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# INDOOR NOISE PREDICTION: FROM MYTH TO REALITY.

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## 1. PREAMBLE

This paper is devoted to the general topic of noise prediction in workshops. The intention is not to get into the scientific details of the methods that allow such a prediction to be made. It is rather to describe why, how, where and by whom this topic was handled, starting from the origins to 1993.
This overview is based on the literature available but also and mostly on the experience acquired at I.N.R.S. through 20 years of investigations of various types in the area of sound propagation in workshops and indoor noise prediction throughout this paper abbreviated to INP. Sound prediction in auditoria which has also a long and bright but distinct history is not covered by this paper.

## 2. THE MYTH

Practical industrial situations with regard to noise are formidably complex. Machines are among the most intricate sources of sound; acoustical boundary conditions on walls and objects present in a workshop are seemingly untractable considering the infinite variety of shapes and materials. Most basic acoustical phenomena are present and mixed: radiation, specular and diffuse reflection, simple and multiple scattering, diffraction, propagation in closed spaces. With this in mind, thinking of predicting sound pressure levels in a workshop before it is built was a real challenge.
However, some acousticians in the world have been brave enough to take it up.

## 3. HOW THE MYTH WAS ATTACKED

### 3.1 The Starting Point

It is of course impossible to state that INP was invented by Mr. X on day D of year Y. However, the names of RAYLEIGH and SABINE can certainly be put forward as those scientists who proposed for the first time basic equations that describe sound propagation. There is always a potential prediction method behind an equation that links physical parameters together. The whole INP story lies in between the inverse squared law of free field propagation and the SABINE description of the pure reverberant field.

The concept of INP was born in the early seventies from the practical need felt by some producers of absorbing materials who wished to quantify in advance how effective their materials would be in situ. FRIBERG's empirical formulas (1) have had a real success and are still referred to by some practitioners.

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However, the concept of INP really developed in the seventies, as a sub-branch of room acoustics, when health and safety at work started in most developed countries to become a subject of scientific and technical interest. Appropriate political decisions were made that allowed research, apparently in GERMANY and in FRANCE first, to be started in the field of noise in workshops which was then recognized as a major health and safety problem. Due to technological progress in the mechanical design of machinery that made possible constantly increasing production rates, noise levels in workshops were becoming higher and higher. In most branches of industry, exposure levels of workers exceeded (and unfortunately still exceed), sometimes in large proportion, safe sound exposure levels. The consequence was that occupational deafnesses started to be recognized and financially compensated by national health and safety organizations. INP developed as a promissing tool to abate noise at work and make industries and, consequently, national communities save money.

3.2 The Time of Research

At I.N.R.S., research started in the seventies with extensive noise measurements made in a variety of factory halls in close collaboration with the Caisses Régionales d'Assurance Maladie (the French regional authorities for health and safety at work). Before predicting noise levels in workshops, it was indeed necessary to understand the main features of sound propagation in such specific spaces and to identify the relevant parameters and descriptors.

It was quickly recognized that the nice and easy INP method provided by the following equation :

$$L_p = L_w + 10 \log \left( 1 / 4\pi r^2 + 4 (1 - \bar{\alpha}) / S \bar{\alpha} \right)$$

however useful for a first step calculation or in some practical cases (fairly cubic reverberant workshops) it may be, had not a wide enough field of application for INP purposes.

In the above equation, based on the SABINE approach, $L_p$ is the sound pressure level at a point in a room located at distance r from a point sound source of sound power level $L_w$. S and $\bar{\alpha}$ are room parameters (area of internal surfaces and mean absorption coefficient of these surfaces, respectively).

It was then necessary to look for other ways. The alternative was to develop either a scale model strategy or a simulation strategy. Building a scale model for a planned workshop and measuring sound pressure levels in it may look to-day rather odd. However, at that time, such a choice could perfectly have been made. Indeed, scale model work proved itself a very useful tool to predict noise in the environment and attempts at the research level (2,3) to work with scale models for INP purposes has provided useful information. The fact is that no countries have developed an INP strategy based on scale model measurements. Simulation techniques were definitely preferred. Time proved that it was the right way. Simulation techniques first developed in optics were adapted to acoustics fairly easily but the limits brought in by the geometrical approach (rays of light/rays of sound) were part of the heritage. The major limit of geometrical acoustics is that the wavelength must be small compared to the dimensions of the room so that many eigen modes are excited. If this condition is met, sound energy does travel along rays. This exclusion of the low frequency range (in practice below 250 Hz) was and is still found acceptable because most industrial machines and equipment radiate sound in a wide range of frequencies. Methods for INP at low frequencies, which implies that the modal structure of the sound field in the room is considered, have been developed successfully for specific applications (4) but are not widely used and routine field methods.

