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REVERBERATION ENHANCEMENT SYSTEMS - AN HISTORICAL REVIEW

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INTRODUCTION

This Paper is concerned with reverberation enhancement systems, their development, their installation and the problems encountered.

The Paper only makes a passing reference to the latest systems since these are better understood by others who will be presenting papers later. The main thrust of the Paper is the activities between 1969 and 1982 when the author was active in this field.

MUSIC, MUSICAL SPACES AND REVERBERATION

The reception of music itself is complex and involves the source, the transportation medium and the receptor. To complicate matters further the analysis of each element in the chain contains sufficient material for many post-graduate thesis.

It is, in a sense very difficult to separate music and musical spaces, since like the chicken and egg situation it is impossible to determine which controlled the development of the other.

I have no definitive research to support the hypothesis that music performances began in 'the church' but I suspect that this premise is accurate.

It is unlikely that the prime objective of these meetings was musical rather than spiritual.

By the 4th Century AD a large number of cathedrals with long or sometimes extreme reverberation times were complicated and the religious expression comprised plain song (Gregorian Chant).

By the 16th Century, music had developed into two distinct categories that for the church and that for the chamber. Hence sonata de Chiesa and sonata de Camera, church and chamber music respectively.

Two good examples of this are Purcell Sonata and Mozart Sonata No. 14. It would be difficult to imagine the Mozart Sonata being performed in a cathedral.

Public performances of music probably started in the late 17th Century and one John Bannister who, according to the Honourable Roger North procured a large room in Whitefriars near the temple back gates and made a large raised box for the musicians whose modesty required curtains. The room was rounded with seats and small tables, Ale House Fashion One shilling was the price and call for what you pleased, there was good mussiek for Bannister found means to procure the best hands in towne'

It is likely of course that the reverberation time of the space was below 1 sec.

Between 1786-1791 Mozart wrote what was generally regarded as his greatest achievements 'The Marriage of Figaro, Cosi Fan Tutte and The Magic Flute'. The decorated counterpoint and recitative requires a shortish reverberation time of around 1.0 - 1.3 secs. at mid-frequency.

Finally we need to consider the musical receptor, whose complication involves the ear and brain.

'The shaking air rattled Lord Edward's membrana tympani; the interlocked malleus, incus and stirrup bones were in motion so as to agitate the membrane of the oval window and raise an infinitesimal storm in the fluid of the labyrinth. The hairy endings of the auditory nerve shuddered like weeds in a rough sea; a vast number of obscure miracles were formed in the brain and Lord Edward ecstatically whispered 'Bach'. (Aldous Huxley, Point - Counterpoint).

RESIN DETRA

From the foregoing we may conclude that different styles of music require different acoustics.

Modern tastes appear to prefer a slightly longer reverberation time. Musicians also prefer the space to provide fold/feed back, presumably to allow adjustment to tempo and timbre.

The table below gives my preferences for mid-frequency reverberation time for various types of music.

Type of Presentation	Ideal Reverberation Time @ 500Hz
Cinema	1.0
Pop Music	1.0
Speech	1.0 - 1.2
Drama	1.0 - 1.4
Comic Opera	1.2 - 1.4
Baroque Opera	1.2 - 1.4
Grand Opera	1.4 - 1.6
Symphonic (Baroque period)	1.2 - 1.5
Symphonic (Classical period)	1.5 - 1.8
Symphonic (Romantic period)	1.8 - 2.5

It can be seen that from baroque to late romantic music the preferred RT is roughly a factor of two.

Multi-auditoria complexes could only be centred in major cities and hence provincial towns would be denied the experience of a wide cross-section of the arts or they would have to be content with mediocre performances.

In 1973 the Department of the Environment published a design bulletin - Multi-Purpose Halls which listed the type of activities expected and provided guidelines on the facilities required.

And although the bulletin acknowledged that the object was to promote multi-purpose halls the concept of an all-purpose hall was probably not attainable.

In fact the acoustic consultant (H.R. Humphries) on a demonstration project was able to convince the steering committee that the intended hall could not be 'all things to all men'.

