk of ‘collision’ among the various wells. Such an event could have dramatic consequences.

Deviation of the well. After reaching the planned depth where the deviation away from the vertical must begin, the next step is to implement the deviation by directing the well in the planned direction and gradually increasing the angle with the vertical until the angle of maximum inclination is reached (see again Fig. 4). The angular increase by unit of length (Build-Up Rate, BUR) may vary, depending on the circumstances, from 1° to 3°–4° every 30 m and can also be zero along certain sections, thus producing a sequence of curvilinear and straight sections. In general terms, the angles of maximum inclination range between 30° and 60° (values smaller than this cause problems in keeping the inclination, whereas greater values present difficulties which gradually become similar to those typical of horizontal wells), although the angle may be significantly increased, even up to 90°. The slower the BUR, the smoother and more gradual – though longer – the passage from the vertical to the deviated section and the smaller the number of operational problems that will have to be faced. However, the conditions of the well do not always allow this criterion to be applied.

The deviation is achieved by means of the old whipstock technique. The whipstock is a tool having a wedge-like shape that is lowered down a well, for instance above a cement plug, and whose function is to force the bit to drill in a specific direction (see below) either using a jet bit (this is a bit where two of the three nozzles are plugged so that the mud flows at high speed out of the only nozzle that is open and is thus steered in the desired direction) or, more commonly, by a suitably equipped bottomhole motor (turbine or volumetric motor). The section in which the deviation is established is, in general, only a few metres long, but has a variable extension depending on the nature of the subsurface and is lengthened up until a certain inclination angle is reached (usually around 3°–4°). A flexible Bottom Hole Assembly (BHA) is then lowered; this string has one stabilizer only, mounted near the bit to increase the inclination up to the maximum value of the project, which can even be higher than 90°. This situation may arise when, navigating through a thin layer, the well comes dangerously near the water table, which makes it necessary to steer it in an upward direction. During this very delicate stage, the deviation measurements must be very frequent. As long as the deviation angle is low, the hole path is rather unstable because the bit tends to spontaneously deviate, and one is obliged to continuously vary the drilling parameters, the BHA composition or orientation in order to carry out the corrections required by the hole path.

Constant inclination. Once the angle of maximum inclination is reached, the well is drilled by keeping the inclination constant until the target is reached or, in the case of wells where an S-shaped hole is planned, until the depth at which the drop-off section starts (see again Fig. 4). To keep the angle at the prefixed values, a suitably stabilized BHA is used.

The distance between the deviation measurements is generally greater, unless there are some difficulties in keeping the inclination and/or the direction, or unless it is a horizontal well. In the latter case, the measurements can be markedly stepped up and, in some cases, even a continuous and real-time data acquisition system can be installed. Respecting the planned direction and inclination is achieved by varying the drilling parameters or the string composition and, in the case that the hole tends to decidedly deviate and runs the risk of going out of the allowed ‘tolerance cylinder’ (the space within which the well path is considered acceptable), suitable equipment is lowered down the well so that it forces the string to follow a well-defined path.

S-shaped hole. If the design envisages an S-shaped hole to reach the target, or a decrease in the inclination angle to a pre-determined value, at the established depth the inclination of the hole path begins to be decreased by a prefixed gradient (Drop-Off Rate, DOR). An S-shaped hole is usually carried out when several mineralized levels located at different depths are concerned, or when it is necessary to avoid certain formations that may cause drilling problems, when there are unstable or fractured rocks or zones having a low fracture gradient, etc. In this case, a pendulum BHA is used that has a single stabilizer mounted 1 or 2 drill collars above the bit. This permits a decrease – more or less rapid – in the inclination. Otherwise, it is possible to use special equipment that has recently been introduced into standard operating practice, such as the steerable...
Configurations of a horizontal well

There are also several types of horizontal wells that can be drilled: horizontal wells can schematically be subdivided into three main categories according to the angular gradient with which the horizontal section is reached, i.e. long, medium and short-radius wells.

Long-radius wells use standard technology to drill directional wells. The BUR may vary between 3° and 8° every 30 m and requires 2 or 3 sections. In the first section, the angle that is reached measures about 40°-50° and is then kept constant throughout the second section which may even be of considerable length before starting the third section. In the third section, the inclination is further increased up to 90°. At this stage, the horizontal section is accomplished and it can even be very long (over 1,500-2,000 m and up to 6,000-7,000 m). There are several examples of wells which have been drilled horizontally with displacements between 8,000 and 10,000 m, for instance the Wytch Farm M-16Z well in the United Kingdom has a displacement measuring 10,727 metres. Many experts of the field go as far as to claim that, in the years to come, displacements up to about 20 miles, i.e. more than 30 km, will be possible.

