INTRODUCTION

Background and early work

C V Raman commenced his acoustical researches at the age of 16 as a student at the Presidency College, Madras. Volume II of the *Scientific Papers* contains articles he published in acoustics either by himself or along with his students. Fifty three papers cover the fields of vibrations and wave motion, the whispering gallery phenomena, bowed strings and the violin, the musical instruments of India and the diffraction of light by ultrasonic waves. This volume also contains two monographs Raman wrote—both classics. The first is entitled *On the Mechanical Theory of the Vibrations of Bowed Strings and Musical Instruments of the Violin Family*. The second, *Musikinstrumente und ihre Klange* appeared in 1927 in the *Handbuch der Physik* edited by Geiger and Scheel. This article was written by him in English but was published as a translation in German. Since all attempts to get at the original English version were unsuccessful, an English translation of the German version appears in this volume. Raman also published a series of papers on the phenomena connected with impact which has some relevance to the vibrations of struck strings. These are included in Volume IV of the *Scientific Papers* in the Miscellaneous Section.

In this introduction, we shall content ourselves with making a few historical remarks and scientific comments on the papers appearing in this volume.

C V Raman's father, R Chandrasekhara Iyer, a teacher of Physics and Mathematics, was a man of accomplishment. He had a remarkable collection of books on varied subjects and he was also a proficient violinist. These must have influenced Raman as a child (Raman himself also became a competent violin player). Before he was 13, Raman read Hermann von Helmholtz's "Popular Lectures on Scientific Subjects" from his father's library. Two of the lectures made a lasting impression on him. The first was on "Ice and glaciers" delivered at Heidelberg in 1865 in which Helmholtz says:

> In the depths of the crevasses, ice is seen of purity and clearness which nothing that we are acquainted with in the plains can be compared. From its purity it shows a blue like that of the sky only with a greenish hue".

Raman mentions this in his well-known paper on *The Colour of Ice in Glaciers* (*Scientific Papers*, Volume I) where he proved that this blue was due to molecular scattering. The second was the lecture delivered in Bonn, the native town of Beethoven, on *The Physiological Causes of Harmony in Music*. Helmholtz's influence is seen by what Raman wrote later:

Scientific papers of C V Raman Vol.2: Acoustics. Ed. S Ramaseshan, Indian Academy of Sciences, 1988

> "It was my good fortune, while a student at college to have possessed a copy of an English translation of his great work *The Sensations of Tone*. As is well-known this is one of Helmholtz's masterpieces. It treats the subjects of music and musical instruments not only with profound knowledge and insight, but also with extreme clarity of language and expression. I discovered the book myself and read it with the keenest interest and attention. It can be said without exaggeration that it profoundly influenced my intellectual outlook. For the first time I understood from its perusal what scientific research really meant, and how it could be undertaken".

Here is probably the answer to the engima of why a 16-year-old boy started doing research at a place where there was no tradition of original research. No wonder too that the earliest acoustical research Raman started at the Presidency College, in 1905 was connected to the vibration curves of a bowed string, a field pioneered by Helmholtz and to which Raman himself contributed so much. Raman's first acoustical paper was published only in 1909 and it was on a musical instrument called the *Ectara* (used by the poorer itinerant musicians of India) which had very distinctive acoustical properties.

As a student (1902–1904) Raman mastered Lord Rayleigh's two volume work on the *Theory of Sound* which laid the foundation for all his subsequent work in acoustics. The Presidency College in those days did not subscribe to scientific journals but the Connemara Library near Egmore did. Raman as a student of 15 regularly bicycled to this library to read the latest scientific papers of Lord Rayleigh and others.

With no possibility of a job in the research field, Raman appeared and topped the list in the examination that chose civil servants for the Finance Department of the Government of India. At 18 he became the youngest Assistant Accountant-General in India. One would have thought that with this his research career would have come to an end. In spite of his being posted to out of the way places like Nagpur in the Central Provinces and Rangoon in Burma, he continued his scientific work carrying his laboratory in his travelling bag from town to town. In a paper sent in 1910 for publication from Nagpur he writes:

> "One source of light was a horizontal slit and the other a vertical slit placed immediately behind the oscillating wire. Both were illuminated by sunlight"

Of course it was his young wife who stood in the hot mid-day sun on Sundays adjusting the plane mirror to illuminate the said slit system while Raman shouted instructions to her from inside the bathroom, temporarily converted into a dark room. One could never believe that the elegant vibration curves reproduced in this paper were taken under these adverse conditions!

