Computerized Analysis of Noise, Vibration, Acoustics and Sound (CANVAS)

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ABSTRACT

Through a brief introduction of the history of acoustics and the methods acousticians use to analyze noise, vibration and sound in architectural spaces, a new computer program is introduced which provides a powerful design tool for acoustical analysis. The program includes instantaneous octave band analysis of reverberation time (RT60) and sound transmission loss in addition to other useful applications through informative and accurate, enhanced color graphics. The program uses an extensive, user adaptable materials selection database on which complete analysis is based.

0 HISTORICAL INTRODUCTION

"In the case of very high sounds, there is little or no appreciation of pitch, so that for musical purposes, nothing over 4,000 need be considered."

John William Strutt, Baron Rayleigh, SC.D., F.R.S.
From the Chapter entitled "FACTS AND THEORIES OF AUDITION" in Volume 2, *The Theory of Sound* (1894) [1]

And so it was that 100 years ago, with limited equipment for experimentation, the practical concern for "musical frequencies" over 4,000 Hz were muted in favor of the fundamental understanding of pitch and harmonics for those frequencies less than 4,000 Hz. Not that Lord Rayleigh was unfamiliar with experimentation, nor the complex analysis of acoustics, as can so well be appreciated in the Nobel Prize physics winner. But practicality at the time lended itself to the closure of the audible spectrum at a frequency in kind with general "appreciation".

Perhaps practicality lends itself to the reasoning behind why electricity and electronics have steadfastly come along light years (or shall we say, sound years). The CD with laser technology has proven that electronic sound is quite manageable and reproducible from input to output in a remarkable manner.

In the 1920's, it was commonplace to find transducers handling an average of one electrical watt for reproduction purposes. This meant power in a range of hundredths of an acoustical watt. Today, values approaching one acoustical watt in a sound field may be considerably low in distortion and provide fidelity well beyond Lord Rayleigh's cutoff frequency.

The phenomenon of acoustics has been attacked more from an electronic management standpoint than from a true harboring of acoustical principles and applications through modern tools and technology. Our ability to perform almost surgical dissection in the reproduction of sound has not met with our crude ability to control sound in space. Yet, this does not show our lack of ability but rather the strong physical phenomenon accompanied by the whole idea of acoustics in nature.

The essential variables in electronics we attempt to control are frequency, amplitude, phase, and time (propagation, delay, etc.). Measurements are two dimensional over the time period. We are now able to make objective measurements and decisions from what used to be subjective perception only 40 years ago.

Acoustics adds three dimensional space to the list of variables already mentioned. Because measurement and analysis are both limited due to the complexity of including time and space, we rely to a large extent on subjective analysis of acoustics. Our auditory system already measures pitch, harmonic content, and direction rather well. Until we can change subjective analysis into objective analysis through analytical tools and instrumentation, we cannot solve what could be a great triumph.

Our ability to direct and negotiate electrons through wire and semi-conductive elements is easier due to the practiced ability to measure, quantify and qualify the varied elements of signals and their paths in the reproduction process. It is just as similarly difficult to measure and record a physical phenomenon in a confined space with absolute certainty since our capacities to measure the minutiae changes is so limited and since there are so many (subjective) variables.

Sound may be considered in a "Modernist" era if related to art. Purveyors of reflected sound systems and direct, time-aligned systems gambit with one another, sometimes criticizing the other, yet both realistically and electronically valid for the intended purpose. Such as the likes, dislikes and general interpretations of a modernist painting.

Acoustics then, might be considered in a "Renaissance" era if related to art. Things are still dealt with in a structured, rigid and painfully accurate manner to control this energy promulgated in the form of acoustics. We are not able to completely be free with our expressiveness nor completely understand. Yet, we add beliefs into the equations of solution which border on conception rather than solidified practice.

1 ACOUSTICS AS SCIENCE

"On the other hand, every individual has an opportunity of experimenting on the composition of two or more musical sounds or noises on the most extended scale, and the power of analyzing even extremely involved compounds of musical tones, into the separate parts produced by individual instruments, can readily be acquired by any one who directs his attention to the subject."