In medium-radius wells standard equipment is still being used, although suitably modified to face the problems arising during horizontal drilling. The BUR increases significantly compared to the preceding case (between 8° and 10° every 30 m), although in theory it is possible to have increases measuring about 50° every 30 m. The length of the horizontal section may even measure over 1,000 m and the hole diameters can have the same values as those of conventional wells or long-radius wells.

Finally, the drilling technique of short-radius wells makes it possible to obtain build-up rates ranging between 30° and 60° every m and therefore has the possibility to arrive to the horizontal section in less than 3 m. Lateral holes up to 300 m long are typical of this well configuration, and it is possible to navigate through layers whose thickness measures only a few metres. However, in this case, it is necessary to resort to special equipment which combines the features of rotary drilling with those that have been devised for the specific purpose of drilling short-radius wells. For example, it is possible to use bottomhole motors having short, thin sections that may easily pass through the curved portions of the well or, in building them, it is possible to use materials having a low module of elasticity such as aluminium alloys. Finally, another option is to resort to pipes having knuckle joints. More than one horizontal hole (called a ‘drain’) is very often drilled from the same vertical part of the well so as to involve a greater reservoir surface.

There are several applications of horizontal drilling. They depend on the location of the surface rig with respect to the prefixed targets, the reservoir features, the nature and properties of the formation fluids or, also, on the general development plan for the field. In general terms, long-radius wells are preferable when it is necessary to obtain a long displacement between the surface and the target at the well bottom (extended-reach wells). Medium-radius wells are planned when the depth and thickness of the mineralized layers require an accurate control of the trajectory. Finally, short-radius wells are drilled especially when the plan is to enter formations having a low permeability but which are fractured and, therefore, drilling a long horizontal section is not crucial, or when the space available to establish the deviation and arrive to the horizontal section from the vertical one is extremely reduced.

Multilateral wells are a variation on these configurations and consist of several horizontal wells starting from the same vertical well. The shapes of these wells depend on the particular situation and the results to be achieved (Fig. 5). There are lateral wells which are drilled in the opposite direction one with respect to the other (Fig. 5 A) and which turn out to be particularly suitable to bring deep wells into production. The aim is also to reduce their costs as the information gathered during the lateral drilling of the first well may be used to optimize the drilling of the second well as the formations have the same features. Moreover, it is possible to drill wells going in the same direction but which are located at different depths (Fig. 5 B). Such a solution is preferable when the plan is to bring into production different mineralized levels as it regularly happens, for example, in Canada in developing heavy oil fields. Horizontal wells have also been drilled that are arranged ‘fanwise’ or like a ‘fishbone’ (for example, as in the Orinoco basin in Venezuela) where lateral wells also have, in turn, other lateral wells with a smaller diameter and which are shorter (Fig. 5 C). Multilateral wells can be drilled both at low depth (250 m) and at great depth (>5,000 m) and in fields of all kinds, be they light oil, heavy oil or gas fields. It is possible to have up to 4 horizontal wells starting from the same well with the horizontal section that may measure over 1,300-1,500 m and at a depth ranging between 5,300-5,500 m.

Planning of a directional well: general features

In addition to the data necessary to plan wells of any kind (see Chapter 3.6), the data needed beforehand to
plan a directional or horizontal well are: a) the geographic coordinates of well on the surface; b) the number of targets, their respective depths and geographic coordinates of the well bottom; c) the lithology, the physico-mechanical and geometric features (thicknesses, slope and direction of the layers) of the formations to be drilled through; d) the general data, concerning deviations, obtained from correlated wells (directional and non-directional) which may have previously been drilled in the area in question.

The sequence of steps to follow to plan a directional well is summarized as follows. First of all, it is necessary to establish the location of the drilling site fixing its geographic coordinates as precisely as possible. It is then necessary to determine the target area with a well-defined margin. The following step involves the determination of the well trajectory in the horizontal plane by calculating the deviation between the starting and the final coordinates, the choice of the well configuration (it is necessary to decide whether the well will have to have a slant hole or a S-shaped hole or whether it will be preferable to drill a horizontal well with long, medium or short-radius with one or more lateral branches), the definition of the deviation’s geometric parameters (angle of maximum inclination, depth of the KOP, BUR, direction and length of the horizontal section, etc.). The trajectory of the vertical section is then established. The final step consists of choosing the casing depths of the various columns depending on the anticipated pressure gradients, the formations to drill through, the configuration taken by the well and the choice of the drilling fluids that are most suitable to face the expected problems.

The main aspects of this operating stage are briefly described in the following section.

**Location of the drilling rig.** The choice of the best location for the drilling rig must be made taking into consideration the position of the targets and the state of the layers. When more than one directional well is to be drilled starting from a single location, the drilling rig must be located so as to minimize the horizontal displacement to the targets. A platform or a cluster must be located at the barycentric position with respect to the targets of the single wells.