This fact was also echoed a year earlier by P.H. Parking in a Paper presented to the Royal Society.

If to achieve multi-purpose we need a multi-acoustic space then we need a mechanism for effecting the change.

On the face of it, adjusting the absorption in the hall seems a viable option.

Almost 100 years ago Wallace Clement Sabine - Professor of Acoustics at Havard University (1895-1918) determined that the reverberation time and geometry of a space relate as follows:

$$RT = RT = \frac{0.163V}{S\overline{\alpha}}$$

where:
RT = Reverberation Time (sec.)
V = Volume (m^3)
S = Surface Area (m^2)
α = Mean Absorption Coefficient derived from

$$\overline{\alpha} = \frac{\sum_{o}^{n} S_1\alpha_1 + S_2\alpha_2 \ldots\ldots\ldots\ldots S_n\alpha_n}{\sum_{o}^{n} S_n}$$

Recalling that we would wish to adjust the space by roughly a factor of two, we have two options.

1. Double or halve the value.

2. Halve or double the total absorption.

Or perhaps a combination of the two.

Doubling the volume to double the RT is clearly a gargantuan task and may be probably discounted.

A change in the total absorption seems much more feasible.

One could readily imagine that the walls comprised rotatable panels, one side absorptive, the other reflective and hence by arranging the properties of reflective/absorptive panels, the RT could be varied in quantised steps between the dead and live conditions.

One quickly realises that the concept is less than viable since the audience and seating comprise over 60% of the total absorption in the space. Hence at best, we can achieve a change of the 40% remaining.

Other architectural solutions have been tried and include highly reverberant adjunct spaces which may be coupled or uncoupled by the use of doors. A moment's consideration of the principles involved will result in the conclusion that the effect will be minimal.

Another means, which with some hindsight, might be electro-acoustical.

SYSTEM REQUIREMENTS

The two basic requirements must be:

1. To increase the reverberation time of the space in a manner indistinguishable from the result had it been achieved by architectural means.

2. Not to adversely affect the structure of the sound (music) and not to introduce audible distortion or colouration.

Although relatively simple requirements, they have both proved difficult (until now) to achieve.

Consider the following:

$$SPL = PWL + 10Lg\,\frac{25RT}{V}$$

where:

SPL_R = Reverberant Sound Pressure Level dB re 20µPa
PWL = Sound Power Level dB re 10^{-12}Watt
RT = Reverberation Time
V = Volume.

If the reverberation time was increased by a factor of two by architectural means, then for the same source power the reverberant sound pressure level would increase by 3dB. If however the increase is provided by an external means, then to provide the same change the power input to the space must be equal to the power of the source.

A large orchestra generates between 5 and 15 acoustic watts. Allowing for loudspeaker efficiency of around 2% and say 10dB for amplifier headroom and the total amplifier output of the system will need to be in the region of 5kW.

If the system output does not match the source then the resultant decay is as shown in fig 1.

When the power is equal, the resultant decay is monotonic, if the system power is well below the source power the decay curve is formed into a 'dog leg' and the longer portion of the later decay would go unnoticed during running music.

It must be clearly understood that the problem of insufficient power is not limited to the available amplification. It is also limited by the propensity for the system to feedback. If the microphone and loudspeakers couple well then the system may become unstable prior to it's ability to deliver sufficient power.

The system should also provide the same development of the reverberant field as one which occurred from an architectural solution . This again is dependent upon the system power and also the distribution of the loudspeakers.

With regard to distortion and colouration this is self-explanatory but does include colouration caused by proximity to the onset of feedback.

Typically the system should not be closer than 5dB to the onset of feedback.

EARLY BEGINNINGS

Interest in these systems started in the 1960's and would include ambiophomy and Assisted Resonance followed by Philips MCR (multi-channel reverberation).

Ambiophomy as far as I am aware is a generic term applied to the principle of sampling sound in a dead space which is then input to a live chamber re-sampled and returned to the dead space.

An example is shown in fig. 2.

