ECHO SOUNDING *

FOREWORD

THE Bureau having received information from the Director of the French Hydrographic Service of a new method of Echo-Sounding by means of ultra-audible (Super-Sonic) sounds, which method of measuring oceanic depths has been invented by Professor LANGEVIN of the University of Paris, the Directing Committee decided that an inspection of the apparatus was desirable, and accordingly at the end of April 1924 I paid a visit to Paris for this purpose.

In addition to making the necessary arrangements for this inspection, the Director o the French Hydrographic Service most kindly detailed Lieut. BENCKER of the Hydrographic Service to accompany me as interpreter ; this officer was also already acquainted with this invention and the benefit gained from his co-operation was very great.

The apparatus was seen at the Works of the " Société de Condensation et d'Applications Mécaniques ", 10, Place Edouard VII, Paris (IX^e^) which Société, it is understood, has obtained all rights of manufacture and sale from Professor LANGEVIN.

On my return through Paris in the month of May the Director of the French Hydrographic Service kindly arranged that I should meet the Professor personally, and again accompanied by Lieut. BENCKER, we met in the University Laboratory where he exhibited a working model of his invention, with the obvious limitations necessitated by circumstances.

The Professor is naturally an enthusiast respecting his own invention, but as everything has been fully tested and practical and satisfactory results have been obtained, his enthusiasm appears to be completely justified ; his explanations were extremely lucid, and as the Professor speaks English fluently, I was able to understand clearly the various details of the apparatus, although possessing no expert knowledge on the subject ; I must here express my gratitude to the Professor for devoting such a considerable amount of his time to ensure my having a thorough understanding of his invention, and also for the extreme cordiality with which he received me.

In these days of the extra-ordinary application of scientific methods to obtain practical results, it will never even be suggested that the last word has been said on this impor-

* These articles have been published separately as Special Publication nº 3.

tant subject, so vital to hydrography and oceanography, but the invention now in question is most certainly another definite step in the direction of that perfection which we all earnestly hope to attain.

A report of Professor LANGEVIN's lecture with reference to this entirely new departure for obtaining measurements of the depth of the sea will be found in the following pages together with a summary of information obtained on analogous subjects.

These have been prepared by Lieut. BENCKER who is now serving in the Bureau as Technical Assistant having been lent by the French Navy for this purpose.

J. F. P.

ECHO SOUNDING

THE *Hydrographic Review* of March 1923, pages 71 and 72, gave a brief account of soundings obtained by echo as the result of certain trials carried out by the United States Navy.

A supplementary report on "Echo Sounding" was published in a *Special publication* by the International Hydrographic Bureau and this was included in the *Hydrographic Review* of May 1924, pages 39 to 50.

The different processes of measuring the depths of the sea by acoustic methods are based on the knowledge of the speed of propagation of sound in sea water, a problem which has been the object of much research; among the most recent, that by Ingenieur Hydrographe MARTI must not be overlooked. He discussed it in an article entitled "A Note on the speed of propagation of sound in sea-water", which appeared in the *Annales Hydrographiques* published by the Hydrographic Service of the French Navy (1919-20, Volume III, page 165, etc.).

The following is a summary, in chronological order, of the results obtained by the different processes of submarine sonic emissions.

Already about twelve years ago Dr. A. BEHM was studying the application of submarine explosions and their reflection from the bottom of the sea for the purpose of obtaining soundings. He applied himself specially to measuring, with the aid of the resonance of a tuning fork under the influence of submarine echo, the extremely short interval of time between the emission of the sound by explosion and the return of the echo. The adjustment of the "Stenochronograph" to a sufficiently precise degree entailed a great deal of laborious research, which resulted in an ingenious sounding apparatus called the "Anschütz Echolot-

Behm ". With this apparatus soundings can be taken with good results up to a depth of 150 metres (82 fms). As stated in the *Special Publication* mentioned above, the description of this apparatus will be found in *Annalen der Hydrographie.* (No. II of 1922, volume 50) published by the " Deutsche Seewarte " of Hamburg.

The "Behm-Echolot Gesellschaft" 31 Haltenstrasse, Kiel, Germany, has undertaken, since 1923, the commercial exploiting of all the most recent apparatus.

An apparatus for sounding by echo has been under trial since 1915, by the Canadian Surveying vessel *Cartier*, and in 1918 the United States Navy concentrated on the subject of submarine research by means of sonic sub-acqueous reflection and utilised the powerful oscillators of the *Fessenden* type produced by the " Submarine Signal Company " of Boston (Mass.). Under the direction of Dr. HARVEY C. HAYES at th- Engineering Experiment Station of Annapolis, these were used in 1918, in conjunction with the submarine sound receiver of the " Standard Navy " type in order to constitute the " Navy Sonic Depth-Finder, " an apparatus which can be used in two ways, as has already been indicated in the above mentioned numbers of the *Hydrographic Review*, namely to sound in depths from 16 to 150 metres (9 to 82 fms) by a measuring process in which a triangle (of which the length of the ship is the base) is used, or to measure depths from 150 metres down to 6,000 metres (82 fms to 3,300 fms) directly.

On page 44 of the *Hydrographic Review*, May 1924, will be found a list of the various elements which constitute the final type of the " Sonic Depth-Finder " which was completed in June 1922, and patented commercially by Dr. HARVEY C. HAYES of the Naval Engineering Research Laboratory, Bellevue (Maryland), and a few technical details relating to the working of this apparatus are given below.

This Sonic Depth Finder was used by the *U. S. S. Stewart* for sounding during her voyage from Newport (Rhode Island) to Gibraltar, from Gibraltar to Port-Said, and from Port-Said to Manilla, from June to August 1922, and various accounts of these soundings by echo have been published by the Hydrographic Office of the U. S. of America. The first were printed on the back of Pilot Charts of the North Atlantic (No 1400) of January 1923, three special sheets relating to the Mediterranean Sea were published also (*i. e.* Mediterranean Sea Sheet 1, Sheet 2 and Sheet 3). Further, it is with this same apparatus that the U. S. Ships *Hull* and *Corry*, which were placed at the disposal of the Carnegie Institute of Washington, drew up, in November and December 1922, the remarkable Bathymetric Chart of California (U. S. H. O. Chart No. 5194 and Pilot Chart, Pacific Ocean, June 1923) covering 34,000 square miles during thirty-eight working days.

This Bathymetric Expedition was dealt with by Dr. Gerhardt SCHOTT in the *Annalen der Hydrographie* of August 1923.

In April 1922, a line of soundings by echo was taken from Marseille to Philippeville (Algeria) across the Mediterranean, by a French Surveying Vessel, utilising submarine sounds produced by fire arms suitably adapted for the purpose : rifle up to 1,000 metres (547 fms) ; 37 m.m. gun for greater depths. This same process was put into practice by the Hydrographic Mission in Algeria in 1923, the diagrams were shown, with the registering oscillograph, at the Physical Exhibition held in the Grand Palais, Paris, in December 1923.

Notice has been received of other trials which took place in November 1922 by a Danish vessel, and in August 1923 in Spain.

The Italian Hydrographic Service, in February 1923, described the use of submarine bombs to produce sound waves in water.

Since 1923, other apparatus for emitting sound have been tried in certain instances by hammering on walls of metallic resonators.

Finally, " la Société de Condensation et d'Applications Mécaniques S. C. A. M. ", 10, place Edouard-VII, Paris (9e), has just secured the exclusive rights for the commercial exploitation throughout the world of an extremely ingenious sound emitter, a patented invention of Professor LANGEVIN and Mons. CHILOWSKY, based on the employment of special vibratory waves, called " ultra sounds " (or super-sonic waves) which propagate themselves through salt water.

On request the " Société de Condensation et d'Applications Mécaniques " can furnish all the commercial electric apparatus which, with the super-sonic emitter, constitute the complete sounding apparatus.

This latest phase of the application of the ultra-sonic waves to soundings has been described in a masterly manner by Professor LANGEVIN in a series of public lectures given at the Collège de France, and before various Physical Science Societies.

The early results obtained by Mons. LANGEVIN were communicated to Washington in June 1917 by the Franco-British Official Mission under the leadership of Messieurs A. ABRAHAM and C. FABRY, Professors of the University of Paris, Sir Ernest RUTHERFORD and Commandant BRIDON.

Likewise during a special Allied Conference, which took place at the French Ministère de la Marine in October 1918, Mons. LANGEVIN described his invention in detail. The American Delegates who attended this Conference were the late Professor H. A. BUMSTEAD, President, and Professor K. T. COMPTON.

The following is a reproduction of the substance of the lecture on " Super-sonic waves and their employment " given by Professor LANGEVIN on 10th May 1924 before the " Society for Encouragement of National Industries ", based on the stenographic report published by the Société de Condensation et d'Applications Mécaniques.

THE EMPLOYMENT OF ULTRA-SONIC WAVES FOR ECHO SOUNDING

THE remarkable solution of the problem of communication and of distant signalling which has been found in the use of hertzian waves and of wireless telegraphy or telephony which employ them, on account of their propagation through the atmosphere above the surface of the and and that of the ocean, is well known to all.

In particular you know that, owing to the application of this new procedure the security of navigation is increased enormously, the importance of which is the more to be considered since it is a matter of safeguarding human life at sea.

Unfortunately, the employment of hertzian waves does not solve every problem of navigation, particularly those which occur when it is a question of *safety of navigation*. In fact, in many cases, it is important to be able to signal or to transmit, not through the atmosphere which rises above the sub-aqueous medium, but through salt-water ; for instance if it is a case of determining the presence of submerged obstacles such as rocks or reefs, or the distance from the bottom of the sea in order to avoid shoals, unexpected or sudden strandings or even the presence of floating obstacles which escape the eye, as also floating dangers — icebergs or vessels — the presence of which is only conjectured. Even the problem of communication by means of submarine signals transmitted through the water comes into this category and is of equal interest.

The question, so important for navigation, of the passage of waves through a sub-aqueous medium, whether it be for signalling at a distance or for the detection by reflection of obstacles, by receiving an echo of a signal from the obstacle, is extremely difficult and practically impossible to solve by means of hertzian waves.

These, which are admirably disseminated in air, are, in fact, absorbed by water and particularly by salt water, which has a high coefficient of absorption, owing to the fact that it is an electrical conductor.

Hertzian waves are electro-magnetic waves whose propagation necessarily implies the existence of an electric field, which, when in water, involves the production of an electric current which produces heat and absorbs the energy of the waves ; consequently the propagation of hertzian waves, even those which are amongst the longest that we know how to use (which are the least absorbed), is arrested within several metres in salt water.

The coefficient of absorption depends on the conductivity of the medium and the result produced is determined by the fact that the amplitude of the electro-magnetic waves produced in a medium of conductivity ν is reduced in the proportion of 1 to e at a distance ε which is given by the formula :

$$\varepsilon = \frac{1}{\sqrt{2\pi\rho\omega\nu}}$$

And if the frequency $\frac{1}{T}$ be given the lowest value compatible with wireless emissions, for instance, that which corresponds to the wave length of 15,000 metres, we find that the distance ε is somewhere about two metres.

If the amplitude is reduced in the proportion $\frac{1}{e}$ the energy given off is reduced in the proportion of $\left(\frac{1}{e}\right)^2$ *i. e.* from 8 to 1, within a very short distance.

It would be impossible to expect to traverse sub-aqueous mediums to any greater distance except by using very low frequencies (as is done for leader cables) but these are emissions which are not available for signalling or detection of echo.

It must not be hoped that hertzian waves can be used for communicating under water, for even light, which in the shape of luminous waves is classed outside of hertzian waves in the scale of wave lengths, is also very rapidly stopped.

For a long time it has been thought possible to use other kinds of waves for propagation : side by side with hertzian waves or luminous waves which affect *ether* (or that which we prefer to call *vacuum*) there exsit some waves, such as *sonorous waves*, more tangible materially (these are called *elastic waves*), which propagate by compression or dilation of the material medium which they are crossing. The speed of propagation of these elastic waves in a certain medium is determined by the formula $V_0 = \sqrt{\frac{E}{\rho_0}}$ in which the density of the medium is ρ_0 and E the inverse of its compressibility.

In water these elastic sound waves have a speed of propagation of nearly 1,480 metres (4,855 feet) per second (that is to say nearly five time faster than in air in which the velocity of sound is about 330 metres 1082 ft) per second).

An essential fact is that this propagation does not involve such rapid absorption as in the case of hertzian and electro-magnetic waves, because there is no electrical field produced and it is by the mere working of alternate compression and dilation that the damping of these waves occurs.

Therefore, they are propagated in the sub-aqueous medium to a more considerable distance than are hertzian waves.

The alternating waves are produced with predetermined frequency.

These frequencies can be those which produce audible sound, comprised between 100 and several thousand vibrations per second, and which, according to personal limit of hearing, are perceptible to the ear from 10 vibrations per second to 20,000. When this number of 20,000 alternations per second is exceeded it may be said that sound waves are no longer under consideration but *ultra-sonic* waves, which cease to be perceptible to the ear.

But whatever this frequency may be and whatever the rapidity with which the alternate compressions and dilations succeed one another, their propagation through salt water is always with the same velocity of about 1,500 metres (4,915 ft.) per second.

There is still some absorption and a progressive reduction of the energy comes into play, due to the fact that, in their propagation, these waves alternately compress and dilate the medium under consideration. This is due to the *viscosity* of the medium. This viscosity varies according to the nature of the medium of propagation : water, for instance, is not very inspissate, it has but low viscosity, nevertheless it has some and that is one of the reasons for the damping of the waves, for the viscosity transforms their energy into heat by shearing and internal friction.

A second factor of absorption is produced by the *calorific conductivity* of the whole medium in which propagation takes place, which, under the action of the variations of temperature produces, in the form of calorific loss, a reduction of energy by dissipation in the form of heat.

Waves which cause compression and expansion produce changes of temperature which are quite appreciable in air (the air becomes heated or cooled according to whether it is compressed or expanded). Likewise, if we take some indiarubber and it is alternately compressed and dilated, it will become heated. In water a similar action occurs : a wave which is propagated through water is represented by regions of compression and expansion separated by intervals which are called *wave lengths* and the distance between the points of maximum compression and maximum expansion is half a wave length.

For this reason, the propagation of the waves cannot continue indefinitely and it is an important point to know to what degree the inherent energy of sonic elastic and ultra-sonic waves becomes absorbed by the medium of propagation.

There exists a very simple formula which indicates, as a function of the coefficient of viscosity, at what distance the initial energy which has been expended to produce these waves is reduced in the proportion $\frac{1}{e}$ ($e = 2.7183$) on account of the viscosity.

If a_0 be the initial amplitude and a that remaining after a distance ε has been covered, then :

$$a = a_0 e^{-\frac{8\pi^2\mu}{3\lambda^2\rho_0 V_0}\varepsilon}$$

This formula shows that the initial energy is reduced in proportion of 1 to e (about one-third of its value) when the wave has travelled over a distance such that the exponent is equal to 1.

This absorption is consequently expressed by the formula :

$$\varepsilon = \frac{3\lambda^2\rho_0 V_0}{8\pi^2\mu}$$

in which therefore ε represents the distance at which the amplitude of the displacement of the particles of the medium is reduced to $\frac{1}{e}$ and μ represents a characteristic modulus of the medium called *coefficient of viscosity.*

This distance ε is the greater as the viscosity λ is the less.

The above formula may be used as a basis to obtain the amount of *the coefficient of penetration* of energy in the medium in spite of its viscosity. This is :

$$\frac{3\lambda^2\rho_0 V_0}{8\pi^2\mu}.$$

By this coefficient it may be seen that the penetration will be greater as the wave length is increased.

The waves of the lowest frequency will be least absorbed ; those of high frequency on the other hand will be more rapidly absorbed.

It appears suitable at this stage to indicate the scale to be considered between frequencies N and wave lengths λ in salt water in the developments which follow.

The table below indicates the connection between these two quantities according to the known relations : $\lambda = VT$ and $T = \frac{1}{N}$.

N = 1.000 periods per second .... (Which is the frequency at which the human ear has maximum sensitiveness)		Corresponds to a wave length of..	1.5 meter.
N = 40,000	ultra-sonic frequencies	..............do................	3.5 cms.
N = 100,000	ultra-sonic frequencies	..............do................	1.5 cms.

Scale of Wave lengths λ

Waves	λ	λ in water		Periods per second	
Hertzien Waves W/T	15,000 meters		................(Lyon)	N = 20,000	
	7,500 —		Time Signals	N = 40,000	
	2,500 —		................(Eiffel Tower).	N = 120,000	
	2,000 —		Communications between fixed stations	N = 150,000	
	600 —		Communications between ship stations	N = 500,000	
	300 —			N = 1,000,000	
	100 —		Early hertzien beam stations	N = 3,000,000	
	30 —		Aeroplanes	N = 10,000,000	
			Short-waves, wireless telephony.		
				N = 10	Acoustic (sonorous) waves audible
Electro-magnetic waves	21 —			N = 16 (ut-2)	
				N = 27 (piano)	Musical waves
			Human voice	N = 64 (bass)	
	0 m. 78			N = 435 (la-3)	
	0 m. 68			N = 500 spoken tones	
	0 m. 50			N = 800 spoken tones	
	0 m. 40	1.5		N = 1,000	
	0 m. 33			N = 1,024 (soprano)	
Elastic waves	0 m. 20			N = 2,048 (lady soprano)	
	0 m. 17			N = 4,700 (fife)	
	1 cm.			N = 30,000	
	9 mm.			N = 38,000	
	7 mm.	3.5 cm.		N = 40,000	Ultra-sonic waves.
	3 mm.	1.5 cm.		N = 100,000	
	2 mm.				
	314 μ		Mercury arc (Infra-red.)		
Luminous waves	100 μ		Incandescent mantle (Infra-red.)		
	0.8				
	0.6		Red (Visible spectrum.)		
	0.5		Green (Visible spectrum.)		
	0.4		Violet (Visible spectrum.)		
			Ultra-violet.		
	0.1		Schumann's rays.		
Radio-active waves	12 angström		X rays.		
	0.2 —		X rays.		
	0.1 —		γ rays.		
	0.05 —		γ rays.		

