The Smithsonian was the pioneer, and ever since has been among the leaders, in all scientific research dealing with the aboriginal peoples of the Americas. These now are conducted largely by a Government-supported division—the Bureau of American Ethnology. At the time this work started just after the American Civil War, scientific interest in the remains, languages, and ways of primitive peoples was in its infancy. Thus the work of the Bureau, with the exceptional facilities at its disposal, has been fundamental in the development of the entire science of ethnology, and its publications are considered basic documents of this science all over the world.

Samuel P. Langley was a pioneer in the development of aviation. His steam-driven model "aerodromes" flew without a pilot repeatedly for distances of more than half a mile as early as 1896. The Smithsonian collection of aeroplanes which have played notable parts in aviation history is probably the largest in the world.

Study of precise solar-terrestrial relationships has been a major Smithsonian activity for many years. This has involved especially very exact measurements of periodic variations in the sun's radiation and the mechanism of photosynthesis in green plants. Observations now are carried out daily at three observatories on high mountain-tops in California, New Mexico, and Chile. This work has required development of measuring instruments of almost incredible delicacy—one of them capable of measuring a change of heat as small as one-millionth of a degree.

In the United States originated such devices as the telegraph and telephone, the cotton gin, the sewing machine, the harvester, and scores of others. The original machines are objects of historic interest to the American people. The Smithsonian has the responsibility for collecting and preserving these historic prototypes. The Museum collections of the Smithsonian are visited by more than two million persons each year.

The American history collections are especially rich. Perhaps the best-known items are dresses of ladies of the White House from Martha Washington to Mrs. Franklin D. Roosevelt.

In carrying on "the diffusion of knowledge", the Institution has published more than 7,500 individual books and pamphlets in nearly every field of science, most of them based on original research. It also maintains a large library of scientific books and pamphlets, covering all the fields in which it is chiefly engaged.

In the field of art the Smithsonian has three bureaux, as follows:

The National Gallery of Art, given to the nation by the late Andrew W. Mellon and containing his own collections, as well as other famous collections. The National Gallery is administered by a separate Board of Trustees.

The Freer Gallery of Art, one of the most important collections of Oriental art in America, a gift to the people of the United States from the late Charles L. Freer of Detroit.

The National Collection of Fine Arts, a generalized collection which is temporarily housed in the U.S. National Museum, pending authorization of a new building.

A FREQUENCY ANALYSER USED IN THE STUDY OF OCEAN WAVES

By N. F. BARBER, F. URSELL, J. DARBYSHIRE AND M. J. TUCKER

Admiralty Research Laboratory, Teddington

A WAVE-ANALYSER was developed at the Admiralty Research Laboratory, Teddington, in 1944 in order to analyse ocean waves and swell and ship movement. The apparatus has been in regular use since February 1945 drawing the frequency spectra of records of wave motion taken near Lands End.

These records of water pressure or depth are taken continuously for 20 minutes, and appear in the form of a black trace of variable width on white photographic paper. Fig. 1 shows a short length of record. On one side of the record is a time trace consisting of a black strip interrupted every 20 sec. By attaching the paper record to the outside of the rotating wheel in Fig. 2, photocells, illuminated by the reflected light from a narrow light beam falling on the record, give a fluctuating electrical output which is a repetition at high speed of the fluctuating trace on the record.

