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ACOUSTICS AND RAYLEIGH

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I am deeply honoured, and with myself I include my many young associates at Imperial College during the last twenty years, in being asked to give the second Rayleigh lecture. Eminent men of science like Lord Rayleigh are intellectual giants whom most of us can merely admire but can never dream of emulating.

Hence it was with this sense of humility that I gratefully accepted the Society's award. It gives me added interest now to recall that my entry into Imperial College as a physics undergraduate was a year too late to have received lectures from Lord Rayleigh's son, the fourth Baron, who had just resigned following the death of his father. His subject of research however was radioactivity.

Professor Erwin Meyer set a high standard with the initial Rayleigh address which subsequent speakers will find difficult to achieve. He showed in describing some of the work in his world-famed research group at Gottingen that there is still ample opportunity in acoustics for making ingenious and scientifically worthwhile contributions.

In choosing the title of my talk I felt it appropriate to widen the content and to make some general reference to Rayleigh as a person and to the breadth of his work, and in particular to his contribution to the establishment of British and world acoustical science. Such an approach will also indicate how closely acoustics is entwined with many other disciplines. In keeping also with the objectives of the award some aspects will be described of our recent work at Imperial College which has some relevance to the investigations of Lord Rayleigh. The selection of the particular topics in one sense was not difficult for I soon found that the breadth of his acoustical activity was even wider than I had supposed previously. Remembering also that Rayleigh was an experimentalist I am going to follow the habit of the old-time lecturers and the pertinent advice of Dr.Samuel Johnson "People have now-a-days got a strange opinion that everything should be taught by lectures .... I know nothing that can be best taught by lectures, except where experiments are to be shown".

In choosing the title of my lecture I was mindful that acoustics formed only about one-fifth of Rayleigh's scientific research output. This fact surprises many acoustical workers who forget, or did not know, that Rayleigh was awarded in 1905 the Nobel prize in physics mainly for his pioneer work on Argon. The preface of Schuster's classical work on Theory of Optics (1904) is dedicated to John William Strutt, Baron Rayleigh,O.M.,ScD.,F.R.S. with the words " who by his writings has added clearness and precision to nearly all branches of optics". It is interesting to record Schuster wrote that the problem of light will only be solved when we have discovered the mechanical properties of the aether. So he continues a theoretical study of light must be introduced by a careful treatment of wave propagation through media of known elastic properties - hence a study of sound and of the old elastic solid theory of light should precede the introduction of electromagnetic equations.

In order to appreciate the state of acoustical thinking at the time of Rayleigh's advent into the field let us look back briefly in time. By the end of the 17th century the term "acoustics" was beginning to be used in the modern sense of embracing all problems connected with sound and hearing and already some advance had been made in the knowledge of hearing mechanisms. In fact at this time there was a surge of acoustical interest, associated largely with the development of string and percussion instruments, and a number of books on acoustics appeared, such as 'Die Akustik' by Chladni (1756-1824), who is renowned for his experimental technique of displaying vibrational modes of excited plates. It was towards the end of the 17th century that Newton in his Principia gave the first mathematical theory of sound wave propagation in fluids but the disagreement of his theory with experiment was not explained until over 100 years later, by Laplace (1816). It is significant to mention here that Newton had to re-cast the proofs of his Principia, changing the calculus notation to the classical geometrical form familiar to readers of Euclid and Archimedes, in order that his work might be more generally understood. This conservative attitude in technique was probably the main cause of the sterile period of mathematics in Britain, at the end of the eighteenth century, the last British mathematicians of distinction in this period being Maclaurin(1698-1746) and Simpson (1710-1761) Except for Robert Young (1773-1829), who laid the foundations of the wave theory of light and sound during the first decade of the 19th century, mathematical physics was in the hands of the European scientists Fresnel, Fourier, Poisson, Laplace etc. They developed the theory of propagation of elastic and thermal waves, thus relating acoustics with mechanics and thermodynamics. The introduction of continental mathematical methods by the Cambridge Analytical Society early in the 19th century soon bore fruit in the evolution of a group of British mathematical physicists equal to any in Europe viz: - Kelvin, Stokes, Maxwell, Rayleigh and J.J.Thomson. Such was the stimulating atmosphere in which Rayleigh developed his talents. Additionally preceding him in time was the great German acoustician and all-round physical scientist, Helmholtz. The third edition of his book 'Die Lehre von der Tonempfindungen' in fact appeared eight years before Rayleigh's "Theory of Sound". The latter generally regarded as the bible of acoustics being a complete study of vibrating systems, of sound propagation in free space and of diffraction phenomena. Rayleigh derived inspiration from this work from the earlier elastic media theory formulated by Stokes and from the reading of Helmholtz' book, and it is noteworthy that he commenced his writing while on a health recuperating boat trip up the River Nile. It would be pointless, and in fact impossible, for me, in one lecture, to give details of the many acoustical topics pursued by Rayleigh but these are admirably chronicled by Professor Bruce Lindsay in his recent book entitled 'Lord Rayleigh, the Man and his Work'. A full biographical account of Rayleigh's life is contained in the second edition of "Life of William Strutt", edited by John Howard, the first edition published in 1924, being written by Rayleigh's son, the fourth Baron.

Rayleigh had a clear style of writing and in the main he chose practical problems, specialising in what is now termed engineering physics. This choice provides a reason why his work is still basic for many of the present day practical problems such as friction, lubrication etc. and I was interested to find a distinctive reference to him in 'Men of Lubrication' - no this does not refer to any inebriate habits - published by the American Society of Lubrication Engineers. His work on the dynamical properties of liquid surfaces is of current interest and I shall be making further reference to to this subject.

It is appropriate to mention here that Rayleigh had a live interest in the history of physics and with it a desire to do justice to the pioneer efforts of earlier workers, as is exemplified by his resurrection from the Archives of the Royal Society (1845) of a memoir due to J.J.Waterston. This Scottish engineer established the theoretical basis for the molecular theory of gases, but only a brief reference was made to the work in The British Association Report for 1851, and nearly fifty years elapsed before it received rightful recognition, due to Lord Rayleigh. The referee who said that 'the paper is nothing but nonsense, unfit even for reading before the Society' effectively held back the development of the subject by fifteen years - until Maxwell's paper.

It is worthy of note that Waterston's memoir contained the first calculation of gas molecular velocity and of its relation to the velocity of sound in the gas.

In the two following diagrams I hope to convey firstly (Fig.1) some idea of the numerous activities,not including his dairy business, of Lord Rayleigh,and secondly, the breadth of his acoustical work, which has provided in effect (See Fig.2.) the corner-stones for many active areas of investigation today.

In technical developments acoustics is very much a live science and Rayleigh himself was on the look-out always for a present or future application of his work. By way of example it was in 1886 that he became concerned with surface waves and he voiced the belief that they might play an important part in earthquakes as was confirmed later by Wiechert. Such waves move with a slower velocity than the solid dilational waves and this fact receives application in geophysical prospecting. In the laboratory they may be generated on the rims of gear wheels etc., as shown for example at Imperial College by Sinclair, and there is at the present time considerable activity in the generation of Rayleigh and other types of surface waves at GigaHertz frequencies for use in filters and delay lines.

In mechanical engineering Rayleigh's influence is detected in the useful application of his energy principle to the approximate determination of critical loads and frequencies of mechanical systems. This principle states that in the fundamental mode of vibration of an elastic medium the distribution of kinetic and potential energies is such as to make the frequency a minimum.

Turningto hydrodynamics, the contributions of Rayleigh are closely paralleled by those of Lord Kelvin and in fact both were among that eminent band of 18th and 19th century classical hydrodynamicists which included Euler, Lagrange, Newton, Barnouilli etc. Rayleigh's investigations of wave characteristics ranged from surface oscillations in reservoirs to the evaluation of wave profiles of finite amplitude. He studied the instability of liquid jets, and Osborn Reynolds' observations on the sound emitted by the partial or complete collapse of bubbles in water, during the boiling stage in a kettle, inspired him to study the dynamics of bubble collapse in a liquid. The wide industrial and fundamental academic importance of this topic which still exists today and is having continued technical application is illustrated in Fig.3. Cavitation results from the production of a tension within a liquid and may be obtained hydrodynamically, as with a ships' propeller, or under ultrasonic irradiation of sufficient intensity to overcome the ambient pressure.

