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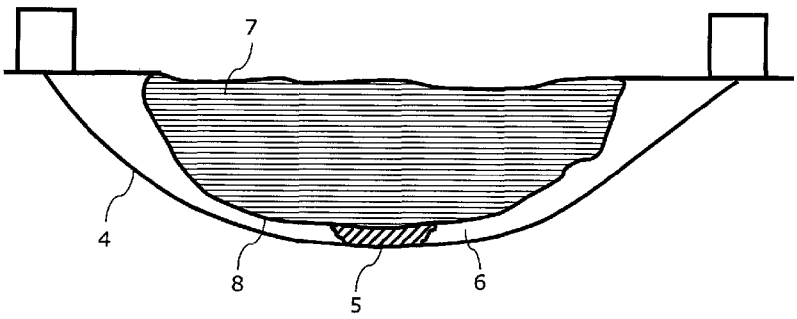


Fig. 1

(57) Abstract: The present invention concerns a method for monitoring the thickness of soil (6) between a soil surface (8) and a device (4) buried in said soil (6), possibly underwater, the device (4) comprising at least one heat source (1), the method comprising steps of (i) measuring at least one temperature using at least one temperature sensing element (3) located in the vicinity of the heat source(s) (1), and (ii) calculating an estimated soil thickness using a pre-determined thermal distribution function (20) which links measured temperatures and soil thickness. The present invention concerns also an instrumented device (4) and a system implementing the method.

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« Method for monitoring soil erosion around buried devices, instrumented device and system implementing the method »

Field of the invention

The invention relates to a method for monitoring the soil erosion or the scouring around buried devices such as cables or pipes.

The invention relates also to an instrumented device and a system implementing the method.

The field of the invention is, but not limited to, the monitoring of underwater pipes or cables.

Background of the invention

Subsea electrical power cables are usually buried in the seabed. Normally, the cable running underwater is covered everywhere by a certain amount of rock and sands used as protection.

The cable may be uncovered by fishing activities (trailing fishing nets may move rocks and erode the seabed), dragging anchors, seabed migration due to see current etc. At some point, the cable may even become exposed to see water.

This phenomenon is known as scouring.

Once exposed, the cable may be moved sideways by ice, anchors, fishing nets, etc. The resulting strain may potentially exceed cable rating, leading to reduced lifetime and/or cable breakage. This is the case for instance in Alaska with combined action of ice and seabed migration.

If erosion goes below the cable bottom surface, the cable may become free hanging between both sides of the eroded area, resulting in additional strain and possibly breakage due to bending.

In addition, exposed cable may locally impact the nearby sea life due to local temperature increase. In Germany for instance, by law, some soil thickness must be guaranteed and the cable is surveyed once a year to check the integrity of the sand layer.

The cable integrity is in the interest of the cable user whilst wild life protection is in the interest of local government. In both cases, the scouring effect must be at least recognized for efficient repair, and possibly monitored so that action can be taken prior to the cable being exposed.

This issue is of course not limited to electrical cable but applies also to subsea pipes or ducts such as pipelines, flow lines, umbilicals, ..., and optical communication cables which are also protected by layers of sand or rock when lying on the seabed.

So, by law or simply to guarantee cables or pipes integrity, scouring must be monitored.

This can be made for instance by direct inspection, or by measuring the remaining thickness of soil above a pipe or a cable using an acoustical method (sonar). However, it is difficult and costly to inspect the whole length of the cable, which can be several kilometers long, with such method.

We know also the paper from Xue-Feng Zhao, Le Li, Qin Ba, Jin-Ping Ou, "Scour monitoring system of subsea pipeline using distributed Brillouin optical sensors based on active thermometry", Optics & Laser Technology, Volume 44, Issue 7, October 2012, Pages 2125-2129, which describes a method to detect free spans of pipelines, or parts of pipelines which are outside the soil, using distributed temperature sensors (DTS).

The system described in this paper comprises a thermal cable running parallel to the pipeline. This thermal cable comprises a heating element which generates heat by Joule losses, and a Distributed Temperature Sensor (DTS) for measuring locally the temperature of the heating element. The DTS is a Brillouin optical sensor which allows measuring the temperature along optical fibers running against the heating element.

The electrical power in the heating element is varied dynamically, causing local temperatures variations which are measured by the DTS. On the basis of a dynamic analysis of the temperature using a transient heat method, the authors are able to localize portions of the thermal cable which are surrounded by water instead of soil.

However, this method does not allow detecting scouring before a portion of the pipeline or the cable is completely out of soil, which is quite late and does not allow for preventive actions to be undertaken.

In addition, the method requires a specific heating element powered with a dynamically varying electrical power. This heating element induces excess power losses, especially for long distance cables or pipelines.

It is an object of the invention to provide a method for the monitoring of soil erosion and scouring around cables or pipes which avoids the drawbacks of the prior art.

It is also an object of the invention to provide such method which allows detecting soil erosion along cables or pipes well before having parts standing in free water.

It is a further object of the invention to provide such method which allows easy integration in cables or pipes, without substantially increasing power consumption.

Summary of the invention

Such objects are accomplished through a method for monitoring the thickness of soil between a soil surface and a device buried in said soil, possibly underwater, the device comprising at least one heat source, the method comprising steps of:

- measuring at least one temperature using at least one temperature sensing element located in the vicinity of the heat source(s), and
- calculating an estimated soil thickness using a pre-determined thermal distribution function which links measured temperatures and soil thickness.

The thermal distribution function may comprise a static or a quasi-static function.

In that case, the thermal distribution function comprises no time-dependant parameters. Of course, the parameters may be slowly varying with time, but each calculation of the thermal distribution function uses steady values or snapshots of these parameters.

The thermal distribution function may take into account at least one of the following elements:

- the relative location of the heat source(s) and the temperature sensing element(s),
- a power dissipation in the heat source(s),
- a temperature at the soil surface,
- a heat transfer model in the soil,
- a heat transfer model in the device.