This type of system has been used in a number of halls mostly in Europe and the USA. Kuttruff reported that it had been used to reasonable effect in the Jahrhunderthalle Hoechst (which had a mid-frequency reverberation time of around 1.1 sec. which was increased to 1.8 sec. by the ambiophomy system.

The reverberation chamber had a volume of 144m^3 and a reverberation time of around 2 secs. (mid-frequency).

Around 90 loudspeakers were used in the installation together with some low frequency units. Signal delays were produced by rotating magnetic discs.

Kuttruff reported two important facts. Firstly, the level of reverberation was important , by this I think he was referring to the system power and secondly be said "of course the reverberation curves were no longer straight lines when the system was in operation." A clear indication that insufficient power was applied or was able to be applied.

He also reported that subsequently modifications had been made to the system and that these included the addition of a reverberation plate and springs, to counteract the low number of eigenfrequencies associated with small rooms.

I believe however that the major cause of problems was colouration due to close proximity of the onset of feedback.

During this time other attempts were made.

Foweather et al were attempting to utilise a space above a concert hall (with presumably a longer reverberation time) to enhance the reverberation time of the main hall and at much the same time Fransen published a theoretical Paper on a regeneration system using a large number of channels (50+) in order to double the RT of a space. This idea was subsequently adopted by Philips and became MCR.

The system was based on the fact that reverberation time in a space may be expressed in terms of the source sound power and the energy density within the space vis:

$$RT = 14V.\frac{E}{W}$$

where:
RT = Reverberation Time (secs.)
V = Volume of space (m^3)
E = Energy Density Jm^{-3}
W = Sound Power to the space in Watts.

It is possible to deduce that to increase the energy density by a factor of 2 (and hence the RT) N becomes 33. Note each channel is operating at -15dB re onset of feedback. Fig. 3 shows a schematic of an MCR channel.

Four years earlier than Fransen's theoretical Paper Parkin et al had installed an experimental system in the Royal Festival Hall. This system was known as Assisted Resonance.

The desire to improve the acoustics of the Royal Festival Hall had been around for some time. Various studies and investigations had been carried out over the preceding years.

In 1953 two years after the hall had opened, Parkin et al published a Paper on the acoustics of the Royal Festival Hall.

The Paper concluded that the definition was excellent but the fullness of tune was lacking. work must have continued during the late fifties and early sixties. I am not sure at what point Parkin decided to test an electronic solution but whenever, it was an extremely bold decision given the fact that the Royal Festival Hall was (and is still) a national shrine, the musicians reaction and the relative infancy of audio electronics. The results of the experimental system were reported by Morgan in 1965.

An Assisted Resonance system comprises a number of microphone-amplifier-loudspeaker channels (see fig. 4), each channel operating over a narrow frequency band. The channel width and its independence from all other channels was achieved using acoustic filters (see fig. 5).

It was possible to produce extremely high Q's of the order of 30-40 with these devices.

Morgan determined two important factors. Firstly that the total system power required was of the order of 1kW and secondly that the channel spacing needed to be in the region of 3Hz. The spacing was determined on the basis of Kuttruffs statistical work which demonstrated that the average spacing between peaks in the room response was given by 3.91/RT.

Following the success of the experimental system, the then London County Council decided to find a permanent installation with an increased bandwidth from 40Hz to 1kHz involving 320 channels.

The results of the permanent system were variously reported and the results looked extremely encouraging.

The new system covered the range 58Hz to 700Hz and comprised some 172 channels. The Helmholtz Resonators and loudspeakers were housed in the roof space and the amplification equipment in a control room.

The results are shown in fig. 6.

Parkin stated in his conclusions that "It is clear that the system works ....but several points about the design of such a system are unresolved.'

He went on to discuss the channel spacing which he believed could be increased (for commercial reasons) and additional that there seemed to be a difference between the subjective effect and the objective measurements.

It is interesting to note that from around 1967 to the late 1980's an operator was in attendance for every rehearsal and every performance. In addition a line was installed between the Royal Festival Hall and Parkin's home (at Watford) and every concert was recorded.

Subsequent to the success of the Royal Festival Hall installation, a license was granted to Acoustic Investigation and Research Organisation (AIRO) and more (commercial) installations were planned.

