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NEW ASPECTS FOR PETROLEUM RESERVOIR EXPLORATION BY REAL-TIME EXPERT SEISMOLOGY

Ladopoulos E.G.
Interpaper Research Organization, Athens, Greece
e-mail: eladopoulos@interpaper.org

Abstract. *The new theory of "Real-Time Expert Seismology" is proposed in the present research, by using a non-linear 3-D elastic waves real-time expert system for the exploration of the marine and land oil reserves all over the world. This Generic Technology will work under Real Time Logic for searching the marine and land petroleum reserves developed on the continental crust and on deeper water ranging from 300 to 2000 m, or even much more. Hence, the above real - time expert system, will be the best device for the exploration of the continental margin areas (shelf, slope and rise) and the very deep waters, as well. Moreover, the proposed real-time expert system will be suitable for the exploration of land oil reserves, too.*

The main objectives for exploration of marine and land petroleum reserves are to locate, characterize and evaluate the size of such resources in the whole world. Thus there is a research and development responsibility for the acquisition and analysis of geophysical, geological and reservoir engineering data for the land and the seas all over the world, in order to be explored their oil and gas reserves. So, through the new technology of "Real-time Expert Seismology", will be effected the exploration of a significant part of marine and land oil reserves fastly and by a low cost.

Keywords: *real-time expert seismology, real-time logic, non-linear real-time expert system, generic technology, land oil reserves, marine oil reserves*

1. Introduction

Three are the basic areas for the research and investigation aspects of land and marine oil reserves:

(A) The determination of the necessary standards and data for the safety to offshore and land operations.

(B) The acquisition and analysis for the geophysical, geological and reservoir engineering data to enable an appreciation to be made of the petroleum reservoir.

(C) To assist the development of the offshore and land supplies industry, and to enable it to play a full part in the development of the marine and land oil and gas resources in worldwide markets in the future.

Generally, there is a considerable feeling by worldwide oil companies and scientific petroleum institutes that the unexplored land and marine petroleum & gas resources should be too many, many times more than the terrestrial reserves of Middle - East. Also, many recent test drillings in the Continental Shelf of Europe and rest world have shown the existence of petroleum reserves.

Furthermore, the usual probability considerations indicate that marine oil reserves will be found in areas of thick sedimentary sequences developed on the continental crust. Hence, if this is true, then the continental margin areas (shelf, slope and rise) should offer good prospects of containing petroleum and gas resources. However, up to present the potential of sediments both on and off the shelf remains unquantified. Also, there are deep waters prospects in the seas in the whole world, but because of the paucity of the available information it is not possible at present to quantify the amounts that may be recoverable from them.

As it is well known, since 1920 the basic and prevalent theory on petroleum reserves exploration, has been "Reflection Seismology". According to the above method the basic idea is to collect reflections of elastic (seismic) waves and then through various mathematical operations, by using Snell's law and Zoeppritz equations to convert them to maps of the earth's structure. [1 - 9]. Infer location of oil and gas from structural maps, sometimes of character of reflections, too. Thus, the method of "Reflection Seismology" for almost a century, has been used with several improvements for oil and gas reserves exploration.

On the other hand, in the present investigation for the marine and land oil reserves exploration the new theory of *"Real-Time Expert Seismology"* is investigated, as was very recently proposed by E.G. Ladopoulos [10 - 12]. Beyond the above, this is an extension of the non-linear methods for fluid mechanics as proposed by E.G.Ladopoulos et al. [13 - 24]. Hence, *"Real-Time Expert Seismology"* is a very "*innovative*" and "*groundbreaking*" method on oil reserves exploration. According to the new theory a non-linear 3-D elastic waves real-time expert system is proposed and investigated for the exploration of the oil reservoir worldwide, including the marine oil reservoir, of the seas all over the world. This Generic Technology will work under Real Time Logic [25 - 29] for searching marine reserves developed on the continental crust and on deeper water ranging from 300 to 2000 m, or even much more. So, the proposed real-time expert system will be the best device for the exploration of the continental margin areas (shelf, slope and rise) and the very deep waters, as well. Furthermore, this expert system will be suitable for the exploration of land oil reservoir, too.