The phenomenon is the basic mechanism involved in industrial cleaning and chemical processes but it is a limiting factor in the intensity of operating transducers in underwater sonar work and care has to be exercised in avoiding its occurrence in the human body. A colleague, Dr.Ayad has recently used cavitation to quicken haemolysis testing by the ultrasonic irradiation of blood samples Fig.4.(a). The academic interest is in the mechanism which results in the high temperatures developed in the void collapse, under some conditions leading to luminosity. One theory attributes the discharge to the joining of electrical charges and the other to rapid adiabatic compression. The latter seems to be in favour and is supported by the observation of luminescence in liquid metals by Young at Imperial College, see Fig 4.(b). We have also recently detected infra-red radiation and Peters has carried out some model-type experiments to simulate bubble collapse. In these experiments thin glass spheres, Fig 5. of 3 to 5 cm. diameter are fractured underwater and the large amplitude outgoing sound waves are measured by a suitable hydrophone. Various methods of breakage were tried but although altering the nature of the implosion, had seemingly little influence on the magnitude of the resulting shock wave amplitude. This technique permits a variation in the rate of collapse, Fig 6. by changing the initial gas pressure within the sphere and by using surrounding liquids of different viscosities.

With this renewed interest today in model experiments, it is interesting to note that although Fourier had laid the foundation of the principle of 'dynamic similarity' in 1822, it was not until Rayleigh's first attempt to generalise the principle in 1899 that it began to attract attention. Later (1910-11) he applied the method to general circulation problems in meteorology, just after his appointment to the first British Committee in Aeronautics, and no doubt he exercised significant influence in this new scientific field. Rayleigh's work on turbulence was complementary to that of Osborn Reynolds and Prandtl and their combined efforts had far-reaching practical repercussions on the building of ships and aeroplanes.

Towards the end of the 19th century Rayleigh stimulated a live interest in physiological acoustics by the experiments he conducted, in1876, on the binaural effect. By considering the head as a spherical object he showed that direction finding was not the result of an intensity difference at the two ears. He returned to the subject some thirty years later and became inclined towards a phase difference explanation, but this subject does not seem completely resolved today. If it is purely a question of phase difference at the two ears considerable doubt would exist as to the possibility of direction finding by humans underwater, having in mind the much greater velocity of sound in water compared with air (a factor of five). Underwater binaural experiments were carried out during three consecutive summers in the warmer waters of the Mediterranean at Malta under the site direction of B.Ray of Imperial College, and I will give a brief account of this work.

The investigation was designed to ascertain with what accuracy a diver can localise a wide-band source in the open sea. A wide-band source was chosen as being more representative of natural and man-made sounds, and Klump and Eady have shown, in air, that it produces better binaural discrimination than a pure tone. Although anechoic conditions at audio frequencies are virtually impossible underwater yet the results obtained should be directly applicable to the real environment. The final form of sound source, which had to be reasonably portable for the diver and to produce a wideband, non-continuous source of sufficient amplitude, took the simple form of an actuated hammer, which was arranged to strike one side of a water-tight metal container (see Fig.7). The procedure adopted in the 'free-choice' experiment was for the accompanying diver to switch on the sound source and for the subject in his own time to point, Fig.8. to where he thought it was located, and the operator swam to a new position after every test. (The experiments were often terminated after a shorter run than intended due to the subject suffering from cold.) In the 'two-choice' experiments a triangle was marked with tapes on the sea bed at a depth of 30 feet and the subject sat on a heavy steel box at the apex of this triangle and he was allowed to study the lay-out before closing the mask black-out. The sound source was positioned at one of the two distant vertices and the subject was required to raise his left or right arm to indicate his judgement of the course position. A third diver recorded the results. In both series of tests the diver subject was 'blind-folded' by wearing a facemask incorporating a metal flap which hinged-down to obscure virtually all light.

It was found that freely suspended subjects were able to indicate the sound direction within a standard deviation of 50° whereas the seated subjects indicated to with 20°. This difference could be explained as arising from the latter observers having a fixed reference environment, so further observations were made of the 'free-choice' type in which the subject was provided with contact with the sea-bed. In these cases the deviation was reduced to 20°, thus supporting the explanation. The overall conclusion of these experiments is that directional hearing is possible underwater, although the majority of the diver-subjects had the impression that they were not, or at best only marginally, able to localise the source. However when forced to a choice he would be accurate to a degree which surprised him.

In the realm of architectural acoustics we find Rayleigh giving pronouncement on the phenomenon of the Whispering Gallery of St.Paul's Cathedral. He explained it in terms of the creeping of sound around the circular wall immediately surrounding the narrow gallery, and at the same time disputing the suggestion of the Astronomer Royal, the celebrated Sir George Airy, that it was due to reflection from the surface of the dome overhead. Rayleigh's explanation, however, was not quite complete as the efficiency of the effect of St.Paul's is due to the slight inward sloping of the walls. (It is interesting to note that Rayleigh (and other workers) received some criticism from W.C.Sabine for in his opinion not taking sufficient account in their experiments of the acoustical properties of the boundary surfaces or terrain.)

Another phenomenon which attracted Rayleigh's attention and has topical relevance today is concerned with thermo-acoustic oscillations (Fig.9). Two distinct types are recognised, Sondhaus oscillations, which are sustained by the addition of heat at the closed end of a gas-filled pipe in which there is no net gas flow, Fig.10., and Rijke oscillations which arise on adding heat to an internal metal grid located within the lower half of a vertical metal pipe, having open ends to permit an internal upward flow of gas. The Rijke phenomenon has been investigated under varying conditions and forms of gas systems, such as flame driven standing-wave systems or the use of combustion in air columns, and in general the results confirm the Rayleigh criterion for the maintenance of the oscillations. He argued that for these to be encouraged heat must be transferred to the gas at the moment of greatest compression.

In demonstrating this Rijke type of experiment a piece of bunsen gauze is fashioned to occupy the cross section of an iron tube at a location about one third of the length from one end. On heating the gauze with a bunsen burner and removing the flame the tube, held in the vertical, should speak quite loudly. If the gauze were located in the upper half no response would be forthcoming, but as suggested by Rayleigh, and subsequently verified by Bosscha and Riess using a cold refrigerated grid in the upper half, oscillations could be maintained by abstracting heat at the moment of greatest rarefaction. It is not essential for the tube to be vertical but if horizontal a steady flow of gas has to be circulated through the tube. Such a system was used by Friendlander and Smith in America and also by Carl Humblein at Imperial College. The set-up employed by him is shown in the next Figs 11 and 12

The type of performance obtained with the tube is given in Fig 13. and it may be concluded that the system is capable of producing high intensity sound at low frequencies, although the efficiency is quite low. The maximum sound pressure level appeared at a definite flow-rate. If this is decreased then the tube oscillates at smaller and smaller amplitudes while increasing the rate above the optimum excites other vibrational modes. For greater efficiency of operation the heating element should be kept as thin as possible.

If the air be at its normal density at the time when the transfer of heat takes place then the vibration is neither encouraged or discouraged but the pitch is altered. This type of phenomenon may be illustrated by a simple depth sounding device consisting of a steel tube some 40 to 50 cm.long, capped at one end with an open cylinder or small horn, closed by a rubber membrane. On bringing the open end into contact with the surface of liquid He in a vacuum flask a change of pitch should be heard. I am indebted to an old colleague R.Finch for reminding me of the application to depth finding, when a liquid surface is not directly visible.