The first commercial installation was carried out over the period 1972-1973 at the Central Hall York University partly funded by an NRDC grant. The channel spacing was increased and was based on a constant percentage rather than a constant frequency. The York installation used 72 channels covering the frequency range 125Hz to 921Hz. The York system, as all later systems, had a number of settings.

Following the York (first commercial) system, there followed systems at Concord Pavilion in California, Alfred Beck Theatre, Hillingdon, Scottsdale Centre for the Performing Arts, USA, Hexagon Theatre, Reading, Kansas City Music Hall, USA, the conference centre in Harrogate.

In the meanwhile a number of MCR systems had been installed.

MID-LIFE CRISIS

Both systems were not without their problems, since they both relied upon positive feedback to increase reverberation they tended to be unstable. The net result was that when the gain was reduced to a stable level the effectiveness of the systems was greatly reduced. The other problem was colouration and certainly as far as Assisted Resonance was concerned, the problem was acute.

Incongruously, although Assisted Resonance had been around for over 10 years, a proper theory had not been developed. AIRO in an attempt to overcome the colouration problem set about developing a basic theory.

Unfortunately, in parallel with this, two more orders for systems had been taken, Theatre Royal Plymouth, Palãk Kutury Prague and Silva Hall Eugene, Oregon.

The system for Prague had a small computer to assist with the calibration method. For Plymouth and Eugene the concept of computer control was taken a step further with a computer in control of the gain settings. This meant that gain steps could be precise and of course many settings could be stored.

Colouration in both systems (AR and MCR) manifested itself as a metallic ringing quality to the decay process.

In the case of Assisted Resonance it was attributed to channel interaction and continuous filtration during the decay process.

During a decay the effective Q of the acoustic filter increases with the number of times successive sounds are followed?

It can be shown that the Q multiplication process is described by the following equation:

$$Q_{(n)} = \frac{Q_{(o)}}{\left(10^{\frac{3}{10n}} - 1\right)^{\frac{1}{2}}}$$

where:
$Q_{(n)}$ = resultant Q after n passes through the filter
$Q_{(o)}$ = Initial Q
n = No of passes through the filter

The resultant Q is shown in fig. 7.

The resultant Q could be as high as 100 which would go some way to explain why the decay would sound metallic.

To counteract this, AIRO developed a second order acoustic filter which compared 2 No. $\lambda/4$ tubes whose outputs were summed to give a steeper slope to the filter . This slightly improved the situation. Fig. 8 demonstrates this principle.

The high resultant Q's also resulted in filter ring , the RT of a band pass filter is given by

$$RT = \frac{70}{\pi f}$$

where
f = frequency
RT = Reverberation Time

Fig. 9 illustrates filter ring.

With systems that comprise high Q filtration either resulting from acoustic filters or the interaction of room modes there is a further type of colouration that can result.

An oscillatory system may be defined in terms of the usual second order second degree differential equation.

$$\frac{d^2y}{dx^2} + 2k\frac{dy}{dx} + n^2x = n^2f(t)$$

If the system is forced to oscillate at some frequency other than its fundamental then as soon as the forcing frequency is removed, the system, albeit not instantaneously, will decay at its fundamental frequency. The rate of change of frequency would depend on the ratio of kinetic to potential energy within the system at the point of the cessation of the force in frequency, together with the difference in the forced and fundamental frequencies.

Clearly in terms of music therefore, this would represent an undesirable type of colouration since the decay may not contain the same tonal components as the music.

When the pitch change problem was realised, I remembered a musician at the Royal Festival Hall who complained that for some woodwind sounds there was a pitch change during the decay. His idea was dismissed on the basis that there was no frequency-specifying mechanism in the circuitry.

THE END OF THE BEGINNING

Positive feedback systems were unstable and this combined with the colouration problem caused the popularity of these systems into decline.

The last two AR systems Plymouth and Eugene were difficult due in part to the introduction of digital control but also due to the better understanding of those who were specifying the systems in the first place. In addition, the initial 1960's distrust of electronics was returning.