Hermann L.F. Helmholtz on the comparison of visual color to sound from the chapter entitled "ON THE ANALYSIS OF MUSICAL TONES BY THE EAR" (Chapter IV), *On the Sensations of Tone as a Physiological Basis for the Theory of Music* (1885) [2]

Over 100 years have been spent in mathematical tedium to derive, analyze and theorize on acoustics and associated phenomenon. But mathematics has also required something which is only yet being discovered and applied in what soon will become rudimentary and required analysis for the application and understanding of acoustics and the theory of sound. The tool is the computer. And it has only started to become a tool invaluable to acoustical analysis.

Computers have improved our ability to solve complex mathematical problems, display and provide advanced techniques for engineering analysis. They can provide direct application in acoustics. Small elementary programs for use on hand-held calculators, small listing/calculator programs for PC's, proprietary "speaker CAD" programs and rudimentary acoustical source programs have become available over the past years. Computers for analysis and measurement of acoustical spaces, or more correctly sound sources in acoustical spaces, are available from several sources. But a true design package to bring acoustics to the practical level of designer and researcher has not been available and is not designed for the technical user. What do we do when the design is still in schematic development on paper?

PC's are remarkable tools waiting for engineering applications and program design applications. This paper discusses how the need for a solution, the application of fundamental engineering and scientific formula, compilation of a modifiable and accurate database, training based programming and custom output tailoring has created a personal computer program based on the 8088 (up to 80486) processor with DOS operating system. The program solves and displays complex acoustical problems in reverberation, noise and vibration control, sound pressure and articulation; fast.

2 ACOUSTICIANS AND THE PROGRAMMING OF ARCHITECTURAL SPACE

"Programming" is used by architects/engineers/consultants (A/E/C) to qualify, quantity and define an architectural space for fit, form and function. This programming of a user's space is the single, most important aspect of communication between the design professional (acoustician) and the client (architect, owner). During programming, the acoustician gathers as much information as possible about the planned space and the associated requirements for the space in regard to its final usage.

Programming may start with an evaluation of an existing property, survey and analysis to establish current conditions and to review what is to be the intended change. However, programming can also start when the design is strictly on paper. The acoustician on the design team may assume total responsibility for fulfillment of client goals by means of experience, mentor training and basic grass roots understanding. Synergistic relationships develop in the A/E/C team if tools are available and thought processes are eased during the analysis and design of what may be a completely conceptual space.

Two of the most critical tools used for the development of the space are standard acoustic formulae and materials data lists. Unfortunately, the formulae are extensive, cumbersome and extremely time-consuming and the materials data is extensive, unavailable from one single source, often proprietary and difficult to utilize in an efficient way. By example, the use of the remarkable Shure reverberation calculator [3] makes the job of finding a relative RT60 for design space considerably easier than the tedious task of manually performing the Fitzroy equation [4] over and over again. In trying to establish expected reverberation values in an acoustical space used for conferencing and lectures, the author found that each iterative equation to better "fit-out" the space (with materials) required approximately 20 minutes of rectification of the data already available and subsequent derivation of the final value through the use of this calculator. Its use is cumbersome and the accuracy questionable because of the interpretation and interpolation needed to record the final value.

The same is true for determining Sound Transmission Loss (STL) compliance for the design space, though the problem is more related to the data available than the absolute abundance of variables that may be constructed into a ceiling, wall, or floor framing system.

3 THE COMPUTER PROGRAM

It was understood that a good personal computer program could provide a powerful opportunity to analyze the conceptual planning of new spaces and the renovation or analysis of existing spaces. The personal computer can provide enough data and perform calculations to meet the requirements of a designer in such a way that the tool may aid in the understanding of the problem at hand and to provide greater efficacy toward a proper solution. Thus, the minimum goal was to design a computer program that:

A. Was easy to use;

B. Utilized an extensive modifiable database;

C. Computed the RT60 and STL values for frequencies between 125 Hz and 40,000 Hz instantaneously;

D. Provides graphical solutions that are easy to read, contains the engineering output data required and even helps place the data with respect to the "norms" that would be expected for the solution, i.e., to show the data relative to expected norms of the space.

The program is not designed for those who have not had experience in elementary acoustics and sound, noise and vibration transmission. Like any computer program, its limitation is directly associated with the understanding of the person and the intent for which it is to be used. There must be a practical appreciation of the limitations of a computer and its use in acoustics, just as there are limitations in the use a computer for analyzing linear or non-linear filters in electronic circuitry. Our own experience has shown how the computer program can be a valuable tool in analysis and control of sound in spaces in a more predictive way than relying on simple experience or iterative hand solutions.