According to some modes of realization,

- the power dissipation in the heat source(s) may take into account resistive losses due to electrical currents flowing in an electrical conductor in the device;

- the power dissipation in the heat source(s) may take into account temperatures of fluids flowing in the device;

- the temperature at the soil surface may be the temperature of water covering said soil surface, for instance when the device is buried in the seabed or a riverbed.

The method of the invention may further comprise a step of computing the thermal distribution function using at least one of the following method:

- finite elements simulation and modeling,

- experimental measurements.

According to some modes of realization, the method of the invention may further comprise steps of:

- measuring temperatures on several measurement locations along a device of an elongated shape comprising at least one heat source extending along the device, using at least one distributed or quasi-distributed temperature sensing element located in the vicinity of the heat source(s) along the device, and

- calculating an estimated soil thickness on said measurement locations along the device.

According to some modes of realization, the method of the invention may further comprise at least one of the following steps:

- comparing the evolution with time of measured temperatures and/or estimated soil thickness,

- comparing measured temperature and/or estimated soil thickness on different locations along the device.

Such comparisons may be used to improve the accuracy and/or the reliability of the calculations of soil thickness, and/or detect erroneous estimations.

According to another aspect, it is proposed an instrumented device of an elongated shape, able to be buried in soil, possibly underwater, comprising:

- at least one elongated heat source extending along the device, and

- at least one distributed or quasi-distributed temperature sensing element located in the vicinity of the heat source(s) along the device,

said temperature sensing element being arranged and located relative to the heat source(s) so as to be able to provide temperature measurements on several measurement locations along the device which allow calculating an estimated soil thickness between a soil surface and the device on said measurement locations, using a pre-determined thermal distribution function which links measured temperatures and soil thickness.

The temperature sensing element(s) and the heat source(s) may be spaced apart, or separated by some distance, so as to allow an optimization of the thermal distribution function (20).

The instrumented device of the invention may comprise a distributed temperature sensing element with at least one optical fiber extending along the device, so as to allow a determination of the temperature using stimulated Brillouin scattering in said optical fiber(s).

According to some modes of realization, the instrumented device of the invention may comprise a monitoring cable able to be attached to optical cables, electrical cables or pipes buried in soil, possibly underwater, said monitoring cable comprising at least one electrical conductor able to be used as heating element, and at least one distributed or quasi-distributed temperature sensing element.

According to some modes of realization, the instrumented device of the invention may comprise an electrical cable able to be buried in soil, possibly underwater, said electrical cable comprising at least one electrical conductor able to be used as heating element, and at least one distributed or quasi-distributed temperature sensing element attached to said electrical cable.

According to some modes of realization, the instrumented device of the invention may comprise an electrical cable able to be buried in soil, possibly underwater, said electrical cable comprising several electrical conductors able to be used as heating elements, and at least one distributed temperature sensing element included in said electrical cable.

The instrumented device of the invention may comprise a distributed temperature sensing element positioned:

- at the center of the cable between the electrical conductors, or
- outside of the area delimitated by the electrical conductors.

According to some modes of realization, the instrumented device of the invention may comprise a pipe for carrying fluids able to be used as heating

element, and at least one distributed or quasi-distributed temperature sensing element.

According to another aspect, it is proposed a system, comprising:

- an instrumented device of the invention,
- electronic means for obtaining temperature measurements using the distributed or quasi-distributed temperature sensing element(s), and
- calculation means for implementing the method of the invention.

According to some modes of realization, the system of the invention may further comprise a distributed strain sensor.

It is an advantage of the invention to allow evaluating the thickness of remaining soil above a buried device such as an underwater cable or pipe, and so to allow estimating scouring amplitude and speed. So, the buried device can be secured before being exposed to water, for instance during scheduled preventive maintenance operations.

It is another advantage of the invention to allow evaluating the thickness of remaining soil above a buried device such as an underwater cable or pipe all along the device, using sensors which are easy to integrate on the device. So, cost on scouring monitoring can be significantly reduced.

Description of the drawings

The methods according to embodiments of the present invention may be better understood with reference to the drawings, which are given for illustrative purposes only and are not meant to be limiting. Other aspects, goals and advantages of the invention shall be apparent from the descriptions given hereunder.

- figure 1 illustrates a cable running underwater, and the effect of soil erosion,
- figures 2(a) and 2(b) illustrate the temperature distribution around a 3 phases power cable buried in the seabed, with on figure 2(a) the temperature distribution within +/-1m around the cable, and on figure 2(b) a close view of the center area,
- figure 3 illustrates the temperature distribution with respect to soil thickness above a heat source, for 3 different thicknesses of soil,
- figure 4 illustrates the variation of temperature measured by a temperature sensor at a given location, in function of the erosion,

- figure 5(a) and 5(b) shows cut views of exemplary modes of realization of scouring monitoring devices of the invention,

- figure 6 shows a schematic view of a distributed temperature sensor based on Brillouin scattering.

Detailed description of the invention

We will now describe modes of realization of the invention for monitoring the scouring effect along subsea power cables.

With reference to figure 1, subsea electrical power cables 4 are cables which are intended for conveying electrical power and/or communication signals (for instance) across a water expanse or a sea 7. Such cable 4 may for instance be used for bringing electrical power from a power station in the mainland to an island, or for conveying the power generated by seaborne wind turbines.

These cables 4 are usually buried in the soil 6, at a depth of about one meter under the seabed 8, so as to be covered everywhere by a certain amount of rock and sands used as protection. Due to seabed migrations, currents and so on, the soil 6 may move so that water may ultimately come in contact with the cable in some locations 5. As explained before, this process is known as scouring.

A power cable 4 usually comprises some conductors 1 with an electrical current flowing in, which behave as heat sources and which change locally the temperature distribution of the environment.

Figures 2(a) and 2(b) illustrate the temperature distribution in the soil 6 around a power cable 4 with three conductors 1 (such as a three-phase power cable). The cable 4 is buried under 1 meter of soil (H = -1 m). The surrounding (water and soil) is assumed to be at a stable temperature condition of 4°C, prior to applying power to the cable.