RELATION BETWEEN VARIOUS METRICAL UNITS EMPLOYED IN VALUATION OF WAVE LENGTHS λ

+		—												
10 exponent	0	1	2	3	.	4	5	6	.	7	8	9	.	10
	0,meter	0	0	0	.	0	0	0	.	0	0	0	.	0
	Meter : m.		Centimeter : cm. — 10^{-2} meter.	Millimeter : mm. — 10^{-3} meter.				Micron : μ — 10^{-6} meter.				Millimicron : μμ — 10^{-9} meter.		Angström unit — 10^{-10} meter.

If the formula giving the absorption due to viscosity be applied to water, then :

$$\varepsilon = 2 \times 10^5 \lambda^2$$

and it is ascertained that, for a frequency of 40,000 this absorption will occur at a distance of about 30 kilometers (32,760 yds.) at which the energy expended at the starting point will be reduced to a third of its value. If a frequency of 100,000 be taken, and this involves a wave length two and a half times smaller, the distance will be about 5 kilometers (5,460 yds.), so that if it be true that it is of interest to use waves of high frequency, as will be seen presently, it is not advisable to go very far in this direction, for absorption due to viscosity intervenes. The reduction of energy by calorific conductivity is entirely negligible in the case of water. If on the other hand, we use sonic waves in water, such as those of submarine bells, absorption does not have any appreciable effect : 1,000 periods per second would involve an absorption 10,000 times less.

It may be interesting to note, by the way, that if we apply this result to air instead of water, the absorption due to viscosity would be always represented by the same formula, but the constants for water must be replaced by those for air, and :

$$\varepsilon = 2 \times 10^{3} \lambda^{2}$$

Further, in the case of air, which is compressible, loss by calorific conductivity intervenes and produces an absorption which approximates to that which is due to viscosity itself alone. Therefore, if the calorific conductivity be taken into account also, it produces an absorption equal to that of viscosity and the total absorption becomes doubled as both viscosity and conductivity act simultaneously. The range when the amplitude is reduced in the ratio $\frac{1}{e}$, becomes twice as small.

In water the position is very different, the calorific conductivity has scarcely any effect, water being but very slightly compressible. There is not an appreciable variation of temperature and absorption is almost entirely due to viscosity only.

For instance, waves of a frequency of 100,000 which, in water, will travel as far as 5 kilometers (5,460 yds) before being absorbed to the extent of two-thirds, would scarcely travel 2 or 3 metres in air. A sound of 100,000 periods per second would be almost completely lost within several metres in air.

However, Lord RAYLEIGH has demonstrated that, at a great distance from a source, the tone of the sound perceived is modified, the very low components remaining " infinite " in relation to those which are higher.

Confirmation of the theoretical conclusion is found in the foregoing *viz* : in air, that which might be called a high note is absorbed quicker than a low note and this in proportion to the square of frequency.

The lowest waves are less absorbed because their wave length is longer, and it is the square of the wave length which, in the formula, is the determining factor of the range.

If the numerical data referring to water and air be introduced into the formula, it is observed that, for equal wave lengths, the absorption is 100 times smaller in water than in air. And if waves of equal frequency be considered, since the velocity of propagation in water is five times greater than in air, this gives $\frac{100}{5}$ *i. e.* 20 times more, and consequently, for equal frequency, the absorption in water is 2,000 times less than in air. In other words much greater ranges can be attained in water.

If it be laid down, as a necessary condition, that the absorption must not be too considerable, for instance that it be reduced to $\frac{1}{3}$ in about 10 kilometers (5.4 naut. m.) then :

$$\varepsilon = 2 \times 10^5 \lambda^2 = 10^6$$

which shows that the corresponding wave length must be more than 2.2 cms. *i. e.* the frequency which can be deduced by the well known formulae :

$$\lambda = VT \text{ and } TN = 1$$

must be less than 70,000 periods per second.

This would give an advantage to waves of low frequency ; however there is a limit in this direction, for waves of low frequency would have the inconvenience, as will be seen presently, of not permitting " directional " emission and reception.

The question of absorption is of great interest for it determines the limits of frequencies of the waves to be employed. In practice, the use of waves of more than 100,000 periods per second should not be attempted.

The earlier investigators who attacked the problem of sub-aqueous communication limited themselves to the domain of sonic-waves, in which there is no appreciable absorption. It is the domain of what may be called the submarine bell. Mr. FESSENDEN, an American Engineer, in particular has devised a most ingenious submarine bell which, at frequencies which can be heard by means of a submerged microphone, can produce four or five H. P. of sound at a frequency of 1,000 periods.

Of course, practical interest in these submarine bells had considerably diminished since the invention of wireless telegraphy. Where it is easy to pass through the atmospheric medium it is preferable not to pass through the submarine medium.

But the use of elastic or sonic waves in water, affords possibilities which hertzian waves do not afford, and which elastic waves would not afford if propagated in air.

In addition to signalling or transmission at a distance which can be obtained so easily by means of hertzian waves, there is the problem of *detection*, that is to say, the problem of recognising the presence of an obstacle at a distance without running up to it, and this problem happens to be solved by a process which was indicated a long time ago and which consists of utilising an echo.

If we send out waves, if we utter a cry, and if an obstacle reflects the elastic waves, we can be warned of the presence of the obstacle, the bottom of the sea for instance, by means of the echo returned thereby.

But to perceive the echo, it is necessary that its return be delayed as regards the departure of the signal. Hertzian waves do not allow of this owing to their extremely high speed which is 300,000 kms. (162,170 naut. m.) per second, a velocity which is 200,000 times greater than the velocity of propagation of elastic waves.

So that, up to the present day, even if such proposals have been put forward, at any rate no one has succeded in practice in disclosing the presence of an obstacle by means of hertzian waves, whereas sonic and ultra-sonic waves, which are propagated at a reasonable speed, will produce an echo with a delay of two seconds when they have struck an obstacle situated at a distance of 1,500 metres (1,640 yds.) from their source.

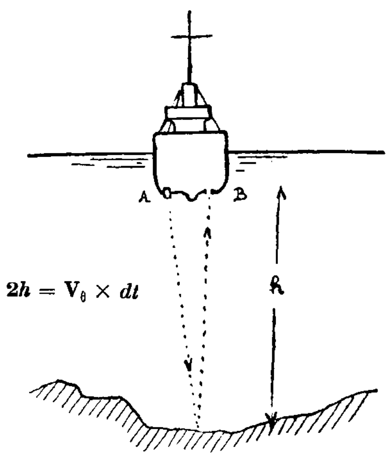

Fig. 1.

Besides the fact that they are propagated without much absorption, elastic waves have the great advantage that they allow the distance of the bottom of the sea to be obtained by the echo method. This method consists of sending a signal, more or less brief according to the distance at which the detection is to be made, then of measuring the interval of time *dt* between its departure *A* and the return *B* of the echo. The distance *h* is deduced from this interval by multiplying it by the known or presumed velocity V_θ which gives $2h$ directly *i. e.* twice the distance required since the course was travelled over twice, *viz* : going and returning.

Fessenden's apparatus, which had somewhat lost its importance on account of wireless telegraphy, regains practical interest when it is a question of sounding. In fact the American Navy has recently used Fessenden's apparatus to measure depths in the deeper parts of the Pacific up to about 8,000 metres (4,375 fms.).

However, from the point of view of this problem of detection, the sonic method, which uses frequencies of this order, presents this difficulty, *viz* : that it can only be utilised for rather considerable depths, since, in order to obtain a signal which is audible, of a period of vibration of one thousandth of a second, it must last at least several thousandths of a second, say one-hundredth of a second, and in this latter interval of time the propagation has already extended over 15 metres (nearly 50 ft.).

Consequently, in order to have a measurable interval, it is necessary that the distance be fairly considerable (100 metres *i. e.* 50 fms.).

This method suffers from another difficulty which must not be overlooked when a frequency, the wave length of which is 1.50 m., is used. It is that the emitter must not be of enormous dimensions, especially if it is to be taken on board a ship. Fessenden's apparatus has a diameter of 30 to 40 centimetres (12 to 16 ins.), and this size may be considered as the limit which must not be exceeded.

It is well known that under these conditions, the waves spread in all directions. There is not what is called *directional emission* so that if a signal is sent and an echo be received, the delay of the echo obviously allows the distance of the obstacle to be ascertained, but not the direction in which it lies.

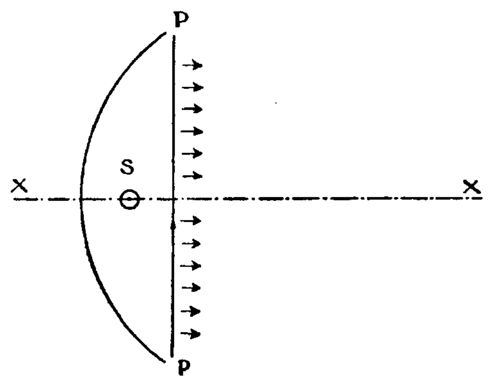

Fig. 2.

On the other hand, both distance and bearing will be obtained if a source, the dimensions of which are large in proportion to the wave length, could be used and, as the size of the source cannot be indefinitely increased for reasons of space, the solution consists in diminishing the wave-length employed in order that it should remain small with reference to the size of the source.

This is the essential fact which was pointed out by Lord RAYLEIGH The latter was a very great physicist and a Master in a great many spheres, but above all others he was wonderful in acoustics. His book *The Theory of Sound* is epoch making; it is the most wonderful book that can be found on the subject. He studied particularly this phenomenon of emission of sounds by sources of varying dimensions. Directional emission could be obtained by means of a whistle placed at the focus of a reflector so as to obtain a parallel pencil of rays; but if the wave length corresponding to the disturbance produced is great in proportion to the aperture of the reflector, it would be useless to employ a reflector on account of the phenomenon of *diffraction*.

If it be supposed that the emission is made by a source, the effect of the reflector being to render the reflected disturbance synchronous on the whole surface *PP*, the whole would act as if there were a single source *PP* and the wave produced is synchronous throughout the plane section perpendicular to the direction *XX* of propagation.

From the theory of diffraction developed by FRESNEL, which is applicable in acoustics as well as in optics, it follows that, if for this emission by means of a surface the whole of which is excited synchronously, the result will occur exactly as if there were a plane screen with an aperture of the same size as the source and as if a plane wave impinged on the back thereof. The problem consists in ascertaining what will occur on the other side of the aperture.

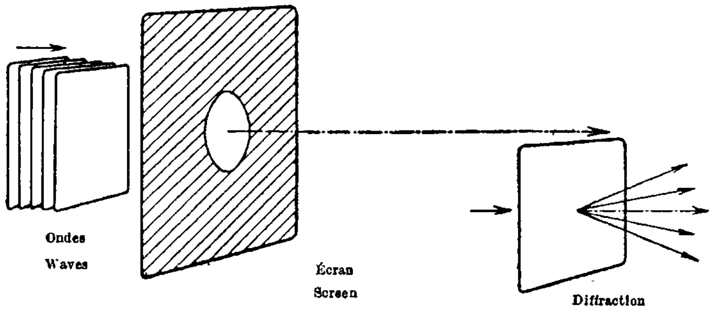

Fig. 3.

It is well known that if the dimensions of the aperture are small in relation to the wave length (in the case of light shining through a very small hole), the light is not propagated in a straight line, but spreads in every direction. An aperture in a screen does not let one sonic ray pass through but the sound spreads out in all directions.

Take a wave of frequency 40,000 and for the sonic source a diameter of 20 centimetres (7.9 ins.), so as to have a wave-length which would be approximately a sixth of the diameter. Then matters will turn out quite differently, and the ultra-sonic pencil instead of producing an emission which spreads in every direction, will find itself confined to a sort of cone similar to that of the light from a motor-car head light. The *angle of spread* of this cone is determined by the relation between the wave length and the dimensions of the aperture, and everything that happens beyond the aperture in the direction of propagation is determined by this relation.

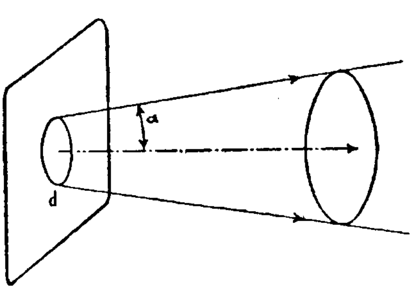

Fig. 4.

If this source be assumed to be circular and its diameter be *d*, the emission will occur with maximum intensity in a direction perpendicular to the plane of the source and the perturbation spreads out in the medium of propagation in the shape of a pencil which will be the narrower the shorter the wave-length is in relation to the diameter of the aperture.

It is the problem of distant diffraction caused by a circular opening.

It is assumed that the perturbations emanating in an oblique direction from different points on the source would differ in speed of travel among themselves and this would be greater as the direction is more inclined from the normal.

The theory presumes that there will be on each side of the central maximum which corresponds to the varying propagation along the normal (on which every perturbation arrives in phase agreement) a minimum of no intensity at all which extends over all the directions in which the phases arrive in opposition.

By calculation it may very easily be proved that the angle α between the normal direction and the direction of nil intensity is given by the very simple formula :

$$\sin \alpha = 1.2 \frac{\lambda}{d}.$$

Beyond this principal cone, through which radiation passes, there is yet another series of secondary maxima and minima, but these are much less pronounced and thus the major part of the emitted energy (more than 90 %) is concentrated in the principal cone, which is narrower as the wave-length is smaller with reference to the size of the source.

The existence of this concentration of radiation is particularly useful when it is desired to make directional signals, and still more, if directional detection, *i. e.* the determination of the bearing of the obstacle, is required for the echo will reach maximum intensity when the normal passes through the direction of the echo. (The distance also may be known if the interval of time, which elapses between the departure of the wave and the reception of the echo, be measured.)

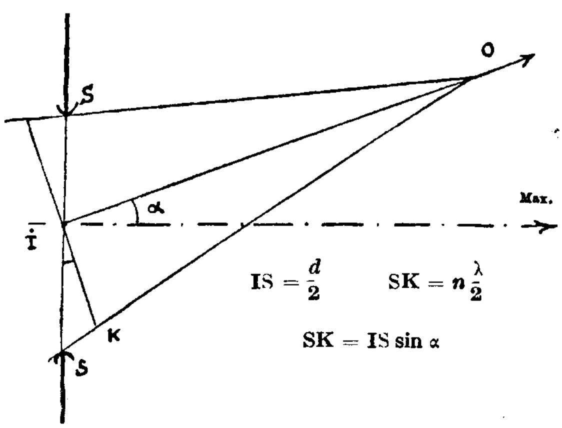

Fig. 5.

Moreover, this property also affects the problem of reception.

A receiving apparatus will reach the maximum degree of sensitiveness when the waves fall perpendicularly on its surface, but when these waves are inclined, the reception will be modified the more rapidly as the diameter of the receiver is large in relation to the wave length.

This possibility of using a directional effect naturally involves the question of determining the degree of divergence which should be given to the pencil.

It is obvious that this pencil must not be made too narrow, for the search for the obstacle would be too difficult. This angle of divergence, which is governed by conditions of the search, must be neither very great nor very small.

In practice, in ordinary cases of signalling or detection of an obstacle this ratio should be approximately one-fifth or one-sixth of the aperture, which corresponds to an angle of about ten degrees at the summit of the cone.

This lays down a proportion between the wave-length and the diameter of the source.

As sources whose diameter is very great cannot be employed, the higher limit of the wave-length must be determined in accordance with the admissible diameter of the source. If a diameter of about 20 centimetres (7.9 ins.) be adopted it will be found that :

$$\lambda \leqslant 3.5 \text{ cms. } (1.4 \text{ ins.})$$

Thus the wave-length must be shorter than 3.5 centimetres. Consequently, this wave-length, whose lower limit is determined by the conditions of absorption, is also limited at its maximum by the conditions which are due to the angle of spread of the pencil.

Now a wave-length of 3.5 centimetres in water corresponds to 40,000 periods, and it is this number which has been ordinarily adopted in practice. Thus the problem, as it now appears, gives very precise limitations under which it is necessary to work.

In practice a wave-length of 3.7 centimetres (1.5 ins.) and a diameter of the source of 22 centimetres (8.7 ins.) can be used and this gives an angle of divergence of about 10° which contains nearly the whole radiation. This offers the advantage of making it possible to search for an obstacle with this pencil in the same way as with a searchlight one area is lit up more than another.

From the foregoing the considerable advantages inherent in the employment of these ultra-sonic waves may be understood, and these waves have in addition the property of being imperceptible to the ear, and thus they are, to a certain extent, secret. With the FESSENDEN bell, the power of which reaches 4 H. P. ; an infernal noise had to be endured on board.

The proposal to use ultra-sonic waves was put forward in a very clear manner by an Englishman, Mr. RICHARDSON, who, of course, saw no other means of producing these waves except by mechanical devices. He proposed a reflector in the form of a segment of a sphere at the focus of which is placed a form of hydraulic whistle ; the sonic waves were reflected by the reflector and then were propagated through a predetermined cone of diffraction. This whistle never worked satisfactorily. Mr. RICHARDSON simply indicated the possibility, but in practice the attempts gave no result, as insufficient power was produced.

Subsequent experiments have been made and in particular, the inventor of the Turbine, Sir Charles PARSONS, tried a hydraulic siren under the sea to give a sufficiently high frequency, but he has never been able to produce a quantity of these ultra-sounds in any way comparable with the H. P. of sound that FESSENDEN succeeded in producing.

The question remained to some extent in the domain of theory, until towards the end of 1914, when Monsieur CHILOWSKY had the very ingenious idea that, since it is a matter of working with the same frequencies as those employed in Wireless Telegraphy (40,000 periods in fact correspond to Hertzian wave lengths of 7,500 metres), it would perhaps be possible to use in this domain the very great advantages presented by Fessenden's apparatus, which in reality is an electro-magnetic apparatus.

The submarine bell is simply an electric motor using alternating current and alternating motion, which strikes the water at a cadence of 1,000 blows per second, thus transforming the electric power into elastic power.

These frequencies, suitable for directional signalling and for directional detection, are precisely the frequencies which wireless experts can produce with as much power as is desired.