There are many basic benefits of the new theory of "*Real-Time Expert Seismology*" in comparison to the existing theory of "Reflection Seismology". Some of them are the following:

A) The new theory *"Real-Time Expert Seismology"* is based on the special form of the geological anticlines of the bottom of the sea, in order to decide which areas of the bottom have the most possibilities to include oil reserves.

On the other hand, the existing theory is only based to the best chance and do not include any theoretical and sophisticated model. Currently oil companies by using the existing method must make many expensive test drillings in big areas of seas, if they want to have a chance to find petroleum reservoir.

B) The new theory of elastic (sound) waves is based on the difference of the speed of the sound waves which are traveling through solid, liquid, or gas. In a solid the elastic waves are moving faster than in a liquid and the air, and in a liquid faster than in the air. On the contrary, existing theory is based on the application of Snell's law and Zoeppritz equations, which are not giving good results, as these which we are expecting with the new method.

C) The new theory *"Real-Time Expert Seismology"* is based on a Real-time Expert System working under Real Time Logic, that gives results in real time, which means every second.

Existing theory do not include real time logic.

From the above mentioned three points it can be well understood the evidence of the applicability of the new method of "*Real-Time Expert Seismology*". Also its novelty, as it is based mostly on a theoretical and very sophisticated Real-time Expert model and not to practical tools like the existing method.

2. General Aspects of Real-time Expert Seismology

In general, marine operations consist of 90 % of all data collected worldwide for petroleum and gas reserves exploration. Beyond the above, international oil companies and research organisations by studying geological surveys in the whole world indicate that oil reserves do not necessarily end at the edge of the continental shelf. Hence, there is serious expectation that main resources will be found in areas of thick sedimentary sequences developed on the continental crust. So, there are good possibilities for finding marine oil reservoir in deep waters, too. These reserves will be on the shelf, slope and rise of the Earth's margin, and the depths of water would not only range up to 300 m, but also in deep waters ranging from 300 m to approaching 2000 m, or even much more.

Furthermore, the behavior of a reservoir, depends not only on the properties of the liquid and gas, but also on a series of factors that may be termed as the "*properties of the environment*". Among them are items like capillary-pressure effects, the reaction of rock when subjected to high stress, pressure and temperature gradients at the shallower levels in the Earth's crust and influences of the compressibility as pressure are reduced by fluid withdrawals.

On the contrary, there are four basic conditions that must be satisfied so that a geological formation, or a part thereof, should form a suitable reservoir, for example for the accumulation of oil or gas. These are porosity, permeability, seal and closure. Porosity defines the pore space in the rock – space in which the oil may collect. Per-meability is the attribute of the rock that permits the passage of fluid through it. In general, it is a measure of the degree interconnectedness, of the pore space, but some reservoir (e.g. in the massive limestone deposits, or in igneous intrusions) depends for fluid flow on a network of fractures within the rock.

Also, the seal is the "cup" of the reservoir and prevents the oil from leaking away. Moreover, closure is a measure of the vertical extent of the sealed trap or, in the case of resources accumulation bounded below by a moving body of water, of the "height" of the sealed trap where that height is measured along a line perpendicular to the oil-water contact.

There is a general believe that almost all resources occur in porous standstones or limestones and in sedimentary basins, and that seal or cap rock is often a clay or shale, or massive unfractured limestone having little or no permeability. Beyond the above, three general categories of resources can be mentioned for marine reserves: structural traps, stratigraphic traps and combination traps.

Furthermore, elastic waves are sound waves, generally three-dimensional which may be transmitted through matter in any phase – solid, liquid, or gas. In general, any body vibrating in air gives rise to such waves, as it alternately compresses and rarefies the air adjacent to its surfaces. Also, a body vibrating in a liquid, or in contact with a solid, likewise generates similar longitudinal waves. The frequency of the waves is of course the same as the frequency of the vibrating body that produces them. So, there are two types of elastic waves produced: a) P-waves, which are primary or “compressional” waves, and b) S-waves, or shear waves.

The distance between two successive maxima (or between any two successive points in the same phase) is the wavelength of the wave and is denoted by l. Since the waveform, travelling with constant velocity u, advances a distance of one wavelength in a time interval of one period, then it follows that the velocity of sound waves u is given as following:

$$u = l\,v\,, \tag{2.1}$$

where v denotes the frequency.