The temperature distribution shown in figures 2(a) and 2(b) corresponds to a stabilized or quasi-stabilized regime (without transient effects), with a known average power dissipated in the cable. These temperatures are obtained by numerical simulation and finite element modeling, taking into account:

- Joules losses in the conductors 1, which depend on the current flowing in and of the electrical resistance of the conductors,

- a heat transfer model of the cable 4 and of the soil 6, mostly based on thermal conduction,

- a heat transfer model of the water 7, which takes into account thermal conduction and thermal convection, and

- the temperature of the water 7 and of the soil 6 without the cable 4 and the heat sources 1.

The heat transfer model of the water 7 may be approximated by an assumption that the temperature of the water 7 is constant, which corresponds to considering a very efficient thermal dissipation in water. The temperature of the water 7 and of the soil 6 without cable may be obtained from survey data.

As it can be seen on figure 2(b), the temperature in the conductors 1 which are heated by joules effect due to the current flowing is high. But at larger distance, as shown on figure 2(a), the temperature gradually decreases and eventually becomes equal to the initial conditions, in particular at the water interface 8. The closer view of figure 2(b) around the cable shows that thermal gradient is larger in vicinity of the cable.

So, for a subsea power cable 4 buried in soil 6 such as sand and dissipating a given average power, a temperature gradient ranging from a higher temperature Tc in the cable 4 to a lower temperature Tw corresponding to the temperature of the water 7 at the seabed 8 when unaffected by the cable can be found while moving from the cable 4 through the soil 6 to the seabed 8 and the water 7.

When scouring occurs (for instance on a location 5), part of the soil 8 is removed so that water gets closer to the cable 4. As a result, the whole temperature distribution is locally modified and this affects the temperature in the cable 4 as well.

Figure 3 shows temperature profiles 11, 12, 13 in the soil 6 for different thickness of soil, respectively H1, H2, H3, above a heating element such as a conductor 1 of a cable 4. For each temperature profile 11, 12, 13, the heating element 1 is at H = 0 on the graph. The temperature profile 11 corresponds to the smallest thickness (H1) of soil 6, while the temperature profile 13 corresponds to the largest thickness (H3) of soil 6 above the cable 4. It can be seen that the temperature profiles 11, 12, 13 decrease from the temperature of the heating element 1 for H = 0, down to the temperature Tw

of the water towards the interface 8 between water and soil which is at the distance H1, H2 or H3, respectively, of the heating element 1.

According to an important aspect of the invention, it has been recognized that the soil thickness influences the thermal distribution around the cable 4, or even in the cable 4, in such a way that it may be calculated using temperature measurements done in the vicinity of the heat-generating conductors 1, for instance at a distance Hs from the heat-generating conductors 1 as shown on figure 3.

These temperature measurements may be done with a temperature sensing element 3 located in the vicinity of the heat source(s) 1, as illustrated in figure 2(b).

For instance, in the situation of figure 3,

- if the thickness of soil above the heating element 1 is H1, a temperature sensor located at a distance Hs from the heating element 1 measures a temperature T1,

- if the thickness of soil above the heating element 1 is H2, a temperature sensor located at a distance Hs from the heating element 1 measures a temperature T2,

- if the thickness of soil above the heating element 1 is H3, a temperature sensor located at a distance Hs from the heating element 1 measures a temperature T3.

So the thickness of soil may be deduced from the temperature measurements provided that the relationship between them is known.

This relationship between the temperature measured on a given location such as Hs near the heating source(s) 1 and the thickness of soil may be calculated using for instance finite element modeling and/or experimental measurements on field.

Figure 4 shows a thermal distribution function 20 which links temperature measured on a given position (corresponding for instance to a distance Hs from the heat source 1 on figure 3) and soil erosion dH. The soil erosion dH corresponds to a thickness of soil removed relatively to an initial thickness of soil of 1 meter (for dH=0).

This thermal distribution function 20 is calculated using finite element modeling, and taking into account at least some of the following parameters:

- relative positions of heat source(s) 1 and sensing element 3, or at least distances Hs between them,

- Joules losses in the conductors 1, which depend on the current flowing in and of the electrical resistance of the conductors,

- a heat transfer model of the cable 4 and of the soil 6, mostly based on thermal conduction,

- a heat transfer model of the water 7, which takes into account thermal conduction and thermal convection, and

- the temperature of the water 7 and of the soil 6 without the cable 4 and the heat sources 1.

As explained before, the heat transfer model of the water 7 may be approximated by an assumption that the temperature of the water 7 is constant, and the temperature of the water 7 and of the soil 6 without cable may be obtained from survey data.

The thermal distribution function 20 may be used to compute an absolute thickness of soil. For instance, in the example of figure 4 a measured temperature of 25.6°C indicates a soil thickness of 1 meter.

The thermal distribution function 20 may also be used to deduce directly soil erosion dH from the temperature measurements (knowing the initial soil thickness). For instance, in the example of figure 4, a measured temperature variation of -2 °C indicated a soil erosion of dH=0.5 meters, starting from a soil thickness in the order of 1 meter.

The parameters on which the thermal distribution function 20 depends may vary along the cable, and this may introduce some uncertainty on the calculations.

In practice however, it is not necessary to have a very accurate knowledge of the environment. It is sufficient to use a thermal distribution function 20 corresponding to average parameters.

Even if using only an approximated thermal distribution function 20, a temperature decreasing with time on a portion of a cable 4 indicates that the thickness of soil is decreasing in that area. And the larger the difference of temperature, the more material is removed. So even with an uncertainty on the model's parameters, a time follow-up of the temperatures variations still allows detecting scouring well before the cable 4 appears in free water.

The temperature of the environment (which is a stable or very slowly varying parameter) and the amount of power dissipated in a power cable 4 may be monitored. The seabed is frequently composed, at least on large areas, of known materials such as sand or mud. So, either by using a simulated curve or by field calibration, it may be possible in practice to evaluate in most cases to within 10 centimeters the magnitude of the scouring.

With reference to Figures 5(a) and 5(b), we will now describe examples of modes of realization of scouring monitoring devices of the invention built around power cables.