When an electro-magnetic wave-length of 7,500 metres is under consideration it means that the electric oscillations which produce the hertzian waves are precisely of the necessary frequency.

Monsieur CHILOWSKY thought that it was but necessary to take these electric oscillations with the full power which they are capable of developing and to transform then into elastic oscillations, doing for these frequencies what Mr. FESSENDEN had done for sonic frequencies, *i. e.* transforming their alternating current into alternating mechanical motion which will strike the water 40,000 times per second.

Monsieur CHILOWSKY's idea, in order to produce this transformation, was to take a rigid surface as a source and to give this surface the alternating motion necessary to give off radiation, that is to say to make it attack the water, it being attacked from the other side.

This type of effort can be obtain easily by electro-magnetic action.

Monsieur CHILOWSKY was thinking of an apparatus closely analogous to a telephone receiver. A telephone is a magnet with a coil and an iron or steel membrane. When a periodic current passes through it, the attraction exerted on the membrane varies and communicates to it an alternating motion. If a telephone receiver of sufficiently large dimensions be taken and a current of 40,000 periods be passed through it, by putting the membrane into contact with water the production of an emission might be expected and for receiving such emission a similar receiver might be used.

A carbon microphone receiving ultra-sonic waves introduced into an electric circuit permits the detection of the arrival of waves by means of the periodical current set up in the circuit, into which it is introduced, by the changes in resistance of the microphone.

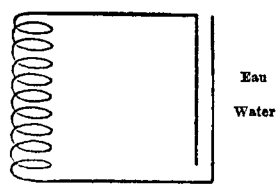

Fig. 6.

The problem thus set by Monsieur CHILOWSKY, which is, in principle, to change the electric oscillations, which we know how to produce with great power, into elastic oscillations of the same power, was communicated to Monsieur LANGEVIN by Monsieur PAINLEVÉ, and it struck him at once that the telephone would be of no use on account of the great frequency dealt with.

Then Messieurs LANGEVIN and CHILOWSKY turned their researches in another direction and experimented with the *singing condenser*. Instead of having recourse to magnetic action they thought that the electro-static action of the attraction of the arma ures of a condenser would provide a more suitable solution to the problem.

The oscillating circuit of the wireless telegraphist involves, as you know, a *self-induction* and a condenser and when oscillations are produced by any form of excitement the condenser is charged and discharged alternately. When it is charged, its two armatures are charged with electricities of opposite signs so that the electrical oscillation in the circuit is accompanied by periodical attractions. These attractions, which are produced at each half period, are capable of giving movements which could be transmitted to water provided that the inner armature of the condenser be fixed and that the outer be placed in contact with the water.

The main difficulty consisted in the magnitude of the power to be produced. It is certain that if communication at considerable distances is required, or if an obstacle, such as a rock, a ship, *etc.*, is to be revealed at a fairly great distance, the returning wave has but the smallest fraction of the power emitted ; in order that some should return it is necessary to emit a great deal of power, and it is in emitting a great deal that difficulties are encountered.

In order to realise this difficulty, it is necessary to consider the magnitude of the power which must be emitted. Even now, ultra-sounds cannot be emitted with as much power as that of the sound emitted by FESSENDEN, the modest power of about 100 watts, *i. e.* 1/7 of one horse power, is the ordinary limit, though Mons. LANGEVIN has been able, in exceptional cases, to emit up to 1 K. W. *i. e.* more than 1 H. P. of ultra-sound.

In practice a power of about 100 watts only is required, and that amounts, in principle, to 1 watt per square *cm.* with the apparatus, of which the dimensions are limited, as has been said, to a diameter of about 20 centimetres, and whose surface consequently will be approximately 100 square centimetres.

A simple calculation shows that the amount of pressure to be exercised must be approximately 1.5 atmospheres, and consequently if we wish to produce the necessary attraction by means of the singing condenser, it is necessary that it be of a power corresponding to 1 or 2 atmospheres, *i. e.* of the order of from 1 to 2 kilogrs. per square centimetre.

It has been possible to obtain these conditions which allow of the use of a singing condenser to emit ultra-sounds, and thus the possibility of transforming electric waves of high frequency into elastic waves of the same frequency of appreciable power, is confirmed.

During the course of operations it was necessary to be guided constantly by the intensity of the ultra-sonic emissions produced, and for this purpose a convenient and valuable process based on the existence of "*pressure of radiation*" was used.

Pressure of radiation is due to the fact that any radiation, which is not material but consists of a modification, when propagated through matter, strikes an obstacle, it exercise pressure there on.

MAXWELL foresaw the existence of pressure of radiation. A luminous ray in fact exercises pressure on any obstacle which it encounters. The effort exercised on each unit of surface of the obstacle, represents the density of the energy of the radiation on the front of the obstacle.

It is remarkable that this same property exists in the case of elastic waves; if a flood of words be directed against an obstacle, pressure is exerted on this obstacle. It is easy to calculate the pressure of radiation.

If the amplitude of the oscillation of the medium be designated by a, at the departure, it may be easily calculated that the amplitude of the pressure corresponding to the propagation of these waves, is in proportion to the amplitude of displacement, in accordance with the formula :

$$p_0 = \omega \rho_0 V_0 a_0$$

in which ω is equal to the pulsation of the waves, ρ_0 is the density of the water, V_0 the velocity of propagation of sound in water.

The power emitted per unit of surface (sq. cm.) is given by the expression :

$$\frac{p_0^2}{2\rho_0 V_0}.$$

When this radiation is directed onto a pallette suspended by a torsion wire, the pallette, if its thickness be appropriate, is pushed by the ultrasound and the torsion of the wire permits the measurement of the power emitted. Thus the results obtained during the course of experiments in the transformation of electric energy into elastic energy can be checked continuously.

Under the conditions which exist when the singing condenser is used, it is necessary to produce periodical variations at the same frequency as radiation is required, and these variations correspond to amplitudes which can be deduced easily from the preceding formulae.

If the frequency of 40,000 periods for a pressure of 10^6 dynes be taken, an amplitude a_0 which equals 3×10^{-5} cms (*i. e.* 3/10 *of a micron*) is produced.

This results from the fact that water is a medium which is but very slightly compressible.

The above is the amplitude at departure, but the amplitude on return, when the waves are received as an echo from an obstacle, is of the order of 10^{-10} cms.

The periodical displacements undergone by the molecules of water when they strike the obstacle are of the order of one hundredth of the dimensions of a molecule, and in order to emit considerable power the amplitudes which must be obtained are 10^{-5} cms. This is much the more difficult in that this entails high pressures. The electro-static pressure given by the formula $\frac{Ku^2}{8\pi}$ shows that in order to obtain attractions of this intensity *in vacuo* electric tensions u of the order of one million volts per centimetre are necessary.

However, it is this electro-static solution which permitted the first emissions to be obtained and gave proof of the possibility of emitting ultra-sonic waves. But the conditions under which they are obtained were too close to the utmost possible limit of the electric field, sparks were given off in the inside of the condenser, which consequently had but an extremely short life.

At the same time much trouble was experienced with the microphone receiver. Immersion of the microphone is not without disadvantages; first of all, in order that it be sensitive a certain definite pressure between the grains of carbon is necessary, and in water the motion of the ship caused this pressure to vary.

Monsieur LANGEVIN then thought of returning to a possibility which he had considered in the beginning, but which he discarded rather hastily. His excuse is that Sir. E. RICHARDSON had considered the same possibility also and likewise dropped it for he believed that it could not solve the problem. It was the turning to account of the phenomenon of "*piezo-electricity.*"

In principle, if we consider the problem in its general form, it is a question of transforming electric oscillations into elastic oscillations. Naturally, every phenomenon which brings into play mechanical action of electric or magnetic origin can solve the problem.

It has been specially indicated above that the first idea of Mons. CHILOWSKY was to utilise magnetic action as in the telephone. The two inventors considered the employment of electrostatic action between the two armatures of a condenser, and the phenomenon of magneto-striction presented by iron when it is magnetised or when it is in a state of electric polarisation was examined also, but this was quickly eliminated from the field of possibilities.

As soon as Monsieur LANGEVIN thought of utilising the piezo-electric properties of quartz the problem of emission and reception of ultra-sonic waves, and of their application to navigation for the detection of submarine obstacles and for sounding, was solved.

The piezo-electric phenomenon, which was discovered in 1880 by Pierre and Jacques CURIE, represents one of the most remarkable examples of the power of thought on scientific work, for it is after having foreseen it that Pierre and Jacques CURIE discovered the phenomenon, which represents exactly the best means which can be selected, as experience proves, between electric phenomena and elastic phenomena.

Piezo-electric properties are met with in certain crystals, for instance quartz, which is used and which in nature ordinarily appears in the form of hexagonal prisms, which is also the form of the perpendicular section thereof of which the three diagonals, which are at 120 degrees from one another, are three dyad axes of the crystal; they are called also " electric axes " on account of the phenomenon now under consideration.

If a sheet *AB* be cut from the crystal perpendicular to one of these electric axes, the thickness of which lies in the direction of a dyad axis *XY* and the surface contains what is called the triad axis of the crystal, it is found that if this sheet be compressed it will become electrically polarised although quartz is an inert substance. If two sheets of tinfoil be placed on the two faces they form the armature of a condenser and if

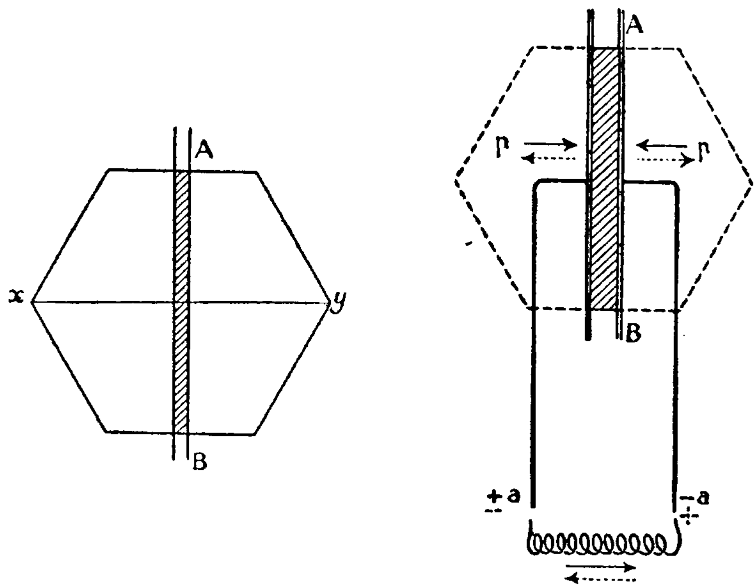

Fig. 7.

these two sheets be connected by a wire, when the plate is compressed it takes up what is known as an electric polarisation which causes the passage of a current in the circuit.

The electrical charge *A* of polarisation is proportional to the pressure *p* exercised and to the surface *S* compressed with a coefficient δ called *piezo-electrical modulus* the value of which, for perfect quartz, was determined by Pierre CURIE :

$$A = \delta p S \quad \text{and} \quad \delta = 6.45 \times 10^{-8} \text{ cgs.}$$

If the combination so formed be compressed, the armatures will be electrified and a current in a definite direction will be obtained; and if the pressure be released a current in the reverse direction is produced. This is the direct piezo-electric phenomenon. The same arrangement can be used to detect the arrival of elastic waves; if the two armatures of the condenser are placed one in contact with the water and the other insulated therefrom and ultra-sonic waves reach them, the variation of pressure in the water periodically compresses the quartz and produces periodical currents. If a self-induction be inserted so that the period proper to the electric circuit is exactly the same as that of the incident waves, the current which tends to be produced will be amplified by resonance, and an electric oscillation will have been produced with ultra-sonic waves, due to the piezo-electric properties of the quartz.

This provides the means of direct transformation of elastic oscillations into electric oscillations in a circuit, and if the quartz condenser be tuned in accord therewith the resulting effect may be amplified.

Further, if the two extremities of the quartz condenser be connected to an amplifier of the same type as that which is used for Wireless, the arrival of the waves can be detected by the same process of detection as is used in Wireless. It is as though the whole formed a sub-marine " aerial " sensitive to elastic waves as an ordinary " aerial " is sensitive to electro-magnetic waves, and this system replaces the microphone with advantage.

As soon as M. LANGEVIN had tried it, it worked admirably and due to the recent developments which have been introduced into the process of amplification, the use of triode valves, a satisfactory solution of the problem was found.

Thus the necessary process of amplification, which enables this little phenomenon of piezo-electricity to be used, was at hand. Since then reception has not given any trouble. It was sufficient to place in juxtaposition a piece of stone, two plates of tinfoil – one in contact with the water and the other insulated inside – and then to follow it up with the usual wireless apparatus.

But emission was always giving trouble and once more it was quartz which overcame the difficulty, although at first glance this would never have been thought possible.

It provided the solution of the problem of emission because the phenomenon discovered by Pierre and Jacques CURIE has the important peculiarity that it is reversible, as LIPPMANN foresaw, *i. e.* if the quartz be compressed, it polarises electrically, and produces a charge in the armatures of the condenser, but conversely if the condenser be charged, the quartz contracts spontaneously, and if the condenser be discharged the quartz expands. The same piezo-electrical modulus comes into action. If pressure be exercised on the quartz, it polarises electrically in proportion to the pressure, the coefficient of the proportion being the modulus $\delta = 6.45 \times 10^{-8}$ and then, inversely, if between the two casings a difference of pentential u be established the plate of quartz will contract to an amount in proportion to u with the same coefficient

$$\alpha = \delta u$$

The reciprocal action is thus very simple ; a pressure produces a polarisation and a difference of potential established between the faces of a plate of quartz produces contraction or expansion proportionate to the difference of potential. Thus the solution of the problem is obtained.

If a condenser be taken such as the condenser of an oscillating circuit and electric oscillations be produced therein, they will induce contractions and expansions of the quartz.

The condition which appears necessary is that the magnitude of these contractions and expansions must be precisely of the amount of amplitude desired.

What deformation and, consequently, difference of potential would be necessary in order to emit the desired power ?

It is easy to calculate the corresponding amplitude a_0 which must be obtained at departure from the source as a function of the frequency and the power to be emitted by cm² $\frac{P}{S}$:

Thus $$a_0^2 = \frac{2P}{S \rho_0 V_0 \omega^2}.$$

For 40,000 periods and a power given per square centimetre of 1 watt, the amplitude at the source is in the neighbourhood of 5×10^{-5} cms.

This figure is already small, but the figures are still much more surprising when that which happens at the return is considered and also that it is the same organ which serves both as a projector to emit the radiation and as an ear with which to perceive the echo sent back. When a signal or an echo is received the amplitudes are very much reduced for they diminish in accordance with the law of the square of the distance ; the amplitudes on return, which press on the quartz thus producing the currents which must work the amplifier, are of the order of 10^{-10} cms. that is to say a very good ultra-sonic reception must be available, for the molecules of water have movements the amplitude of which does not exceed one billionth of a centimetre, the movement of each molecule of water in contact with the quartz is only about 1/300 of the dimensions of the molecule itself.

Given the amplitude which it is necessary to produce at the point of departure the amplitude of the necessary difference of the potential is deduced from the formula. It is found that 50,000 volts are required. In a ship, where it is necessary to carry the wires down into the holds, such high tension cannot be considered.

This difficulty had already been commented upon by Sir E. RUTHERFORD, who, in a communication to the British Admiralty, put forward various suggestions with reference to the employment of piezo-electric phenomena.

Even if the necessary difference of potential remains as high as 3,000 volts, which is admissible on board ship, the energy, which is proportional to the square of the difference of potential, would be 400 times too small. The problem therefore appeared to be insoluble.

But the introduction of the phenomena of resonance led to its solution.

At the receiver arrangements are made so that the electric circuit containing the quartz has the same frequency of oscillation as the exterior excitement ; thus an amplification is obtained which is in addition to that resulting from the use of the valve-amplifier.

For emission, an elastic resonance is introduced. If a sheet of quartz of a certain thickness be taken, it will vibrate somewhat like a rod with a frequency in inverse proportion to its thickness ; again if, when this quartz plate is excited by an alternating current of a certain frequency, matters be so arranged that the elastic oscillation of the sheet shall be exactly in resonance with the exciting waves the amplitude of the mechanical movements which the sheet takes up will be augmented.

Let a quartz sheet of 15 mms (0.6 in.) in thickness be taken. It possesses a period of elastic vibration in the direction of its thickness, which proper period is determined by the condition that there are two displacements, " maximum amplitudes ", on the two sides, consequently that the sheet must have a thickness of half a wave length for the frequency under consideration and for the material of which the sheet is constitued.

The speed of propagation of sound in quartz is about 4,500 metres (14,750 ft.) per second and a sheet of 15 mms. in thickness will correspond to a half wave vibration of 150,000 periods.

It coincides with 150,000 periods, *i. e.* a wave length of 2,000 metres. f the condenser of which it is part is connected with an oscillating circuit tuned on this wave length and if electric oscillations be excited, the action of compression and expansion due to the alternating difference of potential would act in resonance with the oscillation proper to the quartz : amplification of the amplitude will thus be obtained.

Calculation has shown that if a sheet be in contact with water through one armature of the condenser and if the other armature be in air, the amplitude obtained by means of the same difference of potential is multiplied by the factor $\frac{2m}{\pi}$ the quantity m being equal to

$$\frac{\rho_1 V_1}{\rho_0 V_0}.$$

This quantity is practically equal to 8, and consequently the ratio of amplification is 5.

Thus amplifications of 5 are obtained for the amplitude and of 25 for the energy, which is proportional to the square of the amplitude.

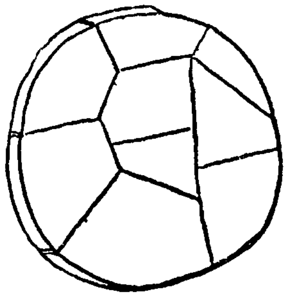

Fig. 8.
Mosaïque de quartz.

Thus for the same amplitude of difference of potential, the amplitude of the movements transmitted is quintupled if this resonance be employed and the transmitted energy is multiplied by 25. So that in order to emit 1 watt per square cm. only 12,000 volts are necessary instead of 60,000 volts.