It is obvious that the velocity u differs when the sound waves are travelling through solid, liquid, or gas. In a solid the elastic waves are moving faster than in a liquid and the air, and in a liquid faster than in the air. If therefore we are searching for example for oil marine resources over the sea, by transmitting sound waves, then there will be a difference in the velocity of the waves in the sea, the solid bottom and in a potential reservoir.

In order the new technology to be better explained, consider the example of Fig. 1. In this case consider that in the bottom of the sea there is a potential petroleum reservoir. Then, the speed of the elastic waves in the air (u_{air}), will be different from the speed in the water (u_{water}), and different from the speed in the solid bottom (u_{solid}) and different from the speed in the potential reservoir (u_{oil}), while the frequency of the elastic waves remaining the same when transmitted through every different matter.

So, a real-time non-linear 3-D plane-polarized elastic waves expert system is proposed in order to explore the marine and land oil resources, according to the new theory of *"Real-Time Expert Seismology"*, in contrast to the old theory of "Reflection

Seismology". This Generic Sound Waves Technology will work under Real Time Logic for searching marine oil reservoir developed on the continental crust and on deeper waters ranging from 300 m to 2000 m, or even much deeper (Fig. 2). There are many deeper water prospects around the seas all over the world, but because of the paucity of the available information it is not possible at present to quantify the amounts that may be recoverable from them.

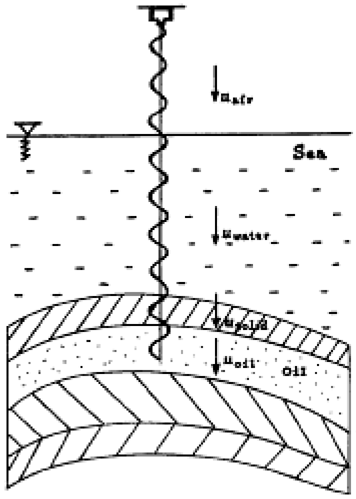

Fig. 1. Elastic waves method for the exploration of oil reserves

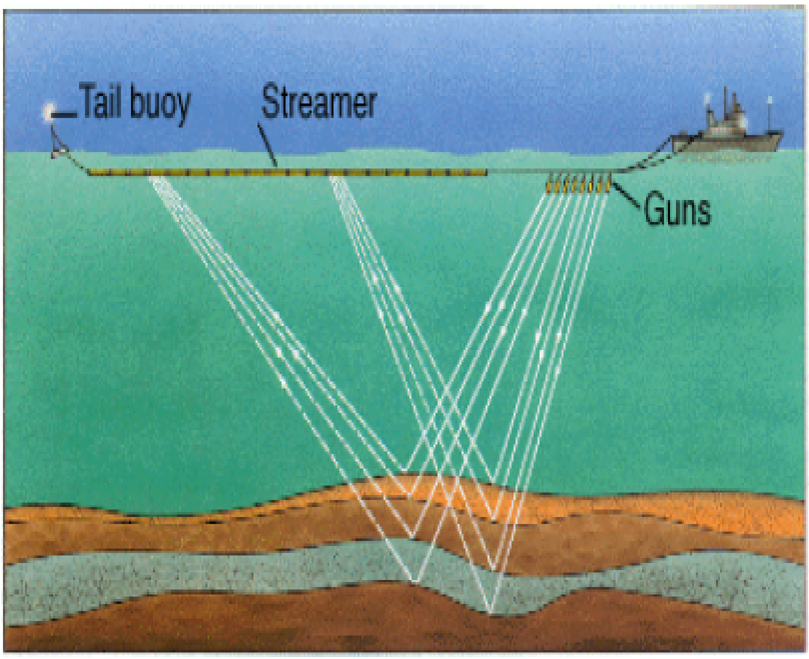

Fig. 2. Real-time Expert Seismology

Thus, the proposed real-time elastic waves expert system will be the best device for the exploration of the continental margin areas (shelf, slope and rise) and the very deep waters, too. So, through the new technology of "*Real-Time Expert Seismology*", will be effected the exploration of a significant part of land and marine petroleum and gas reserves very fast and by a low cost.