I have dwelt a little long perhaps on these thermal phenomena but today when we are concerned with audio and infrasonic sound pollution, these thermo-acoustic oscillations are often the hidden causes in industrial gas furnaces. The problem of vibrating plates also received some attention from Rayleigh at an early date (1873) in a paper entitled 'The Nodal Lines of a Square Plate'. This is an area of investigation which illustrates extremely well the impact of developing technology on acoustic measurements from the time of Chladni with violin bow excitation through electrodynamic excitation and the intriguing use of solid carbon dioxide by Dr.Mary Waller to holographic methods. In the older methods sand or fine powder on the surface of the plate was used as the mode indicating medium but with holography an optical fringe system may be observed which does not subject the plate to even a light mass loading. In the experiment carried out in our laboratory by Fryer a simple stroboscopic holographic system was developed, using a disc excited at a point on the rim to simulate a gear wheel. Various modes and their amplitude of vibration could be estimated from their optical fringe patterns and an effort made to correlate with the sound output, the system being contained within a small reverberant room. Figs. 14 and 15 show a schematic diagram of the experimental system together with a typical 'picture' of a vibrational mode.

The main advantages of holographic vibrational analysis are its simplicity, sensitivity and the possibility of measuring with high accuracy, either in real time or at leisure, vibrational amplitudes over the whole of the object surface. When viewed and illuminated normally each fringe encountered simply indicates that the vibration amplitude has increased by one half-wavelength of the laser light used.

Rayleigh was interested in instrumentation also and his most significant contribution is the Rayleigh disc for measuring the absolute intensity of sound, although in practice there is a slight dependence on the relative geometrical dimensions of the disc and containing tube.

The development of the device by Rayleigh followed upon Helmholtz's modification of classical hydrodynamical theory concerning mechanical resistance of fluids. Helmholtz maintained that there was nothing in the nature of an ideal fluid to forbid a finite slipping between contiguous layers, so that at the edges of a lamina submerged in a fluid stream a surface of discontinuity is formed which 'bounds' the fluid behind the lamina. As always Rayleigh was alive to an application and calculated the couple acting on a disc suspended with its plane set obliquely to the sound beam.

This partiality to applied problems was again in evidence when Rayleigh followed in the steps of Faraday and Tyndall by accepting the post of Scientific Advisor (1896-1913) to Trinity House. His main contribution there was in the design of fog-horns, in which he demonstrated that for maximum horizontal spread of sound over the sea the horn should be of elliptical section with the major axis as vertical. He was also involved with illumination from lighthouses and the possibility of floating the revolving mechanism on mercury to minimise friction. This was being opposed on the grounds of expense to which he replied by reminding his critics 'that it is the mercury which is not there which floats it'.

As a natural result of expanding frontiers and new technical developments the demarcation line of any subject is being repeatedly revised, which has the effect of injecting new ideas and preventing stagnation. This is an appealing aspect of acoustics because of its wide inter-disciplinary nature. Non-linearity considerations for example, particularly in solid mechanics, has made notable progress since the first World War, stimulated on the one hand by International Congresses of Applied Mathematics and on the other by advances in engineering technology i.e. increased working temperatures and operating speeds of prime movers, gas turbines, jet engines, rockets, reactors etc. Rayleigh's main contribution to the field of non-linearity was a paper in the Proc. Soc. (1910) on 'Aerial Plane Waves of Finite Amplitude' in which he reviewed the work of earlier theoreticians but also introduced some original ideas on the formation and behaviour of 'shock' waves, although he did not use this term. Furthermore it must not be forgotton that he was very interested in radiation pressure, a non-linear property of sound propagation. This radiation pressure is proportional to the sound intensity so that in an attenuating medium a continuous wave will give rise to a pressure differential and hence a flow of the medium away from the source, termed acoustic streaming. This effect may be simply demonstrated with a loudspeaker in which the cone opening is blocked off except for a central hole. Some light threads are hung from a wire 'bridge' spanning the hole, and on energising the speaker the central threads should set themselves axially and directed away from the sound source, while the threads near the edges of the hole are sucked inwards i.e. there is a pump-like action.

A distinctive area of development since Rayleigh's day in which perhaps his work has been less contibutory, is the use of acoustical techniques in investigating the structure of matter. This field of research looks at resonance and relaxation phenomena on an atomic scale, and effectively involves the wedding of basic resonance theory with quantum theoretical considerations.

It is perhaps not altogether surprising that Rayleigh, although not actually spurning the modern approaches, found difficulty in absorbing them for it was not many years before his birth that Newton's corpuscular theory of light had been superceded by Young's wave theory. The latter held sole sway for nearly 100 years, until the appearance of the photon concept Strangely however it was the dilemma created by Rayleigh in his 'founding' of the Rayleigh-Jeans radiation law that actually led to Planck's development of his more general radiation law using quantum considerations.

By analogy with the photons of electromagnetic waves the quantised sound waves are known as phonons, those associated with the lattice vibrations being termed thermal phonons. Interaction between these will occur at a temperature when the interatomic forces become anharmonic and provides an explanation for internal friction in solids, an important parameter in mechanical non-destructive testing of materials. Rayleigh's contribution to this latter area of acoustic application is his law of scattering, originally used by him to explain the colour of the sky but equally applicable to estimation of average grain size in polycrystalline media, by the change in attenuation of propagated ultrasonic waves.

Interaction acoustics is a field which has emerged during the last decade in various forms such as acoustic-acoustic, acoustic-optic and the interaction of ultrasonic waves with the atomic and nuclear magnetic moments of solids. I will say a few words about the latter since it is one in which we at Imperial College had some interest a few years ago. An ultrasonic wave passing through a medium, in the presence of a suitable magnetic field, can lose energy in exciting components of the spin system to higher magnetic energy levels. This will occur when the frequency of the sound wave is equal to $\Delta E/h$, where ΔE is the energy spacing between spin levels and h is Planck's constant. In conventional N.M.R.technique this energy level transition is induced by applying an appropriate radio frequency electric field, the spins returning to equilibrium with the lattice via a spin-phonon interaction. This latter fact suggested the possibility of the excitation of the spin system by an applied phonon field at the resonant frequency.

In one of the two possible procedures the change in attenuation of the ultrasonic wave on exciting the spins is observed. This change is comparatively easy to observe with ionic crystals but very careful experimentation is required in taking measurements with metals. Barnes at Imperial College was in fact the first to obtain the effect with a metal, using a copper single crystal. It should be mentioned that Acoustic N.M.R. applied to metals has the advantage of exciting a larger spin population in the bulk material than the conventional N.M.R., which is restricted by the 'skin-effect' to the outer 'layer' of the specimen.

Another topic attracting a great deal of attention is that of sound propagation in aelotropic media, a domain, on a planetary scale, which up till now has been the interest of seismologists and to a certain extent also of oceanologists. The laboratory interest has heightened with the advent of carbon composites and similar media and with the use of deposited materials for surface wave propagation at Gigahertz frequencies. Starting with Stoneley's extension of Rayleigh's surface wave theory to the propagation of similar waves at plane interfaces between isotropic solids, there has been considerable development in the theory of acoustic propagation in anisotropic media and it is significant that a book has just appeared (by Musgrave) entitled Crystal Acoustics.

Around 1875-80 Rayleigh showed an increasing interest in dynamic liquid drop phenomena and associated surface tension forces, and he returned to the subject in the early 1890's, making particular reference to the effect of surface contamination. This ability to diagnose the essential parameters of a problem, e.g. to sort out the reasons for small butrepeatable differences from expected results was characteristic of Rayleigh as evident in his discovery of argon. The surface effects are of topical interest today in the matter of pollution, involving such problems as oil slicks on the ocean etc. At Imperial College we have been interested in the subject in connection with the use of high polymers, such as polyox, in effecting drag reduction on bodies moving through water.

