LEO BERANEK – A LIFE IN ACOUSTICS 1914 – 2016

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Leo Beranek was a major figure in the world of acoustics and reached the remarkable age of 102. This celebration of his life will cover his early years, his setting up of the consultancy Bolt, Beranek and Newman, his involvement with auditorium acoustics and his absence running a television station. He subsequently involved himself again in auditorium acoustics, participating in the design of two auditoria, publishing many papers and attending acoustics meetings, even beyond his centenary. He left behind a host of books on acoustics plus an autobiography. Remarkably until the very end, he welcomed discussions of points of mutual interest in acoustics.

Keywords: biography, auditorium acoustics

1. Introduction

Leo Beranek remained a participating acoustician for his whole adult life, which ended suddenly in October 2016. The word 'suddenly' might seem strange for a man aged 102, but he was still communicating with colleagues until the end. He claimed to have written 150 papers and 12 books, some with joint authors. Latterly many of us kept in touch with him and met up with him at conferences. He will be missed. The following is a brief acoustical history of his remarkable life. Many details have been taken from his autobiography *Riding the waves* of 2008 [1].

2. Early years

Leo Beranek was born in September 1914 in Iowa state in the rural mid-West. His father was working on the family homestead farm at the time of his birth. Conditions at home were rudimentary: no electricity, no running water and an outdoor privy. His great-grandparents had immigrated from Bohemia in mid-19th century. His education started when he was five, getting to school could however be difficult, most roads in that part of Iowa were still mud (Fig. 1).

Figure 1. School transport in Iowa, 1920

The family moved regularly and by the time of his first year at high school they were living in Mount Vernon, Iowa, where his father had become co-owner of Beranek Hardware Store. His father suggested that Leo might learn how radios worked, and hence install and service radios sold in the store. Radio repair thus became an important business sideline, invaluable when college fees had to be paid. Another side line was playing drums on a set of trap drums as they were called (Fig. 2); this also proved lucrative later ($4 a session). His undergraduate years were spent at Cornell College, Mount Vernon, still in Iowa, studying Physics and Mathematics. During his final year at college, he had a remarkable encounter.

Figure 2. Trap drummer, Leo in 1950

In 1935 the main route from New York to San Francisco, the Lincoln Highway, passed through Mount Vernon. Leo Beranek was strolling down Main Street one day when he came across a Cadillac with Massachusetts plates, its owner bemused by how to deal with a flat tyre. Beranek offered to help and soon learnt that the driver was Glenn Browning. It turned out that Beranek had just that morning been reading a paper on the Browning radio tuner. When asked where he intended to go after university, he said he was planning to submit scholarship requests to the University of Iowa. Browning enquired whether he had thought of applying to Harvard Graduate School of Engineering and if so, he offered to act as one of his references. Thus a man from the provinces moved into the Ivy League, first for a Masters and then PhD at Harvard, Cambridge, Mass.

3. Wartime research

Beranek had a good war, to use the traditional phrase. At the beginning of hostilities in Europe, he was working on his doctoral thesis at Harvard University. His topic was to develop a way to measure acoustic impedance, with his PhD being awarded in June 1940. He remained in academia but was soon invited to be the effective leader of a research group looking for an efficient sound absorbing material to reduce noise in bombers. The work was done at Harvard; a parallel laboratory was set up to investigate the effects of high noise levels on human behaviour. The funds available for this project were an order of magnitude greater than those for the research Leo had been doing before. In his early days at Harvard, he had had to cut down to two meals a day; it was definitely three meals from now on!

The first outcome of the project was the development of a more efficient absorber, using more fine fibres than hitherto. The Owens Corning Fiberglas Company managed to produce glass fibres one-tenth the diameter of a human hair by squeezing glass through extremely small holes. With the absorber problem 'solved', it then transpired that there was very little room to apply the material in the pilots' compartments! Subsequent work shifted to developing a noise-cancelling headset to overcome severe communication problems for pilots.