According to our proposed theory of *"Real-Time Expert Seismology"* the average velocity of the sound waves is calculated by providing important information about the composition of the solids through of which passed the sound waves. For example the velocity of the sound waves through the air is 331 m/sec, through liquid 1500 m/sec and through sedimentary rock 2000 to 5000 m/sec. Also, according to the law of Reflection the angle of reflection equals the angle of incidence (Fig. 3). Then according to the new method the arrival times of the seismic waves are analyzed. After the sensor measures the precise arrival time of the wave, then the velocity of the wave can be calculated by using the following method.

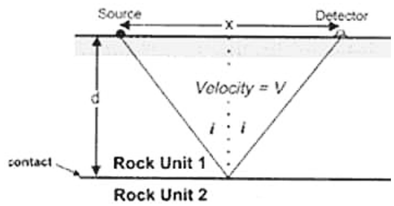

Fig. 3. Law of Reflection

The travel time T of the seismic waves is given by the relation:

$$T=\frac{2\left(d^2+x^2/4\right)^{1/2}}{v}, \tag{2.2}$$

in which d denotes the depth, x the distance between source of wave and the geophone or hydrophone detector and v is the average speed.

From (2.2) follows equation (2.3):

$$T^2=\frac{4\mathrm{d}^2+x^2}{v^2}. \tag{2.3}$$

Furthermore, the normal incident time T_o is given by the formula:

$$T_o=\frac{2\mathrm{d}}{v}. \tag{2.4}$$

From eqs (2.3) and (2.4) follows:

$$T^2-T_o^2=\frac{x^2}{v^2} \tag{2.5}$$

and finally from (2.5) the mean velocity is equal to:

$$v=\left(\frac{x^2}{T^2-T_o^2}\right)^{1/2}. \tag{2.6}$$

Thus, a real-time expert system is used and the apparatus permitted excitation of any combination of elements and reception of any other, visual analysis of the responses, and transfer of the signals to the PC for post processing. The sequencing of transducer excitation, digitiser configuration and subsequent data analysis was performed by a rule based Real-Time Expert System. Then from the information gathered, the Expert System applies knowledge via a series of software coded rules and provides any one of the following conditions:

speed in the water (u_{water}), speed in the solid bottom (u_{solid}) and speed in the potential reservoir (u_{oil}),

3. New Aspects for Refraction of Real-time Expert Seismology

Generally, the seismic refraction method is similar to the reflection method in that the same instruments and shock wave sources are used. However, as the name implies, the objective is to measure refraction of shock waves as they pass across formation or structural boundaries (Fig. 4). Refraction is governed by Snell's Law, which relates velocity to the angle of incidence and to the angle of refraction.