4 USING THE PROGRAM

The computer program asks in simple terms to define the listening space. For the RT60 Fitzroy calculation, the dimensions of the room must be provided with the number of surface panels, i.e., the number of differing material elements on walls, ceiling and floor that may appear. Each different surface requires establishment of the acoustical absorption coefficient value at each frequency automatically by the program. Once each element is defined in the program, and the data is thus recorded in the program for the materials selected, the computer instantaneously graphs the expected reverberation time on the screen and may even present a "window of acceptability" for the reverberation times with respect to the type of listening environment being established. By providing a program which instantaneously can calculate the reverberation time, you are, in a sense, painting the "canvas" of the proposed acoustical environment of the space.

Modifications can be made so quickly that the program can provide a better feeling for the space than tedious calculations that tend to frustrate and reduce the productivity of the person analyzing the data. The same holds true for STL analysis of noise. The instant analysis of walls, ceiling or floor construction by using the program is ideal in both establishing the minimum requirements and where the requirements fit onto a noise criterion (NC) curve that has been defined during programming. By having an extensive list of materials and construction types for the space already in the computer, with associated data, a relative set of transmission values can be obtained instantaneously.

Many materials stored in the database have not changed in 100 years with respect to their acoustical properties (though importantly, construction has). Other materials, such as state-of-the-art barriers which simulate lead shielding in their attenuation properties are also listed to provide a database which can be valuable for different operator levels. Because certain materials are not listed does not mean that a relatively accurate analysis cannot be made. Often, materials already listed mimic other materials that may be required or found on the project, though never measured nor data obtained previously. Careful and conservative consideration are always needed in acoustics.

Modification and expandability are keys to success. The program is "data-friendly" so that the user may store new materials or establish different criteria for specific materials to augment and supplement the program and its database for further study and for future projects.

Unfortunately, computer analysis and the use of complete data does not necessarily reflect the real world under what may not be ideal measurement conditions. Just as the computer program user may choose between the Sabine equation and a Fitzroy equation, the user must also choose between what will be reality and what will be a mere "computer reflection" (what comes out is only as accurate as what went in). This may only be resolved through experience and good and reasonable care in the use of the program and its interpretation for real world use. Typical examples are reverberation calculations for higher frequencies. Reverberation at high frequencies never reach calculated expectations due to defractive effects, specular relationships of reflection, humidity, temperature and the general shapes of the surfaces and volumes within the space. Obviously, even knowing all the reverberation values throughout the computed spectrum, does not mean that the space will be acceptable from a listening standpoint. Forty years ago, Beranek [5] showed that there were minimum subjective criterion that must be used to establish the quality of a listening space. Today, most acoustical consultants will not agree on the importance of each bit of subjective criteria that is used to evaluate a listening space. The concept of acoustics practiced as art while design of the space and material selection likened to painting a canvas, applies today as it probably will for quite a while. [6]

5 DEVELOPMENT OF ACOUSTICAL ANALYSIS MODULES

During development of the computer program, it was decided that the package should be modular, so that items may be added, deleted or modified in a fashion such that improvements could be made to the system. Refinement into a practical user program was laborious and time-consuming, but rewarding.

The RT60 module provides a basis for establishing reverberation time graphs by using either Sabine or Fitzroy calculation methods. The RT60 module allows the use of an extensive database to construct a mathematical equivalent of the room based on the number of surface areas in the room and their associated attenuation coefficients over the analysis spectrum. Again, data may be modified, added or deleted at any time by the user to provide more accurate analysis.

The STL module is similar in that the user may calculate for expected sound transmission loss of a particular construction by using a database. Attenuation between spaces may be viewed as quickly as the construction type is entered. Noise Criterion curves may be overlaid to establish standards of acceptability. Calculations are made instantaneously by the computer and a graph may be printed out to reflect the level of sound transmitted.

For STL, the modifiable database is extremely important and practical. For instance, perhaps the user has a double stud, gypsum wall assembly which is easily found in the database. However, the client wishes to increase the acoustical properties between the gypsum wallboards without increasing the depth or providing major changes in the construction between the spaces. Perhaps the solution is to add a hi-tech sound attenuation barrier of only 1/8" thickness between the double studded partition. By allowing the database to be modified, the user can intuitively grasp the increased attenuation due to this essentially high-mass product into the total attenuation value of the standard double wall assembly. By example, perhaps there is a flat 3dB added to the frequencies from 500 Hz to 4000 Hz but below 500 Hz there is no reasonable attenuation. (We assume one-half of 6dB because of the doubling of the mass in the specified case.) It is a simple procedure to take the original data entries for the standard construction wall and add the attenuation at the relative frequencies, enter it into the database and re-calculate almost instantaneously. The new graph will show a "modified double stud partition" and this will be in the database for historical reference.