It is an advantage of the invention that a scouring monitoring device for monitoring scouring along a power cable may be done with only a few modifications to the cable. The result is an instrumented cable 4.

The scouring must be monitored all along the instrumented cable 4. This can be done by implementing a temperature sensor allowing distributed temperature measurements along the cable 4, using optical fibers as temperature sensing element 3.

Thus, the combination of a sensing element 3 and of the heat sources formed by the electrical conductors 1 of a power cable, under the form of an instrumented cable 4, is in fact a distributed scouring monitoring device 4 of the invention.

Figure 5(a) shows a mode of realization in which the sensing element 3 is embedded in a three-phase instrumented power cable 4.

The instrumented power cable 4 comprises three individual electrical cables 2 with a conductor 1 surrounded by a gaining. In operation, the conductors 1 act naturally as heat sources for scouring monitoring, due to the current flowing through them.

The instrumented power cable 4 comprises also a sensing element 3 with an optical cable running along the optical cables 2. The sensing element 3 is placed outside the electrical cables 2.

As a matter of example with no intention to be limitative, an instrumented power cable 4 such as illustrated on figure 5(a) may have an outer diameter in the order of 235 mm. The outer gaining of the individual cables 2 may have a diameter of about 90 mm. The conductor 1 diameter may be in the order of 30 mm. The sensing element 3 may comprise a steel

tube of about 4 mm diameter with the optical fibers inside, and a sheath with an outer diameter of about 10 mm. So, the distance between a conductor 1 and the sensing element 3 in this mode of realization may be larger than 40 mm, in the order of 40-60 mm.

According to another mode of realization, the instrumented power cable 4 may comprise a sensing element 3 placed between the electrical cables, in the center of the instrumented cable 4.

The electrical cables 2 and the sensing element 3 are further embedded in an external gaining, so as to constitute a stand-alone instrumented power cable 4.

In these modes of realization, all elements are assembled during the fabrication of the instrumented power cable 4.

Figure 5(b) shows another mode of realization in which the sensing element 3 is just tied to an electrical cable 2 with a conductor 1, so as to constitute an instrumented cable 4 allowing scouring monitoring with the method of the invention.

In the same way, the sensing element 3 may be tied to an already-existing three-phase cable as shown in figure 5(a).

A sensing element 3 such as an optical cable may be added to an existing power cable so as to allow monitoring scouring. It may be tied using for instance an external gaining, or glue, or ties of any kind.

As explained before, the thermal distribution function 20 depends on the relative positions of the heat sources 1 and the sensing element 3, or at least on the distance Hs between them. So the overall sensitivity of a scouring monitoring device 4 of the invention may be optimized by optimizing these parameters.

For instance, in the case of a three-phase instrumented cable, a better sensitivity to scouring may be obtained:

- by putting some distance between the conductors 1 and the sensing element 3, so that they are not in contact,

- by placing the sensing element 3 outside the area delimitated by the conductors 1 as shown on figure 5(a), rather than between them.

With reference to figure 6, the temperature measurements are done using a distributed temperature sensor (DTS) based on stimulated Brillouin scattering.

Brillouin scattering occurs when a light wave propagating in a medium (such as an optical fiber) interacts with time-dependent density variations of the medium. These density variations may be due for instance to acoustic waves or phonons propagating in the medium, and they modulate the index of refraction. A fraction of the light wave interacts with these variations of index of refraction and is scattered accordingly. Since acoustic waves propagates at the speed of sound in the medium, deflected light is also subjected to a Doppler shift, so its frequency changes.

The speed of sound in the medium depends on the temperature of the medium and on the strain. So, a variation of any of these parameters induces a variation of the frequency shift of the scattered light due to Brillouin scattering, and so may be measured.

When an intense beams such as a laser beam travels in a medium such as an optical fiber, the variations in the electric field of the beam itself may produce acoustic vibrations in the medium via electrostriction. The beam may undergo Brillouin scattering from these vibrations, usually in opposite direction to the incoming beam. This phenomenon is used in stimulated Brillouin scattering (SBS) sensors as explained later.

The distributed temperature sensor (DTS) comprises a sensing element 3 which comprises basically a portion of single mode optical fiber 30 protected by a small tube or casing which is rigid enough so as to avoid any strain on the fiber along the sensitive part. The length of the fiber in the casing is longer (of an "excess fiber length" EFL) than the casing so that the casing may be stretched in some extends (the EFL) without applying strain to the fiber. The fiber is also usually embedded in a gel in the casing for a better decoupling of strain. So the sensor is sensitive only to temperature and is not affected by strain, provided that strain applied to the sensing element 3 remains within some limits (the EFL) so that it does not affect the fiber.

The distributed temperature sensor (DTS) comprises also electronic and optical means.

The measurements are done as follows:

- A pulsed "pump" laser lightwave 31 is injected at one end of the single mode fiber 30;

- a tunable continuous wave (CW) "probe" laser lightwave 32 is injected at the other end of the sensing fiber 30. Its frequency is varied with time;

- pump and probe signals interact through SBS when a resonance frequency condition is met. This interaction between pump and probe signals is at its maximum, or at the resonance, when the difference of frequency between the pump and probe signals matches the local Brillouin Frequency shift. This local Brillouin Frequency shift depends precisely on the temperature 33 and the strain along the fiber 30. The probe signal is amplified by this interaction and so carries the local temperature and strain information available from the SBS phenomenon;

- the probe signal carrying the information is detected by a detector 35, after filtering by a Fiber bragg grating rejecting the Rayleigh scattering.

An optical circulator 35 allows coupling the pump wave 31 in the fiber 30 and directing the probe signal resulting from the probe wave 32 to the detector 35.

The probe signal at the detector 35 carries the information about the event (the local temperature and strain), and its location for processing: since the pump lightwave 31 is a pulse, the probe signal at the detector 35 carries also time domain information which may be converted into distance knowing the speed of light in the fiber 30.

Repeated frequency scanning using the CW tunable probe signal 32 allows the identification of the Brillouin frequency shift containing the temperature and strain information at every location along the sensing fiber 30.