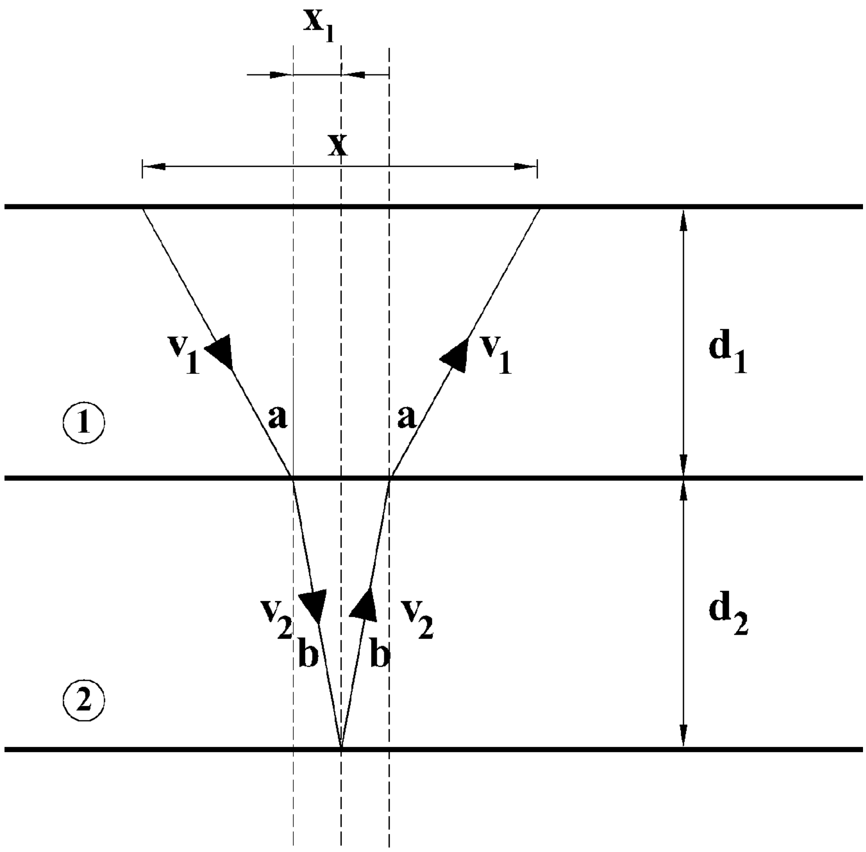

Fig. 4. Law of Refraction

The travel time T_1 of the seismic waves in the first solid is given as following:

$$T_1 = \frac{2\left(d_1^2 + (\frac{x}{2} - x_l)^2\right)^{1/2}}{v_1} \tag{3.1}$$

in which d_1 denotes the depth, x the distance between source of wave and the geophone or hydrophone detector, x_l the distance between the ends of the two waves (Fig. 4) and v_1 is the speed of the wave in the first solid.

From (3.1) follows equation (3.2):

$$T_1^2 = \frac{4\left(d_1^2 + (\frac{x}{2} - x_1)^2\right)}{v_1^2}. \tag{3.2}$$

Also, the normal incident time T_{1o} is given by the relation:

$$T_{1o} = \frac{2d_1}{v_1}. \tag{3.3}$$

From eqs (3.2) and (3.3) follows:

$$T_1^2 = T_{1o}^2 + \left[\frac{2(\frac{x}{2} - x_1)}{v_1}\right]^2. \tag{3.4}$$

Also, by replacing (3.3) in (3.4) one obtains:

$$d_1 = \frac{(\frac{x}{2} - x_l)T_{1o}}{(T_1^2 - T_{1o}^2)^{1/2}}. \tag{3.5}$$

By the same way the travel time T_2 of the seismic waves in the second solid is given by the following formula:

$$T_2 = \frac{2\left(d_2^2 + x_l^2\right)^{1/2}}{v_2}, \tag{3.6}$$

in which d_2 denotes the depth, x_l the distance between the ends of the two waves (Fig. 4) and v_2 is the speed of the wave in the second solid.
From (3.6) follows equation (3.7):

$$T_2^2 = \frac{4(d_2^2 + x_l^2)}{v_2^2}. \tag{3.7}$$

Furthermore, the normal incident time T_{2o} is given by the formula:

$$T_{2o} = T_o - T_{1o} = \frac{2d_2}{v_2}. \tag{3.8}$$

From eqs (3.7) and (3.8) follows:

$$T_2{}^2 = T_{2o}^2 + \left(\frac{2x_l}{v_2}\right)^2. \tag{3.9}$$

Also, by replacing (3.8) in (3.9) one obtains:

$$d_2 = \frac{x_1(T_0 - T_{1o})}{\left[(T - T_1)^2 - (T_o - T_{1o})^2\right]^{1/2}} . \tag{3.10}$$

Moreover, because of Snell's law it is valid:

$$\frac{v_2}{v_1} = \frac{\sin b}{\sin a} \tag{3.11}$$

where *a* denotes the angle of incident and *b* the angle of refraction.
Finally, if *T* is the total travel time of the waves in both solids ($T = T_1 + T_2$) and by using (3.2), (3.7) and (3.11) follows:

$$\frac{T_1}{T - T_1} = \frac{x_1\left(d_1^2 + (\frac{x}{2} - x_1)^2\right)}{(\frac{x}{2} - x_1)(d_2^2 + x_l^2)} \tag{3.12}$$

from which can be calculated x_l.

4. Real-time Logic for Petroleum Reservoir Exploration

In general, Real-time logic (RTL) is a reasoning system for real-time properties of computer based systems. Thus, the computational model of Real-time logic consists of events, actions, causality relations, and timing constraint. This model is expressed in a first order logic describing the system properties as well as the systems dependency on external events. The Real-Time Logic system introduces time to the first logic formulas with an event occurrence function, which assign time values to event occurrences. This kind of real-time logic systems were studied by F. Jahanian and A. Mok [25, 26].