The colouration that was deemed acceptable in the 1970's was deemed unacceptable in the 1980's, the need to constantly tune the systems with the attendant cost made the positive feedback systems unpopular.

Even before the completion of the last systems, the earlier systems were in disuse and by the mid-to-late 1980's most if not all of the early systems had been turned-off.

THE NEW ORDER

In the early 1980's it became patent that the large positive feedback systems which were incidentally expensive due to the protracted installation time had no future.

Since the need however was genuine other systems would be required.

In 1983 Jaffe Acoustics commissioned a study to evaluate the problem and to provide outline conceptual design for a system operating on a different principle.

The study concentrated on the effects of colouration and its results.

A system known as RODS evolved and this in conjunction with Jaffe Acoustics ERES systems was used with good effect until quite recently.

Lately other systems have developed that use sophisticated processing to develop apparently colourless reverberation with high RT magnification possibilities. Those that I have heard have been extremely good.

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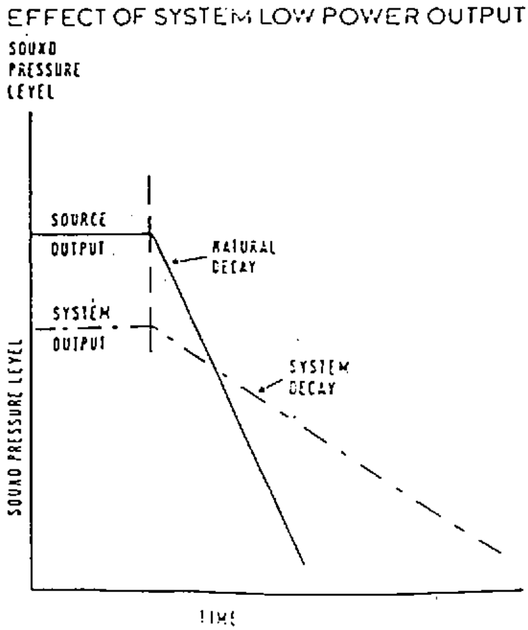

EFFECT OF SYSTEM LOW POWER OUTPUT
SOUND PRESSURE LEVEL
SOURCE OUTPUT
NATURAL DECAY
SYSTEM OUTPUT
SYSTEM DECAY
SOUND PRESSURE LEVEL
TIME

Fig 1

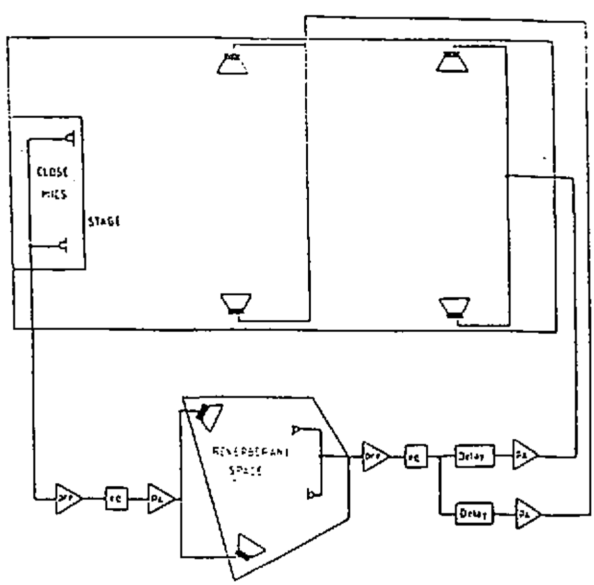

CLOSE MICS
STAGE
REVERBERANT SPACE
Delay
Delay

Fig 2

SCHEMATIC MULTI-CHANNEL REVERBERATION SYSTEM
(SINGLE CHANNEL)