Also of some interest are the observations he made during this period (1907–1911) on the aerial waves generated by impact which he never published. Lord Rayleigh had shown that the sound emitted when two bodies impinge on each other could not be due to vibrations of the entire body as it would be at a frequency too high to be audible. Raman concluded that sound could not also be due to the compression of air between the two objects, for in that case the sound would be loudest across the line of impact of the balls. His observations, made with the unaided ear, that the sound was loudest at the back of the ball gradually diminishing and almost vanishing at certain angles and again increasing to a feeble maximum in the plane perpendicular to the line of impact convinced him that the air following the moving ball has its motion stopped suddenly so as to produce a compression wave which generated the sound. This problem he gave to his first student, the talented Sudhanshu Kumar Banerjee, who not only verified these qualitative observations but made very precise quantitative measurements and also worked out the complete theory. This also illustrates a trait in Raman that when he felt that he had basically understood a phenomenon his interest in pursuing it waned rapidly.

The whispering gallery

He noted a remark made by Lord Rayleigh in a footnote that his theory of the whispering gallery should be applicable not just to sound but to electromagnetic waves as well. Raman therefore initiated a series of studies (along with his student Bidhu Bhusan Ray) on the optical analogue of the whispering gallery which gave results conflicting with some of Rayleigh's. Raman planned to verify the correctness (or otherwise) of these by experimenting in St. Paul's Cathedral when he went to Europe for the first time, the voyage that inspired him to start his researches on molecular scattering of light. In the experiments he did there (with G A Sutherland) Raman showed that the theoretical conclusion of Lord Rayleigh, that the sound waves travel in a comparatively narrow belt skirting the wall, was right, but two others that the intensity in this belt decreased continuously as one proceeds radially inwards, and it does not fluctuate markedly as one proceeds circumferentially were not in accordance with facts. Using a high pitch source of sound and a sensitive flame detector they found pronounced oscillations as one proceeded inward radially (the overtones being heard clearly, while the fundamental was almost inaudible) – the distance between successive zones of silence being about half the wavelength of the source. There were also distinct periodic fluctuations while proceeding circumferentially parallel to the wall – completely in accord with the prediction made from the optical experiments.

On his return to India after his six week stay in England Raman energetically went round the country, experimenting in new whispering galleries, of which he discovered two in the newly built Victoria Memorial, one in the General Post Office in Calcutta and one in a granary at Bankipore (a curious paraboloid shaped building, 96 ft high). This was intended to store grain during famine but was never used.

Indian musical instruments

In the *soirees*, held in his father's house in Visakhapatnam and in public concerts Raman heard South Indian music at its best—for those were the days of the great *Vidwans* (maestros). He was particularly fascinated by the *Mridanga* or the concert drum played with the hand and fingers by experienced drummers, using a highly developed technique. He marvelled at the manner of striking the drum head, the regulation of the region of contact between hand and skin which elicited the requisite tone quality, intensity and duration of the sound.

His keen ear recognised that certain strokes appeared to bring out the first, second or even the third harmonic. Therefore he was somewhat surprised when he read in the *Theory of Sound* that the natural vibrations of a circular stretched membrane (of uniform thickness) do not give rise to any harmonic sequence and so it is not simple to ascribe any particular pitch to them. Raman would not believe that the *Mridangam* was in any sense musically defective as the normal drums were. So he went on to demonstrate that the Indian musical drum produced as many as five harmonic overtones having the same relation of pitch to the fundamental tone as in a stringed instrument. He also showed that this was due to the central loading of the stretched membrane and its behaviour presented a remarkable analogy to the law of vibrations of the homogeneous string.