As previously explained, the fiber 30 is protected from strain so that only temperature is measured.

With such sensor, temperatures may be measured along sensitive elements 3 up to 50 km long, or even much more using for instance optical amplifiers such as Erbium Doped Fiber Amplifier (EDFA), with a longitudinal resolution of a few meters or less.

A system of the invention, which allows monitoring scouring along an underwater cable for instance, comprises:

- an instrumented cable 4, with a temperature sensitive element;
- a temperature measurement device; and
- calculation means for conducing the measurements, and computing the soil thickness.

Before operating the system, a thermal distribution function 20 must be determined, taking into account the parameters of the instrumented cable 4 (location of heat sources 1 and temperature probes 3, ...) and environmental parameters.

During the exploitation, the thermal distribution function 20 may be adapted in function of the variations of the environment (seasons, ...).

The temperature measurement device being quite expensive, it may be connected to instrumented cables 4 just during measurements campaigns, or shared between several cables 4, for instance using optical switches. So, the cost of the instrumentation which is permanently installed on the cable may be set very low.

According to some modes of realization, the accuracy of the measurements may further be improved by comparing local temperature along the cable 4, and/or by analyzing temperatures with respect to time. This may allow improving the accuracy of the model relative to variations due for instance to the fact that:

- the temperature distribution along the cable (without heating effects) may not be homogenous, due to the environment;

- the electrical power which flows through the cable 4 may vary with time, as it depends on the electrical production and/or consumption of the connected devices. So the Joules losses in the conductors 1 may also vary with time.

A reference temperature profile along the cable 4 may be acquired, for instance when no power flows in the cable 4 for enough time to allow the temperature to stabilize at environmental conditions.

During measurements:

- the evolution of the temperature on each location can be monitored with time, and compared with the corresponding value in the reference temperature profile;

- The time evolution of temperature on different locations along the cable 4 may also be monitored and compared.

This may allow detecting portions of cable 4 which shows singularities in the evolution of the temperature relative to other or neighboring portions. For instance, portions of cable 4 in which the temperature and/or the amplitude of the variation of temperature with respect to power dissipation in the cable are

different may indicate that the cable 4 is closer to the water or that scouring is occurring.

In addition, as scouring is expected to be a slow process, a gradient filtering mechanism may be applied to distinguish between transient temperature variations and long term behavior.

According to some modes of realization, an instrumented power cable 4 may comprise several sensing elements 3. They may be used together. They may also be installed to provide some degree of redundancy in case of failure of a sensing element 3.

According to some modes of realization, one or several temperature sensor(s) allowing quasi-distributed temperature measurements along the cable 4 may be used. Such sensor may comprise a sensing element 3 with optical fibers connected to fiber Bragg gratings (FBGs) distributed all along the cable 4 and used as local temperature sensors. For instance, the fiber Bragg gratings may be implemented so that their spectral signature is different for each of them (for localization) and vary with temperature (for local temperature measurements).

According to some modes of realization, any other kind of distributed temperature sensors (DTS) may be used, such as for instance DTS based on spontaneous Brillouin scattering, or Raman scattering.

According to some modes of realization, a strain sensing element may be added to an instrumented cable 4. This element may comprise optical fibers. It may implement a sensing scheme based for instance on measurement of elongation of optical fibers by reflectometry, or on Distributed Strain Sensing (DSS) using spontaneous or stimulated Brillouin scattering in the fibers.

Distributes strain sensing (DSS) may for instance be used for providing information on the cable integrity prior to repair the soil or sand bed, thus allowing the operator to minimize cost and optimize the intervention. In particular, it may allow the operator to verify that the sand bed repair does not add additional strain to the cable 4. More generally, strain measurements may for instance indicate that the cable has been dragged by an anchor or moved away due to the current once exposed to water.

According to some modes of realization, the temperature sensing element 3 may also be used for Distributes strain sensing (DSS). As explained before, a distributed sensor based on Brillouin scattering (stimulated or

spontaneous) is naturally sensitive to the temperature and strain applied to the optical fibers of the sensing element 3. If the strain applied to the sensing element 3 (comprising fibers protected from strain effects) exceed some limits, the fibers become affected by strain and the temperature measurements are affected accordingly. This effect may be detected if the sensor measures unexpected or unrealistic temperatures for instance. So any signature in the temperature signal which is for instance too large to be thermal can be understood as strain, even quantified provided that the excess fiber length (EFL) is known, and may provide valuable information on « fast effects » like for instance dragging of the cable 4.

A pipe or a duct such as a pipeline or a flowline carrying fluid warmer than the environment may impact on the local temperature in a way similar to what is shown on figures 2(a) and 2(b). When the pipeline is heated (for instance electrically), the effect is reinforced. Power umbilicals also transport electrical power or hydraulic power and are therefore the cause of similar local temperature increase.

So, it is clear that, even if the detailed description of the invention is based on power cables, it may be easily transposed by a person with average skills in the art for the monitoring of scouring around any pipe or duct. An instrumented pipe or duct may so be done in a very similar way by implementing a temperature sensing element 3 in the vicinity of a heat source 1 of said pipe or duct, and by computing a corresponding thermal distribution function 20.

According to some modes of realization, the scouring or the erosion around a pipe or a duct (or any other structure) may be monitored by providing an instrumented cable 4 distinct from the structure, comprising a heat source 1 and a temperature sensing element 3. In that case, the sole function of that instrumented cable 4 may be scouring monitoring. The instrumented cable 4 may then be a scouring sensing element of the invention.

According to some modes of realization, the invention may also be implemented for the monitoring of scouring or erosion around terrestrial pipeline or cables, for instance due to sand movements with wind.

While this invention has been described in conjunction with a number of embodiments, it is evident that many alternatives, modifications and

variations would be or are apparent to those of ordinary skill in the applicable arts. Accordingly, it is intended to embrace all such alternatives, modifications, equivalents and variations that are within the spirit and scope of this invention.