A further project called for a space in which to test very large scale loudspeakers. Highly efficient absorbers were required. Beranek's team tested nearly a thousand options for wall treatment with a high degree of absorption over a wide frequency range. The best performer was a glass fibre wedge 46 inches long (1.17 m); "Beranek's Box", as it became known, was the first anechoic chamber using principles still applied today. The discoveries made during the war years led to the commissioning of Beranek's first book *Acoustical measurements* (1949) [2]. In 1946, Beranek moved the short distance away from Harvard to work as an assistant professor at MIT. One product from this period was the book *Acoustics* [3], which first appeared in 1954 based on courses he had been giving. The book was revised in 1986 and was available until recently from the ASA.

4. Bolt, Beranek and Newman (BBN)

It was probably inevitable that an acoustic consultancy would arise in the Boston area, Massachusetts, given the concentration of acoustic expertise there. The clinching project was the acoustic consultancy for the new United Nations Center in New York City, which was offered in 1948 to Dick Bolt, director of the MIT acoustics laboratory. He soon realised that this was more than one man's work and invited Leo Beranek to join him in a partnership to be called 'Bolt and Beranek'. They were joined two years later by Bob Newman.

New projects poured in including quieting ventilation systems, test cells for testing jet engines and achieving speech privacy in offices. This last resulted in the development of NC curves. Another major project originated from the Port of New York Authority in 1956 at the birth of commercial jet passenger flights. They were concerned about complaints of excessive noise from neighbours of airports. The initial criterion was that the new jet aircraft were no louder at take-off than 4-engine propeller aircraft. Boeing rightly claimed that their new 707 aircraft achieved this criterion in (linear) decibels. BBN however soon showed that, because of the different frequency spectra of the two types of aircraft, the jet aircraft was significantly noisier. To cut a long story short, from work at BBN the PNdB (perceived noise level) scheme was developed from subjective tests by Karl Kryter, which became the standard for aircraft noise. In October 1958, the Boeing 707 and Comet 4 flew into and out of Idlewild airport (now J.F. Kennedy) as the first commercial jet aircraft flights in the US and there were no complaints of noise. The jet engines had been quietened and levelling off on take-off at 1200 ft had become mandatory.

An elephant was materialising in the BBN offices in the form of early computers. J.C.R Licklider was a pioneer within BBN, who requested in 1957 of Beranek (as a partner) $30,000 for the latest machine. Beranek admits that he blinked "more than a little taken aback", but approved the purchase! Within a year, the BBN visitor's lobby was filled with the prototype of a PDP-1 from the Digital Equipment Corporation. Engagement with the digital world proved however "to be a winner": the partnership's work in the digital world blossomed and included developing the internet and emails; they can claim the idea of using the @ symbol for email addresses. Eventually the digital work overtook the acoustic, with the latter spinning off as Acentech. The discussion here now turns to room acoustics.

5. Sound absorption by audience

Many people will be familiar with a major piece of research conducted by Beranek, which first appeared in 1960 [4]. Sabine's revolutionary paper 'Reverberation' had been published in 1900 [5] but a sequence of auditoria were found to have shorter reverberation times than had been predicted; Beranek mentions our Royal Festival Hall here in London, the Jubilee halls in Edmonton and Calgary and the Beethovenhalle in Bonn. Confronted by reverberation time values in the new halls that were lower than predictions, Beranek questioned the method used to calculate the absorption by audience and seating. With little evidence one way or the other, Sabine had proposed that individual persons should be assigned an absorbing power, so many sq. ft of absorption per person. Beranek investigated whether audience and seating should be treated in the same way as other materials, namely on an area basis. He found that this gave much more consistent results and from reverberation time measurements in real halls proposed absorption coefficients for audience and seating. The audience area includes an edge effect to account for diffraction and the 3-dimensional nature of seating. (Measurement of audience absorption in a reverberation chamber is problematic since only small numbers of seats can be fitted in.)

The 1960 paper was included in revised form in his book of 1962 *Music, acoustics and architecture* [6], further revisions were published in 1969 [7] and 1998 [8]. Fig. 3 compares the earliest estimate of audience absorption with the latest. One notices in the latter that audience absorption is influenced by the standard of the seat upholstery. This result allows the possibility of increasing the reverberation time of an auditorium by using seating with less upholstery.