The computer program is (1) highly expandable for future needs and customization, (2) is an excellent tool for basic acoustical analysis and (3) is simple to operate, yet should be used by an individual with acoustics training. A technical review of the design development aspects of the program will solidify concepts further.

6 PROGRAM REQUIREMENTS

The development of CANVAS began in early March of 1990 when one of our engineers was working on a large acoustical project for teleconferencing and lecturing at a major university. The project involved repetitive reverberation time calculations at each of the octave band frequencies. Because the reverberation time formula for a room with heterogeneous materials can be quite complex, it took the designer twenty minutes to complete one calculation. It was at this time that we realized a more practical solution must exist. Simple listing programs for basic programs or scientific calculators were deemed primitive.

The most critical steps in the design of the program was to determine the type of data the program would require from the designer and the type of reports or output would be required from the computer. Determining what variables the program required was simple. The Fitzroy formula requires the room dimensions and the absorption coefficients for each material used on each surface. Determining what information the designer would find useful in the output was slightly more difficult. We decided that besides the numerical results of the calculations at each octave frequency band and the NRC reverberation value for comparison, simultaneous display of the line graph of the reverberation time in seconds across the octave bands would be useful in giving a graphic "feel" of the room (see figure 1). The final development part of the program was to find a simple way to enter the necessary information. After several prototypes, a data entry screen was created that allowed the user to enter the necessary information into the program. This data entry screen prompted the user to enter the room dimensions and from a database, select the surface materials to use in the calculation (see figure 2).

The program calculates and displays the reverberation time at each frequency in about a second. Being able to decrease the amount of time needed for calculations is only one of many derived benefits. Another major advantage is accuracy. Since there is no chance for human error in the calculation process and there is no approximation, the only place for error is in the data entry screen. The program therefore validates all entered data to be sure it is acceptable before processing. Not that it corrects or identifies bad design, but it will not accept things like one foot wide rooms.

The second module developed was for calculating STL of typical construction. We felt that it was important to include variables such as the mass law and allowances for sound leakage in the program. This was accomplished by allowing the user to make manual adjustments for each wall construction as discussed previously. Like its predecessor, the output consisted of a line graph with the results numerically displayed on the left hand side of the screen. Because noise criterion curves (NC) are important when finding the required noise reduction, we felt it necessary to add NC curves to the module. These curves, at the user's option, are overlaid on the line graph so the user can identify what octave bands remain problem areas (see figure 3).

7 OUTPUT GENERATION AND FUTURE DEVELOPMENT

Because the output from CANVAS is most important to the user, be it an acoustician, acoustical engineer, architect and/or client, the greatest amount of detail was spent on the report generation process. We felt that in addition to sending graphs and reports to the printer, the user should be able to save any report to disk. This filing system allows the user to recall and compare any past project at a moments notice.

With two successful modules under our belt, we continued to add several other programs such as articulation index and sound pressure calculations. With the development of these additional modules, a menuing system was needed. A pull down menu structure was implemented to organize and simplify the selections for the program. This program eventually became the third version of CANVAS.

CANVAS is proposed to be updated and modified with new modules and utilities added. Future CANVAS modules may calculate reverberation time based on ray tracing algorithms. This new module would work with a major accepted CAD drawing package to acquire the actual layout and dimensions of the room. Further versions of CANVAS may be written for other platforms.

8 REAL WORLD PROGRAM ASPECTS

Unfortunately, many programs that engineers and business people use do not provide the information, output or capabilities that are often advertised or inferred by marketing innuendo. Expert "use" is subject to experience with both data and real world results. We have modified a widely used acronym of WYSIWYG (What You See If What You Get) to WYSINNWYG (What You See Is Not Necessarily What You Get). Ideal calculations versus real world measurements reflect limitations in the program's usefulness. The limitations are the room shape, area, volume, diffusion, correctness of data, and so forth. The program will not identify that you do not have enough diffusion in the room to provide for the subtleties of a piccolo in the far left corner of the room. Nor will it tell you that the reverberation times at specific frequencies are not high enough for the soloist who is expected to play in the room. Experience, intuition and good common sense are required for all technical analysis programs used by a design professional.