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CLAIMS

1. A method for monitoring the thickness of soil (6) between a soil surface (8) and a device (4) buried in said soil (6), possibly underwater, the device (4) comprising at least one heat source (1), the method comprising steps of:

- measuring at least one temperature using at least one temperature sensing element (3) located in the vicinity of the heat source(s) (1), and
- calculating an estimated soil thickness using a pre-determined thermal distribution function (20) which links measured temperatures and soil thickness.

2. The method of claim 1, wherein the thermal distribution function (20) comprises a static or a quasi-static function.

3. The method of claim 1 or 2, wherein the thermal distribution function (20) takes into account at least one of the following elements:

- the relative location of the heat source(s) (1) and the temperature sensing element(s) (3),
- a power dissipation in the heat source(s) (1),
- a temperature at the soil surface (8),
- a heat transfer model in the soil (6),
- a heat transfer model in the device (4).

4. The method of claim 3, wherein the power dissipation in the heat source(s) takes into account resistive losses due to electrical currents flowing in an electrical conductor (1) in the device (4).

5. The method of claims 3 or 4, wherein the power dissipation in the heat source(s) takes into account temperatures of fluids flowing in the device.

6. The method of any of claims 3 to 5, wherein the temperature at the soil surface (8) is the temperature of water (7) covering said soil surface (8).

7. The method of any of the preceding claims, which further comprises a step of computing the thermal distribution function (20) using at least one of the following method:

- finite elements simulation and modeling,
- experimental measurements.

8. The method of any of the preceding claims, which further comprises steps of:

- measuring temperatures on several measurement locations along a device (4) of an elongated shape comprising at least one heat source (1) extending along the device, using at least one distributed or quasi-distributed temperature sensing element (3) located in the vicinity of the heat source(s) (1) along the device (4), and
- calculating an estimated soil thickness on said measurement locations along the device (4).

9. The method of claim 8, which further comprises at least one of the following steps:

- comparing the evolution with time of measured temperatures and/or estimated soil thickness,
- comparing measured temperature and/or estimated soil thickness on different locations along the device (4).

10. An instrumented device (4) of an elongated shape, able to be buried in soil (6), possibly underwater, comprising:

- at least one heat source (1) extending along the device (4) and
- at least one distributed or quasi-distributed temperature sensing element (3) located in the vicinity of the heat source(s) (1) along the device (4),

said temperature sensing element (3) being arranged and located relative to the heat source(s) (1) so as to be able to provide temperature measurements on several measurement locations along the device (4) which allow calculating an estimated soil thickness between a soil surface (8) and the device (4), using a pre-determined thermal distribution function (20) which links measured temperatures and soil thickness.

11. The instrumented device of claim 10, wherein the temperature sensing element(s) (3) and the heat source(s) (1) are spaced apart so as to allow an optimization of the thermal distribution function (20).

12. The instrumented device of claim 10 or 11, which comprises a distributed temperature sensing element (3) with at least one optical fiber extending along the device (4), so as to allow a determination of the temperature using stimulated Brillouin scattering in said optical fiber(s).

13. The instrumented device of any of claims 10 to 12, which comprises a monitoring cable able to be attached to optical cables, electrical cables or pipes buried in soil, possibly underwater, said monitoring cable comprising at least one electrical conductor (1) able to be used as heating element, and at least one distributed or quasi-distributed temperature sensing element (3).

14. The instrumented device of any of claims 10 to 12, which comprises an electrical cable able to be buried in soil, possibly underwater, said electrical cable comprising at least one electrical conductor (1) able to be used as heating element, and at least one distributed or quasi-distributed temperature sensing element (3) attached to said electrical cable.

15. The instrumented device of any of claims 10 to 12, which comprises an electrical cable (4) able to be buried in soil, possibly underwater, said electrical cable (4) comprising several electrical conductors (1) able to be used as heating elements, and at least one distributed temperature sensing element (3) included in said electrical cable (4).

16. The instrumented device of claim 15, which comprises a distributed temperature sensing element (3) positioned:

- at the center of the cable between the electrical conductors (1), or
- outside of the area delimitated by the electrical conductors (1).

17. The instrumented device of any of claims 10 to 12, which comprises a pipe for carrying fluids able to be used as heating element, and at least one distributed or quasi-distributed temperature sensing element (3).

18. A system, comprising:

- an instrumented device (4) according to of any of claims 10 to 17,
- electronic means for obtaining temperature measurements using the distributed or quasi-distributed temperature sensing element(s) (3), and
- calculation means for implementing the method of any of claims 1 to 9.