The study by Raman of the string instruments—the *veena* and the *tanpura* (*tambura*) which are of undoubted antiquity disclosed to him a remarkable appreciation of acoustical principles on the part of their ancient designers. Raman had noticed (probably when his wife played the veena) that the overtones did not die away as fast as the fundamental mode, but they steadily seemed to increase in volume. When he investigated the causes a surprise was in store for him. His simple experiments showed that the overtones having a node at the plucked point (a mode not permitted by the Young–Helmholtz law) sing out powerfully and that the position of plucking hardly appeared to make any difference in the intensity of overtones thus appearing to violate known acoustical principles. Raman traced this peculiar behaviour to the curved shape of the bridge in which the strings do not come clear off a sharp edge (as in European stringed instruments). The forces exerted by the string on the bridge near this grazing contact are in the nature of impulses occurring once in each vibration. These cause the retinue of overtones including even those absent initially in the vibration of the string. The woollen or silken thread traditionally slipped between the string and the bridge when adjusted properly enhances these effects making the sound very pleasing to the ear.

Bowed strings and the violin

During the decade 1908–1918 Raman investigated several aspects of the vibrations of stretched strings culminating in his *Mechanical Theory of Vibrations of Bowed Strings of the Violin Family*, his *magnum opus* in acoustics. In the course of this work he developed ingenious techniques for exciting the vibrations and observing them. (This is all the more remarkable when one recalls that during most of this time he had no scientific position in a laboratory and had to perform his experiments after his regular duties in the Finance Department in which he was employed.)* In his studies on the wave motion of strings with discontinuous velocity distribution, Raman invented an amazingly simple way of producing an initial velocity distribution that varies linearly with distance from one end and suddenly drops to zero at the other end. He arranged the string to carry a weight at one end and made it execute a pendular swing about the other. The string was suddenly brought to rest at the desired point by a suitably placed knife edge in its path. Using carbon arc lights, mirrors, tuning forks and photographic plates, he obtained curves that rival the oscillographic pictures of today.

Raman was clearly dissatisfied with the state of knowledge of bowed strings, let alone that of the violin. In the opening paragraphs of the monograph on bowed strings, he remarks,

> “The present position of the subject cannot be considered satisfactory in view of the fact that no complete and detailed dynamical theory has been put forward which could predict and elucidate the many complicated phenomena that have already been found empirically by those who have worked in the field and that could also pave the way for further research. It was this defect in the present state of knowledge of the subject that induced me to undertake the investigations”.

The starting point of Raman’s mechanical theory of vibrations of bowed strings was the basic observation of Helmholtz that the bowed point of the string moves with the bow with a constant velocity up to a point and then releases itself from the bow and moves back with constant velocity until the bow catches it again and carries it with the same forward velocity as before. Thus the bowed point is forced to change its velocity discontinuously from one constant value (in the direction of the bow) to another in the opposite direction.

Raman set himself the task of establishing the correctness (or otherwise) of this description of the bowed string on the basis of kinematic considerations

---

*In one of his papers he thanks Dr Amrita Lal Sircar, the Hon. Secretary for the Indian Association for the Cultivation of Science, Calcutta “for putting the resources of the laboratory of the Association and the services of the staff unreservedly at my disposal during hours at which few institutions, if any, would remain open for work”.

alone, pursuing the argument, as he said, to its logical conclusions. He discarded from the beginning the normal mode analysis stating that it is unsuitable and adopted, instead, what would be called in current parlance the time-domain approach, although he merely called his method a graphical analysis. Considering the geometric requirements which waves travelling on a finite string fixed at its ends must satisfy, Raman arrived at the following two results: (a) "During one or more intervals in each period of vibration, the bowed point has a forward movement which is executed with constant velocity, equal to that of the bow, and (b) during the other interval or intervals the bowed point moves backwards, also with a constant velocity this being the same for all such intervals if there be more than one", thus confirming but also extending Helmholtz's observations to cover the case where there is more than one discontinuity in the velocity of the bowed point in one period. In his analysis Raman found a classification of the vibration patterns of bowed strings on the basis of the number of discontinuities in the velocity waves in the string.

After investigating the motion of the bowed string under more or less ideal conditions, Raman turned his attention to the effect of the bow pressure, bow velocity and bowing distance from the bridge upon the mode of vibration of the string and the resulting quality of the tone. From the point of the violin player these relations are extremely important. The player knows by his experience the limits of these parameters within which he can perform, but the physicist must establish these within a theoretical framework. Raman obtained limits for the minimum and maximum bowing pressures and considered the instabilities that can arise. He considered also the effects of the finite width of the bow, the yielding of the bridge and the coupling between the bridge and the string.