The sheet of quartz which M. LANGEVIN used for his experiments was a very fine sample measuring 10 × 10 cms. (15.5 sq. ins.) and 16 mms. (0.61 in.) thick, cut by WERLEIN, and it was with this exceptional sheet as regards dimensions and purity, and operating under conditions of resonance, that 1 kilowatt of ultra-sonic power was obtained. This power was measured by means of a pendulum, and the fishes which happened to be in the container were killed though the mechanics of this action could not be clearly explained.

However, some difficulties still remained ; the 12,000 volts necessary are still too much for the convenience of technical practice and also piece of quartz sufficiently large and pure cannot be found (this diminishes the piezo-electric modulus).

Under these circumstances Monsieur LANGEVIN utilised a thin sheet of a few millimetres in thickness, instead of a thick sheet of quartz, and as big pieces are difficult to obtain, he built up a mosaic 10 cms. (4 ins.) in diameter with pieces 2 mms. (0.1 in.) thick.

Further, instead of obtaining the elastic resonance from quartz, it is procured from steel. This mosaic of quartz is stuck between two plates of steel, of which one formed the cover of the watertight box. The other steel plate is placed inside the box, insulated and in contact with the quartz, and an opening was made through which passes the conducting cable connected with the other plate of steel. The whole of the interior can be filled with a more or less insulating thick mixture. These two plates of steel are each 3 cms. (1.2 ins.) thick, *i. e.* 6 cms in all. The sandwich thus formed constitutes a compact solid of stone and steel without any movable organ which might have a period of vibration of its own.

If the resonance be commenced at the proper period, it is the total thickness which determines the half wave-length, and consequently, the power at which resonance is obtained.

This arrangement led to a very surprising and unexpected result, which was that, far from acting very much worse than with a fine piece of quartz, everything happened as though the steel itself had become piezo-electric.

If the quartz be thin in relation to the steel, the factor of amplification becomes :

$$m_1 = \frac{\rho_2 V_2}{\rho_0 V_0}.$$

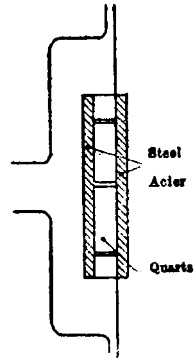

Fig. 9.

In view of the density of steel this factor is equal to 25, so that in utilising this remarkable property an emitted energy 625 times greater is obtained with the same difference of potential. Where 60,000 volts were necessary, only 2,500 are required now, which corresponds to ordinary conditions of practice.

Increase of power in emission is accompanied by an increase of sensitiveness in reception.

This system of a triple plate, quartz inserted between two plates of steel, has already been utilised in order to establish standards of wave-length. It is evident that thus a system is available which has a definite proper period and which, when excited, reaches a maximum of resonance when the frequency which excites it is equal to the frequency proper to it.

When endeavours are made to deal with the problem of the working of an organ such as the piezo-electric sandwich in connection with an oscillating electric circuit, in the same way as we are led, in order to characterise the working of the " aerial " in wireless, to introduce the conception of the energy which it borrows from the oscillating current and to characterise it by a *resistance of radiation* so, in the present case, the ultra-sonic waves emitted are said to constitute energy derived from the quartz ; the apparatus may be compared to a resistance introduced into the circuit and would likewise have a certain " resistance of radiation. "

A rather curious result, which deserves to be noticed, is that, if it be supposed that this resistance of radiation is shunted on the condenser, it becomes quite independent of all conditions with the sole exception of the angle of spread of the ultra-sonic pencil emitted, and this angle is definitely limited. It is found that, for angles commonly used, this resistance of radiation is about 100,000 ohms.

But on the other hand if the resistance which must be placed in series

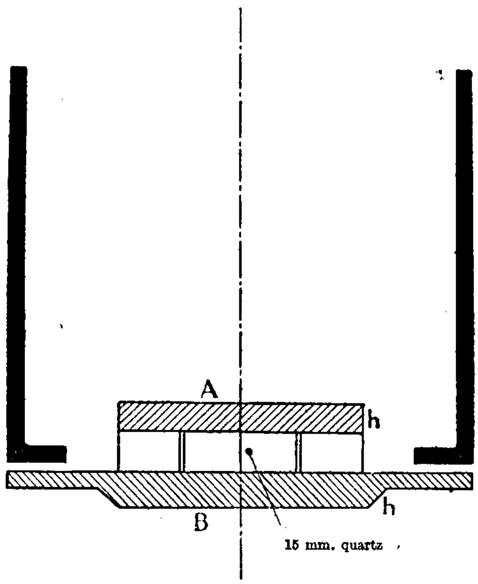

Fig. 10.

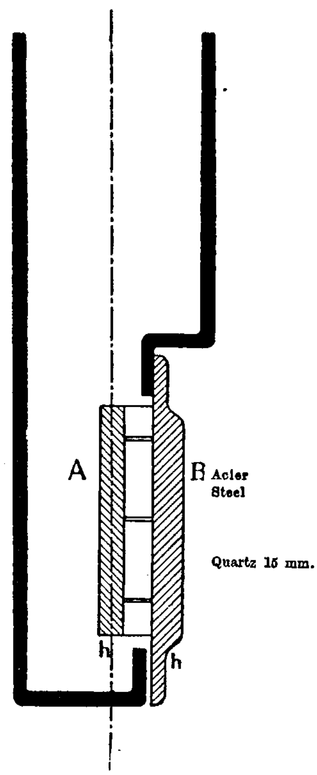

Fig. 11.

be sought, it will be found to vary according to circumstances ; in the apparatus constructed by the inventors it is about 200 to 300 ohms.

Naturally, these appliances of a new type have hardly commenced to enter into practical use, and the problem which they present will most likely cause new solutions of the question or further improvements to appear.

The results obtained were most satisfactory from the very first.

In practice :

The armatures of the condenser consist of two plates of steel *A* and *B* of equal thickness *h*.

One of these plates is in contact with the water and closes a tube which fits into a well built into the ship.

The other plate, insulated by the sheet of quartz, is charged, to a varying potential at the desired frequency, by a triode valve acting as heterodyne.

If it be desired to produce waves of frequency N in the steel, then h must be made equal to one quarter of the wave-length in steel at this frequency.

Then the plates become resonant by pressing on each other through the sheet of quartz and the movements of the surface of plate B easily attain an amplitude of 10^{-4} mms.

If the apparatus is to be used for taking soundings the axis of the steel plates coincides with that of the tube (Fig. 10) but if it is intended for exploring the waters surrounding the vessel the plate-axis is at right-angles to that of the tube about which it may be turned, as shown in Fig. 11.

The charge acts on a transformer and the induced current, which is increased by an amplifier such as is used in wireless telegraphy, is registered by a simplified oscillograph fitted with a chronograph. The commencement of the curve obtained gives the moment of emission of the first wave. As soon as an echo is produced the shape of the curve changes suddenly and a sharp angle marks the moment of the return of the first wave reflected.

Thus not only is an echo noted but it is also known that the wave has taken t seconds on its outward and return journey. Therefore the reflecting body lies $\frac{1435 \times t}{2}$ meters $\left(\frac{4{,}708 \times t}{2} \text{ feet}\right)$ from the point of emission.

Originally transmission from point to point was tried, as with optical signals. The range obtained was 9 kms. (4.9 nautical miles).

Then trials were made to fix the position of floating bodies by echo. This was succesfully done at 2,000 metres (2,187 yards). It was found possible to disclose the presence of mines also.

Finally, the French Hydrographic Service experimented with this system for taking soundings and was quite satisfied with the results obtained.

The depths found were perfect between 6 metres (20 feet) and 450 metres (245 fathoms). This is not astonishing for the sound rays diverge but very slightly and cover, at the bottom of the sea, an area of a few square decimetres (square feet) only.

Thus the depth obtained is that of a point and not the average of a more or less extensive area.

The above, without doubt, should show the great advantages of the system and the importance of its application. In fact, it appears probable that it will be adopted for use by all vessels whose safety will be enormously increased thereby.

The following figures, which were thrown on a screen during the lecture delivered by Professor LANGEVIN, show the different devices employed.

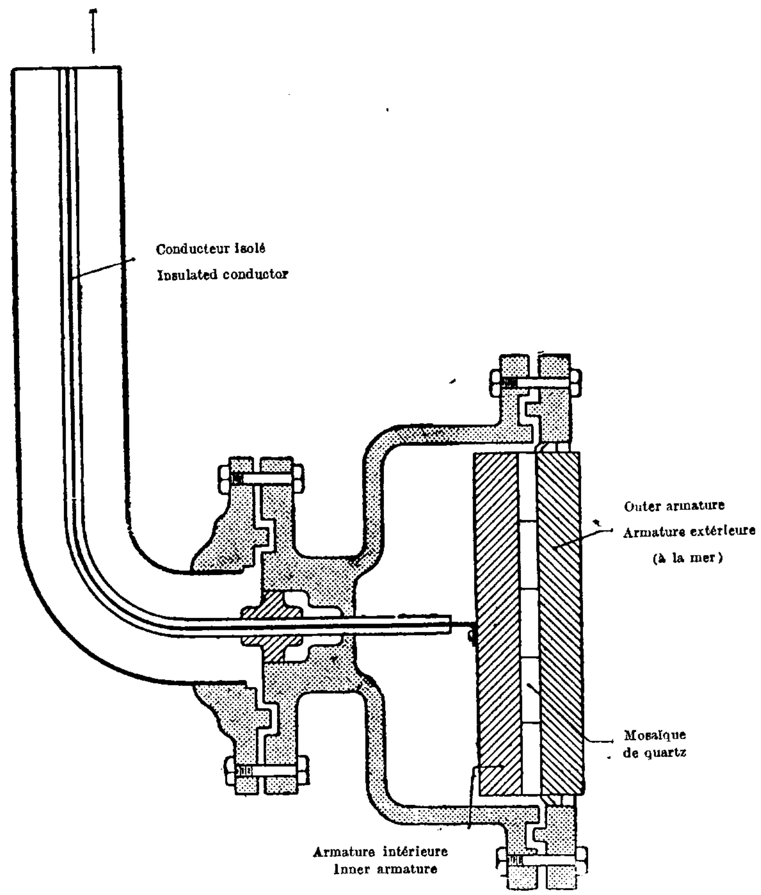

Fig. 12.

EXPLANATORY REFERENCES

Fig. 13.

Ultra-sonic apparatus for horizontal detection by means of continuous waves, fed by continuous current, and aural observation.

A set of valves produces electrical oscillations in a circuit tuned in accord with the frequency of the ultra-sonic waves to be emitted, *e. g.* 40,000.

1. Lamp valve with three electrodes (triode valve).

2. Continuous current generator.
3. Condenser, voltage regulator.
4. Condenser of oscillating circuit.
5. Grid-plate transformer.

The oscillating circuit, fed by the action of the valve, acts by induction on another circuit in resonance with it. This circuit included the following condensers coupled in parallel :

6. One variable oil-condenser to regulate the frequency.

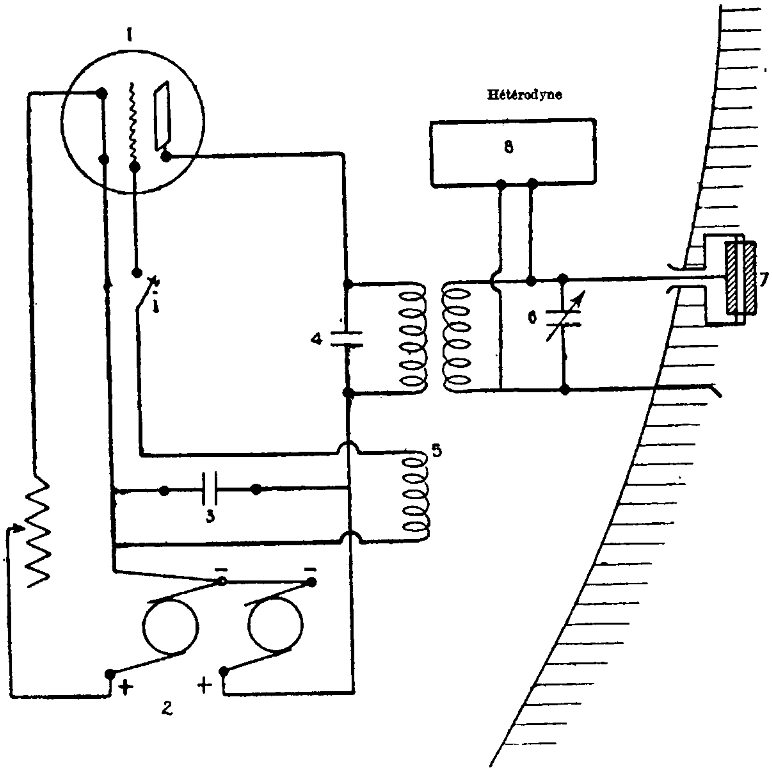

Fig. 13.

7. The quartz condenser (*see* drawing attached, Fig. 12) which allows the electric oscillations to be transformed into ultra-sonic waves of the same frequency.

For receiving; the same quartz condenser receives the ultra-sonic waves and transforms them into electrical oscillations in the oscillating circuit (5-6-7).

An amplifier (8) is connected, permanently, to the terminals of the quartz condenser and the detection of the ultra-sonic echo by the usual methods of Wireless is thereby obtained.

Fig. 14.

Ultrà-sonic âpparatus for accurate sounding in medium depths with visual reading.

1. Primary circuit of a Ruhmkorff coil.
2. Accumulators for feeding the coil.
3. Cam-switch producing one interruption per second in the primary of the coil and rotating synchronously with the oscillograph (13).

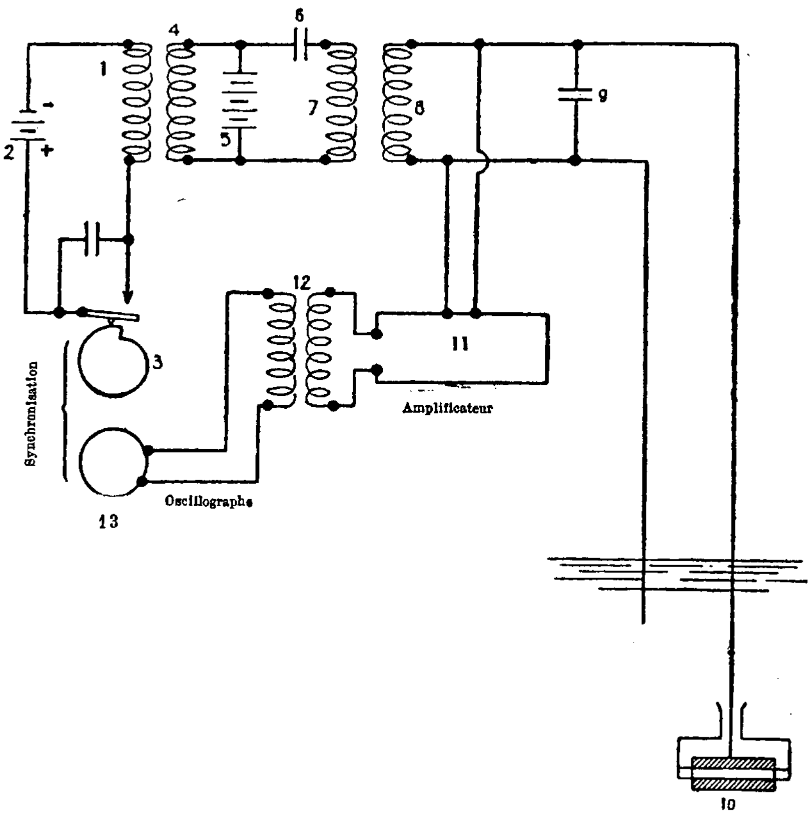

Fig. 14.

4. Secondary of the coil feeding the exciting circuit by shock.
5. Multiple spark-gap of shock circuit.
6. Condenser.
7. Self induction of the shock current.
8. Self induction of the oscillating circuit which generates ultra-sonic waves.
9. Tuning condenser.
10. Quartz condenser.
11. Amplifier.
12. Transformer, the primary of which is placed in the circuit of

the plate of the last valve of the amplifier, the secondary being in the circuit of the oscillograph.

13. Oscillograph, the movement of which is synchronous with that of switch (3).

If a precise measurement is to be made, and this is of particular interest when it is a question of sounding, it is necessary to have a method of measuring the interval of time between the departure of the wave and the echo.

It was necessary to employ very brief signals at emission by producing one spark in the primary circuit of the Ruhmkorff coil and, consequently, producing a short group of damped waves in the oscillating circuits. The quartz then emits a group of damped ultra-sonic waves.

At every revolution of the switch (3) a spark is produced in the primary of the coil and a group of ultra-sonic waves is emitted by means of the "shock circuit" and the damped oscillation thereby produced in the circuit of the quartz condenser. The duration of the emission of this group of waves is at the most one-thousandth of a second.

Its emission produces a current in the oscillograph by means of the amplifier, and also a displacement of a luminous spot from a fixed position on a scale due to the synchronism established between the movement of the switch and that of the oscillograph.

The echo produced by the bottom returns to the quartz condenser after an interval of time which is proportional to the depth and produces another deviation of the oscillograph. The distance on the scale between this deviation and that due to the emission gives the depth within about a metre since a variation in depth of this order produces a variation of $\frac{1}{750}$ of a second in the interval of time between the departure and the return which variation is easy to discover with groups of waves of which the duration of the emission is less than $\frac{1}{1000}$ of a second.

The above process has been used and has given excellent results, it being very easy to measure depths by this method, but Monsieur LANGEVIN has recently introduced another arrangement which consists of transforming the above method into a method of *direct reading, i. e.* instead of measuring the interval of time between the departure of the signal and the arrival of the echo by means of an oscillograph, he turned once more to a method which has been known for a long while and which has been utilised particularly by COTON in the process for sound ranging.

It consists in the measurement of an interval of time by means of the quantity of electricity which has passed through a measuring apparatus, either a galvanometre or a fluxmetre.