Scott has conducted an acoustic investigation employing surface generated ripples and observing them with the Moiré fringe technique. The existence of such fringes was explained initially by Rayleigh towards the end of the last century but the idea lay dormant until revived by John Guild of the National Physical Laboratory in the late 1920's. Scott's experiment has therefore knit together two apparently diverse areas of Rayleigh's interests. Moiré fringes are in general produced by the simple geometrical superposition of two straight line gratings, and are observed when their line pitches are of the same order and the two systems are included at a small angle (Fig 16 (a)). The image distortion of a line grating produced by the surface ripples is shown in Fig 16 (b) and the resulting fringe pattern on combining with the reference grating is given in Fig 16 (c). The schematic diagram of the apparatus is shown in Fig 17. The passage of the travelling surface wave displaces the fringes perpendicular to their rest direction by an amount which is proportional to the slope of the wave at any point of the wave-train. From an eletronic flash picture both damping and wavelength can be evaluated. With polymer monolayers the system shows surface elasticity and the damping of the waves is greatly increased compared with that for pure water. This high attenuation is attributable to the existence of longitudinal surface waves, a resonance phenomenon occurring at surface elasticities for which the velocities of the two types of waves are equal.

Conclusion.

I would like to conclude with a brief commentary on Rayleigh's success as teacher and head of the Cavendish Laboratory at Cambridge. During his period of office, with the help of Glazebrook and Shaw, he laid the foundation of what became the traditional undergraduate practical physical course in British Universities. He showed a preference for including experiments requiring some degree of skill and persistence and to quote his words 'anyone who could handle a thing without knocking it off the table was an acquisition'. An illuminating comment upon Rayleigh's running of the laboratory, which is not without a moral, is given by Mrs. Sidgwick (who worked with him in the setting-up of electrical standards) ' I think that the way he affected other people and his success in inspiring work and in getting others to work with him and for him, was largely due to his gentleness and sympathetic interest in what others did. He hardly ever betrayed any irritation, or hustled or worried people, and he never put himself forward unduly or allowed personal ambition to prevail. His desire was manifestly for the general good and the advancement of knowledge in whatever way was best'.

In mentioning electrical standards I am reminded that Rayleigh played a prominent part in the establishment of the National Physical Laboratory of which his former demonstrator, Glazebrook, was the first director. So incidentally Rayleigh had a hand in the creation of one of the bastions of acoustical work in Britain during this century.

This has been an era of specialisation and I think research groups have been often too restrictive in their interests. By contrast Rayleigh would usually have a number of problems on hand so that he could rapidly turn to the one in which he had immediate inspiration. There are happy signs that we are moving back to more rational and broader courses of study in science such as I was privileged to enjoy in the 1920's.

I hope that my talk has served to indicate that Lord Rayleigh's work on 'Sound', although almost unbelievably comprehensive, has still left much of the acoustic picture to be filled in by future investigators. He gave us a broad canvas of many hues the main colours of which remain basically the same, but with modern investigational developments the boundaries no longer appear distinct. The picture in fact become more complex, but by the use of computers and other aids we are able to tackle problems which would have been impossible in Rayleigh's day.

In the words of Mark Twain 'It is difficult to make predictions - particularly about the future'. We cannot readily visualize where technology will lead us. One of the pressing needs however in acoustics is the accurate measurement of sound intensity,important alike from the legal aspect of noise control as in the safe dosage of ultrasonics being applied to a human.

We are at present vitally concerned with the nuisance of noise perhaps in a decade hence we will be involved in the sociological aspects of silence. Whatever the future holds however, I am sure that acousticians will still be looking backwards for some light from that remarkably illuminating scientific edifice called Rayleigh's 'Sound'.

I do thank you for your kind attention to my talk especially for the forebearance of the mathematically-minded. I apologise to you for the absence of equations and formulae but I felt that these are best omitted from a broad-based talk and are better digested by reading of the original papers.

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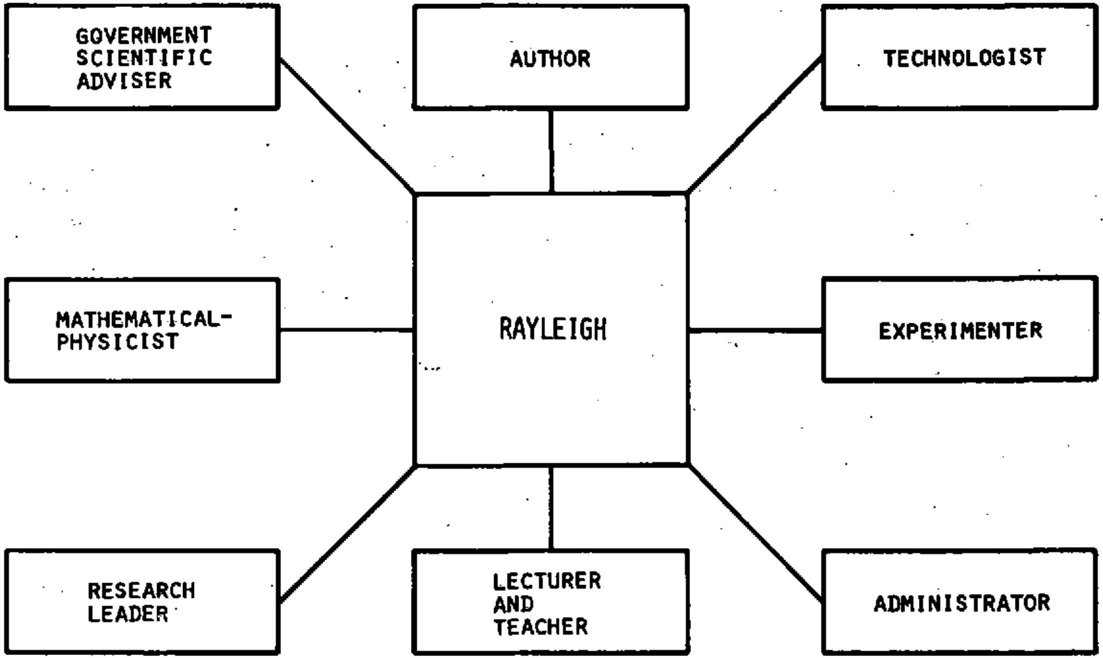


FIG. 1: RAYLEIGH'S ACTIVITIES.

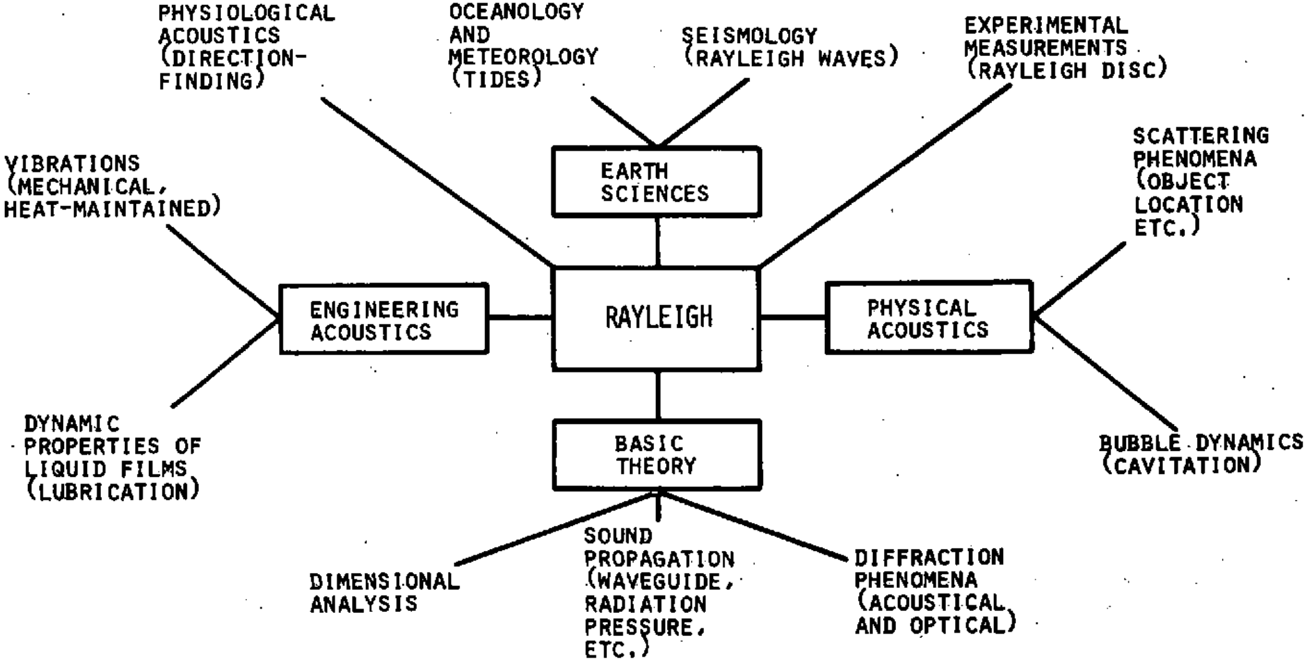


FIG.2: THE SPREAD OF RAYLEIGH'S ACOUSTICAL INTERESTS.