A further criterion is to choose the rig location so as to take advantage of the natural tendency of the formations to be drilled through in order to favour the deviation. In some cases, a well that deviates naturally may turn out, in fact, to be easier to drill as it may be easier to keep the hole inside the cylinder of prefixed tolerance, provided the formations are known and it is possible to anticipate a preferential direction of deviation.

Once the surface rig position has been established, it is necessary to exactly determine its geographic coordinates.

**Limits of the target area and definition of the radius of tolerance.** The target may be defined as the area that must be reached by the hole at a certain pre-established depth. The horizontal extension of the target may be imposed by the structure’s dimensions, the distance between the wells, the limits of the concession, etc.

During the planning stage one builds a cylinder with generatrices that are parallel to the theoretical axis of the well and with a radius equal to the so-called radius of tolerance. The real trajectory of the
well must be kept within this radius of tolerance until the target is reached. Thus, the target area turns out to be bounded by a circle whose radius is equal to the radius of tolerance. It is important for the target area to be as wide as possible given that a small area causes an increase in the rig-time as the deviation measurements must be carried out more frequently and because of the corrections to be made while drilling the well. In general, the radius of tolerance is given values ranging between 30 and 50 m but, sometimes, this value may be extremely reduced, in particular when thin layers are being navigated and it is imperative to keep away both from the top and the bed of the layer. In addition, in some cases, because of particular geological structures, the target area takes an elliptic shape, therefore the radius of tolerance has different values in directions which are mutually perpendicular. During the drilling stage, if the hole tends to come out of the cylinder of tolerance, the trajectory is suitably corrected by varying the drilling parameters and by acting on the BHA composition.

In areas where directional wells have already been drilled and, thus, the effects of the formations are known, the limit represented by the radius of tolerance may be interpreted in a more flexible way. For example, if in these areas it is observed that the hole trajectory comes out of the cylinder of tolerance in a section still far from the objective, instead of drastically correcting the well path, a gradual re-entry is preferred. On the contrary, if the area is unknown, such an operation is not acceptable as the behaviour of the formations when the drilling is carried out will be unpredictable. On the other hand, close to the target, respect for the radius of tolerance is binding under all circumstances as there may be a risk of missing the target.

A number of innovative technologies have been devised permitting the automatic and continuous correction of the deviation without having to interrupt drilling. A number of systems have, in fact, been developed which make it possible to modify the orientation and inclination of the string in real and continuous time by processing suitable signals transmitted from the surface to the bottom of the well. These techniques, requiring greater economic investments, must be chosen for each single case according to the prefixed targets.

Particular care and frequent controls are required when planning and drilling the initial and most superficial section of a directional well; this is especially true when several wells have to be drilled starting from the same cluster. In this case, the distance between the wellheads at the surface is extremely short; in fact, it goes from about 5 m for onshore wells – where the space is slightly bigger – to about 3 m for those offshore. Consequently, there is a high risk of collision among wells, with consequences that are easy to imagine.

**Determination of the horizontal and vertical projections and choice of the well configuration**

In order to determine the horizontal and vertical projections of a directional or horizontal well, it is necessary to know the position of the surface rig where the well will start from and the planned position of the target, or targets. These positions are usually expressed as geographic coordinates, i.e. in terms of latitude and longitude, as well as their planned vertical depths.

The horizontal projection (frontal view) is defined by two parameters, i.e. the direction and the horizontal deviation of the well bottom with respect to the starting point, which is represented by the centre of the *slot*. The latter is a tube, already embedded into the ground, starting from which that given well will be drilled. These two dimensions can be represented in different ways, among which the most common are:

- **Grid coordinates.** Starting from the latitude and longitude values of the starting and arrival points of the well, the angular differences between latitudes and longitudes are calculated. These differences are later turned into metric lengths by means of suitable equations or charts. On the basis of such a method, taking the surface location as the origin of a system of Cartesian axes oriented towards the East and the North, the derived pair of metric coordinates \(N_T\) and \(E_T\) identifies the position of the horizontal projection of the arrival point compared to the starting point.

- **Field coordinates.** The field coordinates, those most commonly used, express the position of the arrival point compared to the origin by means of the distance \(r\) of this point from the origin, and the angle \(\beta\) formed by the segment joining the origin and the arrival point to the North-South axis. This angle is calculated by knowing the metric coordinates, \(E_T\) and \(N_T\), determined in the preceding point.

- **Polar coordinates.** The polar coordinates of the target \(P\), called the pole, with respect to the origin \(O\), are the polar radius \(r\), which is equal to that expressed by the coordinates above, and the azimuth \(\nu\) which is the difference between 360° and the angle \(\beta\), as determined in the preceding point.