Fig. 1. A WAVE-PRESSURE RECORD

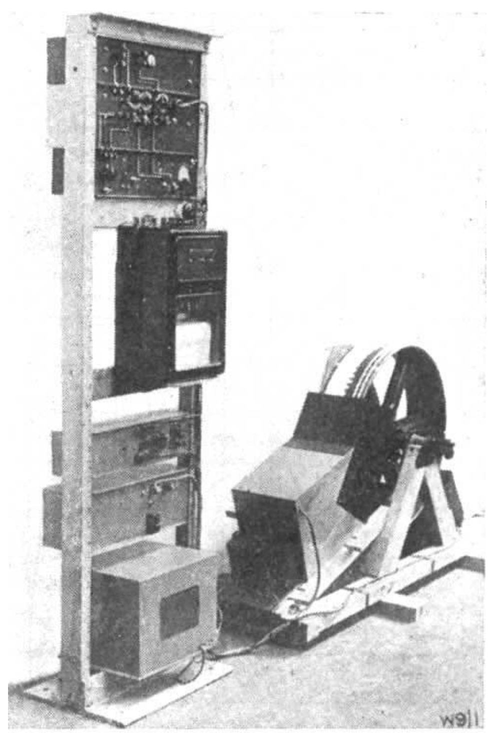

Fig. 2. THE FREQUENCY ANALYSER

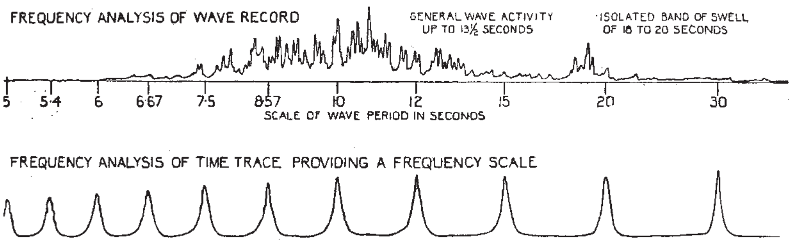

Fig. 3. TYPICAL FREQUENCY ANALYSIS

This electrical output is amplified and made to drive a vibration galvanometer. By allowing the speed of the rotating wheel to decrease slowly, the vibration galvanometer is caused to resonate in turn with the various component wave-lengths on the original record. Thus the vibration galvanometer of natural frequency 120 c. per. sec. resonates with the output of a wave-length 1/30 of the periphery of the wheel when the wheel is turning at 4 rev. per sec., but resonates with the output from a wave-length 1/40 of the periphery of the wheel when the speed of the wheel has fallen to 3 rev. per sec. Regarding the record as being compounded of its Fourier harmonics, each having a whole number of wave-lengths on the periphery of the wheel, one can see that provided the vibration galvanometer is sharply tuned and that the speed of the wheel decreases very slowly, the vibration galvanometer will show individual resonances to each Fourier component.

The motion of the galvanometer is detected photo-electrically and the output is amplified, rectified and made to drive a pen recorder the deflexion of which at any instant is, therefore, a measure of the amplitude of vibration of the galvanometer. The most recent model uses a vibration galvanometer with an electrical output, developed by G. Collins. The sample pen record shown in Fig. 3 is the analysis of the record of which Fig. 1 is a portion.

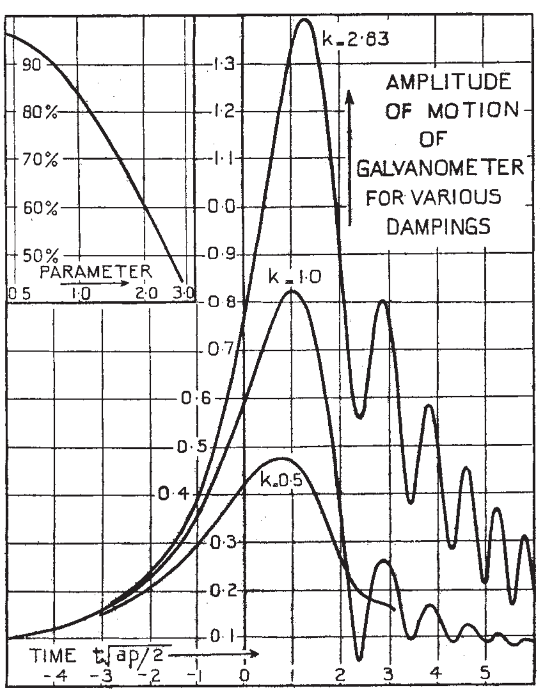

Fig. 4. AMPLITUDE OF OSCILLATION OF GALVANOMETER FOR VARIOUS DAMPINGS

A frequency scale is drawn automatically by a second pen giving the lower trace in Fig 3. This pen is actuated by a second channel working photo-electrically from the time trace and using a resonant filter tuned to 360 cycles. The second pen, therefore, draws a frequency analysis of the time trace, and this consists of a series of isolated peaks which can be used to interpolate a scale of frequency for the trace of the first pen. Because of the 3 : 1 ratio in the resonant frequencies of the two channels, these peaks are equivalent to wave-periods of submultiples of 3 × 20 or 60 sec., that is, 60, 30, 20, 15, 12, 10 sec., and so on.