The data is the one thing that is accurate with respect to the way it was measured and the reproducibility of the measurement. This strictly means that a specified material will act in the same manner and that the same data will be measured under the same conditions as imposed by the acoustical laboratory using accepted testing methods. The fact that the measurements have been made in a confined room under certain conditions of a test does not mean that the material will react the same in a large room with differing patterns of materials on floors, ceilings and walls.

Reverberation time is almost always lower. High frequency attenuation is almost always higher. The program will not deliver information on frequency scattering, flutter echo, or infrasonic leakage through walls. The STL will always be lower. Performance of proprietary deadening materials in real world applications will rarely meet test specifications. Construction of spaces to obtain the standard frequency losses listed in the data will never be equivalent to the test data. Construction methods on the site vary, sealants change and walls are never perfect. Acousticians will always have a job.

Can we define what form of reverberation this CANVAS program provides the user? Perhaps we can categorize reverberation into three segments of analysis. Similar to the analysis of control systems, reverberation can be broken into two components - transient and steady state. The transient character of reverberation is composed of essentially two segments; the impulse (with the associated first, second and third reflection components) and the associated decay component. The analysis of the first, second and third reflections arriving at the listener are not calculated within the program and have to be analyzed through other means.

The third component in analysis is the steady state response of the system. This is when an energy is continuous and non-modified over some periodic frequency to energize the space from the beginning of time to infinity. Thus, the transient criteria is established with the impulse of the sound and digresses to the decay of the transient as the sound diminishes throughout the space. The steady state analysis provides for the character of the sound associated with ensemble from instrumentation, voice and chorus. Steady state analysis forms a time base for establishing the quality of the sound with respect to the effects of flutter echo, fullness of the space, diffusion of the space, etc. It is obviously more than a little frustrating in trying to cut a clean line in acoustics between transient and steady state analysis.

The venue in which the analysis must take place is just as important as the determination of the results. For many years, the steady state analysis of a room was all that was required for rock concert level audio. The noise floor was so high in the room that there was no such thing as the "subtle" quality of sound. Sound emanated from everywhere and the dynamic range was extremely limited. Conversely, transient analysis for classical music is extremely important since dynamics of 60dB to 90dB are possible. The transient attack in a concert space is so critical that in the first few passages of a classical piece, a room may be disqualified as unsatisfactory. This is why the "understanding" of a space relative to its acoustical properties are so important for the conductor and the musicians. The control of the transient aspects, the impulse and its decaying properties are absolute with respect to the listener's appreciation of both the space and the musicality of the production. The steady state quality is likened to the

character of the space during full excitation of frequencies - exiting room modes, creating standing waves, inducing interference patterns and so on. Without an appreciation of this steady state character, the space can sound "free field" or "confusing" like a box, instead of being surrounded or enveloped by the musicians. We must always analyze all three components.

The CANVAS program uses a simplified decay formulae to simulate the after-effects of the impulse in time related to an absorption of the frequencies within the space caused by the materials and dimensions of the space. The program does not rectify the important first or second reflections nor the steady state qualities of sounds reflected within the space due to periodic patterns. By definition, the program's accuracy and usability is high since it provides a basis to qualify a room and its materials in a highly regarded fashion and to set a basis for establishing fundamental listening characteristics of spaces.

9 CONCLUSION

A program has been developed which provides user-friendly interface, extensive database, options to analyze two formulae of reverberation, STL and other elements for the acoustical analysis and review of existing or prospective rooms. State-of-the-art programming has been used to allow for fast, accurate results, expanded graphics capabilities and professional "feel".

10 ACKNOWLEDGMENT

CANVAS is the software programming result of Jeffrey E. Wilkinson, without whose efforts the program might never have been written.