Once the horizontal projection has been identified, the next step is the *vertical projection*. In order to define it, various designs are generally formulated, all of which, at least theoretically, can reach the target, and each will be characterized by different combinations of values concerning the length of the
Calculating the angle of maximum inclination is done analytically by means of dedicated software and applying one of the various approaches available. If the value taken for the KOP and the angle of maximum inclination, which is calculated starting from the established angular gradients, are deemed acceptable and in accordance with the good engineering practice, the next step is to precisely define all the necessary parameters to describe the hole trajectory. If, for whatever reason, the values of the inclination angle and of the KOP were considered unacceptable or at least difficult to achieve, the calculation can be repeated according to different combinations of parameters until the most practicable solution is found. Such a solution may involve a directional hole, whether it be an S-shaped or slant hole, superficial or deep, or a single or multiple horizontal well.

At the end of this process, in which the experience of the design engineer plays a crucial role, the horizontal and vertical projections are put at the disposal of the drilling engineer. These projections indicate the ‘ideal’ trajectory that the well will have to take and the geometric parameters that will have to be applied throughout the various stages of the well drilling, whether it be directional or horizontal. A three-dimensional representation of the well trajectory is very useful when several wells are to be drilled starting from the same cluster and is fundamental especially in the high section of the wells when the distances between one well and the other come down to a few metres and the risks of collision are high. The ‘theoretical’ well trajectory will then be compared to the real one, which is derived from the interpretation of the deviation measurements. The latter introduce further approximations that have to be taken into due account by means of the construction ellipse of uncertainty (Fig. 6).

**The casing design**

In most cases, the casing depths of the columns in directional wells are determined by the same criteria used for vertical wells, i.e. the trend assumed by the pressure gradients, the presence of fractured or unstable formations, the location of mineralized levels and the expected drilling problems. However, when
choosing the casing depths, especially in the case of deep deviated and horizontal setting wells, it is particularly important to evaluate the risks of the string becoming stuck. This may take place either by means of jamming (the string may be pushed inside the keys mentioned above with the risk that the string, getting stuck, may no longer be pulled out to the surface) or by sticking (the string in directional wells tends to lean on the lower part of the hole and, if the formations are very permeable and the mud is unsuitable, the string may ‘stick’ to the hole wall with no possibility of being recovered). If these risks are high, it is good practice to cover the build-up and drop-off curves with a column as quickly as possible.

In the case of wells drilled from a single cluster, the superficial columns are generally run in hole, not only apart from each other in the horizontal plane, but also at slightly staggered depths. The aims of this measure are twofold: firstly, to reduce the interferences that the steel of the casings may cause on the correct survey of the deviation parameters; and secondly, to minimize the collision risks among the various wells.

**The choice of the mud**

The choice of the mud for a directional well must take into account a few main necessities, in particular the need to minimize the risk of sticking of the string. To this end it is necessary, on the one hand, to keep the weight of the mud as low as possible, while remaining compatible with the pressures at play and, on the other hand, to adequately formulate the composition. The use of specific additives and the optimization of the rheological and the chemical and physical characteristics of the mud, in addition, allow the minimization of the friction between the hole and the drill string (in this case by the addition of lubricants) and of the risk of pressure differentials caused by filtration processes due to the creation of a thin, elastic and impermeable ‘mud cake’ (the mud cake is the layer formed by the deposition of solid particles in the mud onto the walls of the well during the filtration process) which prevents pushing of the pipes against, and thus their ‘sticking’ to, the walls of the hole. Both problems can be markedly reduced by using inverted oil-emulsion or oil-based mud. In this case, it is advisable to consider whether it is convenient, economically speaking, to use mud that is so expensive and to take into account the environmental problems that the these types of mud can pose depending on the ecological features of the area taken into consideration.

**3.2.3 Methods for assessing and surveying the deviation**

**Establishing the deviation**

There are several systems to establish and carry out the deviation and some of them have been highly improved in recent times, particularly since the carrying out of extended-reach horizontal wells or those having a particular shape have become more common. In fact, the drilling industry has gone from using the whipstock and jetting to the systematic use of bottomhole motors, steerable systems and the geosteering.

*Establishing the deviation by means of the whipstock.* The most commonly used tool to put a deviation in place was, for many decades, the whipstock (Fig. 7). Basically, this is a tool having a wedge-like shape about 6 metres long which has, on top, a collar inside which a drill bit is inserted. This drill bit has a smaller diameter than that of the hole in which the deviation will be carried out, for example a 6" bit will be used in a 8 e 1/2" hole. Above the drill bit, a stabilizer and then a pipe are screwed. At first, the drill bit-string system is joined to the whipstock by means of a shearable pin to permit its descent into the hole. Once the system has arrived to the bottom of the well, i.e. the depth where the deviation is to begin, the
tool is oriented in the direction where the well will have to proceed. Once the correct direction of the whipstock face has been established, the whipstock is inserted into the ground by means of a suitable weight, which also causes the stop pin to be sheared. In this way, the drill pipes are free to rotate while the whipstock stays still at the bottom.