If a current of constant intensity be passed through a measuring apparatus, this current being started at the commencement of the interval of time to be measured and cut off at the end of this interval, that is to say, starting the current at the moment of emission of a signal and cutting it off by means of the echo, the measuring apparatus will give an indication which is proportional to the interval of time.

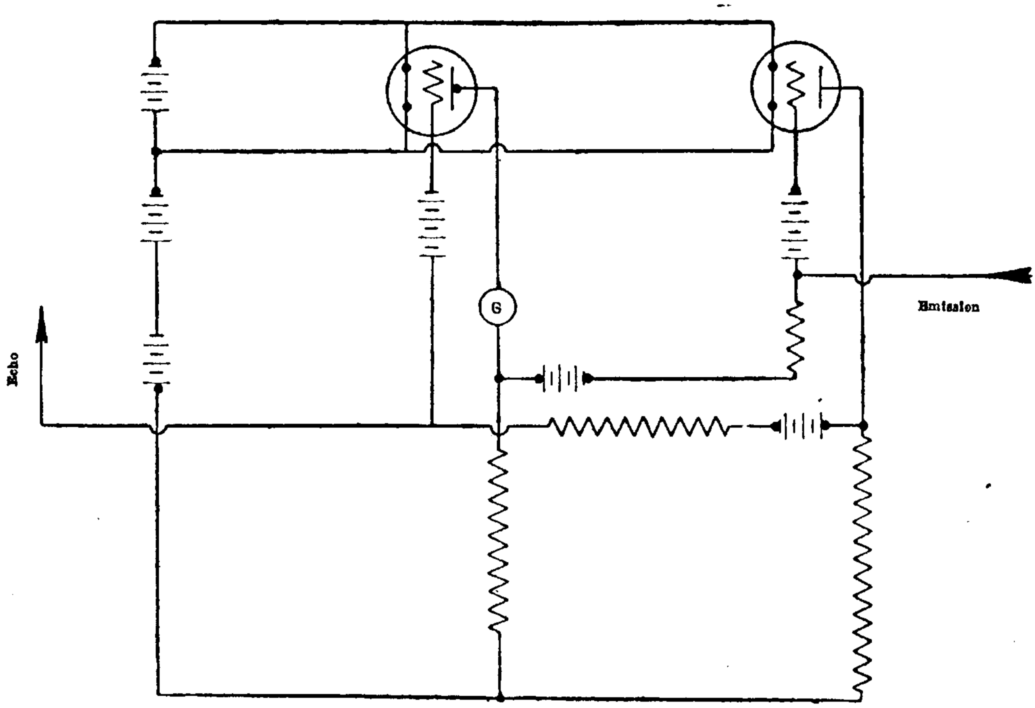

Fig. 15.

Various solutions of this problem have been found, but in particular by a process which is entirely automatic.

The essential role is carried out by a swinging organ with valves containing two triode valves cross connected, as indicated by Fig. 15.

This system, under the ordinary conditions of stability, has only two stable conditions ; either the current passes into the first valve and does not pass into the second at all, or *vice versa*. It is commonly expressed by saying that it cannot act otherwise than by swinging from one condition to the other.

The action sought was that when the system is in its normal situation, the emission of the signal should make it swing and the arrival of the echo should send it back to its original position.

With reference to the action exercised by the echo, this arrives through the amplifier and acts on one valve, while the other is suitably coupled to the circuit of emission.

On emission, there is considerable current in the quartz, and the action exercised on the entry valve carries it over to that exercised on the other.

On the other hand, on reception a very feeble current at the amplifier passes through the oscillating circuit of the quartz and it is the current at the exit valve which preponderates.

This works with very great rapidity and therefore makes the use of very short groups of waves possible, and this is essential for sounding in very shallow water because of the high velocity of transmission of each group of ultra-sonic waves.

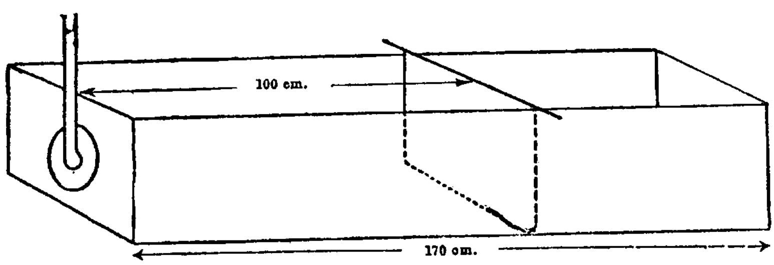

Fig. 16.

The first trials were made with a container 3.50 metre (11 1/2 ft.) long and M. LANGEVIN has been able to measure the length thereof by reflection from the end.

Soundings have even been taken in a small experimental basin the dimensions of which are 50 × 50 × 170 cms (19.7 × 19.7 × 145.6 ins.) and in which the maximum space was 1.70 metres. An iron plate could be moved longitudinally in this basin in order to produce the return of the echo from the desired distance. The return of an echo has been received distinctly from 1 metre only (*see* Fig. 16).

The different methods of employment of ultra-sonic waves have just been enumerated; that of *continuous waves*, which allows prolonged or permanent hearing of an echo, and that of the *oscillograph* which allows the exact distance to be measured directly by means of a galvanometer or of a fluxmeter; these latter can be placed on the bridge, and the signal is sent at will by pressing a bell-button; the fluxmeter which indicates the depth, can be placed beside the compass, the helmsman or the officer on the watch (*see* Fig. 17).

But there are also *Recording Processes.*

Engineers have already a recording device which consists of the shock excitation apparatus, the reflecting oscillograph being replaced by a recording oscillograph. This is how those soundings were obtained which were exhibited at the Exposition de Physique Industrielle at the Grand Palais, in December 1923. It is a shock excitation apparatus and an Abraham oscillograph which constitute the Marti sounding apparatus.

Another extremely simple method of recording consists in connecting

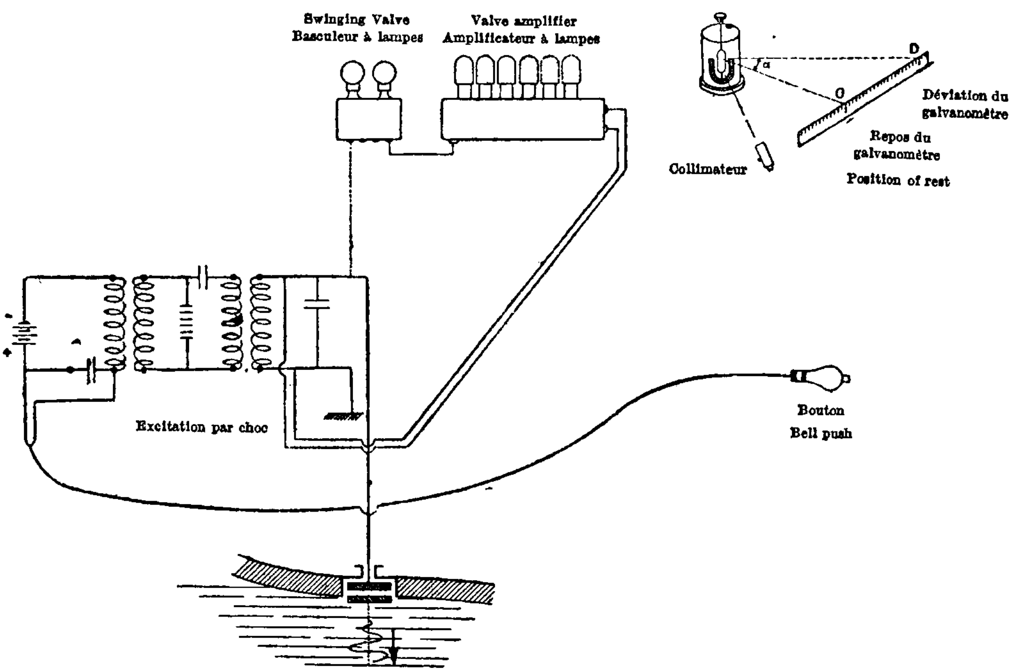

Fig. 17.

a cylinder and a stylus to the plate and to the filament of a triode valve controlled by respectively ; this grid is connected with the receiving and emitting circuits in such a manner that a current passes from the stylus to the cylinder at each emission of a signal and reception of an echo (*see* Fig. 18).

The stylus is of iron and the recording cylinder is covered with a sheet of ferrocyanide paper. Whenever a signal is sent or an echo returns a spot appears in Prussian blue on the paper. The cylinder revolves at a known constant speed, and the emission of the signals is made at each revolution in synchronism with the rotation. The pencil moves sideways parallel to the axis of rotation of the cylinder. All the marks registering the emission of each group of ultra-sonic waves are thus found along the same generator of the cylinder; the marks registering the reception of the return of each echo are to be found at variable distances from this generator on an arc of the cylinder, and if the surface

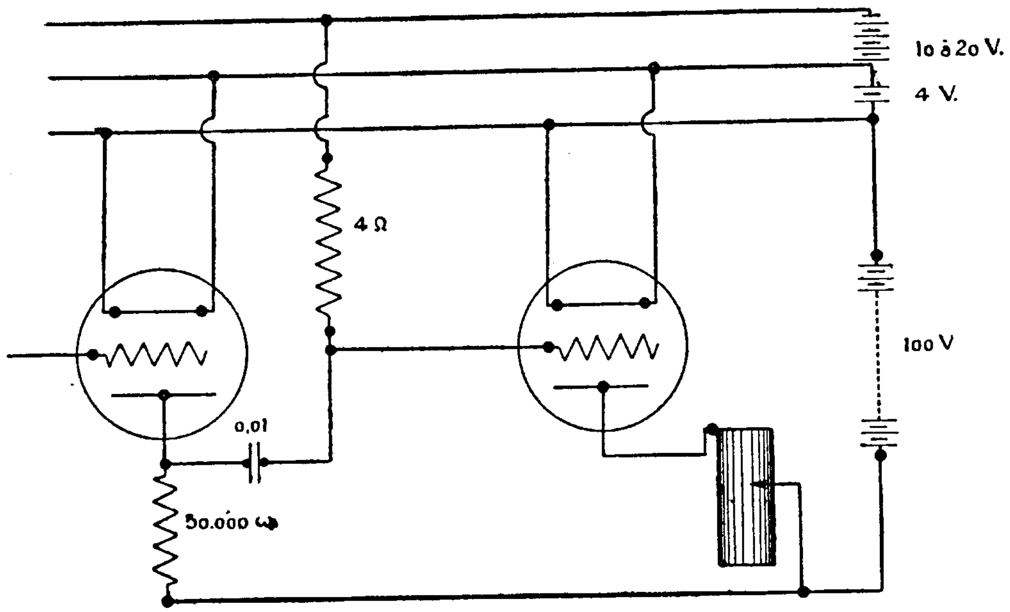

Fig. 18.

of the cylinder be developed on a plane the curve of the bottom of the sea will be found to have been traced on the paper.

MEASURING OCÉAN DEPTHS BY ACOUSTICAL METHODS

To amplify the information already given in the *Hydrographic Review* of May 1924 (Page 39) as to the methods of acoustic sounding, several theoretical notes made by Dr. Harvey C. Hayes, Research Physicist. U. S. Navy, are reproduced below. These notes were presented at the State Meeting of the Franklin Institute held 21st March 1923. (Extract from the *Journal of the Franklin Institute*, Vol. 197, No. 3, March 1924.)

THE possibility of measuring ocean depths by acoustical methods has been recognized for a number of years and numerous methods and devices developed and designed for this purpose are listed in the patent office. Most of these devices attempt to determine the depth in terms of the time required for a sound signal to travel to the sea-bottom and reflect back again to the surface.

One of the first patents pertaining to this art was granted to A. F. EELLS, of Boston, Massachusetts, wherein he was allowed two broad claims covering the method of determining depths by measuring the time intervening between the transmitting of a sound signal near the sea-surface and the return of its echo from the sea-bottom. Since then numerous patents have been taken out covering specific apparatus designed for measuring this time interval, but none of these devices has proved to be practical for the reason that they have failed in most cases to measure the time interval in question with sufficient reliability and accuracy, and in many cases have proved to be too delicate to withstand the adverse conditions often met with on sea-going vessels and too complicated to be operated by a ship's personnel. A brief description of some of these devices follows :

Fig. 1 shows the principle of operation of a sounding device invented by Reginald A. FESSENDEN. [1] — Numeral 1 represents a disc made of insulating material that is rotated at a uniform speed by motor (2). The disc carries a conducting segment (3) that closes the electrical circuit through a submarine sound transmitter (4) when it passes beneath brushes (5), thereby sending out a sound signal. This segment also closes the circuit through a telephone receiver (6) when it passes across the brushes (7). If the echo of the signal meets the microphone or other type of sound receiver represented by numeral 8 at the instant segment (3) short-circuits brushes (7), it will be heard in the telephone receiver (6) and the time of sound transit from the transmitter to the receiver by way of reflection from the sea-bottom will be equal to the time required for segment (3) to travel the angular distance subtended between the two pairs of brushes and indicated by the pointer (9) on the scale (10). This condition is brought about by rotating brushes (7) about the insulating disc (1) by means of the handle (11).

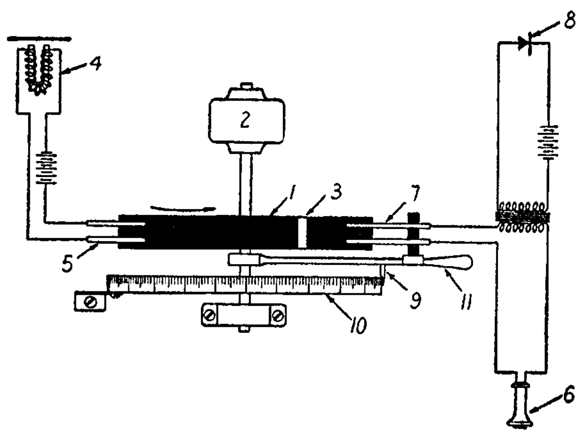

Fig. 1.

In practice the disc must be rotated at considerable speed or the angle swept out by the segment while the sound travels to the sea-bottom and back will be too small to measure with sufficient accuracy. This results in sending out sound signals in rapid succession and the return of echoes from the sea-bottom in still more rapid succession for the reason that a sound signal usually echoes back and forth between the surface and sea-bottom several times before its energy is absorbed. Under such conditions sound can be heard in the telephone for numerous settings of the brushes (7) and the relation between the depth and the scale reading becomes indefinite.

Another device for measuring this time interval makes use of an electromagnetic recorder. This device, illustrated in principle in Fig. 2, attempts to determine the short-time intervals involved in taking shallow soundings by recording the transmitted signal and its returning echo on the magnetic tape (1), while it is driven rapidly by means of variable speed motors (2), and then measuring the time interval between the two

[1] For a more complete description of the Fessenden depth-sounding apparatus, see U. S. Patent No. 1,217,585.

records when the tape is run at a much slower speed. This measured time interval multiplied by the ratio of the reduced speed to the recording speed gives the time interval between signal and echo. In the figure, numeral 3 represents the recording and reproducing magnets. These also serve for erasing the record. Numeral 4 represents a double-throw double-pole switch by means of which magnets (3) can be inductively connected with transmitter (5) and receiver (6) for recording the signal and its echo, or with the telephone head set (7) for hearing the reproduced record. The rheostat for controlling the speed of the motors is indicated by numeral 8.

This method, while excellent from the standpoint of theory, has not proved to be practical for the following reasons :

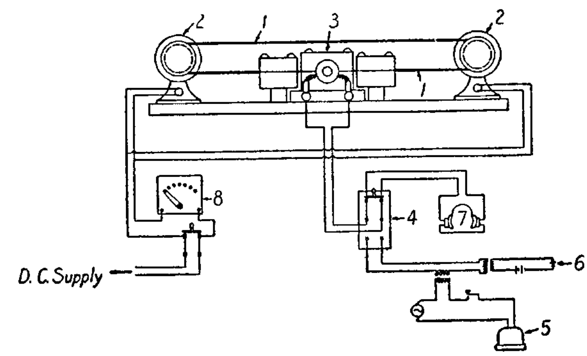

Fig. 2.

(*a*) The magnetic tape does not record the signals unless their intensity is above a certain threshold value, which is comparatively high, and the echoes cannot be kept above this value over regions where the coefficient of reflection of the sea-bottom is low or over regions where the depth is great.

(*b*) The local disturbing noises always present on shipboard are comparatively intense and their record ofttimes distorts the record of the signals and echoes to such an extent that they cannot be readily recognized, and as a result the time interval cannot be accurately measured.

(*c*) It is difficult to determine accurately the ratio between the reproducing and recording speeds of the motor.

(*d*) The time interval, as measured at the retarded speed, cannot be determined with a high degree of accuracy for the reason that the record of both the signal and the echo then becomes less sharply defined ; and although this method of determining the short interval between signal and echo results in some gain in accuracy, the gain is not proportional to the ratio between the recording and reproducing speeds.

(*e*) Finally the method is too slow to give soundings on short notice, as is ofttimes desirable when a ship is in dangerous waters.

Samuel Spitz, of Oakland, California, has attempted to measure ocean depths with apparatus that first records the signal and its echo on a magnetic tape and then amplifies the reproduced record. He utilizes this increased electrical output to operate a complicated system of relays and magnetic clutches and claims to accurately record by means of a pointer and dial the depth corresponding to the time interval between signal and echo as recorded on the tape. His method and apparatus, as disclosed in U. S. Patent 1,409,794, would appear to have the inherent weaknesses of the « magnetic tape method » plus the difficulties and uncertainties that are always present to a greater or less degree in complicated relay systems. But even if the relays should function perfectly, it would seem that the local disturbing noises, caused by propellers, auxiliary machinery and slapping of waves, which (no matter how selective the receiving system may be) are recorded on the magnetic tape to some extent, would ofttimes trigger off the automatic recording apparatus and give erroneous records of depth that might be misleading. A depth-sounding device is worse than useless unless it can be absolutely depended upon to give reliable sounding data at all times.