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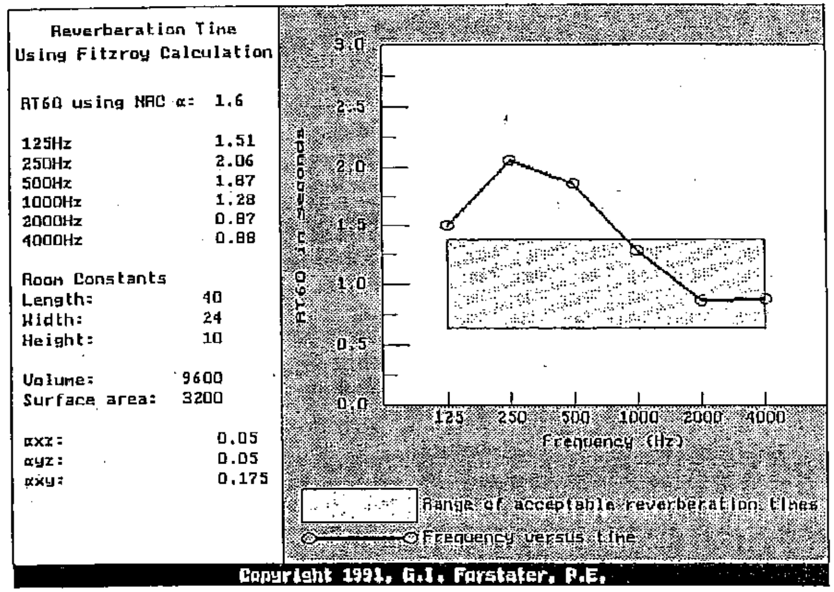

figure 1

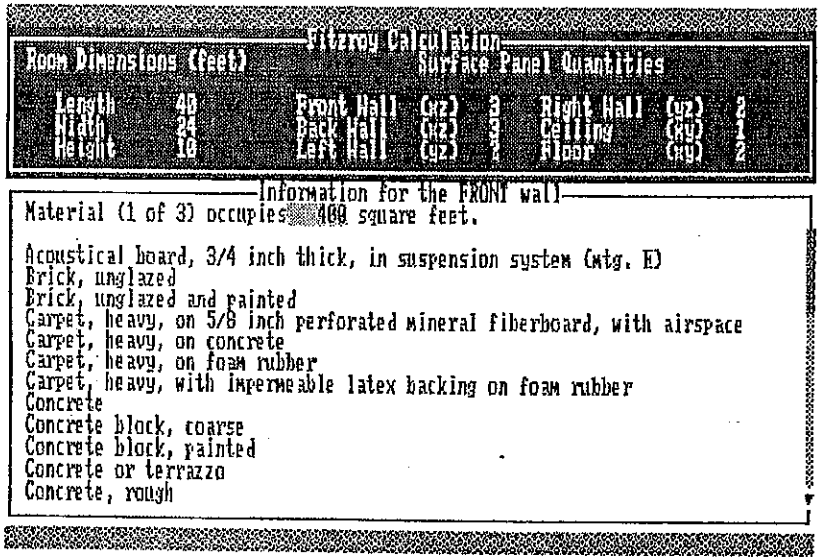

figure 2

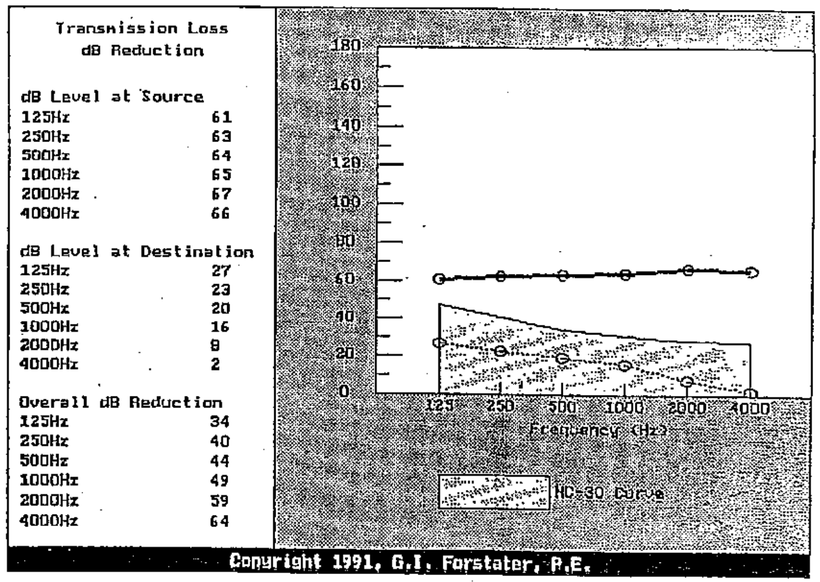

figure 3