Furthermore, real-time computing in common practice is characterized by two major criteria: deterministic and fast response to external stimulation, and both human and sensor and actor based interaction with the external world. Thus, it is clear that Real-time is an external requirement for a peace of software; it is not a programming technology. There are some special software tools for the implementation of real-time systems. Such real-time programming languages were investigated by some scientists like R.Emnis et all [27], W. Fritz, V.H. Haase and R. Kalcher [28] and V.H. Haase [29].

In general, Real-Time Logic uses the following three types of constraints:

A. Event constants are divided into three cases. Start/stop events describe the initiation/termination of an action or subaction. Transition events are those which make a change in state attributes. This means, that a transition event changes an assertion about the state of the real-time system or its environment. The third class, which are the external events, includes those that can be impact the system behavior, but cannot be caused by the system.

B. Action constants may be primitive or composite. In a composite constant, precedence is imposed by the event-action model using sequential or parallel relations between actions.

C. Integers assigned by the accurance function provide time values, and also denote the number of an event occurance in a sequence.

Also, the Real-Time Logic System introduces time to the first order logic formulas with an event occurance function denoted by e. The mechanism to achieve a timing property of a system is the deduction resolution.

So, consider the following example: Upon pressing button ≠ 60, action TEST is extended within 600 time units. Dusting each execution of this action, the information is sampled and subsequently transmitted to the display panel. Also, the computation time of action TEST is 100 time units.

This example can be further translated into the following two formulas:

$$\forall\ x : e(\ \Omega\ \text{button}\ 60,\ x) \le e(\uparrow\ \text{TEST},\ x) \wedge$$
$$e(\downarrow\ \text{TEST},\ x) \le e(\ \Omega\ \text{button}\ 60,\ x) + 600$$
$$\forall\ y : e(\uparrow\ \text{TEST},\ y) + 100 \le e(\downarrow\ \text{TEST},\ y)$$

5. Oil Reserves Exploration by Elastic Seismic Waves

Suppose that a seismic wave of any sort travels from left to right in a medium. Then the equation of the travelling wave is valid as:

$$y(\zeta, t) = A\cos(\omega t - k\zeta) \tag{5.1}$$

where k denotes the wave number given by the relation:

$$k = 2\pi / \lambda\ , \tag{5.2}$$

and λ is the wavelength, t the time, A the amplitude of the motion and $\omega = 2\pi v$, v the frequency.

A sinusoidal transverse wave travelling toward the right , at intervals of period 1/8 can be seen in Fig. 5.

Furthermore, it is important to distinguish between the motion of the waveform, which moves with constant velocity u along the string, and the motion of a particle of the string, which is simple harmonic and transverse to the string. In order to be understandable the mechanics of seismic waves, consider Fig. 6.

Also, by differentiating the wave equation (5.1) one has:

$$\partial y / \partial \zeta = kA\sin(\omega t - k\zeta)\ ; \tag{5.3}$$

$$\partial y / \partial t = -\omega A\sin(\omega t - k\zeta)\ . \tag{5.4}$$

By combining eqs (5.3) and (5.4) and as the velocity is equal to:

$$u = \omega / k\ , \tag{5.5}$$

then finally we obtain:

$$\frac{\partial y}{\partial \zeta} = -\frac{1}{u}\frac{\partial y}{\partial t}\ , \tag{5.6}$$

which by a second differentiation reduces to:

$$\frac{\partial^2 y}{\partial t^2} = u^2 \frac{\partial^2 y}{\partial \zeta^2} \,. \tag{5.7}$$

In general, in a transverse wave motion the individual particles vibrate in a direction perpendicular to the direction of propagation of the wave. But there are many such directions – indeed, there are infinitely many. So, in Fig. 7 can be seen three transverse waves, all travelling in the same direction, but lying in different planes from one another: A in a vertical plane, B in a horizontal plane, C in a plane inclined at an angle of 45° to each of these. In each case the motion of each individual particle is restricted to a single straight line, and the entire wave to a single plane. Each of these waves is said to be plane-polarized. Beyond the above, because of their non-linear behavior, are called non-linear plane-polarized. But more complex seismic waves could be generated by moving one end in any periodic manner, not restricted to a single straight line. In such cases, each particle has two-dimensional motion (it moves in a plane) and the entire wave is three-dimensional. Even then the wave is not necessarily un-polarized, while if the vibrations are ordered in any case, the wave is to some degree polarized.