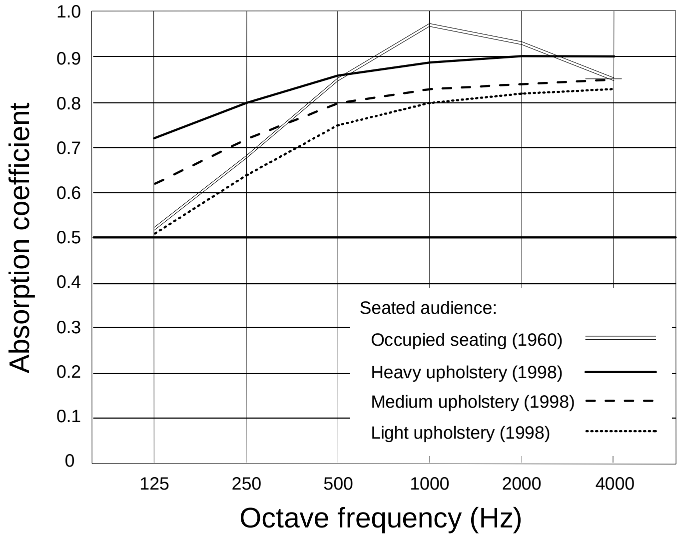

Figure 3. Proposed absorption coefficients for seated audience by Beranek in 1960 [4] and 1998 [8].

6. Tanglewood Music Shed, Massachusetts

The Tanglewood estate is the summer home of the Boston Symphony Orchestra with a fan-shaped music shed as its largest auditorium. Bolt, Beranek and Newman consultants were asked to review the acoustics and in 1959 introduced an orchestra enclosure and suspended canopy, which covers the front third (in distance terms) of the hall. The canopy establishes short time delay reflections and overall the changes transformed the acoustics of the venue [9].

7. International acoustic survey

R T Beyer in his book *Sounds of our time: two hundred years of acoustics* [10, p.334] makes the pertinent comment: “The field of architectural acoustics in the early 1950s was characterised by optimism”. At that time, reverberation time (RT) was the only recognised measurable quantity in room acoustics, but there was a general understanding that there was more to concert hall listening than the reverberation time. From a subjective perspective, only a limited number of studies had been undertaken. The firm of Bolt, Beranek and Newman decided in 1955 to undertake an international survey of significant concert halls and opera houses. A list of important subjective qualities was developed and views sought from musicians and conductors. On the objective front, RT data was available as well as audience capacities and dimensions derived from architectural drawings. The results of this survey were published in Beranek’s pioneering book *Music, acoustics* *and architecture* of 1962 [6]. Each of the 54 concert halls and opera houses was discussed, with photos and architectural plans. The subjective and objective results were combined and correlated. The conclusions from the objective results proved to be the most significant regarding criteria for good acoustics. The book has been highly influential, as well as opening many people's eyes to the international scene of auditoria.

The most surprising result concerned the most significant parameter linked to subjective quality: the **initial-time-delay gap** (ITDG). It was not cubic volume, the age of the auditorium, the shape of the auditorium or even the reverberation time. The ITDG is simply the time interval between the arrival of the direct sound at the listener and the arrival of the first reflection from the walls or ceiling; it is measured in msec and is calculated for a central position in the stalls, generally from drawings. Beranek found evidence that the best liked halls had ITDG values of less than 20 ms; he estimated that the contribution of the initial-time-delay gap to an overall acoustic judgement was 40%. It was considered as a measure of subjective intimacy.

Additional correlates included reverberation time (15%) as a measure of liveness, warmth (15%) as perception of bass sound (ratio of RT at 125/250 Hz with mid-frequencies) and loudness of direct sound (10%).

(It is appropriate to comment that the initial-time-delay gap has not survived the test of time, statistical assessment by others have not found correlations with either subjective intimacy nor with overall subjective acoustic quality [11, p.41].)