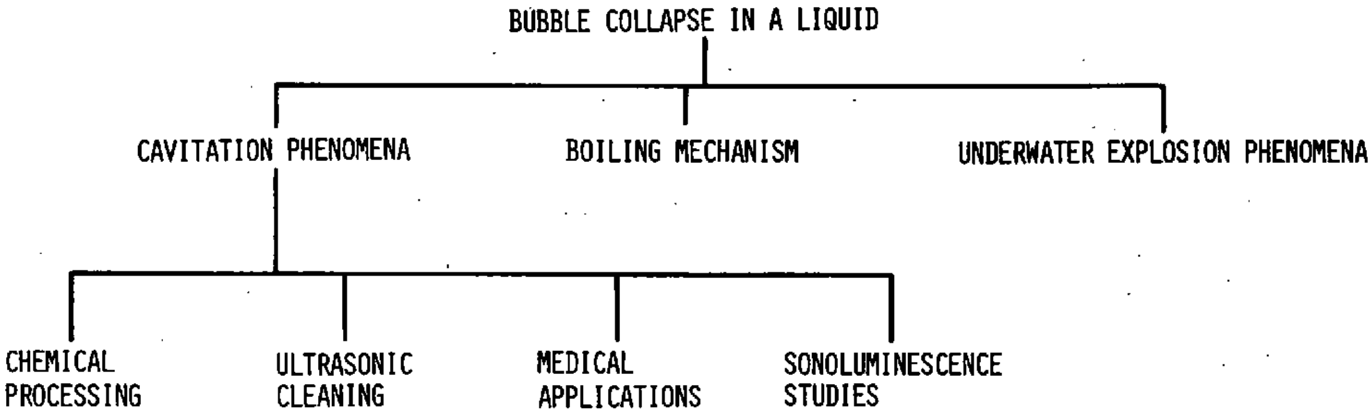
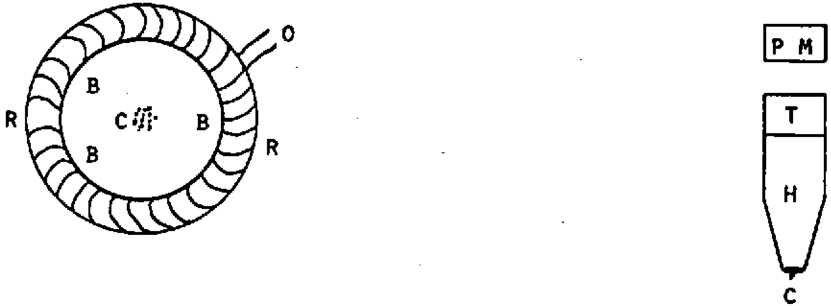


FIG.3: APPLICATIONS OF RESEARCH INTO BUBBLE COLLAPSE.



(A)

(B)

R - MAGNETOSTRICTIVE RING AND WINDING
O - OSCILLATOR AND POWER SUPPLY
B - VESSEL CONTAINING LIQUID
C - CAVITATION CENTRE

P M PHOTO MULTIPLIER
T HOLLOW PIEZOELECTRIC CERAMIC CYLINDER
H ACOUSTIC HORN OF OPTICALLY TRANSPARENT MATERIAL
C CAVITATION CENTRE

FIG. 4.

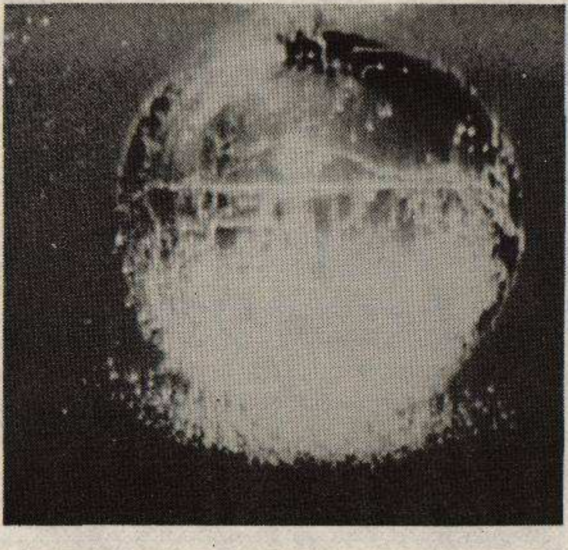


FIG. 5: IMPLOSION OF GLASS SPHERE BY SHOCK WAVE GENERATOR (THUMPER TYPE) SHOWING SIMULTANEOUS CRACKING ALL OVER ITS SURFACE: EVIDENCE OF CAVITATION IS ALSO APPARENT.

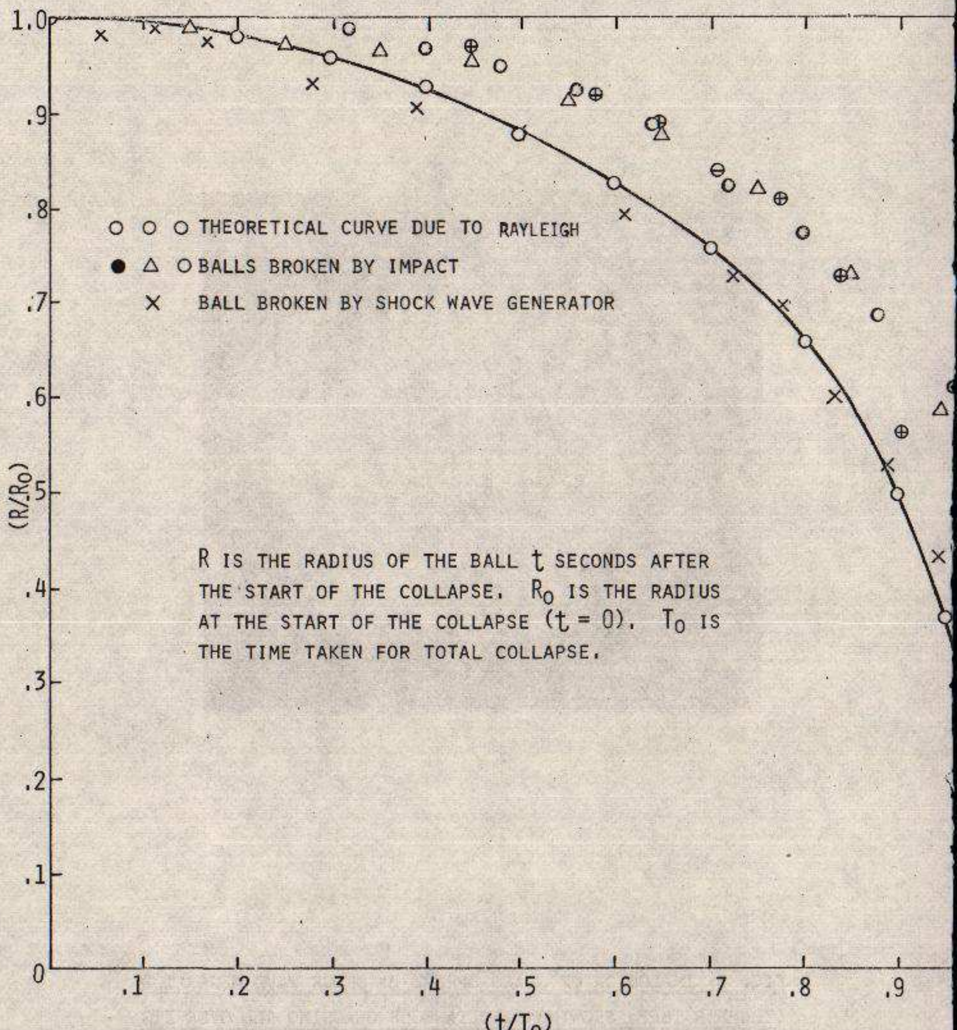

1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
(R/R0)
.1
.2
.3
.4
.5
.6
.7
.8
.9
(t/T0)
THEORETICAL CURVE DUE TO RAYLEIGH
BALLS BROKEN BY IMPACT
BALL BROKEN BY SHOCK WAVE GENERATOR
R IS THE RADIUS OF THE BALL t SECONDS AFTER THE START OF THE COLLAPSE. R0 IS THE RADIUS AT THE START OF THE COLLAPSE (t = 0). T0 IS THE TIME TAKEN FOR TOTAL COLLAPSE.