19. The system of claim 18, which further comprises a distributed strain sensor.

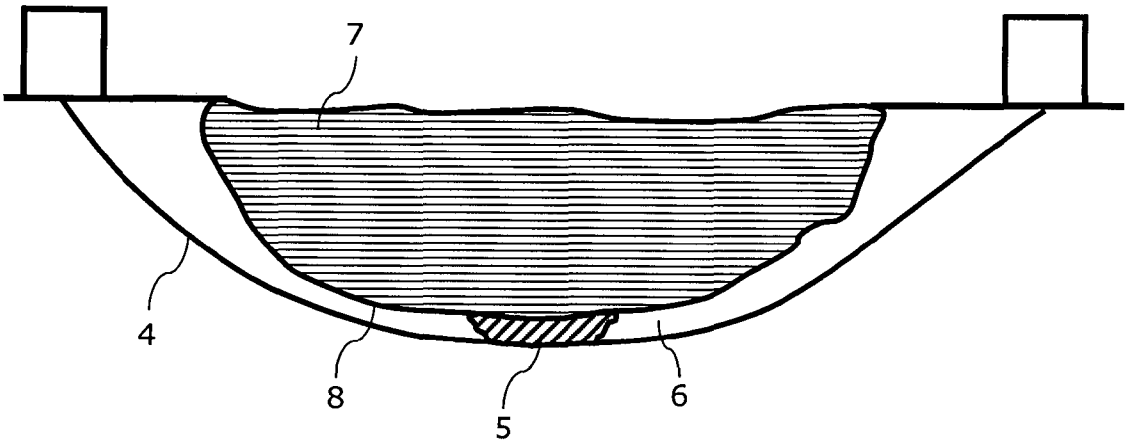

7
4
8
5
6

Fig. 1

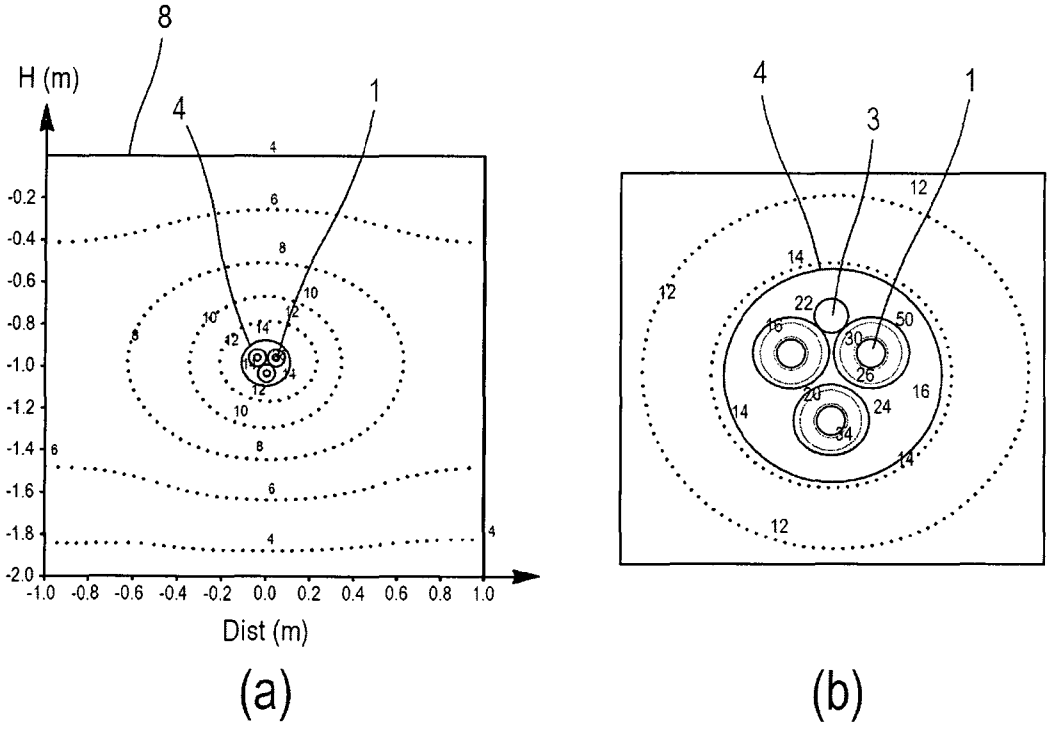

8
H (m)
4
1
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
Dist (m)
(a)
4
3
1
(b)

Fig. 2

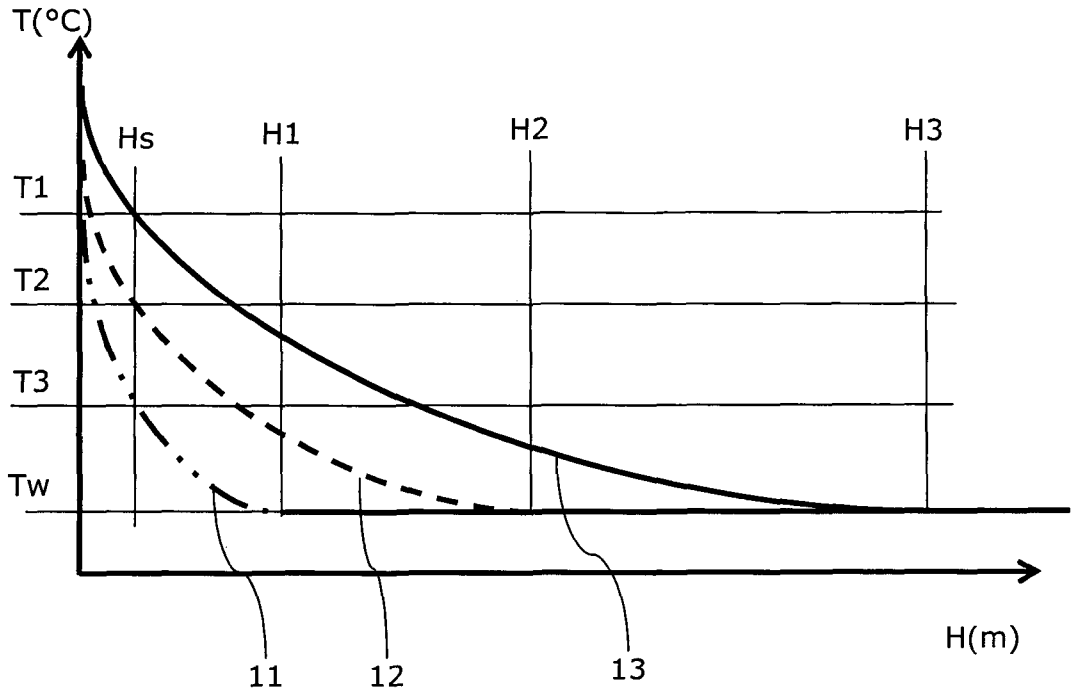

T(°C)
Hs
H1
H2
H3
T1
T2
T3
Tw
11
12
13
H(m)