8. Philharmonic Hall, New York

The survey discussed above had been accelerated to allow its results to be applied to a major consultancy appointment for the firm of Bolt, Beranek and Newman (BBN). This was a new concert space for the city of New York, to be part of its new arts complex of Lincoln Centre (which also includes the Metropolitan Opera House). The original proposal from the acousticians was for a traditional rectangular plan hall, but for various reasons the final design diverged from this precedent. Confronting some design developments that they considered to be adverse for the acoustics, BBN introduced sound reflecting panels suspended from the ceiling to provide reflections with short initial-time-delay gaps, Fig. 4. Some developments were made by the architects late in the design period to increase the seating capacity, such as pushing out the side walls; the acousticians were apparently not informed of these modifications. BBN had also specified sound scattering (diffusing) treatment on the walls, which was eliminated for reasons of cost.

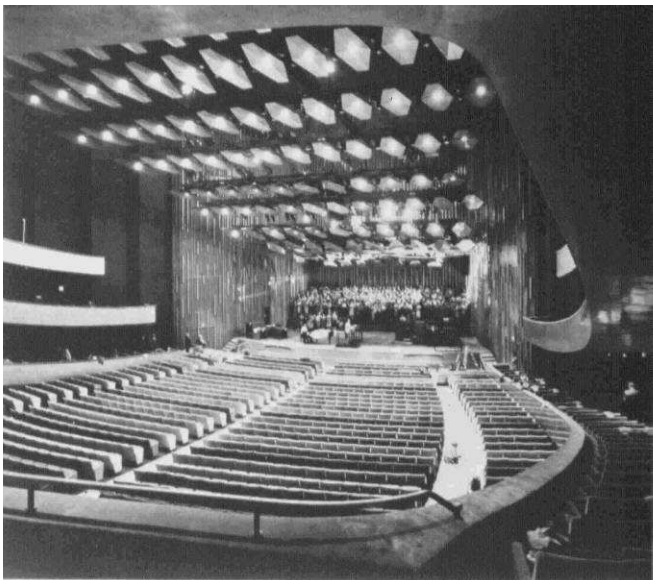

Figure 4. The auditorium of Philharmonic Hall, New York 1962.

After the opening concerts in September 1962, reports in the American press were very critical, noting difficulty hearing bass instruments and reverberation, among other things. Yet, the measured reverberation time was 2.06 seconds at mid-frequencies (500-1000 Hz), within the optimum range then as now. Several groups of acousticians researched the acoustics and numerous modifications were made, not helped by serious overreaction by the press and the board of the hall. Beranek [12] found himself at the apex of a storm which raged over more than a decade, some criticisms were fair but many were not. He described himself as being the ‘whipping boy’ for all questions acoustical. A donation by Mr. Avery Fisher enabled the auditorium itself to be dismantled, leaving the external shell, with a new auditorium built in its place in 1976.

In one respect the acousticians were very unlucky. The poor bass audibility proved to be due to two things: what we now call the seat-dip effect for sound passing over audience and the spacing of the suspended reflectors which resulted in a lack of reflection at similar frequencies. At the time the seat-dip effect was unknown, until revealed by investigations into sound behaviour in Philharmonic Hall. In retrospect the late architectural changes, particularly pushing out the side walls, and the large array of suspended reflectors were most probably detrimental to the sound for audience members.

9. ‘Some say this is America’s best TV station’

A fellow partner at BBN had happened to notice that the TV Channel 5 in Boston was having difficulties with its licence and that it might be awarded to someone elseable to put up a good case. In December 1962 a group of 30 men and women decided to submit an application. Leo Beranek had become President and CEO in January 1963 of the company they set up “Boston Broadcasters Inc.” (BBI). Little must they have realised that a 10 year legal battle confronted them, but finally the new station WCVB went on air in March 1972. The station prided itself on coverage of local matters. One of its high spots occurred in 1981 when a full-page article appeared in the *New York Times* under the heading “Some say this is America’s best TV station”.

Because of his commitments with the TV station, Beranek resigned from BBN entirely in July 1971. He subsequently retired from being President of BBI at 65 in 1979, remaining on the board until 1983. WCVB-TV was sold to Metromedia in May 1982, making Beranek and other shareholders wealthy men and women.

Never one to sit on his laurels, Beranek had during the late 1970s become involved with the Boston Symphony Orchestra, which at the time was seriously in debt. With Beranek’s help, the deficit was converted into surplus and from 1983-6 he was chairman of the orchestra’s board. There is now a ‘Beranek Room’ to be found in the Boston Symphony Hall building.