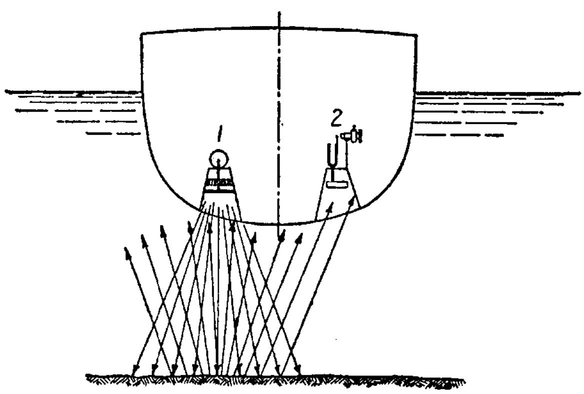

Fig. 3.

Alexander BEHM, of Kiel, Germany, started work on the problem of measuring ocean depths by means of sound waves about twelve years ago. His first efforts were devoted to methods that involved measuring the time interval between signal and echo. Recognizing the inherent difficulties in making such measurements, he turned his attention to the possibility of making depth determinations by measuring the intensity of the echo. His method of doing this can be understood in connection with Fig. 3 wherein numeral 1 represents a submarine sound transmitter designed to produce a fairly pure sound of constant intensity and pitch. The sound passes from the transmitter to the sea-bottom and a portion reflects back to the receiver, represented by numeral 2, where by acting upon a resonant chamber it causes a tuning fork to vibrate. He measures the intensity of the echo in terms of the amplitude of vibration of a small bead carried by one prong of the fork and observes the amplitude of its motion by means of a microscope. And since the intensity of the echo and the amplitude of vibration of the fork are each a function of the depth, he calibrates the microscope scale directly in terms of depth.

While this method avoids the difficulties encountered in measuring short time intervals, it introduces others that are equally hard to overcome and one that cannot be overcome. It is very difficult to generate a sound having constant intensity and pitch under various operating conditions, and it is equally difficult to keep a receiver accurately tuned to this pitch and of unvarying sensitivity. It is probable that Doctor BEHM has gone far toward overcoming these two difficulties, but we fail to see how he can make allowance for the variations of the coefficient of reflection of the sea-bottom where, according to our observations, this factor may change as much as 25 per cent. over comparatively short distances.

It is probable that Doctor BEHM fully recognized these weaknesses in his method and apparatus for he later resumed his efforts to measure the time between signal and echo and has finally succeeded in making this measurement with a high degree of accuracy with comparatively simple and rugged apparatus. His transmitter, represented by numeral 1 of Fig. 4, consists of a tube extended through the ship's skin and the sound signal is produced by exploding a cartridge that has been slipped into position in this tube. The cartridge is fired electrically by closing a key mounted on or near the recording apparatus which is located in the chart house or on the bridge. The receiver is mounted in a similar tube, numeral 2, projecting from the opposite side of the ship's hull where it is shielded from the direct sound generated by the cartridge. The means for recording the time of sound transit between transmitter and receiver by way of reflection from the sea-bottom consists of an ingenious design of chronograph that is started moving when the cartridge is fired and stopped by the fluctuation in the receiver circuit when the sound wave, reflected from the sea-bottom, strikes the receiver.

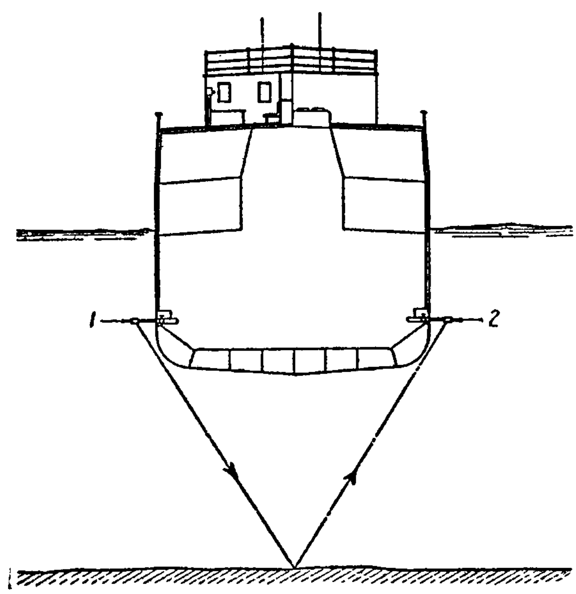

Fig. 4.

This sounding device, which the inventor calls the Behm-Echolot, represents a large amount of excellent research and the exercise of considerable ingenuity. It should give reliable sounding data for depths within about eighty fathoms.

As an instrument for aiding navigation, any depth-sounding device should be able to do more than determine the depth of water occasionally. It should serve to take any number of soundings in rapid succession in order that well-defined charted contours may be identified with certainty and thus serve for determining the position of the vessel. In the case of the Behm-Echolot this would not only require a very large supply of cartridges, but would prove to be expensive.

It has been found in practice that a determination of the slope of the sea-bottom is helpful in locating " landmarks " along a charted route and that the value of a depth-sounding device, as an aid and safeguard to navigation, is greatly enhanced if it will also serve to determine the

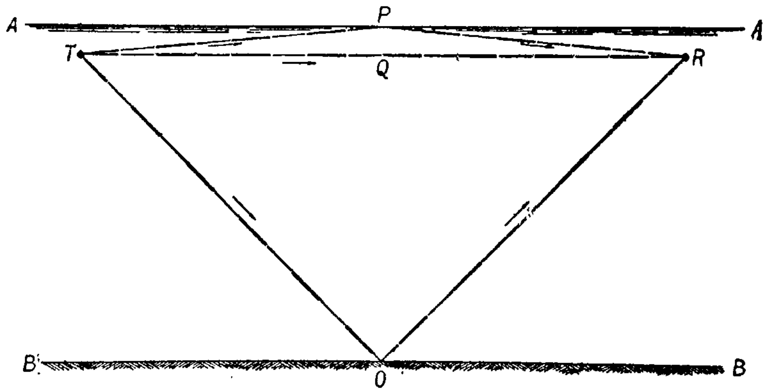

Fig. 5. — Mutual cancellation of direct and surface-reflected rays.

direction of sound beacons at dangerous points along shore and at harbor entrances, and also signals from other vessels. The depth-sounding devices developed in the U. S. Navy, and which will now be described, serve these purposes.

The determination of depth by acoustical methods was assigned as a research problem in the Bureau of Engineering of the U. S. Navy as a result of a discovery made on the transport *U. S. S. Von Steuben* during a trip from New York to Brest in March, 1919. This vessel had been equipped with one of the submarine sound receivers that the Navy had developed at its New London Station for use in locating U-boats and it was proposed to test the value of the device as an aid and safeguard to navigation. It was found that the direction of nearby vessels and submarine bell signals could be accurately determined while leaving New York harbor and when approaching Brest, but that in mid-ocean the propeller sounds of other vessels as well as of the *Von Steuben* herself could not be heard. This fact led to the discovery that the only sounds heard in a submarine sound receiver located near the surface are the components that have been reflected from the sea-bottom.

The explanation of this fact can be readily understood by referring to Fig. 5 wherein (*A* - *A*) represents the sea-surface, (*B* - *B*) the sea-bottom, and *T* and *R* a sound transmitter and a sound receiver, respectively, each submerged a distance represented by (*P* - *Q*). If the distance (*P* - *Q*) is small compared with the distance (*T* - *R*) (as is usually true in practice), then the two sound paths (*T* - *P* - *R*) and (*T* - *Q* - *R*) are practically of equal length. Sound from *T* reaches *R* by the three paths (*T* - *P* - *R*), (*T* - *Q* - *R*) and (*T* - *O* - *R*), but since the two paths (*T* - *P* - *R*) and (*T* - *Q* - *R*) are practically equal and since the surface-reflected ray suffers a change of phase of a half a wave-length upon reflection, the sound traversing these two paths interferes destructively at *R* and only the sound that has been reflected from the sea-bottom can be heard.

As soon as it was discovered that the sounds heard in our receivers had arrived by way of reflection from the sea-bottom, it appeared probable that methods could be developed for determining the depth of the water by means of submarine sound waves, providing the character of the sea-bottom in general is such as to reflect sufficient sound energy to give an audible echo. Before starting this work some preliminary tests on the efficiency of the deep-sea floor as a sound reflector were made on the destroyer *U. S. S. Wilks* which showed that clear audible echoes of signals from submarine sound oscillators could be received from depths as least as great as 2000 fathoms. Since that time good echoes have been received in depths greater than 3000 fathoms and so far as the author knows there has been no case reported where echoes could not be heard.

It should be stated, however, that nothing definite is known regarding the coefficient of reflection of the sea-bottom other than the fact that echoes have been heard over such regions or routes as have been tested. Over certain regions it has been noted that the echoes are much less clear-cut than are the signals. This distortion is doubtless due to a gradual change in the density of the material forming the sea-bottom. But the fact that an echo is heard at all would seem to argue against the somewhat general conception that the deep-sea bottom consists of an ooze-like deposit perhaps hundreds of feet thick, the density of which increases very slowly from the top to the rock foundation beneath. From the character of the echoes one would judge that the density of the ooze does not vary much from that of water throughout its depth or else that it has settled to a dense foundation, except for a comparatively shallow region near its surface. If the first assumption is true, the sound penetrates the ooze and reflects from the underlying rock. If the second is true, the sound reflects from the solidified ooze and the comparatively thin transition layers immediately above this.

Three methods have been developed for determining ocean depths by means of sound waves, two of which serve for measuring depths less than about one hundred fathoms and one of which serves for measuring any depth greater than about forty fathoms. All three methods make use of the time required for a sound signal to travel from a transmitter to a receiver by way of reflection from the sea-bottom. It will be seen that this time interval, which is too short to be measured directly with sufficient accuracy, can be determined indirectly as a function of a much shorter time interval that can be very accurately measured. Of the two methods that serve for determining shoal depths, one has been termed the " Angle of Reflection Method " and the other the " Standing Wave Method ". The method that serves for greater depths has been called the " Echo Method ".

I. — Angle of Reflexion Method.

The angle of reflection method can be understood by referring to Fig. 6, wherein (B-B) represents the sea-bottom (supposed for convenience to be horizontal), and (S-S) represents the surface. The propeller (P) of the vessel represents a sound source and R_1 and R_2 represent two sound

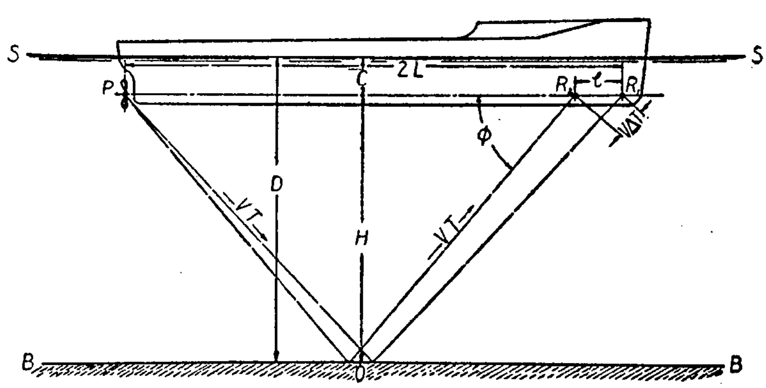

Fig. 6. — Sounding by angle of reflection method.

receivers mounted within the peak-tank or within a blister-like enclosed space on the outside of the ship's skin. These receivers are spaced a distance (l) on a horizontal line passing through the propeller. The distance between P and the mid-point between the two receivers is $2L$. The path of the sound waves from propeller to receivers will be (P-O-R). If the sea-bottom is horizontal the triangle (P-O-R) is isosceles, having the side (P-O) equal to the side (O-R). If $2T$ represents the time of sound transit from P to R, and V represents the velocity of sound in sea-water, then,

$$(1) \qquad H^2 = (V.T)^2 - L^2.$$

$$(2) \qquad \text{and } \frac{V.T}{L} = \frac{l}{V.\Delta T},$$

(corresponding sides of similar triangles)

$$(3) \qquad \text{wherefore } V.T = \frac{l.L}{V.\Delta T}.$$

Substituting the value of ($V.T$) in equation (1) gives

$$(4) \qquad H^2 = \frac{l^2 L^2}{V^2.(\Delta.T)^2} - L^2 = L^2 \left\{ \frac{(l^2 - V^2.(\Delta T)^2)}{V^2.(\Delta T)^2} \right\}$$

$$(5) \qquad \text{wherefore } H = L . \frac{\sqrt{l^2 - V^2.(\Delta T)^2}}{V.\Delta T}$$

where ΔT is the difference in the time of arrival at the two receivers of corresponding increments of the propeller sounds. The total depth (D) is given by the equation :

$$(6) \qquad D = C + H = C + L . \frac{\sqrt{l^2 - V^2(\Delta T)^2}}{V.\Delta T}.$$

All the factors on the right-hand side of equation (6) are constant and known except ΔT. The distance the receivers and propellers are submerged is C, half the distance from the propellers (or whatever source of sound is used) is L, the spacing of the two receivers is l, and V is the velocity of sound in sea-water which may be regarded as constant. The determination of depth therefore depends upon the determination of ΔT. This time factor, though much smaller than the time interval between signal and echo, can be determined with a high degree of accuracy by making use of the so-called binaural sense.

It has been proved experimentally that the direction of sounds is largely determined by the difference in the time of arrival of corresponding portions of the sound waves at the two ears. If the sound strikes the right ear first one unconsciously judges the source to be located at his right, if it strikes the left ear first he judges the source to be located to his left. If the sound strikes both ears simultaneously it appears to be neither to the right nor left and is said to be binaurally centred. The sense of direction of sounds, which is dependent upon the difference in the time of arrival at the two ears, has come to be called the " binaural sense ". When one judges the direction of a sound to be neither to his right nor left, or in other words, when he judges it to be binaurally centred, he unconsciously estimates that the sound waves strike the two ears simultaneously ; and the high development of the binaural sense is such that he estimates correctly to within about one two-hundred-thousandth of a second.

Of the two receivers shown in Fig. 6, suppose the output from one is brought to one ear of the operator, and that from the other receiver is led to the other ear, respectively. If the time of energy transit to the ear from each receiver is the same, the difference in the time of arrival of the sound at the two ears will be ΔT, the time difference in arrival at the two receivers, and, through the operation of the binaural sense, the sound will appear to come from the side of the operator because one ear is stimulated earlier than the other. Moreover, the sound will appear to be located on the side of the observer carrying the ear that receives the earlier stimulation. If now the energy-conducting path leading from each receiver to its respective ear be constructed so that the time of transit over the path can be varied continuously or by very small increments, it will be possible for the operator to make the sound reach his two ears simultaneously by increasing the time of transit across the path leading to the ear that is first stimulated or decreasing the time of transit between the other receiver and its respective ear or by increasing the time of transit to one ear and simultaneously decreasing the time of transit to the other ear by a proper amount. When the sound has been binaurally centred in this way the difference in the time of transit across the two paths, connecting between the two receivers and the observer's ears, respectively, is equal to the time increment (ΔT).

The process of binaurally centring a sound in this way has been called " compensation "[2] and any device used for this purpose is called a " compensator ". It is evident that the compensator can be calibrated to give

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[2] The process of binaurally centring a sound by compensation was developed by the Navy in 1917-18 at its research station in New London, Conn. For a more complete description of the process, see *Proc. Amer. Phil. Soc.*, **59**, No. 1, 1920, or the ***Marine Rev.***, Oct., 1921.

the value of ΔT or any function of ΔT, and as a result can be calibrated to give the depth (D) directly. This is done in practice.

It is to be noticed that the last term of equation (6) can be written as the tangent of the angle (φ) that the direction (O - R) makes with the horizontal line (P - R) and that equation (6) can be written :

$$D = C + L \tan \varphi. \tag{7}$$

When the sounding equation is put in this form it becomes obvious that the sounding data given by the angle of reflection method become more accurate as the depth becomes less, a result much to be desired. On

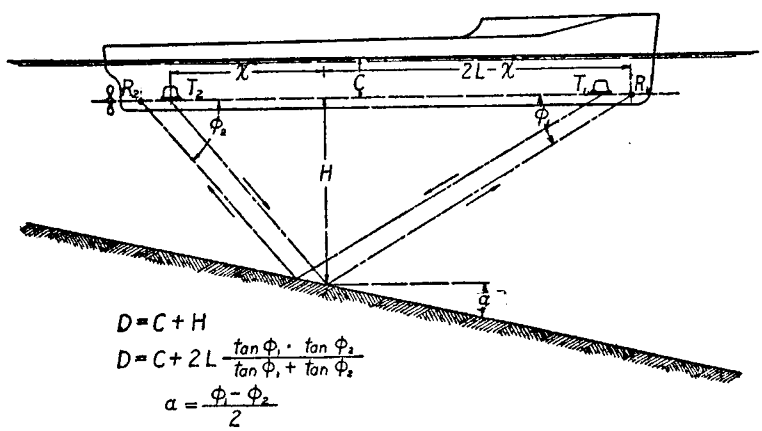

Fig. 7. — Method for eliminating error due to shelving bottom.

the other hand, it shows that the method breaks down for depths so great that the angle (φ) approaches a right angle. It has been found in practice that this method gives reliable soundings to depths equal to about three times the distance between the sound source and the receivers. For most vessels this will cover depths as great as 100 fathoms and ofttimes more.

It is evident that the method, as described, becomes inaccurate when the slope of the sea-bottom varies from the horizontal for the reason that the triangle (P-O-R) will not be isosceles. In general the method gives too great values when the vessel approaches shoaling water and too small when running into increasing depths. In most regions the sea-bottom within the hundred fathom curve is fairly uniform for the reason that it has been leveled off by the action of storm waves and the method described has been found to give fairly accurate sounding data.

By referring to Fig. 7 it will be seen that the method can be made accurate by installing a sound transmitter and receiver in each end of the vessel. The same compensator serves for both sets of receivers as does the same power outfit for driving both transmitters. The operator sounds transmitter (T_2) and with his compensator measures φ_1. Then by throwing a miltpole switch he sounds T_1 and measures φ_2. It can be shown that

$$(8) \qquad D = C\,Œ\,2L \frac{\tan \varphi_1 \,.\, \tan \varphi_2}{\tan \varphi_1 + \tan \varphi_2},$$

and that α, the slope of the sea-bottom, is given by the equation,

$$(9) \qquad \alpha = \frac{\varphi_1 - \varphi_2}{2}.$$

While this more refined method is to be preferred for making hydrographic surveys, the simpler approximate method serves for navigational purposes as can be seen by a consideration of the curves shown in Figs. 8 and 9.