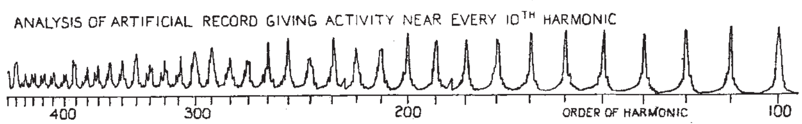

Fig. 5. ANALYSIS OF ARTIFICIAL RECORD SHOWING RESOLUTION OF FREQUENCY BANDS

It will be appreciated that the mechanical parts of the apparatus are simple and that the process of analysis is automatic. There is no mechanical drive to the wheel, which, having been turned by hand to its top speed, continues to revolve under its own inertia at a slowly decreasing speed, the analysis proceeding automatically. In the apparatus already built, the wheel is 30 in. in diameter and weighs 70 lb.; it is carried in ball bearings, and takes about 4 minutes to decrease to half speed. As for the electronic amplifiers, it is not necessary for them to have an amplification which is the same over a wide range of frequency, since the only electrical frequencies that are important are in a narrow belt near 120 c. per sec. It is important, however, that the amplifiers should be linear in the sense that they produce no spurious 120 cycles coming from sum or difference of the various frequencies in the input. Linearity is also important in the optical pick-up from the record, in the sense that the illumination of the photo-electric cell must be strictly proportional to the width of the white part of the illuminated area of the record.

In practice, it is found that an analysis covering four octaves takes place in about 16 minutes, and that an operator can deal conveniently with about fifteen analyses each day.

The analysis approximates to a Fourier amplitude analysis, and it has been found possible to determine theoretically the optimum characteristics of the apparatus. Each of the Fourier components of the record produces an electrical component the frequency of which is slowly gliding as the wheel decreases in speed. If the speed of the wheel decreases at a rate exp $-at$ and the vibration galvanometer has a natural frequency $p/2\pi$ and a natural rate of decay of free oscillations of exp $-bt$, then it can be shown that the manner in which the oscillations of the

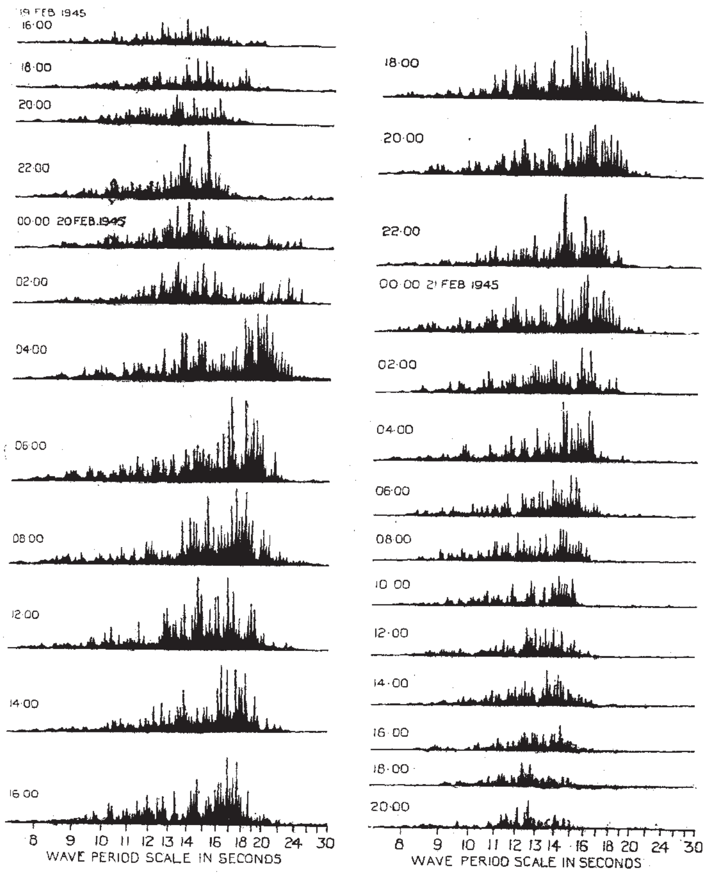

Fig. 6. A SERIES OF WAVE-PRESSURE SPECTRA

galvanometer build up and decay in amplitude as the gliding tone passes through resonance is determined by a parameter k, where $k = \sqrt{a/2pb^2}$.