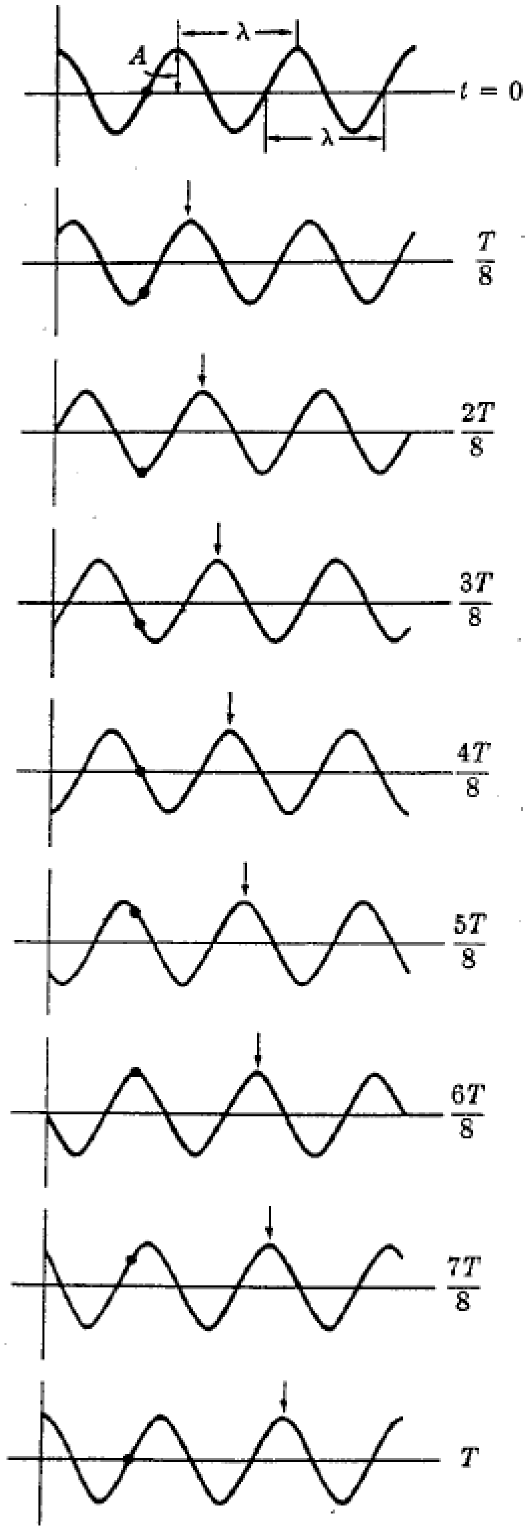

Fig. 5. A sinusoidal transverse wave travelling toward the right,
at intervals 1/8 of a period