Seventy years after its publication, Raman's work is still relevant to the student of the acoustics of the violin and, for that matter, of other musical instruments too. Raman initiated studies in almost all fundamental problems in the physics of the violin, but unfortunately his work remained largely inaccessible to many readers. The physics of the violin is by no means completely understood even today.

The review in Handbuch der Physik

In 1926, when the first encyclopaedic work in physics, the *Handbuch der Physik*, was planned for publication by Springer Verlag, Raman was asked to contribute an article on the Musical Instruments and their Tones (*Musikinstrumente und ihre Klange*). He was perhaps the only non-European scientist to be invited to write in this encyclopaedia. By this time the focus of Raman's scientific interests had shifted to light scattering. Unable to spare time from his researches in optics, he forced himself to write the article during the predawn hours. While our knowledge of musical instruments has advanced vastly in the sixty years since Raman wrote the article, it shows clearly how Raman perceived the significant problems involved in the analysis of the musical instruments.

The Raman–Nath theory

Raman's interest in acoustics waned in 1924. He wrote his *Handbuch* articles reluctantly in 1926. Although Raman did not return to acoustics proper his attention did turn a decade later to a remarkable optical phenomenon occurring when a parallel beam of light is diffracted by ultrasonic waves. This volume includes for completeness* a very well-known series of papers by Raman and Nath on this subject. The original experiments in this field by Debye and Sears and by Lucas and Biquard showed a surprisingly large number of diffraction orders and an apparently irregular distribution of intensity among them, neither of which was satisfactorily explained by the ideas current at that time. The Raman–Nath papers introduced the physical concept of a corrugated (i.e. strongly phase-modulated) wavefront and the associated mathematical tool—a set of first order differential-difference equations for the amplitudes of the various diffraction orders taking multiple scattering into account. Once these ideas were introduced the observations fell into place at one stroke. It may be worth remarking that the actual formula for the amplitudes involves Bessel functions in which Debye was an acknowledged expert!

Even more significant than the specific problem which gave rise to the theory were the ideas which found applications in other fields decades later. The multiple-beam dynamical theory of electron diffraction turns out (in retrospect) to be modelled on the Raman–Nath theory and it plays an important role in the interpretation of electron microscope images. The idea of an equation which is first order in the direction of propagation and second order in the transverse direction (the parabolic equation approximation) is contained in the Raman–Nath papers and now plays a significant role in the theory of wave propagation in a random medium. These applications involve going beyond the approximation of pure phase modulation and including the amplitude variations which this produces—a step which Raman and Nath had already taken in the later papers of the series.

---

*In modern electro-optic instrumentation the phenomenon of diffraction of light by ultrasonic waves is utilized in acousto-optic spectrometers which analyse an electrical signal to obtain its power spectrum.

Conclusion

In reading these Scientific Papers it should be remembered that Raman's research predates the electronic era in acoustic measurements. Lee de Forest's triode valve and Wente's condenser microphone, which were both invented in 1917, were not yet commercially available for use in science laboratories. Even theoretical tools like the delta function and integral transforms which are routinely used today were not part of the repertoire of the physicist during that period. Raman's strength lay in his keen sense of observation, a highly trained and perceptive ear, penetrating insight into the physical behaviour of things combined with enormous powers of concentration. The reader would not fail to notice that Raman does not frequently resort to diagrams to explain his reasoning but expects the reader to follow his arguments by exercising his imagination. Raman's style of writing is confident and stately, with a touch of aristocracy in it. He is never hurried, neither missing a word nor allowing an unnecessary one to slip in. The *mot juste* is always there. With Raman, style is the man himself, whatever Buffon might have meant by his aphorism.

Many acousticians of the later years have wondered why Raman who was so successful in his work in acoustics had left it so suddenly. He stated that his monograph *On the Mechanical Theory of Vibration of Bowed Strings* was the first instalment of more to come later, but these never appeared. When asked about this (*ca* 1969), he merely replied "My studies on bowed string instruments represent my earliest activities as a man of science. They were mostly carried out between the years 1914 and 1918. My call to the professorship at the Calcutta University in July 1917 and the intensification of my interest in optics inevitably called a halt to further studies on the violin family of instruments". Raman, perhaps, never thought of himself as an acoustician; he was a physicist first and foremost and remained so to the last.

RAJARAM NITYANANDA
B S RAMAKRISHNA
S RAMASESHAN