Fig 7   Photograph of the 'buzzer' sound source.
(with lid and '0' ring removed)

Construction of the 'buzzer' sound source.

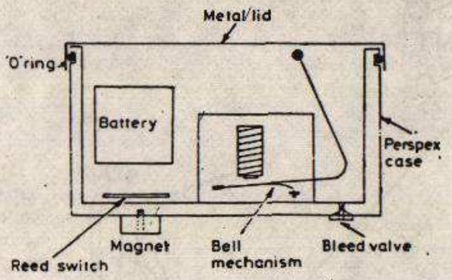
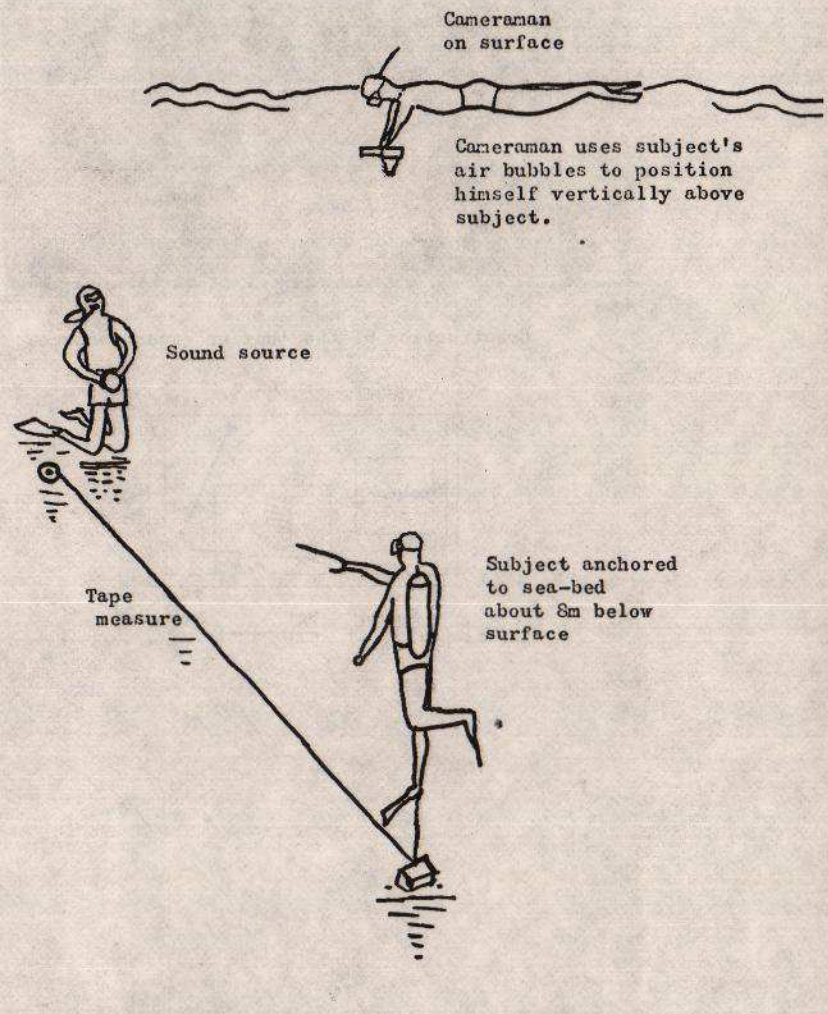


Fig 8   Diagram showing the position of the divers in the free choice experiments.



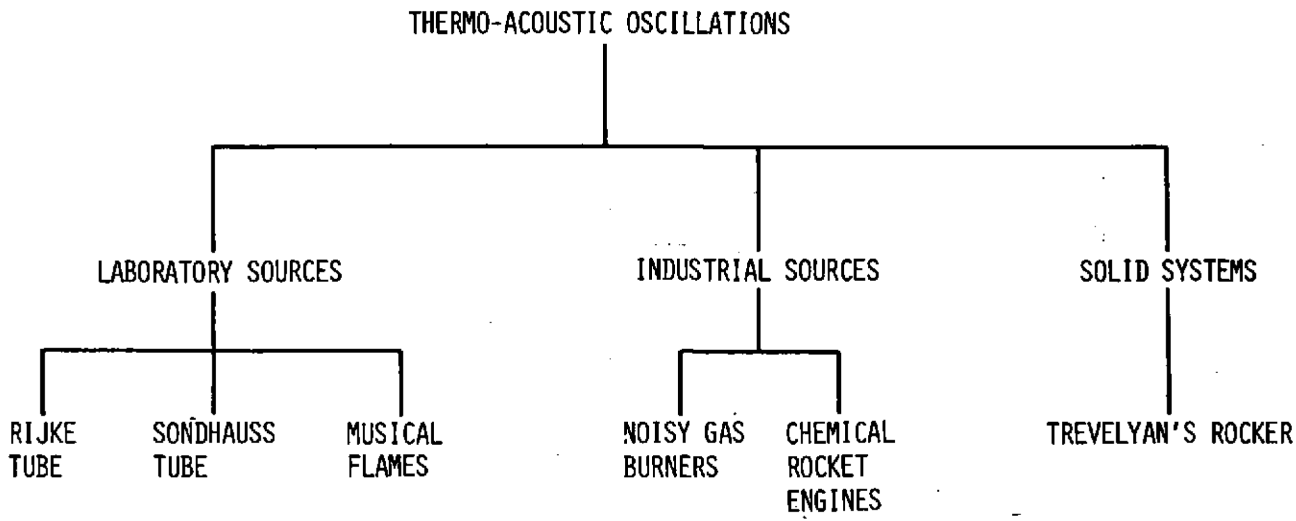
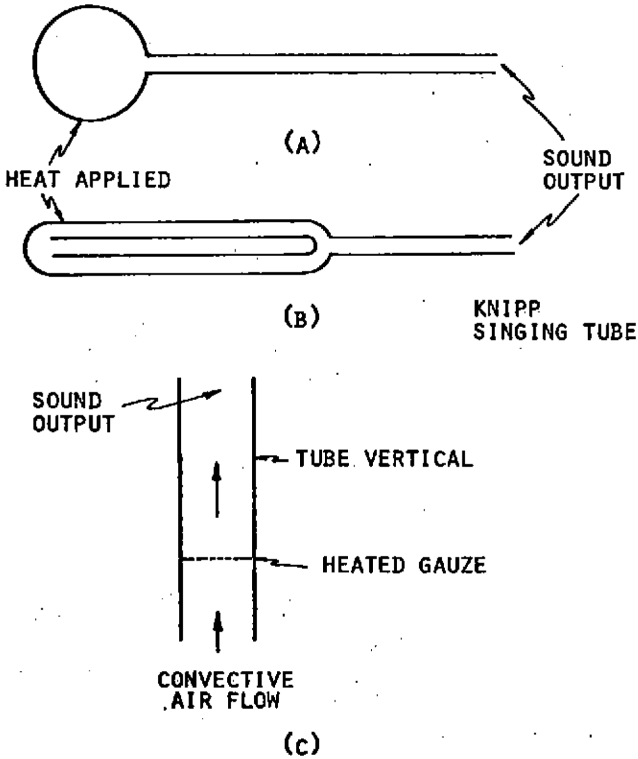


FIG. 9: THERMO-ACOUSTIC OSCILLATIONS AND THEIR RELATED PHENOMENA.