The curves of Fig. 8 represent sounding data taken by the *U. S. S.*

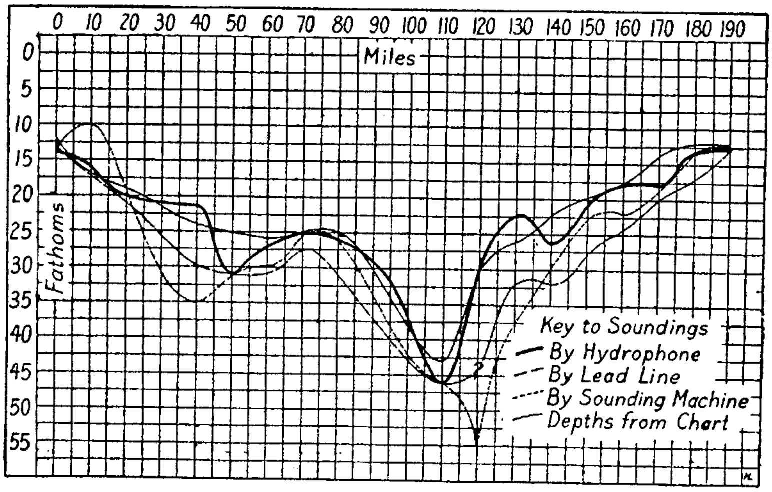

Fig. 8. — Comparative soundings data, electrical Hydrophone M .V. 62. *U. S. S. Breckenridge* en route from Charleston to Key West, January 14,1920.

Breckenridge while en route from Charleston, South Carolina, to Key West. The course ran in part along the edge of the continental plateau, where the sea-bottom was very uneven and erratic. Two successive casts of the hand-lead made not more than a minute apart, while the vessel was not steaming over five knots, ofttimes showed a discrepancy of five or six fathoms. Under such conditions it was not expected that the acoustical sounding data would be at all accurate. However, the curves seem to show that the soundings given by the hydrophone are perhaps more reliable than any of the others. It is certain that these soundings, which are represented by the full heavy line, do not depart from the charted values, which are represented by the light full line, as much as do the soundings taken by the leadline or the sounding machine. Moreover, it will be noticed that, except at the 138-mile mark, the acoustical curve passes through every point where two or more of the other curves coincide. This fact tended to make all who took part in the test believe the acoustical sounding data were, on the whole, most reliable.

The sounding data represented by the curves of Fig. 9 were taken during a run from Newport, Rhode Island, out to the hundred-fathom

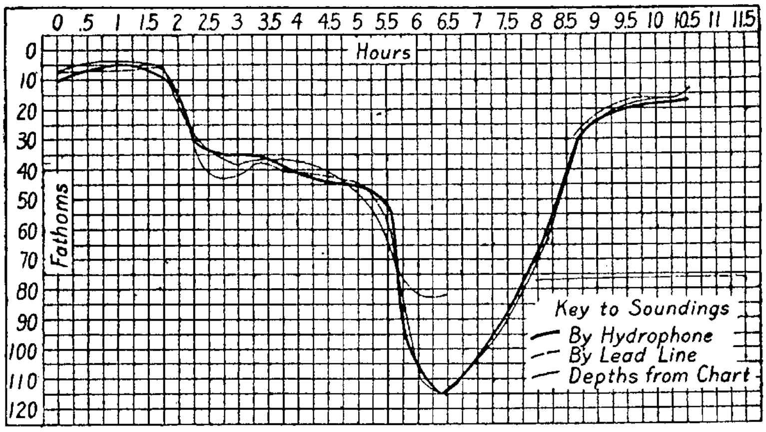

Fig. 9. — Comparative sounding data acoustical hydrophone M. V. 16B, *U. S. S. Blakeley* 150. Cruising off Montauk Point, May 27,1920.

curve and back, and show the accuracy with which the apparatus can give soundings where the sea-bottom is somewhat regular. It will be noticed that the acoustical sounding data agree very closely with the charted depth except at the beginning and end of the run where the water was shoal. In these regions the agreement with the hand-line data is close. All who took part in this test believe the charted depths in the shoal region are too small for the reason that the hand-line soundings consistently gave about two fathoms greater depth ; and there was a general feeling that the acoustical data represented the depth very accurately at all times.

The term " M V - Hydrophone, " used in the caption of both Figs. 8 and 9, refers to the type of submarine sound receiver used for determining the time increment (ΔT). This type of receiver employs several sound receptors instead of two as described above. The receivers are equally spaced along a straight line passing through the propeller (P) and so connected through the compensator that the forward half of the receivers connects with one ear in place of a single receiver as described, and the receivers of the rear half of the line connect through the compensator to the other ear. The compensator itself is so ingeniously designed that when any sound striking the receivers is binaurally centred the responses to this sound from all the receivers arrive at the ears in phase. This results in making the intensity of the received sound considerably greater than it would be if only one receiver connected with each ear. But this is not the only advantage of this type of receiver. Any sound that reaches the receivers and is not binaurally centred will have the responses from the several receivers arriving at the ears out of phase and they will partially destroy one another by destructive interference with the result that the sound heard is less intense than it would be if only one receiver connected with each ear. The M V - Hydrophone, therefore, can be focussed on any sound that the operator desires to hear, so that this particular sound gives a loud, clear response at the ears while all other sounds, and hence the local disturbing sounds, are greatly weakened.[3]

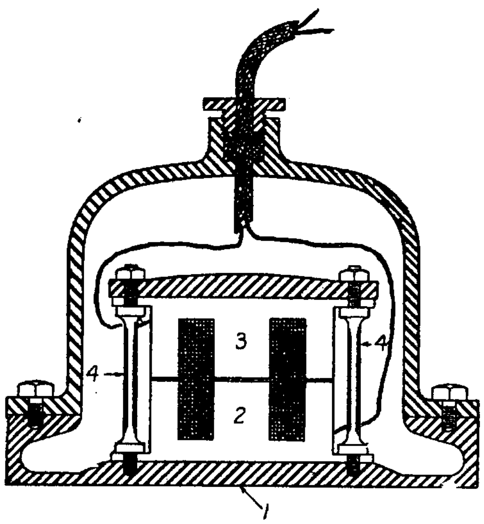

Fig. 10. — Schematic diagram of a submarine sound transmitter.

The ship's propellers form a convenient sound source for use in determining depths by the angle of reflection method, but any submarine sound transmitter of the oscillator type serves equally well. The principle of operation of such a sound transmitter can be understood by reference to Fig. 10, wherein numeral 1 indicates a rigid diaphragm in contact with the water, numeral 2 represents one-half of a powerful electromagnet rigidly attached to the diaphragm, and numeral 3 represents the other half of the electromagnet which is suspended in position by the elastic steel rods represented by numerals 4. When an alternating current is passed through the magnetizing coil, the suspended half of the magnet vibrates back and forth alternately compressing and stretching the rods by which it is suspended and exerting a powerful thrust and pull on the heavy diaphragm that may equal several tons. Because of the incompressibility of water, it becomes necessary to exert great

[3] A description of the M V - Hydrophone will be found in the *Marine Review* of October, 1921.

forces on the diaphragm to produce even a slight amplitude of motion. The submarine sound oscillator can be used for sending code or any other kind of signals by placing a key in the alternating current circuit.

II. — Standing Wave Method.

The " Standing Wave Method " of determining depths can be understood by referring to Fig. 11 wherein T represents a submarine sound transmitter and R represents a submarine sound receiver, the two being separated a distance (L). The sound transmitter is driven by an alternating

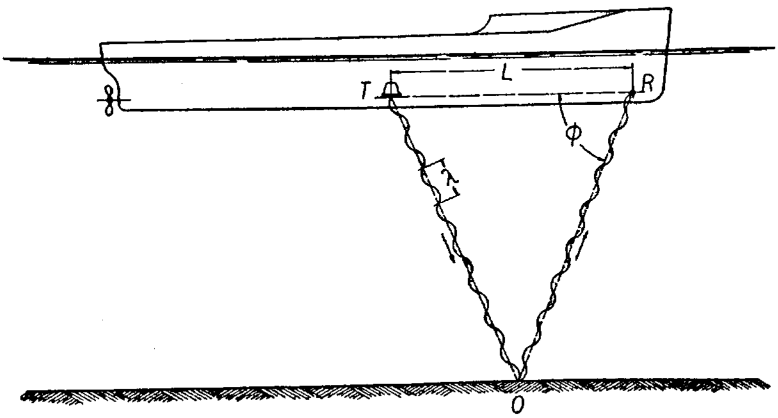

Fig. 11.

current supply so designed that the frequency of the current can be controlled and varied by the operator over the range included between about 500 and 1500 cycles per second. This circuit is provided with means for giving the frequency with a high degree of accuracy at all times. The operator uses a two-telephone head set, one phone of which is inductively connected with the A. C. circuit that drives the sound transmitter. This connection is preferably made through a variocoupler. The other phone is connected with the output from the sound receiver (R). With the phones connected in this way, it will be seen that the sound heard in the inductively connected phone has, at all times, a definite phase relation with the sound waves leaving the transmitter and the sound generated by the other phone has a definite phase relation with the sound waves reaching the receiver. If the operator adjusts the frequency properly, he can make the sound heard in the two phones have the same phase and can recognize this condition through the fact that the sound will then be binaurally centred. If the sound leaving the transmitter has the same phase as the sound waves arriving at the receiver, then (T-O-R), the sound path between transmitter and receiver, represents a whole number of wave-lengths. Calling this path-length, S; and the time required for sound to travel a distance equal to one wave-length, ΔT; and the velocity of sound in sea-water V, we have the relation :

$$S = V . N . \Delta t \tag{1}$$

where $N . \Delta t$ represents the time required for the sound to travel the whole path-length. — But Δt, which represents the time for one wave to pass a fixed point, is equal to one second divided by the frequency (n) of the sound. Expressed as an equation, this becomes :

$$\Delta t = \frac{1}{n}, \tag{2}$$

and by substituting this value in equation (1), we have :

$$S = N . \frac{V}{n}, \tag{3}$$

and the path-length (S) between transmitter and receiver would be known if the number of wave-lengths (N) in the standing wave system were known.

The value of N can be found by varying the frequency of the sound until a second standing-wave system is established. Suppose the operator adjusts the frequency so that the sound is binaurally centred. Call the frequency (n_1). This will be equal to the frequency of the A. C. current. Then suppose he slowly raises or lowers the frequency. He will notice that the sound apparently passes away from binaural centre and finally comes back across centre. Each time the sound comes back across binaural centre, he has varied the number of waves in the standing wave system by one. Suppose he varies the frequency until the number of waves in the system differs from the number in the original system by a and he determines this number by counting the number of times the sound comes to a binaural centre while he slowly changes the frequency. Call the final frequency which he carefully adjusts for a binaural balance, n_2. Then since the path-length (S) is the same in the two cases, we have :

$$S = N \frac{V}{n_1} = (N \pm a) \frac{V}{n_2} \tag{4}$$

$$\text{wherefore } N = \pm a \frac{n_1}{n_2 - n_1}, \tag{5}$$

the sign before a being such as to make N positive. Substituting this value for N in equation (4) gives :

$$(6) \qquad S = \frac{aV}{n_2 - n_1},$$

which gives a very simple working formula for determining S, the sound-path from the transmitter to the receiver by way of reflection from the sea-bottom.

It will be noticed that the determination of S does not furnish sufficient data for calculating the depth except when the sea-bottom is horizontal as shown in the figure. The point of reflection (o) may be anywhere on the surface of an ellipse having T and R as the two foci and the sum of the radius vectors (O-T) and (O-R) equal to S. If, however the M V - Hydrophone is used for the receiver, the angle (φ) that the radius vector (O-R) makes with the principle axis (T-R) can be readily determined. This furnishes data for the complete solution of the depth and the slope of the sea-bottom.

This method has proved to be extremely accurate for measuring shallow depths. It gives greater accuracy as the depth becomes more shallow for the reason that the less the depth the greater the change of frequency that is required to change the number of waves in the standing wave system. The method breaks down at great depths for the reason that a small change in the frequency introduces so many waves into the system and so rapidly that they cannot be accurately counted and thus the factor a becomes indefinite.

From the above description, it might be thought that each sounding taken by the standing wave method requires the solution of a problem in conic sections and would therefore be slow and cumbersome in practice. Such, however, is not the case. Having determined the value of S and φ, the depth can be determined from a family of curves with very little effort or loss of time.

It will be noticed that the apparatus employed for utilizing the standing wave method of determining depths is practically the same as that used with the angle of reflection method. The same receiver and transmitter serves equally well for both methods, but the standing wave method requires, in addition, some means for controlling the pitch of the transmitted signal and a frequency meter for determining the pitch.

The method, as outlined, has been found to give accurate results and to be easily applied. It can be modified somewhat without impairing its efficiency. Instead of energizing one phone by inductive connection with the A. C. circuit of the transmitter, it can as well be energized by a second receiver located near the transmitter. And instead of energizing the two phones separately so that the binaural sense can be utilized for adjusting the frequency to bring about a definite phase relation between the sound leaving the transmitter and that reaching the receiver, both currents can be passed through both phones in parallel, or series, in which case the observer can adjust the frequency to give a maximum or minimum response in the phones. He will then determine a by counting the number of maxima or minima, respectively, that occur during the change of frequency from the first to the second adjustment. This arrangement can be used by an operator who is deaf in one ear.

III. — Echo Method.

The " Echo Method " of determining depths is very similar to the standing wave method. It consists of sending out a continuous series of short sound signals separated by equal time intervals and means for varying continuously the time interval between successive signals from about one-tenth of a second to about ten seconds, the means being such that the interval between successive signals can be accurately determined. If S represents the distance the sound travels in passing from the transmitter to the receiver by way of reflection from the sea-bottom, t represents the time of transit and V represents the velocity of sound in sea-water, then we have the relation :

$$S = V . t, \tag{1}$$

and it becomes necessary to determine t.

If the period between successive signals is made such that a signal returns to the receiver at the same instant that one is sent out from the transmitter, then we have the equivalent of a standing wave system, and if p represents the time interval between successive signals we have the relation :

$$t = N . p, \tag{2}$$

where N is the number of signals that are in transit between the transmitter and receiver. Substituting this value for t in equation (1) gives :

$$S = V . N . p. \tag{3}$$

The factor V is known and the factor p can be determined by the apparatus that is employed to automatically close and open the A. C. circuit through the transmitter. This apparatus, which serves as an automatic sending key, will be described later.

To determine N the operator will vary the frequency at which the sound signals are transmitted until the signals and echoes are heard simultaneously in the two telephone receivers, one of which is inductively connected with the A. C. transmitter circuit and the other of which is connected through the compensator of the M V - Hydrophone to the submarine sound receivers. This is the same arrangement that is employed in the standing wave method. The operator may continue varying the frequency of the signals until the coincidence between signals and echoes has arrived and passed by a times to the final adjustment. Then since the distance the sound has travelled between transmitter and receiver has remained constant, we have the two equations :

$$S = V . N . p_1 = V . (N \pm a) . p_2 \tag{4}$$

where p_1 and p_2 represent, respectively, the time interval between successive signals in the two cases. Solving for N, we find :

$$N = \pm a \frac{p_2}{p_1 - p_2} \tag{5}$$

and by substituting this value for N in equation (4), we have :

$$S = V . a . \frac{p_1 p_2}{p_1 - p_2}. \tag{6}$$

It is obvious that the sign of N must be such as to make S positive.

Equation (6) can be simplified by replacing the p factors, which represent the time between signals, by a set of n factors, representing respectively the frequency of the signals. If this is done, equation (6) reduces to :

$$S = \frac{V . a}{n_2 - n_1}, \tag{7}$$

which is identical with the sounding equation developed in connection with the standing wave method.

The automatic transmitting key, that must serve for varying the value of p and for determining its value, might be a pendulum with arrangements for varying its period of vibration and for closing and opening the transmitter circuit. If this were done the factor p or its reciprocal $\frac{1}{n}$ would be expressed in terms of the well known pendulum laws. But since pendulums do not work well on board ships, it is preferred to use a disc caused to revolve at constant speed, similar to the revolving plate of a graphophone, and a small friction wheel resting on this surface with means for moving it inwards or outwards along a radius of the constant speed disc. With this arrangement the speed of the friction wheel can be varied continuously from zero to a value that is dependent upon the speed of the disc and the ratio of the radius of the disc to that of the friction wheel. The closing and opening of the transmitter circuit is accomplished by contact points operated by a cam-wheel attached to the axis of the friction wheel. If this cam carries one tooth, one signal will be transmitted for each revolution of the friction wheel, while if the cam carries C teeth equally spaced about its circumferenee there will be C signals transmitted for every revolution of the friction wheel.

Suppose the constant period of revolution of the disc is P seconds and that the radius of the friction wheel is r. Also suppose the distance from the centre of the disc to the point of contact between the disc and friction wheel is R. Then since there is no slip between the friction surfaces we have :

$$(8) \qquad \frac{2\pi R}{P} = \frac{2\pi r}{p}$$

and

$$(9) \qquad p = \frac{P \cdot r}{R},$$

if the cam-wheel carries one tooth, for then the period p between signals is the same as the period of revolution of the friction wheel. If, however, the cam-wheel carries C uniformly spaced teeth, then :

$$(10) \qquad p = \frac{P \cdot r}{C \cdot R},$$

and

$$(11) \qquad n = \frac{1}{p} = \frac{C \cdot R}{P \cdot r}.$$

Substituting this value in equation (7) gives for the sounding equation :

$$S = \frac{a \, . \, V \, . \, P \, . \, r}{C(R_2 - R_1)}, \qquad (12)$$

where a is the number of signals in transit that have been introduced in passing from the first to the second condition for coincidence between signals and echoes, V is the velocity of sound in sea-water, P is the constant period of revolution of the disc, r is the radius of the friction wheel, C is the number of teeth on the cam that operates the contact points for closing and opening the transmitter circuit, R_1 is the distance from the centre of the disc to the point of contact with the friction wheel for the first adjustment for coincidence between signals and echoes in the two phones and R_2 is the corresponding distance for the second similar adjustment.