Fig. 4 shows the response curves of the galvanometer for various values of k. They illustrate in particular the effect of changing the damping of the galvanometer without changing the rate of decay in speed of the wheel. With fairly large damping, $k = 0 \cdot 5$, the galvanometer builds up slowly to a small amplitude of resonance and decays smoothly. With smaller damping the peak is higher and sharper, but the decay is executed in a series of beats. With very small damping the galvanometer builds up to a limiting amplitude and proceeds to beat, but the time of decay of the motion is very long. Taking the effective width of the response as the interval in which the response exceeds 1/10 of its maximum value, it is clear that there is an optimum damping at which the width of the response curve is least. This is approximately at

$$k \text{ (optimum)} = 1 \cdot 8.$$

This optimum value of k gives the greatest resolution of the Fourier components. When the galvanometer is giving its peak response to one Fourier component, it is being slightly affected by adjacent components the gliding tones of which have either not yet reached the natural frequency of the galvanometer or have passed through it. If we consider the components to be adequately resolved when the contribution from each adjacent harmonic is less than 10 per cent of the peak response to that harmonic, it is possible to show from the curves of Fig. 4 that in any given apparatus all the harmonics are resolved up to the Nth, where

$$N = 0 \cdot 12\sqrt{p/a},$$

assuming that the damping b is at its optimum value for the p and a specified. It is clear that an analyser can be constructed to resolve any desired number of harmonics.

For the apparatus at present in use

$$a = 0 \cdot 0028 \text{ (decay to } \tfrac{1}{2} \text{ in 4 min.)}$$

$$p = 750 \text{ (natural frequency 120 cycles)};$$

so that for optimum working at $k = 1 \cdot 8$ we should have

$$b = 0 \cdot 001 \text{ (decay to 1/10 in 3 sec.)},$$

and the harmonics are resolved as far as

$$N = 60.$$

At $N = 120$ the adjacent harmonics contribute about 25 per cent of their peaks, and at $N = 240$ they contribute about 50 per cent, so that the peaks merge together. At higher harmonics the mean amplitude of vibration of the galvanometer may be taken as proportional to the square root of the sum of the squares of the amplitudes of the Fourier components in about a 1 per cent range of frequency. Even at high orders of harmonics the apparatus clearly separates isolated frequencies which differ by more than 3 per cent. Fig. 5 shows the analysis of an artificial record producing frequency belts near every 10th harmonic. These belts of frequency are resolved up to about the 400th and 410th harmonic, where the frequencies differ by $2\tfrac{1}{2}$ per cent. It is difficult to construct simple artificial records which have prescribed amounts of high harmonics, but the analysis of such records has shown that the amplitudes of the Fourier components up to the 60th are correct to 5 per cent; this error might be increased to 10 per cent, when a number of adjoining frequencies are present.

A wheel with mechanical drive and variable, controlled, exponential rate of decay, designed by F. E. Pierce, is being constructed in the workshops at the Admiralty Research Laboratory. With this wheel, which can be rotated up to 10 revolutions a second, more favourable characteristics can be chosen for damping and natural frequency, to allow greater resolution in an analysis taking the same time. Complete instruments are being made by Messrs. H. Tinsley & Co. Ltd.

The propagation of waves away from storm areas has been investigated with this analysis. Rules have been found which will allow improvement of methods of forecasting swell, a subject of interest to harbour and shipping authorities.

Fig. 6 shows a series of Fourier amplitude spectra of pressure at the bottom of the sea at a point off the Cornish coast. It is clear that there is a general trend in these analyses; it will be shown elsewhere that this is consistent with classical hydrodynamicla theory. It is expected that rapid progress will continue to be made, particularly after a network of recording stations has been established. A general account of the problem has been published by Deacon in "Ocean Waves and Swell", Occasional Publications of the Challenger Society, No. 1, April, 1946, pages 1–13 (see *Nature*, 157, 165; 1946).

We are indebted to the Board of Admiralty for permission to publish this article.

THEORETICAL PHYSICS IN INDUSTRY*

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Free Electrons in Solids

IN considering the behaviour of electrons in crystalline solids, a well-known theorem by F. Bloch is of great importance. According to this theorem, electrons in a perfectly periodic lattice move freely without being scattered. This does not mean, however, that all electrons contribute to the electric conductivity, because this would also require the possibility of accelerating electrons. To investigate this question we notice that the energy spectrum of electrons in a crystal consists of bands which are well separated in the low-energy region but which overlap at high energies. For simple structures each band contains N levels, where N is the number of unit cells. According to the Pauli exclusion principle, each level can be occupied by no more than two electrons. It thus follows that each energy band accommodates $2N$ electrons. The average velocity of all electrons in a completely filled band vanishes. Thus in the energy region in which bands do not overlap, a completely filled band does not contribute to the conductivity, because there are no empty levels into which an electron can be accelerated. This case is realized in insulators at low temperatures, where the highest occupied level coincides with the upper edge of an energy band in the region where bands do not overlap. In metals, on the other hand, there is at least one energy band which is not completely filled.