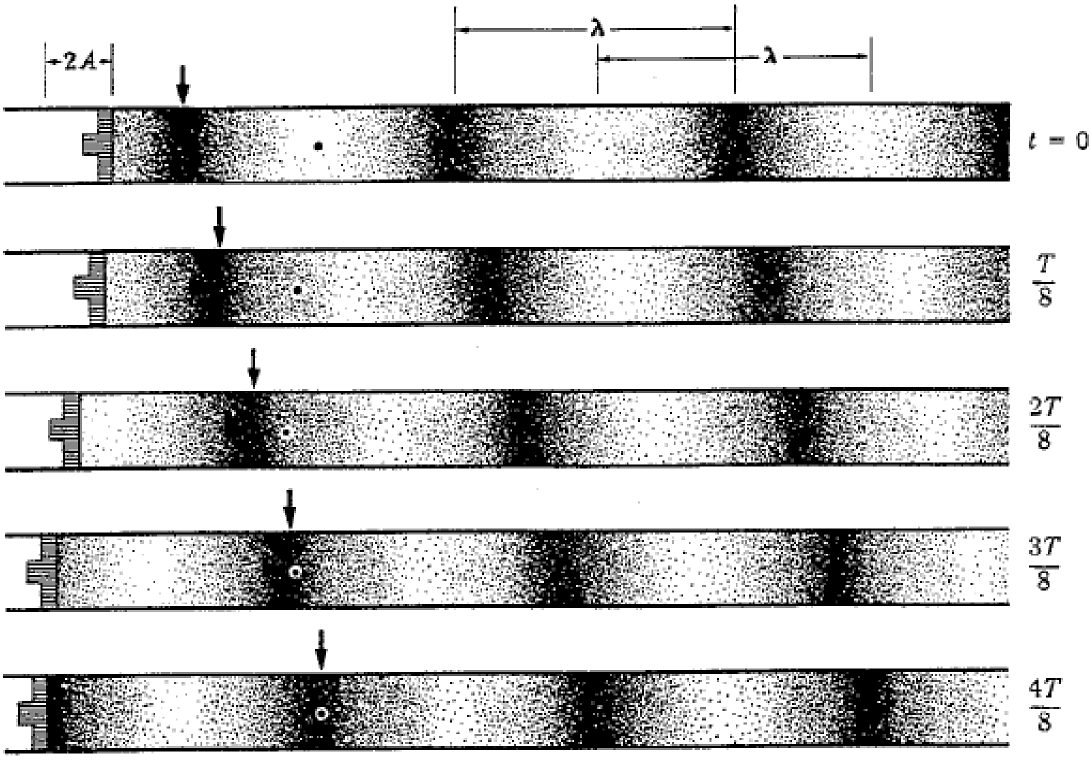

Fig. 6. Sinusoidal longitudinal waves, travelling toward the right, at intervals 1/8 of a period

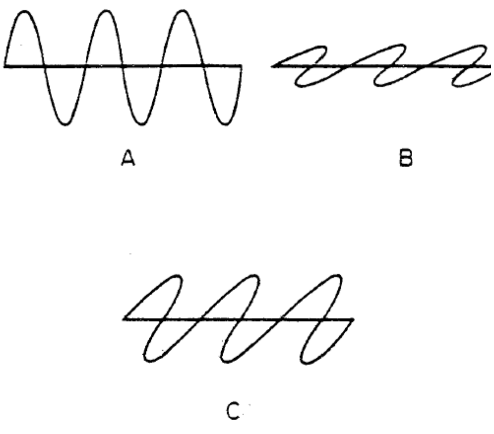

Fig. 7. Transverse waves, travelling in the same direction, but lying in different planes from one another

6. Conclusions

In the present investigation the new theory of *"Real-Time Expert Seismology"* has been introduced and investigated for the exploration of marine and land oil reserves. As the test marine drillings are very expensive with costs of many millions (or billions) of EURO or USD and many times unsuccessfully, which means a big loss of funds, then the highly innovative and groundbreaking technology *"Real-Time Expert Seismology"* has been proposed. By this new and sophisticated technology for energy applications it will be established a strong scientific and technical base for the Science & Technology in the whole world in the emerging areas of oil reserves exploration in the energy field. Thus, through the new technology of *"Real-Time Expert Seismology"*, will be effected the exploration of a significant part of marine and land oil reserves all over the world very fast and by a low cost.

The oil market is a market of many billions every year worldwide. So, this contribution requires an international approach, rather than a local approach, as it is referred to a market all over the world with value of many billions of EURO or USD. It is therefore expected in order the big oil companies to keep and to improve their leading role in the Science & Technology in the whole world, to get involved in the new and groundbreaking technology in the area of Energy, which we are proposing.

Beyond the above, the potential areas and markets of application of the proposed technology will be therefore the oil market all over the world. The method's results will be applicable to all oil companies and scientific organizations working on oil exploration all over the world. It is expected through our proposed new technology the cost for oil exploration to be reduced too much, as there will be no need for so many test drillings, as today. The test drillings cost many millions (or billions) of EURO or USD, and the new technology will reduce them in the possible minimum.

Finally, as our proposed new technique *"Real-Time Expert Seismology"*, is based on a non-linear 3-D elastic waves real-time expert system, working under real logic, then is expected to give the best results. So, our proposed high technology method is based on a very sophisticated model by checking the geological anticlines of the bottom of the sea, in order to decide which areas of the bottom have the most possibilities to include petroleum. It is therefore not necessary to make test drillings in the half ocean in order to find petroleum, like the existing methods.

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