Due to the rotation given to the string, the drill bit slides along the wedge going in the planned direction and producing a hole that has a smaller diameter than the original diameter of the well. After drilling in this way a hole about 3-4 m long, the drill pipes-stabilizer-whipstock-drill bit system is taken back to the surface and an hole expander is lowered down the well, which brings the hole diameter back to its planned size.

Originally, the orientation of the whipstock to the North was done through a telescope: on the surface, the tool face was oriented towards a fixed point of reference, and markers were placed on each pipe, in the course of its running in hole, and thus, by sighting through the telescope the prefixed point of reference, the orientation of the whipstock face could be followed. Once the string had reached the bottom, it was rotated until the tool face was oriented in the desired direction and only at this stage was the tool forced to penetrate the soil. This method, which is rather complicated and approximate, has later been surpassed by introducing into the drilling string above the whipstock a short piece of slightly bent equipment, and for this reason called a bent sub, having a guide set in a sleeve that can rotate and thus be fixed in the desired direction and whose position with respect to the North is known, just as the position of the whipstock face must be known with respect to the guide. When the string has reached the bottom of the well, a tool, for example a single shot, is lowered inside the pipes in order to observe the inclination and direction of the hole. This tool has a small shoe guide that will insert itself into a suitable slot present inside the bent sub. The development of the picture of the compass of the single shot will highlight the point of reference of the guide with respect to the North and, thus, with respect to the position of the whipstock face. At this stage, the string will be rotated by the angle which is necessary to line up the tool face with the planned direction of the well. This orientation system of the string is used for wells that are not particularly difficult to drill or when their cost is to be minimized.

Establishing the deviation by means of jetting. The orientation method by means of jetting (Fig. 8) was widely used up until about the end of the 1980s, when it

![Fig. 8](image_url)
was substituted by new technologies. However, it is still used in wells that are not particularly difficult because, like the preceding method, it allows an appreciable reduction of the costs. Jetting is based on the excavating action on the soil by a jet of mud at high pressure issuing from the nozzles of the drill bit and is suitable especially for shallow, very soft and easily erodible soil. The drilling string used for this purpose usually has a conventional drill bit where two of the nozzles are blind and the mud flows out through a third one having a large diameter (0.75°). Over the bit there are a near bit stabilizer, the bent sub, two non-magnetic collars (called Monel rods), a stabilizer and, finally, the succession of drill collars and normal pipes. On the surface, before the string is lowered into the well, the guide of the sleeve which has been inserted into the bent sub is aligned with the large diameter nozzle and, then, once the system has arrived to the bottom, its orientation is observed by means of a single shot as in the case where the whipstock is used. The string is then rotated by the angle necessary to position the open nozzle of the drill bit in the direction planned. With the string in motion, the available weight is unloaded onto the drill bit so as to have the near bit stabilizer work as a fulcrum, forcing the drill bit to increase the inclination angle. The pumps are set in motion so as to create, at the outlet of the nozzle, a high pressure, high speed jet able to penetrate the rock for a few metres. The build-up curve is produced in this way, alternating the action of the jetting with the traditional rotary mode.

Establishing the deviation by means of a turbine. Before the systematic spread of the bottomhole motors of the volumetric type, the turbine was usually employed in putting the deviation in place. At present, this method is used only in particular cases. The bent sub is installed above the turbine; this sub has the function of creating an angle between the axis of the drilling string and the axis of the turbine-drill bit system: subs with angles of 1°, 1.5° and 2° are available. Establishing the deviation is done in a way similar to what has been previously described about jetting. Once the turbine has reached the bottom, the position of the reduction-turbine axis is determined using a single shot, and then, when the system has been oriented in the desired direction keeping the string still, the pumps are set in motion and the drilling begins. When using a turbine, only the final part of the drilling system rotates, not the entire string: the rotating mode drilling is substituted by the sliding mode. The use of turbines requires a good knowledge of the area of work as such areas may induce a strong torsion reaction which, if not duly taken into consideration, may push the well towards a totally different direction with respect to that planned. If the deviation is being put in place by means of a turbine and a system providing the deviation data in real time is not available, the real path of the hole will be known only after drilling a certain number of metres, when the device for surveying the direction is taken back to the surface. Quite often, it is then necessary to put a cement plug in place and re-start the deviation.

A remarkable step forward in drilling directional and horizontal wells came about when systems for surveying the deviation in real time were coupled to the turbine. The first systems envisaged the installation above the turbine and the bent sub of a number of accelerometers and magnetometers, which were placed in a suitable slot near the bent sub and linked to the surface by an electric cable. Thanks to this technique it was possible to control, in real time, the direction in which the well was going and, thus, balance the effects of the turbine. Such a system, however, had the big disadvantage of having to use pipes equipped with an electric cable, which made the
operations rather difficult and expensive. The system was improved when the cable was substituted by a transmission system like the one included in the MWD (Measurement While Drilling) and the LWD (Logging While Drilling) equipment, and which permits the data to be sent to the surface in the form of pressure pulses transmitted by the circulating mud.