Consider now an insulator. To produce an electric current, electrons must be lifted into a normally empty band. This transition can be made either thermally, optically or by very strong fields. An electron in one of these conduction bands will be treated as a free electron with kinetic energy E. Such an electron will be scattered by any deviations from a strictly periodic lattice such as temperature vibrations or lattice defects. In view of this scattering, the average velocity $\bar{v}$ of an electron vanishes in the absence of an external electric field. In the presence of a field, electrons are accelerated in the direction of the field. In a very crude picture, one can imagine that each electron is accelerated for a time 2τ, after which it loses its additional velocity. Thus the average velocity of an electron is

$$\bar{v} = eF\tau/m, \quad \quad (1)$$

and hence the current density is

$$e^2F\tau z/m,$$

where z is the number of free electrons per unit volume. Consider an ionic crystal without lattice defects, so that the scattering is entirely due to the lattice vibrations. These lattice vibrations can be considered as a superposition of polarization waves of various wave-lengths, but with about the same frequency ν. The scattering of an electron is connected with either an absorption or an emission of a quantum $h\nu$. The probabilities for these processes are proportional to n and $1 + n$ respectively, n being the number of quanta of a given wave-length λ present in the lattice. The momentum of such a wave is h/λ, and the scattering angle θ of an electron is determined by the momentum law. Scattering can be considered to be elastic if $E \gg h\nu$. The probability P_θ for scattering by an angle θ is then the sum of scattering processes leading to absorption and emission of a quantum $h\nu$. One finds

$$P_\theta \propto (1 + 2n)/\sqrt{E} \quad . \quad . \quad (2)$$

The time of relaxation τ is connected with P_θ by

$$1/\tau = \Sigma(1 - \cos\theta)P_\theta, \quad . \quad . \quad (3)$$

where the sum is taken over all angles θ. The average angle θ depends on the energy of the electron. For electrons of several e-volts one finds

$$\tau \propto E^{3/2}/(1 + 2n) \quad . \quad . \quad (4)$$

In the theory of conductivity, it is usually assumed that the energy transfer from the field to the electrons, and from the electrons to the lattice vibrations, is of little importance. This is, however, not the case if the number of electrons in the conduction band is so small that their mutual collisions can be neglected. In this case they do not exchange energy, and the rate of energy transfer A from the field to an electron is thus given by $e\bar{v}F$, that is, using (1) and (4)

$$A = e^2\tau F/m \propto E^{3/2}F^2/(1 + 2n) \quad . \quad . \quad (5)$$

The average rate of loss of energy B to the lattice vibrations, on the other hand, is

$$B \propto \frac{1 + n - n}{\sqrt{E}}, \text{ that is, } B \propto 1/\sqrt{E}, \quad . \quad . \quad (6)$$

because the probability for absorption or emission of a quantum $h\nu$ is proportionally to $n/\sqrt{E}$ and $(1+n)/\sqrt{E}$ respectively. Now so long as B is greater than A, a single electron with energy $E \gg h\nu$ will on an average lose energy at a higher rate than it gains energy. This is reasonable because the Maxwell distribution function exp. $-E/kT$ has its highest value at $E = 0$. From (5) and (6) it follows, however, that B decreases and A increases with E. Thus at sufficiently high energies an electron will on an average gain more and more energy. It will be shown later that this may have important consequences.

A difficulty connected with the motion of slow electrons in ionic crystals concerns the polarization of the crystal near the electron. If ν is the frequency of oscillation of an ion, it will take about $1/\nu$ sec. for an ion to be displaced by the field of the electron. In this time an electron of velocity v moves a distance $r_0 = v/\nu$. This means that only at distances larger than r_0 is the polarization proportional to the Coulomb field of the electron. Hence the energy of polarization depends on r_0. It is of the order $-e^2/r_0 = -e^2\nu/v$. For small velocities this term may become more important than the kinetic energy $mv^2/2$. No detailed study of the influence of polarization on the motion of electrons has been made yet.

Theory of Dielectric Breakdown

Consider a solid dielectric to which an external electric field is applied. If the field-strength inside the dielectric exceeds a critical value, the insulation

* Substance of a course of three lectures delivered at the Royal Institution on March 28, April 4 and 11.