(A) AND (B) SONDHAUSS OSCILLATION

(C) RIJKE OSCILLATION

FIG. 10.

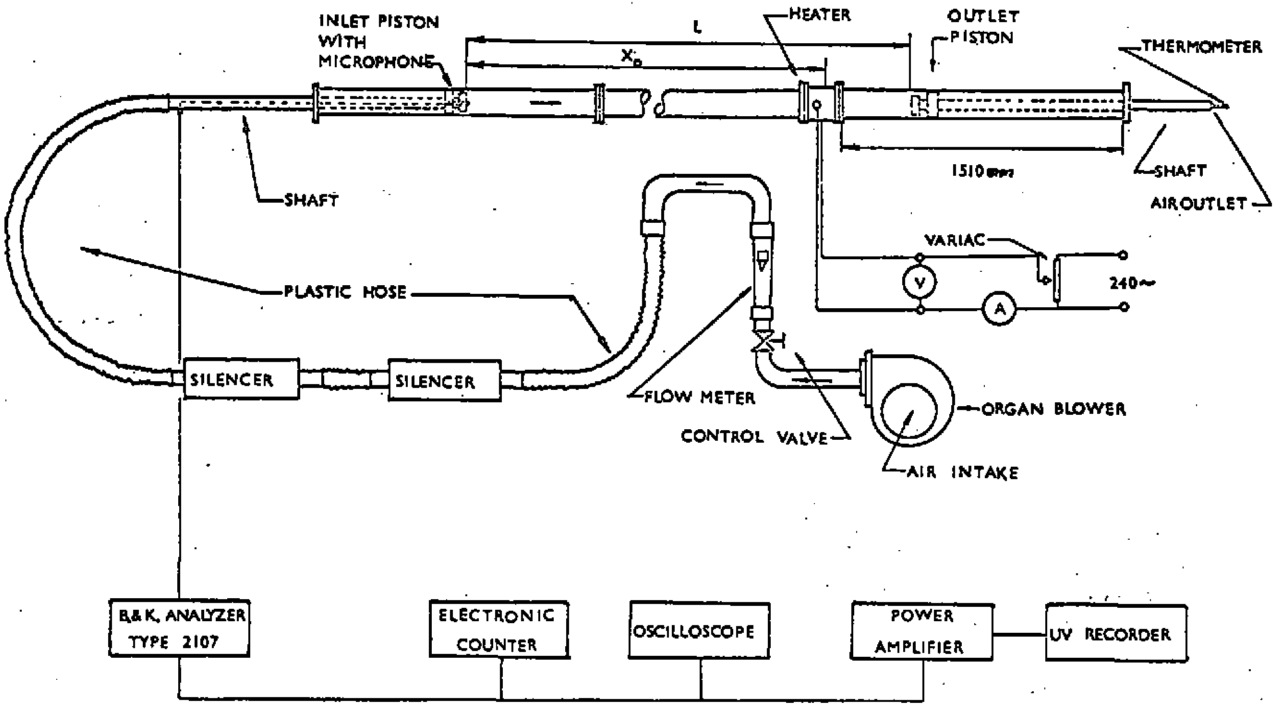


FIG. 11: SCHEMATIC DIAGRAM OF VARIABLE LENGTH CLOSED END HORIZONTAL RIJKE TUBE

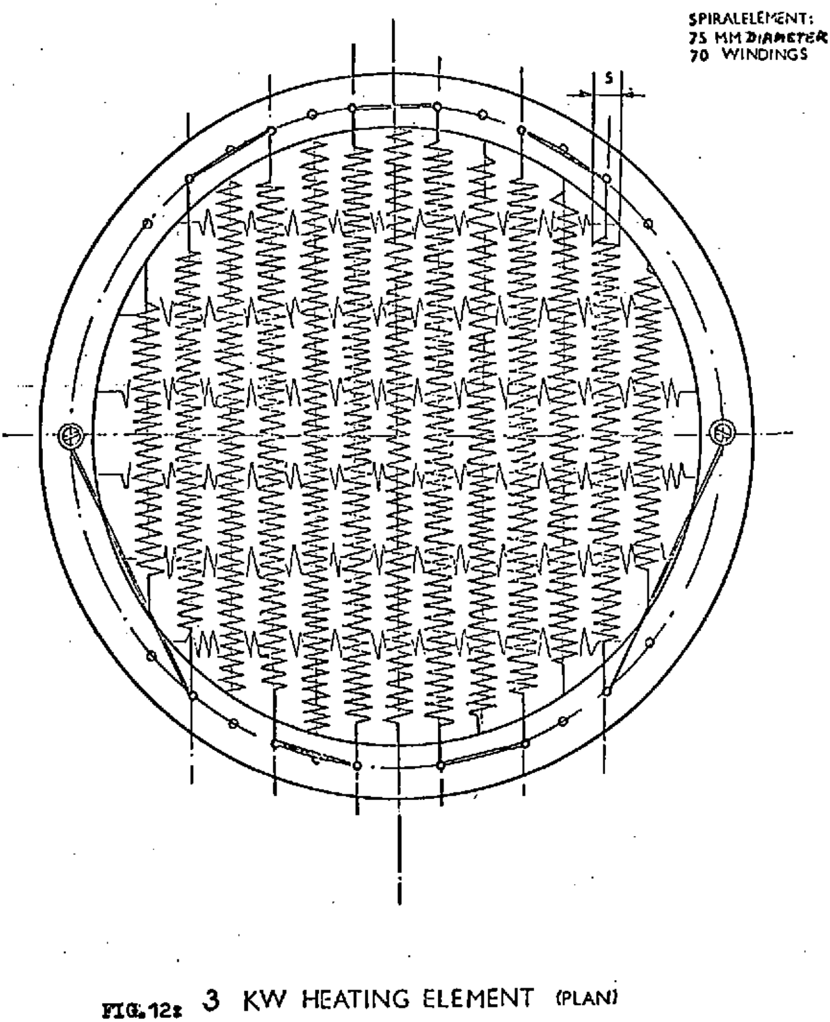


FIG. 12: 3 KW HEATING ELEMENT (PLAN)