Establishing the deviation by means of a downhole motor. Over the last few years, Positive Displacement Motors (PDMs) have been preferred instead of the turbines. They have turned out to be more suitable than turbines for deviation operations, given their lower number of revolutions, the high value of torque and the simplicity of their manufacture, with a considerable reduction in the operating costs and an easier execution of the deviation. The motors used are of the rotating type (see Chapter 3.1).

Steerable systems and geosteering. The last generation of equipment, which goes under the name of steerable systems, is thus made up of a PDM, or of a turbine, on the lower part of which, just above the drill bit, the bent sub is mounted. Above the PDM, either the MWD equipment, which provides in real time the data of interest to the driller (such as inclination, direction, pressure, temperature, real weight on the drill bit, torque stress, etc.) or the LWD equipment is installed. The latter makes it possible to send to the surface, not only the information mentioned above, but also geological data (the gamma ray log, the resistivity, density and sonic logs, etc.). The coupling of sensors providing information on the course of the well trajectory, in real time and in a continuous way, with logs characterizing the formations from a geological viewpoint, goes under the name of geosteering (Fig. 9). This technique makes it possible to navigate, in the true sense of the word, in the subsurface following the most suitable route to reach the prefixed targets.

Thanks to such string configurations, it is possible to establish and carry out all curves with an increasing inclination, to drill sections with a constant inclination and, possibly, to implement an S-shaped curve without ever having to take the drill bit out (as long as it is not necessary to change it because of excessive wear). The drilling is accomplished in a sliding mode and, consequently, while the final part of the string is kept rotating, the part above the PDM is kept still and induced slide along the hole trajectory as the drill bit moves forward, increasing the deviation angle through the bent sub between the PDM and the drill bit. During this phase, every time the operator requires, the MWD or the LWD relays the deviation and geological data to the surface, thus permitting exact knowledge of the deviation parameters of the well and of the formation characteristics; this allows the operator to intervene in due time to make the corrections deemed most appropriate. Once the desired inclination angle has been reached, the drilling is carried on by rotating the drilling string. If, during this phase, in which the well inclination is kept constant, the need arises to make corrections because the hole is going in another direction or is changing its inclination, the string rotation is interrupted, the PDM is re-oriented and the drilling is done with the string motionless until the programmed inclination and the direction values are re-established. A return to vertical, if necessary, will be carried out by means of the technique described above. This technology is also widely used in drilling horizontal wells thanks to the great flexibility of navigation that the steerable systems permit, particularly when thin layers are drilled and when it is imperative to keep away from both the gas cap and the water table.

Other systems. Last generation systems are even more sophisticated as the bent sub may be substituted by more complex equipment from a construction point of view, but much more efficient in controlling the inclination and direction of the well. For example, one uses stabilizers whose blades can be adjusted, making them protrude more or less from their slots, by means of commands sent from the surface. In this way, the blades exert the necessary force against the formation to steer the drill bit in the desired direction and thus allow its trajectory to be changed at will. These tools make it possible to drill, in rotating mode and by means of a PDM, also very complex wells. Even if significant and frequent changes of the well trajectory turn out to be required, it is not necessary to pull out the string to modify its composition. In addition, the azimuth and the inclination angle can be changed even during the build-up and drop-off stages, with undeniable advantages both technically and economically speaking.

Other even more recent solutions envisage the possibility of drilling in rotating mode, always by means of steering systems, also horizontal sections at higher penetration rates compared to drilling in sliding mode, using bottomhole equipment made up of, for example, a rather long transmission mast mounted right above the drill bit and which can bend due to the action of two counter-rotating mast and in this way, it is possible to steer the drill bit in the desired direction by suitably placing the cams. Through a series of pressure pulses of the mud, it is possible to send commands to the well bottom to modify the position of the cams and, on the surface, signals are received confirming that the new inclination and direction have been established. Such systems can be used also in the cases where it is impossible to use stabilizers with adjustable blades, for instance, in the cases of strongly ‘caved’ holes where the stabilizer blades cannot come into contact with the wellbore walls.
Methods of surveying the inclination and direction of a directional well

Once the deviated or horizontal well is in the drilling phase, it is essential that its inclination and direction be assessed as quickly as possible. This is all the more important the more complex the well configuration, the smaller the radius of tolerance, the harder the formations to drill and the stricter the safety requirements.

There are several types of equipment for surveying deviations. Besides the order in which they were developed, they are different with respect to the precision of their measurements, their difficulty of use, the context in which they are used and, ultimately, their cost. The types of equipment most widely used in the oil industry are: the single shot, the multi shot, accelerometers and magnetometers, gyroscopes.