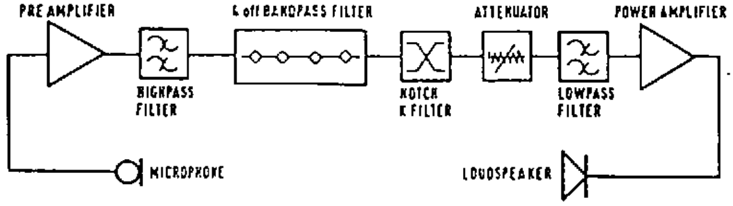


Fig 3

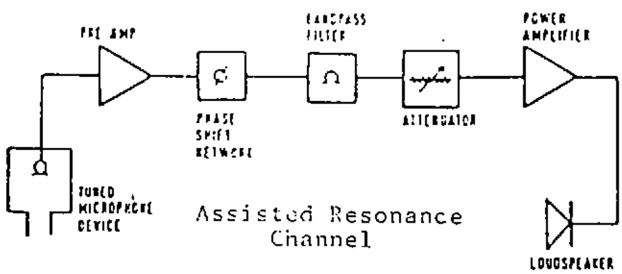
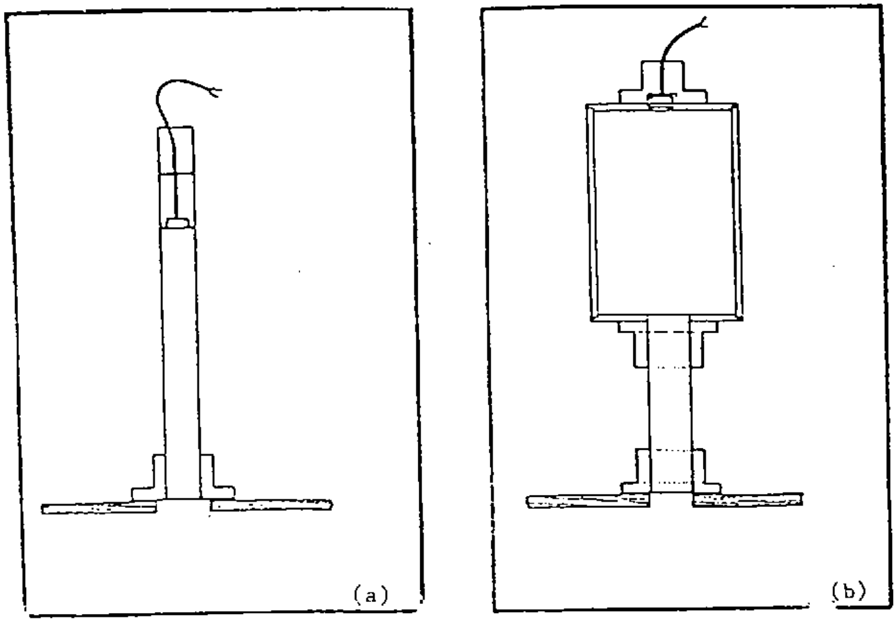


Fig 4



Assisted Resonance Tuning Devices

Fig 5

ASSISTED RESONANCE - ROYAL FESTIVAL HALL LONDON U.K.