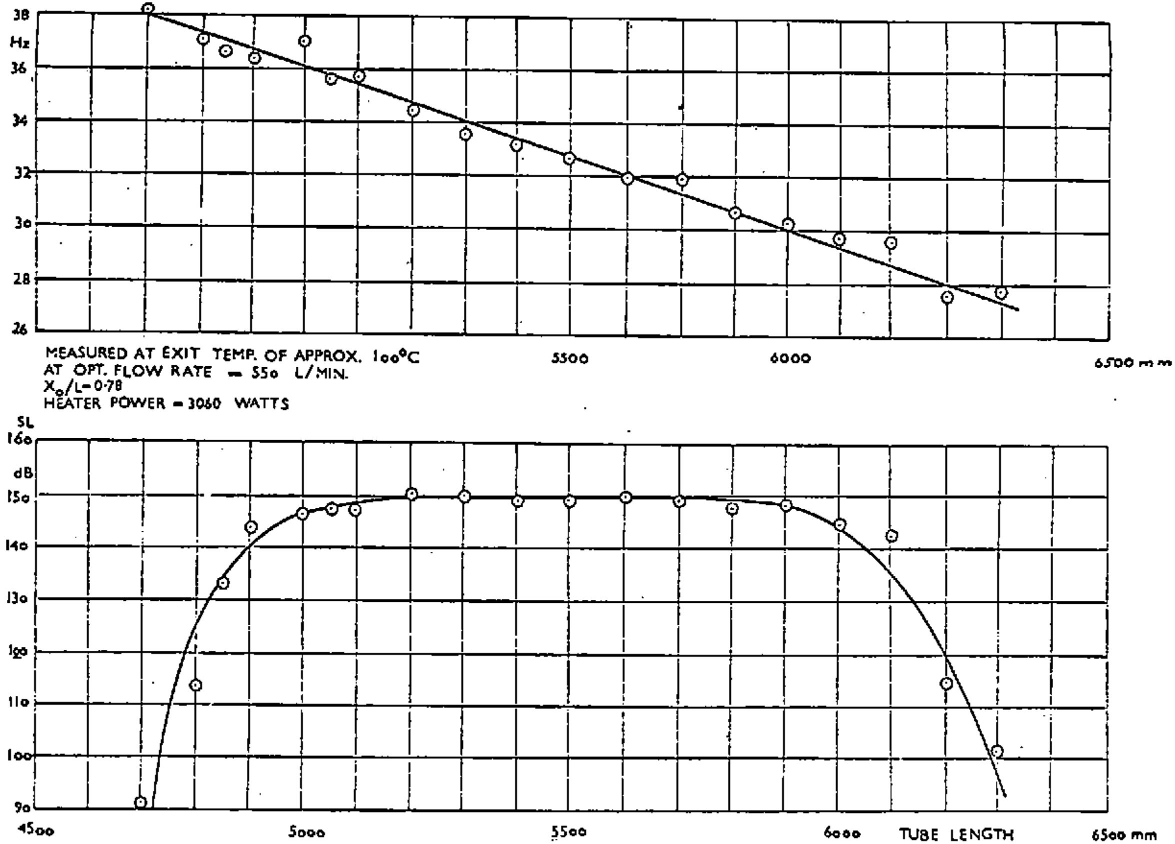


FIG. 13: RIJKE TUBE 3KW ELEMENT WORKING RANGE

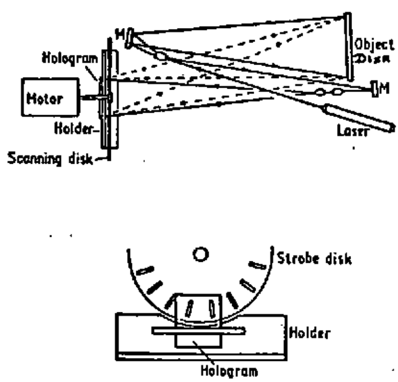


FIG. 14: HOLOGRAPHIC SYSTEM USING SCANNED PLATE

METAL DISC AS OBJECT (AFTER FRYER: PROGRESS IN PHYSICS: 1970)

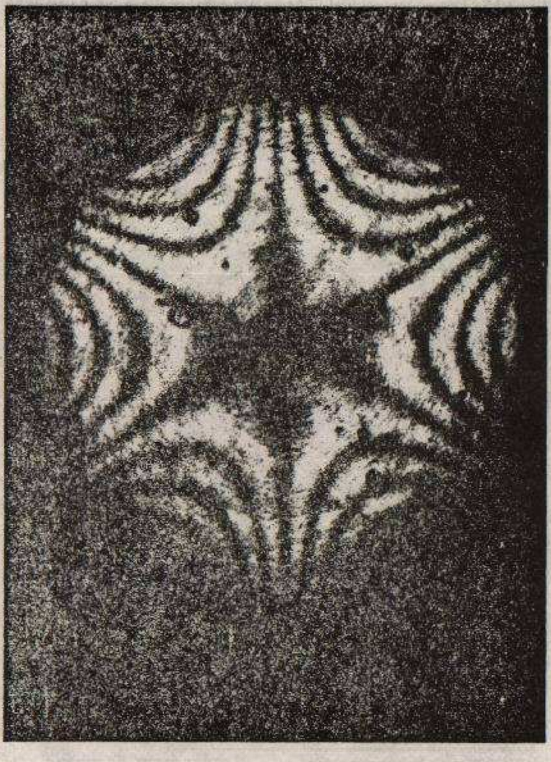
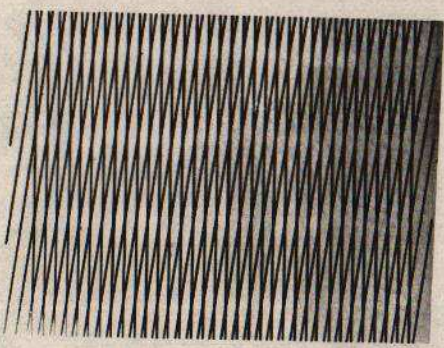


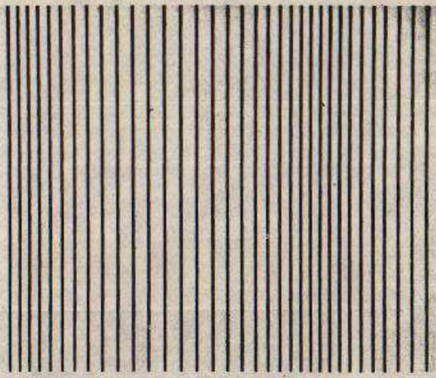
FIG. 15: STROBOSCOPIC DOUBLE-EXPOSED HOLOGRAM: 1:20 ON-OFF RATIO, OF A 30 CM. DIAMETER PLATE VIBRATING AT 1200 Hz.

(FRYER: PROGRESS IN PHYSICS: 1970)

(a)



(b)



(c)

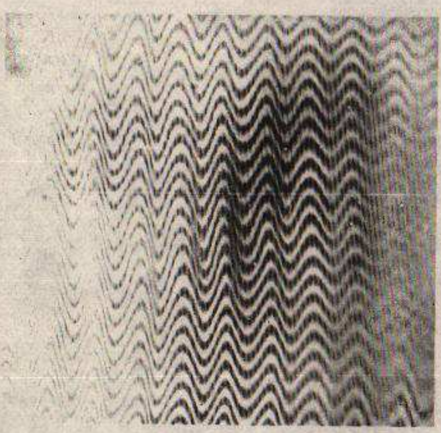


FIG. 16: FORMATION OF MOIRE FRINGES

(a) By two inclined straight line gratings.

(b) Image of a line grating disturbed by surface ripples.

(c) Arising from excitation of 25Hz surface ripples.

(After Scott: Optics Technology, 1969)

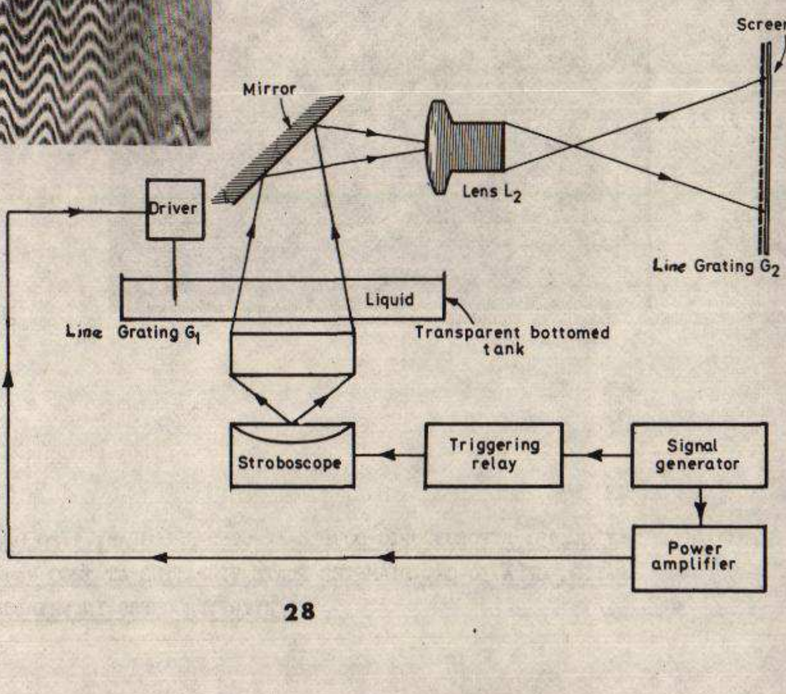


FIG. 17: SCHEMATIC LAYOUT OF APPARATUS.