10. Return to acoustics

After more than two decades away from auditorium acoustics, Beranek decided in 1986 to return to the field. Much had happened in the intervening period, not least the status of the acoustician in the design team. Traditionally their advice had often been overridden by the architect, not ideal when the acoustics are often ‘fixed’ for the life of the building whereas architecture can frequently be a question of fashion. The size and shape of auditoria had been questioned: excessive audience capacity tended to result in poor acoustics and certain forms were also disappointing, particularly the fan-shaped plan. Four new measurable quantities beyond reverberation time had been shown to be useful. In addition, the importance of early lateral reflections suggested by Marshall [13] in 1967 had become accepted as a characteristic of the best acoustics. Testing the acoustic behaviour in acoustic scale models prior to construction had also become commonplace, to be gradually superseded by computer modelling. In the case of concert halls, two precedents had become established for design: the parallel-sided hall and the terraced hall (as pioneered in the Berlin Philharmonie of 1963).

With typical thoroughness, Beranek undertook the process of familiarising himself with the research and practical results over the next three years. He also visited 23 halls to experience them at first hand, halls not only in the USA but in Europe and as far afield as New Zealand. One outcome of this was the invitation from the editor of *JASA* to submit a review article to the journal (of 39 pages), titled “Concert hall acoustics – 1992” [14].

11. An opera house and concert hall in Tokyo

This re-acquaintance with auditorium acoustics proved invaluable when Beranek was approached by Dr. Takayuki Hidaka of the acoustics group of Takenaka Corporation, who wondered if he would be interested in taking part in the consultancy of a new opera house for Tokyo. Beranek was brought in as the ‘Acoustical design consultant’ for the New National Theatre Opera House. His approach to an opera house was based on the fact that opera singers are competing with an orchestra of potentially much greater sound power, even though it is placed in the pit. Complaints in opera houses of the singers’ sound being swamped by the orchestra are commonplace. The appropriate response to this problem is to introduce sound reflecting surfaces that enhance sound from the singers but not from the orchestra. The location of such surfaces has to be close to the proscenium opening in order to be effective. Beranek’s ‘acoustic trumpet’ solution was accepted for the opera house design. Not unusually there were complaints from the stage lighting people, who found they had lost access to usual lighting positions, but Beranek stood his ground, stressing the paramount importance of the acoustics. Regarding reverberation time, Beranek proposed a value between 1.4 and 1.6 seconds. The design developed between architects and acousticians was tested in a 1:10 scale acoustic model.

This opera house was Japan’s first for western-style opera. It has a capacity of 1810 seats in an auditorium volume of 14,500 m^3. The final design has three balconies; in plan it widens beyond the proscenium but has parallel walls at the rear. The occupied reverberation time is 1.5 seconds, right in the middle of the proposed range. The opening occurred in October 1997 in the presence of the Emperor. The result was proclaimed as an acoustic triumph. Careful comparisons of impulse responses with eight other famous international houses show that the energy at 2000 Hz for sound from the stage is noticeably higher in this house than in the others. A thorough account of the design and its acoustic behaviour was published in 2000 [15].

Slightly after the start of the opera house project, Beranek was also engaged in 1991 as an acoustical consultant for a new concert hall in Tokyo, with the same architect and local acoustic team. The architect, Takahiko Yanagisawa, decided on the basic shape of the hall: rectangular in plan with two horizontal balconies. So far, so classical, but the ceiling he proposed was pyramidal and rather than sitting symmetrically over the rectangular footprint, its apex is over the front line of the stage, 27.7 m above the stalls floor. A spherical reflector hung above the stage.

The pyramid design survived the design process but its surface treatment proved to be problematic: the architect imagined a pyramid with smooth surfaces, while the acousticians were aware of a potentially disastrous slap echo for performers on stage with a delay of about 140 ms from the pyramid surface opposite the stage. Each side stuck to its position until almost the last moment, when a horizontally tiered profile was developed for the whole pyramid surface with crucially a scattering QRD (Quadratic Residue Diffuser) treatment on the surface opposite the stage. The overstage reflector became a square, basically plane, reflecting surface, made up of slightly inclined surfaces.