The accuracy with which depths can be determined by this method depends upon the degree to which the speed of the disc can be kept constant and the accuracy with which R can be measured. In practice the disc is driven by a tuning-fork speed-controlled motor operating through a worm and gear. With this arrangement the speed of the disc is kept constant to within a tenth of a per cent. The friction wheel is moved out and in across the disc by means of a spiral thread operating in a nut, and the position of this wheel on the disc is determined by means of a micrometer scale on the end of the member carrying the spiral thread. This arrangement permits of measuring R to within .002 inch.

A factor that lends for accuracy in adjusting the friction wheel results from the fact that each signal echoes back and forth between the sea-bottom and surface several times. And, if the interval between signals is accurately adjusted for coincidence with any echo, the multiple echoes will all be coincident ; while if the adjustment is not quite accurate, the multiple echoes will vary from coincidence two, three, or n times as much as does the first echo. This dispersive effect of the multiple echoes proves to be an aid in making an accurate adjustment for determining depth, whereas they prove to be a disturbing factor in case of Fessenden's method that has been described. It has been demonstrated in practice that the value of R can be determined to within two or three-thousandths of an inch and this results in measuring the time of sound transit to the sea-bottom and back to within one five-hundredth of a second.

The velocity of a sound in sea-water for moderate depths and average temperature is about 4800 feet per second. But the velocity (V), which can be accurately expressed as :

$$V = \frac{1}{\sqrt{\mu \cdot \rho}},$$

where μ is the adiabatic compressibility and ρ is the density, is evidently affected by both the temperature and pressure of the water and will, therefore, vary with the depth. The variation of the temperature of sea-water with the depth is not well known over most of the ocean areas, but it is well established that the temperature conditions below 1000

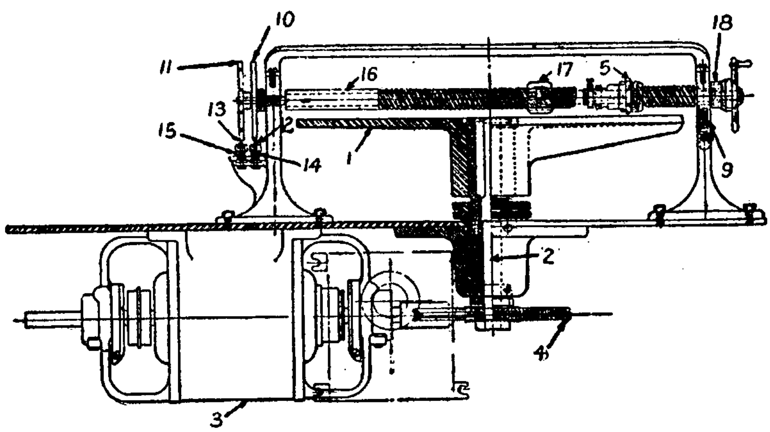

Fig. 12. — Practical design of sonic depth finder.

fathoms or even 500 fathoms do not vary greatly. Therefore, when the velocity is determined for depths beyond these values, the variation of depth, which alone is of value in determining submarine contours, can be determined to within an error represented by the distance that sound travels in sea-water in about one five-hundredth of a second or to within about ten feet. But since in determining depths the distance S that the sound travels in going from transmitter to receiver is divided by two, the error is also halved, and the depth variation will be determined to within about a fathom.

The variation in the velocity of sound, as it proceeds to greater depths, that is produced by increase in pressure, is in opposition to the variation produced by the change of temperature when, as usual, the temperature decreases with increasing depth. As a result the average value of 4800 feet per second for the velocity of sound gives sounding data accurate to within 1, or at most, 2 per cent. The determination of the velocity of sound in sea-water under various conditions of temperature, pressure and salinity is being undertaken by the Navy and its solution will increase the absolute accuracy with which soundings can be taken by the echo method.

Fig. 12 shows the nature of a practical design of the automatic signalling key as developed at the Engineering Experiment Station, U. S. N., Annapolis, Maryland. A disc (1) twenty inches in diameter, carrying a vertical axis (2), is driven at a constant speed of one revolution in ten seconds by means of a dynamotor (3) whose armature shaft carries a worm that engages in gear 4 which is keyed to axis 2 at its lower end. The speed of the dynamotor is kept constant to within a tenth of a per cent, by means of a tuning-fork control for varying the load.

The top of disc 1 is covered with canvas or other suitable material for forming a friction surface for driving friction-wheel 5. This wheel, which is two inches in diameter, engages with shaft 6 by means of a slot and spline arrangement such that member 5 can slide along member 6, but which causes both of these members to rotate in unison. The axis of shaft 6 is so mounted that it is parallel with the friction surface of the disc and intersects the axis of pinion 2 extended upward.

Shaft 6 is supported by self-aligning ball-bearings (7 and 8), the former of which is set in a groove such that it can slide a short distance up and down and thereby allow the pressure between members 1 and 5 to be adjusted by varying the tension on spring 9. It caries two cam-shaped discs near the end supported by bearing 8, one of which (10) carries a single saw-tooth-shaped depression and the other (11) carries ten such depressions uniformly spaced about its circumference.

Two spring members, 12 and 13, bear against the two cam discs, respectively, and by snapping down into the depressions as the cams rotate, serve to operate the two pairs of contact points (14 and 15) in such a way as to temporarily close the alternating current circuit of a submarine sound oscillator transmitter. Arrangement is provided whereby either spring member can be made to operate against its respective cam, but which prevents both members from operating at the same time.

Member 16, which carries a spiral thread engaging in a nut in member 17, serves to move the friction wheel 5 along shaft 6 and measures the radius R of the circle that member 5 scribes on member 1 by means of a micrometer scale on cylinder 18. The smallest scale division represents one one-hundredth of an inch and readings can be estimated to tenths of a division.

The sounding equation (12) :

$$S = 2D = \frac{a \, . \, V \, . \, P \, . \, r}{C(R_2 - R_1)},$$

when applied to this design of key has the following values for the several constants :

V = 4800 feet per second.
P = 10 seconds.
r = 1 inch.
C = 1 or 10, depending upon which cam is used.

Inserting these values, we have for D the depth :

$$D = \frac{48000 \cdot a}{2C(R_2 - R_1)} \text{ feet}$$

or

$$D = \frac{4000 \cdot a}{C(R_2 - R_1)} \text{ fathoms,}$$

where, as before stated, a is the change in the number of signals in transit, brought about by varying the adjustment of the friction wheel through the radial distance $(R_2 - R_1)$, and C is one or ten, depending on which cam-wheel is employed.

When both C and $(R_2 - R_1)$ are given their greatest value, 10 in each case, it will be noticed that the device is then adjusted for measuring its most shallow depth, which is 40 fathoms. With this adjustment the time interval between successive signals is one-tenth of a second and the value of a is one. Under such conditions each signal echoes back to the receiver at the instant the next successive signal is transmitted and the determination will be very accurate for the reason that the value $(R_2 - R_1)$ will be large (ten inches) and any small error in determining this value will only introduce a small percentage error. But suppose a depth of 4000 fathoms were being measured. Then in order that an echo should reflect to the receiver at the same time the next successive signal is transmitted, the time interval between successive signals would need to be ten seconds and the value of $(R_2 - R_1)$ would be only one inch. Under such conditions the slight error made in measuring $(R_2 - R_1)$ would result in ten times as much percentage error as in case of the shallow measurement. If, however, we send the signals ten times as fast, *i.e.*, once per second, then there would be ten echoes in transit and a would become ten and the value of $(R_2 - R_1)$ would now become ten inches, the same as in case of the shallow depth measurement, with the same resulting error in our 4000-fathom sounding that was made in determining the shallow sounding. By choosing a proper value for a, the value of the measured factor

$(R_2 - R_1)$ can always be made large, and this results in reducing the experimental error.

Some idea of the accuracy with which deep-sea soundings are determined by the "echo method" can be gained by referring to Fig. 13, wherein the heavy line curve gives the depth as determined by this method and the light line curve gives the corresponding charted depth over a course bearing southwest from the Ambrose Channel Light Ship to latitude 37 north and thence west to Cape Charles Light Ship. The charted depths in some instances represent interpolations between some-

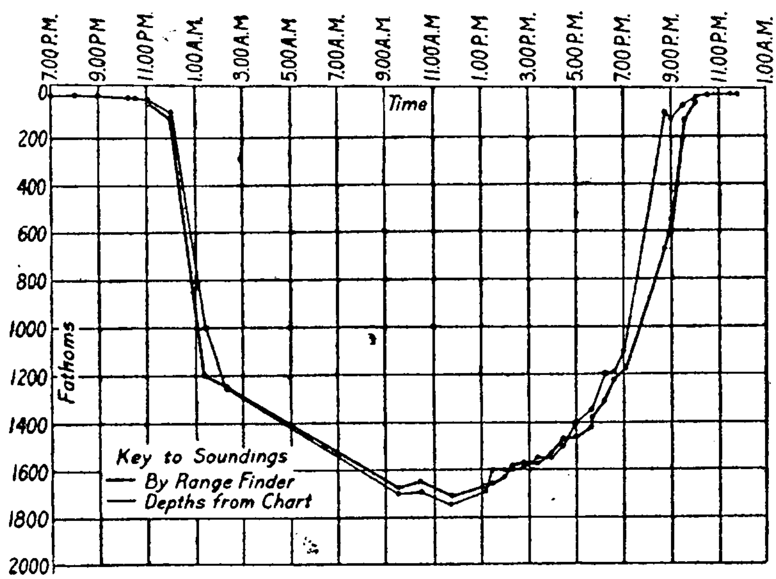

Fig. 13. — Comparative sounding data. Sonic range finder, type 2.
U. S. S. Ohio en route from New-York to Annapolis. February 13-15.

what widely separated soundings on the chart. Nevertheless, the data included between 2 : 00 A. M. and 6 : 00 P. M. are over a fairly uniform sea-bottom and the charted values probably represent the true depth with considerable accuracy.

A line of soundings taken by the author on board the U. S. destroyer *Stewart* while she steamed from Newport, Rhode Island, to Gibraltar, Spain, at a steady speed of 15 knots, has demonstrated the ruggedness, ease and rapidity of operation, accuracy and dependability of the acoustical depth-sounding apparatus that has been described. The apparatus at no time failed to function properly and required no repairs or adjustments during the entire trip. The average time required to make a sounding was about one minute. Throughout the course soundings were taken at least every twenty minutes, and in regions where the depth varied somewhat rapidly they were taken at times as often as every minute.

These soundings determine the profile across the Atlantic along a great circle route from Newport to the Azores and from thence across the Josephine and Gettysburg Banks to Gibraltar[4]. (See Pilot Chart of North Atlantic Ocean, January, 1923.) This profile cannot be reproduced in its entirety, but some idea of the accuracy with which it represents the variations in depth can be gained by considering Fig. 14, which refers to the Gettysburg Bank along a section defined by the course of the *Stewart*. At the time this Bank was discovered by the *U. S. S. Gettysburg*, soundings showed the bottom to consist of sand and rounded pebbles. The profile

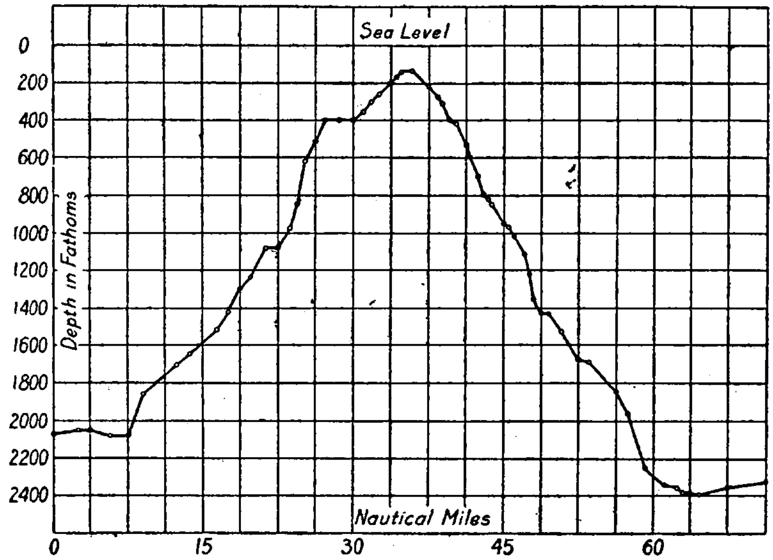

Fig. 14. — Contour of the Gorringe or Gettysburg Bank. Sounding taken by *U. S. S. Stewart*, June 28-1922.

of Fig. 14 gives evidence of old shore terraces at a depth of 400 fathoms, and it therefore appears probable that this region has been above sea-level at some remote age.

During the months of October and November, 1922, the U. S. S. destroyers *Hull* and *Corry*, using the echo method, made a survey of the ocean floor along the California coast from San Francisco to Pt. Descanso from the hundred-fathom curve out to a depth of 2000 fathoms. The area covered was approximately 35,000 square miles and the work was accomplished in thirty-eight days. Over 5000 soundings were taken while the ships steamed steadily at twelve knots. There is no doubt but that these soundings, as assembled in chart form by the Hydrographic Bureau of the U. S. Navy, represent the contour of the sea-bottom with considerable accuracy even though the survey was made at the rate of about

[4] See *Hydrographic Review*, vol. I, No 1, March 1923.

1000 square miles per day. This survey has demonstrated beyond a doubt that the ocean beds can now be charted with a high degree of accuracy and that the survey work can be done with a speed and an economy of expense and effort that has heretofore been believed impossible.

The data represented by this chart furnish subject-matter for an extended paper and, therefore, cannot be covered at this time. It may be stated, however, that this region has been surveyed for the reason that seismographic records for the past ten years show that numerous earthquakes have had their origin within this area. It is proposed to re-survey this area after such records have shown that one or more earthquakes have had their origin herein. It is hoped that a comparison of the two charts will give some definite information regarding the movement of the earth's crust resulting from such disturbances. A comparison of the present chart with the older charted values shows discrepancies of hundreds and even thousands of fathoms in some localities. It is uncertain whether these marked variations are due to errors made in the earlier surveys or to movements of the earth's crust resulting from the numerous earthquakes that have originated within this region since that time. It seems certain that repeated surveys of this and other unstable regions of the sea floor will furnish much valuable data relating to the movement of the earth's surface.

The application of the methods and apparatus for taking depth soundings that have been described are more numerous and valuable than one might at first suppose, as has become evident to the author through the many letters of inquiry that he has received.

Their value as an aid and safeguard to navigation has been repeatedly proved on various vessels of the U. S. Navy. And their value does not cease when a vessel steams into ocean depths for such survey work as has already been done shows that the deep-sea mountains and valleys will furnish numerous "landmarks" for determining the progress of a vessel, as soon as the main trade routes have been carefully charted. Moreover, the M V - Hydrophone receiver, besides determining the direction of sound signals used for sounding purposes, will equally well determine the direction of such signals transmitted from other moving vessels or from light-vessels placed at harbor entrances or at dangerous points along shore. In this way it serves to prevent collisions during conditions of low-visibility and to direct vessels safely into harbor or away from dangerous rocks and shoals. If all ships were equipped with the sound apparatus that has been described and would sound their submarine sound transmitter during fog, the navigator could then know the bearing of every vessel within a radius of at least ten miles, in addition to knowing the depth of water underneath his own vessel. With such information at his disposal, the grounding of, or collision between, vessels could be absolutely avoided.

These sound devices will serve to make a cheap, quick and accurate survey of rivers and harbor entrances through which a channel is to be dredged, thereby furnishing accurate data for computing the amount of material that must be moved. They will also serve to determine the capacity of reservoirs with a minimum of effort and expense.

A study, during the flood period, of the beds of such rivers as the Yangtse, the Mississippi and others that are wont to overflow and cause great loss of both lives and property, would doubtless furnish much valuable information for controlling such streams. The velocity of the water is usually so great that soundings cannot be made with the hand-lead, but by means of the " standing wave method " the beds of such rivers can be surveyed with great accuracy. Such surveys made at numerous sections of the stream should show over what portion erosion takes place and, what is more important, should show where the sediment is being deposited. If erosion at the bottom of the stream becomes active when the velocity of flow exceeds a certain minimum value (as is believed by some engineers), and if it can be determined what this minimum velocity is, then it is quite possible that the proper method of controlling the stream will be to narrow its confines rather than to widen them or raise the dykes, for by so doing the required cross-section to carry the flow will be gained by deepening the stream through the process of erosion. The possibilities of the depth-sounding devices for use in this way are perhaps far greater than we can now appreciate.

The " echo method " of determining depths is not confined to determining submarine depths. It should serve equally well for determining the depth below the earth's surface of abrupt changes or discontinuities in the earth's crust such as are offered by coal and oil deposits or subterranean caverns. These surfaces of discontinuity will reflect to the surface a part of any sound disturbance that may be transmitted to them. And thought it may seem far-fetched, there is a possibility that the methods outlined may also be utilized for locating cracks and blowholes in large castings.

The apparatus employed with the " echo method ", which has been described as a means for determining the distance between two points in a uniform medium when the velocity of sound is known, serves equally well for determining the velocity of sound between two points in any medium when the distance they are separated is known. In this connection this apparatus may serve to determine the velocity of sound through the rock formation of a mountain or between borings or workings in mining operations. And since the velocity so determined is equal to the square root of the elasticity of the formation divided by its density, this information may lead to the identification of valuable ore.

Of the above-named applications of the acoustical depth-finding devices that have been described, only two have been put to practical test. Their ability to aid and safeguard navigation during conditions of low visibility has been repeatedly demonstrated on ships of the Navy, and the survey of the sea floor off the California coast together with a more recent survey of a region off the entrance to the Panama Canal has proved that the sea floors can now be accurately and easily mapped.