The single shot. The single shot was the first instrument to be regularly used to observe the inclination and the direction. The most common model (Fig. 10) is made up of a timer, which is set on the surface, by a pendulum that measures the hole inclination, and by a compass giving the direction. A camera takes a picture of the compass-pendulum system at the time set by the operator using the timer. Between the compass and the pendulum there is a glass disc on which several concentric rings are engraved. These rings serve to measure the hole inclination. To avoid interferences with the compass, all of this equipment is placed inside a non-magnetic container, which is made heavier by a bar. The container may be launched or run in hole by means of a cable inside a pipe that is also non-magnetic.

The operations for surveying the deviation parameters are the following: the timer sets the moment the photo will be acquired, taking into account the well depth, its inclination and the mud density and, thus, the speed at which the equipment will move inside the pipes and how long it will take to reach the measurement position at the bottom. The deeper the well, the steeper it is and the higher the mud density, and thus the longer the container will take to reach the measurement location at the bottom. When the equipment seems to have arrived to the destination, the drill string stops, which meanwhile had been kept rotating slightly in order to avoid it becoming stuck. At this point, one waits for the picture to be taken. On the picture there remain the image of the compass needle (from which the well direction is deduced) and the projection of the pendulum shadow, thanks to which the inclination is inferred. Also, the tool face is indicated on the picture, i.e. the position of the system in the well with respect to the North. The container is then taken to the surface either when the drill bit is pulled out of hole, in the case it had been launched, or when it is recovered by means of a fishing tool lowered inside the well with a cable. Once the inclination and direction values have been obtained (as the direction refers to the magnetic North, it has to be corrected by calculating the magnetic declination of the region) if the course followed by the well differs from that planned, all of the elements to intervene in a relatively short time are available.

The multi shot. Another model of the single shot is the multi shot. The latter uses the same equipment as the single shot with the difference that it is equipped with a camera with an 8 mm film that can take a large number of pictures. The camera is switched on by a timer that unrolls the film and also turns on the battery powered lamp to light up the measurement device. The operating sequence, switched on by the timer, schedules a series of images to be taken at the time required to take the device from one depth to the other. In this way, in a single run, it is possible to acquire all of the elements necessary to reconstruct the trajectory, position and deviation of the hole as a function of depth. Such a system of surveying of the inclination and direction is not entirely compatible with putting in place and carrying out a directional well. The multi shot, in fact, can be used either to increase the number of measurements previously carried out using the single shot or, at the
end of a certain drilling phase, even of a vertical well, in order to know more precisely the location of the well bottom for safety reasons.

Inclinometers, accelerometers, magnetometers. A step forward was made with instruments in which the compass is substituted by a group of three magnetometers to measure the direction, and the pendulum by three inclinometers or by three accelerometers to determine the inclination. The three inclinometers are arranged each in an orthogonal position with respect to the other and they are also compensated for the movements of the probe inside the well. They consist of an electrolytic solution which fills half of the space between the two conductors installed at the opposite ends of a disc-like, glass container. If the container is inclined, the electrolytic solution shifts causing a variation in the electric resistance between the two conductors, which is in proportion to the angle of inclination. The accelerometers, which measure the earth’s gravitational field, are also three in number, generally of the piezoelectric type and placed at 90° with respect to each other. The accelerometers, arranged in a container, register the position and the shift of the mass of a pendulum which, because of the inclination, moves as the position taken by the container itself changes. The mass is taken back into its initial position by a servomotor and the energy absorbed to carry out this manoeuvre is proportional to the extent of inclination.

The direction is measured by means of three magnetometers that are arranged in an orthogonal position one with respect to the other and which register the intensity and the direction of the earth’s magnetic field. In order to measure the direction, these instruments, as mentioned above, measure the earth’s magnetic field and, consequently, the declination of the local magnetic field must be taken into consideration. Although magnetometers may be used in most wells, they have some limitations, particularly when it is necessary to make measurements inside the casings, or when there are irregular local magnetic fields. All these remarks have lead to development of non-magnetic type systems for surveying the direction.

Gyroscopes. Gyroscopes belong to the category of non-magnetic surveying systems. Other than ensuring a very high precision, gyroscopes are not sensitive to the effects of the magnetic field on the material of the pipes and casings. They are usually widely used both during the drilling of directional and horizontal wells and the drilling of infilling wells, i.e. those wells that will have to be drilled into a network of pre-existing wells for which the ‘field data’, in particular the deviation data, are absent or partial. In order to better exploit the old fields it is often necessary, in fact, to drill new wells that are, indeed, called infilling wells, which may interfere and collide with pre-existing wells. In this case, monitoring surveys on the old wells are carried out in order to precisely locate them and, thus, decide the trajectories the new wells may follow.