Fig. 3

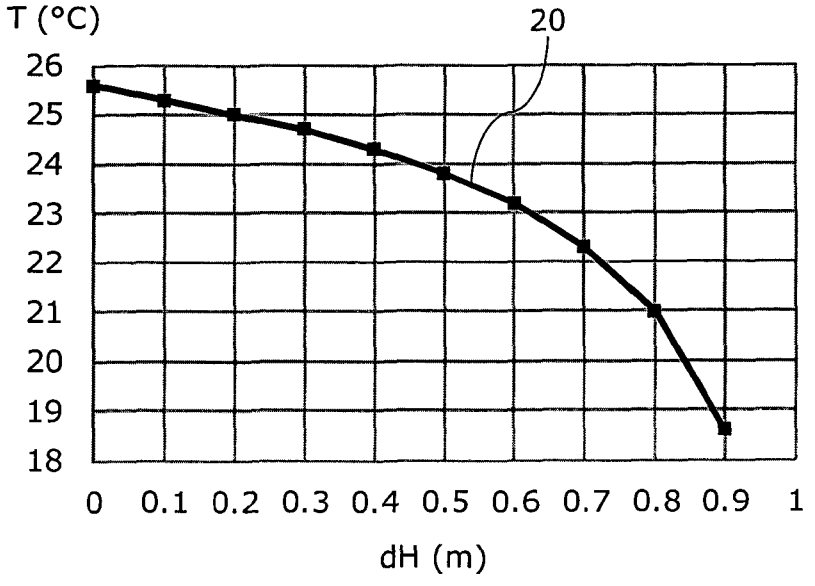

T (°C)
20
26
25
24
23
22
21
20
19
18
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
dH (m)

Fig. 4

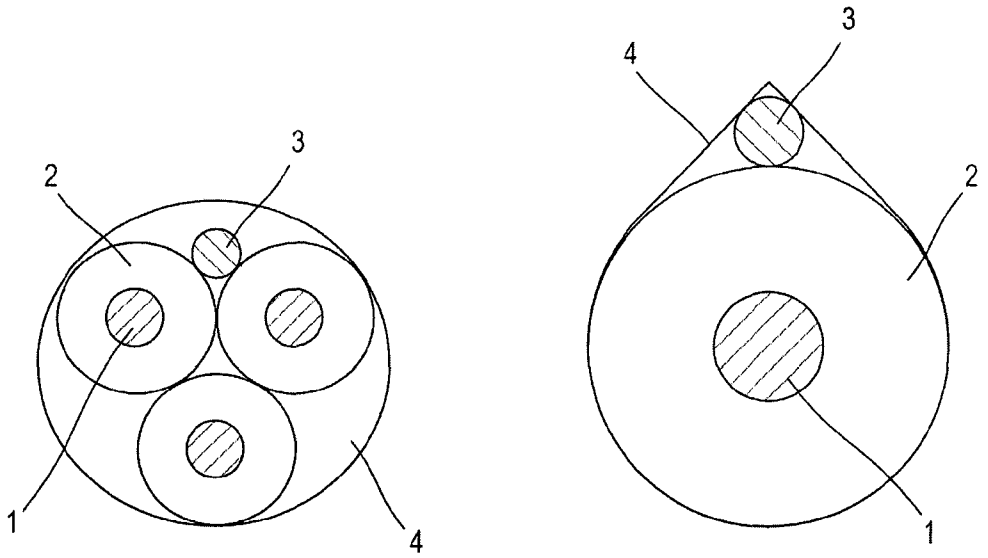


Fig. 5

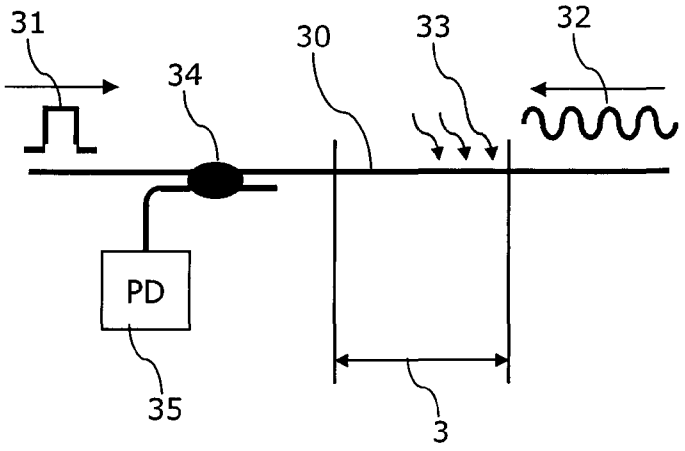


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/070206

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V9/00 H02G9/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V G01B H02G G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 825 459 A2 (SUMITOMO ELECTRIC INDUSTRIES [JP]) 25 February 1998 (1998-02-25) the whole document	1-19
A	CHANG-CHOU HWANG ET AL: "Extensions to the finite element method for thermal analysis of underground cable systems", ELECTRIC POWER SYSTEMS RESEARCH, vol. 64, no. 2, 1 February 2003 (2003-02-01), pages 159-164, XP055066313, ISSN: 0378-7796, DOI: 10.1016/S0378-7796(02)00192-X abstract	7

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 June 2013	19/06/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gilow, Christoph

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/070206

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WOSNIOK A ET AL: "Distributed Fibre Optic Sensor System for Temperature and Strain Monitoring Based on Brillouin Optical-Fibre Frequency-Domain Analysis", PROCEDIA CHEMISTRY, ELSEVIER, AMSTERDAM, NL, vol. 1, no. 1, 1 September 2009 (2009-09-01), pages 397-400, XP026799566, ISSN: 1876-6196 [retrieved on 2009-09-01] "Introduction"; page 397	1-19
A	XUE-FENG ZHAO ET AL: "Scour monitoring system of subsea pipeline using distributed Brillouin optical sensors based on active thermometry", OPTICS AND LASER TECHNOLOGY, ELSEVIER SCIENCE PUBLISHERS BV., AMSTERDAM, NL, vol. 44, no. 7, 12 March 2012 (2012-03-12) , pages 2125-2129, XP028507623, ISSN: 0030-3992, DOI: 10.1016/J.OPTLASTEC.2012.03.015 [retrieved on 2012-03-20] cited in the application the whole document	1-19

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2012/070206

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0825459 A2	25-02-1998	AU 724951 B2	05-10-2000
		AU 3524697 A	26-02-1998
		CA 2213641 A1	23-02-1998
		EP 0825459 A2	25-02-1998
		ID 18071 A	26-02-1998
		JP H10117424 A	06-05-1998
		MY 132514 A	31-10-2007
		NO 973883 A	24-02-1998
		US 6244106 B1	12-06-2001