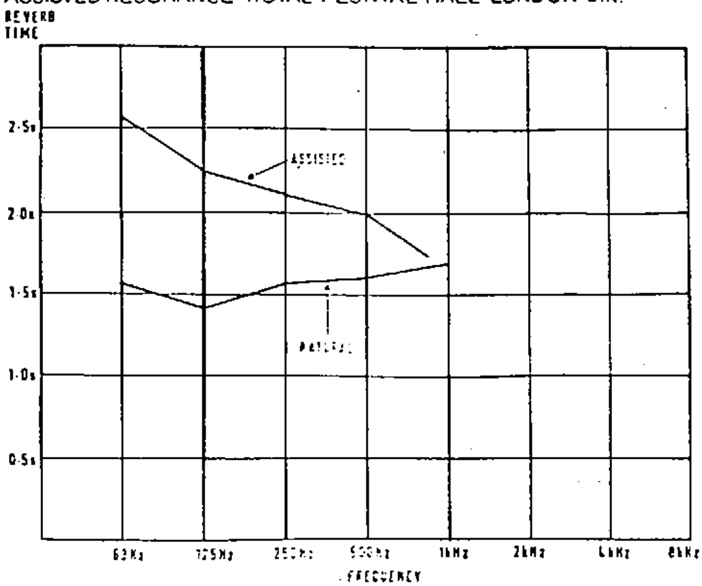


Fig 6

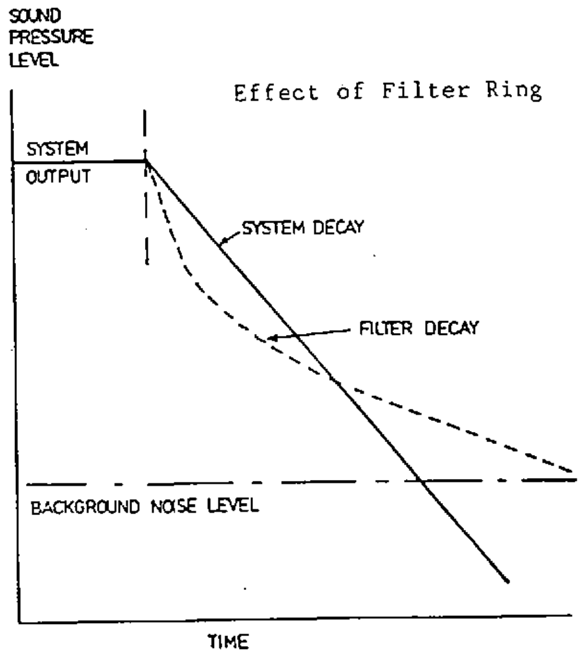

SOUND PRESSURE LEVEL
Effect of Filter Ring
SYSTEM OUTPUT
SYSTEM DECAY
FILTER DECAY
BACKGROUND NOISE LEVEL
TIME

Fig 9

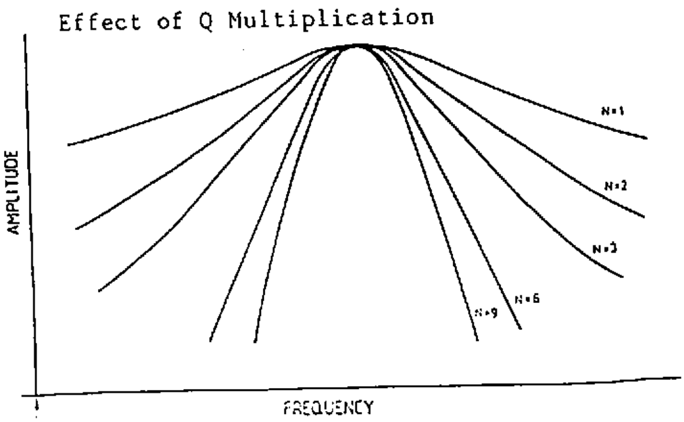

Effect of Q Multiplication
AMPLITUDE
FREQUENCY
N=1
N=2
N=3
N=6
N=9

Fig 7

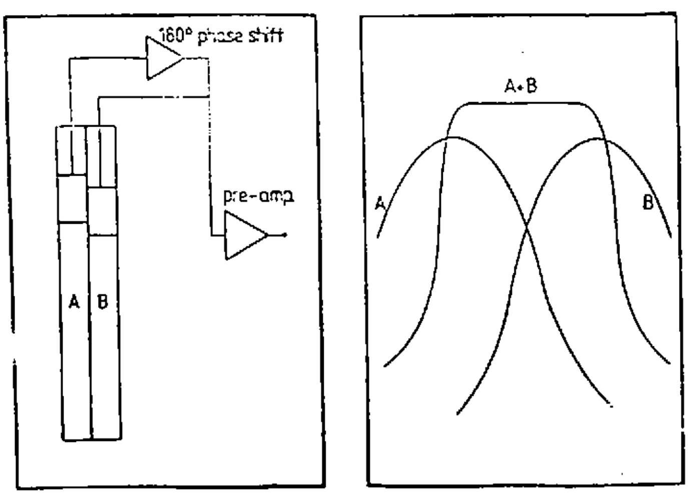

180° phase shift
pre-amp
A
B
A+B
A
B

Fig 8