The basic principle of the gyroscope is rather simple. It is made up of a rotor that quickly rotates around a rod – up to 40,000 revs/min. In turn, the rod is mounted onto a frame that is more or less complex, by means of two gimbals, one on the outside and the other on the inside. The rotor can move freely with respect to the frame, thus taking any orientation and has the characteristic of keeping the initial orientation thanks to inertia of its mass and the high angular speed. The main components of a gyroscope (Fig. 11) are, thus, a rotor, a gimbaling system, the outer anchorage of the suspensions (the frame), a system to measure the angular shift between the outer anchorage and the gimbaling system and, finally, a torquemeter to compensate certain kinds of errors and control the precession phenomenon. A factor to take into consideration is the ‘apparent drift’ of the rotor that is induced by terrestrial rotation. This drift varies with the latitude going from about 15°/h at the poles to zero at the equator.

First-generation gyroscopes usually employed a conventional system made up of two gimbals, one on the outside and the other on the inside, with two possibilities of movement from which the well direction was derived. The inclination was, instead, provided by a plumb line placed inside the device.

Fig. 11. Working scheme of a gyroscope to survey inclination and direction in deviated and horizontal wells.
used for the angular measure. A small camera, set by a timer, took pictures of the plumb line placed over the dial used to measure the direction. In order to obtain good results, the instrument had to be arranged following a known direction before lowering it into a well.

**Second-generation gyroscopes** made it possible to read the data directly on the surface by eliminating both the camera and the timer. The probe was powered by a cable and was linked up to a computer located on the surface. The computer would check the performances of the probe by printing the data as they were gathered: accelerometers were used to measure the inclination, whereas the direction was provided by the conventional system, i.e. the gyroscope having two possibilities of movement.

**Third-generation gyroscopes** are more highly performing and sophisticated. In some systems it is not necessary to orient the instrument on the surface before lowering it down the well. Other systems consist of a platform that has four gimbals and that lets the outer case move in every direction without affecting the rotor position. Finally, other systems make it possible to automatically keep that direction and the horizontal position after orientating the axis of the rotor toward the North.

**Optical gyroscopes**, which in practice have no moving parts, are even more recent. So are systems based on sending a light beam from a source located, for example, at the end of a string of pipes towards a target mounted onto their tip. The inflection the string is subject to causes the deflection of the light beam and this is converted into a variation of the inclination and of the direction.

**Data communication.** Gyroscopes and the ensemble of last generation accelerometers-magnetometers are parts of the most advanced systems for controlling well deviation, for example steerable systems. As has already been described, through these systems it is possible to influence the directional characteristics of a well without pulling the drill string out of the hole and thanks to a number of systems communicating data to the surface they also make it possible to know, in real time, the precise trajectory that the hole is following. The data communication systems most widely used nowadays are the MWD and the LWD, which need no cables to link the surface to the well bottom. These instruments create pressure pulses during the mud circulation obtained by the opening and closure of special valves installed inside non-magnetic pipes. Information regarding the status of accelerometers, magnetometers, gyroscopes which measure the inclination, the direction and the tool face, and the data of the equipment that register resistivity, gamma ray, neutron, density, temperature logs and mud pressure, etc, are transmitted to the surface through the mud in the annulus following a binary logic, and are picked up on the surface by a pulse transducer. The latter registers even the smallest variations in pressure determined by the opening or closure of the valves at the bottom. The pressure pulses are then decoded by a computer. Systems that communicate data by means of low frequency electromagnetic waves instead of through mud are also available. These waves propagate through the soil until they reach the surface, where they are picked up and decoded. The advantages of the electromagnetic MDW are the following. It is possible to relay and receive the signals in two ways, from the bottom of the well to the surface and vice versa, even when there is no mud circulating. This is an aspect that can be very important when the drilling is carried out in situations of total loss of circulation. Moreover, the communication speed is very high, consequently it is possible to receive the signals every 2-3 minutes and a few seconds are enough to communicate every parameter and, on the whole, the system is simpler. However, these positive aspects are counterbalanced by the fact that the system is strongly affected by the depth, particularly when the signals must go through very resistive formations, with the risk that the information communicated will not get to its final destination.
3.2.4 Conclusions

On the basis of what has been stated above, it is clear that the drilling of even very complex directional and horizontal wells is nowadays supported by a wide range of technologies, some of which are still being changed and improved. This makes it possible to use these technologies in all situations, however difficult or demanding. In addition, it is evident that drilling, in particular, extended-reach horizontal wells having a displacement measuring several kilometres, has remarkable consequences not only on the production potentials of each well, which can be markedly increased compared to a vertical or conventionally deviated well and, thus, on the development costs of a field, but also from an environmental viewpoint. Some regulations, especially in the USA, require priority to be given to the drilling of directional or horizontal wells in the development of an oilfield, precisely with the aim of reducing environmental impact of the operations (Fig. 12). A smaller number of wells, located even at a great distance from sensitive and protected areas, implies a significant reduction in the infrastructures necessary to develop and keep a field in production, such as drilling sites, service roads, parking areas, and means of transport. All of this implies less pressure on the area with great advantages for the environment.

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