Confusingly the hall is called the Tokyo Opera City Concert Hall. The design of the ‘ceiling’ has really to be appreciated in real life, photographs render the form puzzling from whichever way it is viewed (Fig. 5). It was opened with 1630 seats in September 1997 with much praise for its acoustics [16].

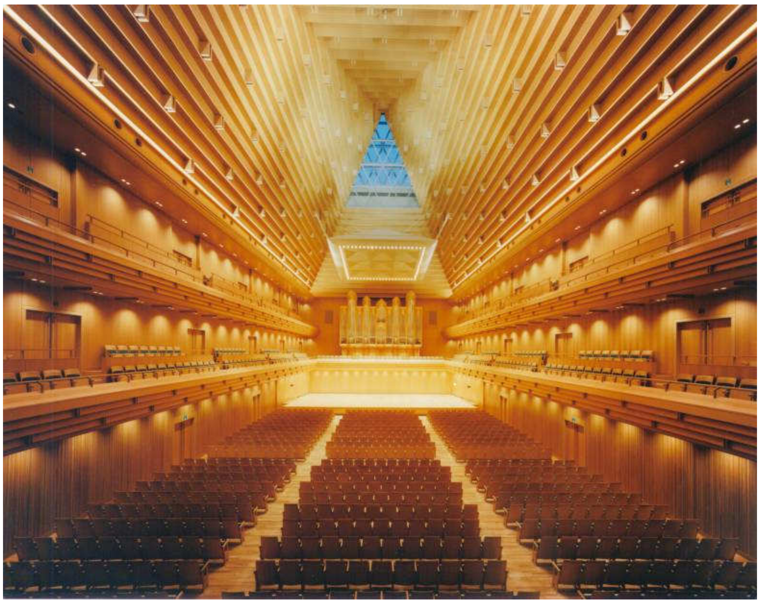

Figure 5. The auditorium of the Tokyo Opera City Concert Hall

Beranek was involved with several other auditoria in Japan, with the last opening in 2001. He decided that his time as a consultant should come to an end, he being by then 87 years old working with acoustical colleagues to whom he could be grandfather or even great grandfather.

12. The final years

An old man wanting to remain active turns to the pen, or rather these days to the keyboard. Beranek managed to publish papers at the rate of almost one per year until his death. Some of these were jointly with his Japanese colleagues, but their content is consequential in each case. They include substantial consideration of the two major Tokyo auditoria mentioned above [15,16], evaluation of 23 opera houses [17], seat absorption again [8,18], subjective rank ordering of 58 concert halls [19], the importance of Strength, G [20] and two further reviews of concert hall acoustics [21,22]. His famous book of 1962 *Music, acoustics and architecture* was revised twice in 1996 and 2004 [23,24].

From very modest beginnings, Leo Beranek became a leading light in the acoustic world of America in the 1940s and 50s, specifically in Boston, Massachusetts. He managed to lead crucial research during the 2nd world war, before becoming an academic at MIT and being joint founder of what became for many years the world's largest acoustic consultancy. His research work into auditorium acoustics was often pioneering. However being lead consultant for the new concert hall at the Lincoln Centre in New York proved a serious acoustic disappointment. Ever the personable, effective manager he subsequently ran a Boston TV station for 7 years, a station which became highly respected. He then re-engaged in acoustic consultancy with colleagues in Japan, including major projects for an opera house and concert hall. Latterly he published comprehensively on the acoustics of auditoria world wide and on the principles behind them.

Over Beranek's long life, he was presented with many awards, including the Wallace Clement Sabine Award (1961) and Gold Medal (1975) by the ASA, the President's Medal from the American Academy of Arts and Sciences (1994), the National Medal of Science (conferred by President G.W. Bush, 2002) and the Raleigh Medal of the Institute of Acoustics in 2014. Fortunately his mind remained remarkably sharp till the end and many of us had the privilege of remaining among his correspondents. Luckily for us he was able to include writing an autobiography [1], allowing full appreciation of an extraordinary life.

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