Geometrical acoustics coupled to an energetic approach, under the daring but in practice acceptable assumption that the many sound waves involved are uncorrelated (no interference effects due to the phase mismatch between waves), allowed one to develop computer-based simulation methods. These methods are based on the well-known image or ray-tracing techniques. These are physically very similar; the basic assumptions are the same but the ray-tracing technique has a wider field of application as TABLE 1 shows. The ray-tracing method developed at I.N.R.S. was available as soon as 1978 but its field of application was limited to empty rooms (5). The next research step, in FRANCE and elsewhere, consisted in enlarging the scope to fitted rooms. This was the next challenge. Taking account in a deterministic manner of all possible obstacles to sound propagation that can be met in workshops (machinery, storage, ducts etc.) was and is still fully irrealistic. The solution to the problem was provided by the fundamental work done by KUTTRUFF (6) on the propagation of sound in an infinite space with uniformly distributed scatterers. The remaining difficulty was to adapt KUTTRUFF's theoretical approach to a finite space. This major achievement was accomplished by LINDQUIST (7,8) who extended in 1982 the image technique to rooms with a uniform distribution of obstacles. JOVICIC's initial image-based method was extended to flat rooms with a uniform distribution of obstacles (9).
Shortly later in 1984, the extension of the ray-tracing technique to non uniformly fitted rooms was achieved by ONDET and BARBRY (10, 11). The above mentioned authors together with many other researchers in the world, such as AULETTA (12), HUNDAL (13), HODGSON (14,15,16), LEMIRE et al (17), KURZE (18), PROBST et al (19,20), NYKÄNEN et al (21) and, more recently, SENAT et al (22), ZHU et al (23), OLDHAM et al (24), DANCE et al (25), de GEEST et al (26) have investigated specific aspects of the different INP methods available and contributed to their scientific validation by comparing predicted and measured data, comparing INP methods between themselves, investigating accuracy aspects, investigating the influence of specific parameters such as room fitting density, adapting INP methods to specific branches of industry etc. More references on INP up to 1990 can be found in the survey paper by LAZARUS (27).

In the course of this research work, a great deal of experience was acquired in the understanding of the acoustical behaviour of workrooms and, particularly, in the way room fittings affect sound propagation. The reverberation time, which historically was the first indoor sound propagation descriptor used, has been progressively overwhelmed by the sound decay curve. This curve indicates how the sound pressure level decreases when an observer moves away from a sound source operating alone in a room. It is now for practical industrial purposes the preferred descriptor especially because it yields an immediately useful information in terms of exposure to noise. Unless the sound field in the room is uniform, a situation that may be approached sometimes in practice but which is certainly not the general case, the sound decay curve, just as the reverberation time, is not unique throughout the room and is frequency dependent. From this curve, two quantities now widely accepted and used can be determined

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i.e. the excess of sound pressure level (in comparison to the free field sound decay curve) and the sound pressure decay by distance doubling. These two quantities can be easily calculated from the predicted data yielded by the now wordly available computer programmes for INP.

3.3 The Time of Development

Establishing methods through research is one thing, having them currently used in the field to solve practical industrial problems is another one. Although it is rather easy to know through publications and conferences what goes on on the research side, it is much more difficult to get information regarding development and know-how transfer activities because this information is usually not made public.

No doubt that those who funded research in INP have used in a way or another the results for practical application purposes. However, how they have done that is not so clear except for three cases met one in SWEDEN and the two other ones in FRANCE.

In SWEDEN, following the successful work of LINDQUIST (7,8), a consultant company (28) developed a practical INP methodology including a simplified INP method based on LINDQUIST's findings.

In FRANCE, E.D.F. (the French Electricity Board) developed specific INP tools based on ray-tracing, adapted to the particular situations met in power plants and taking account of economical factors (29).

Development activities in INP at I.N.R.S. are, as far as I know, a unique example of long term action in the domain.
At the development stage, I.N.R.S. implemented a know-how transfer policy based on the following actions:

- establishment of a methodology for INP identifying the successive steps to be taken when carrying out an INP study in industry,

- wide information on and training in INP practice of the technical parties involved in noise abatement at the workplace (health and safety experts, private consultants, laboratories and technical centres working in the field of industrial noise),

- launching in 1985 of a call for tenders with the objective to boost practical industrial applications of the INP methodology and ray-tracing method developed at I.N.R.S. Several contracts were signed between I.N.R.S., consultant companies and industrial companies who agreed to work together from the start of a noise abatement project for a workroom to the practical implementation of noise control measures selected from the predictive data. This exercise had the great advantage to highligh major practical difficulties. These were not linked to INP itself but to practical constraints specific to industry which leave acousticians too few degrees of freedom. Even though some of these actions turned short, all consultants involved found the exercise useful and now use INP as a routine tool. Through a chain reaction effect, a general encouragement to INP practice followed.

- creation of a French INP Club with the objective to make researchers and practitioners (consultants in industrial acoustics) interact. This Club was created by I.N.R.S. in 1979 with only a few members from major technical laboratories and in 1985 it was enlarged to all consultants who wished to join in. Presently, the Club gather 40 Members and meet several times a year to discuss INP methodology and methods, their application in the field and connected room acoustics topics, exchange views and experience, discuss and interprete results gathered via round robin tests carried out in the Club, etc.

- free dissemination from 1985 to 1992 of the so-called RAYSCAT raw ray-tracing computer programme developed at I.N.R.S.,

- in 1992, I.N.R.S. asked a sub-contractor to make out of RAYSCAT a friendly use computer programme called RAYSCAD+ and to put it on the market as a commercial product. The conviviality of the product is brought in by the use of a CAD routine.

During this long but fruitful know-how transfer period, through information and training, special care was taken to avoid a major drawback i.e. the risk that potential users, fascinated by the apparent easiness of an INP computer programme yielding beautiful and colourful noise maps, believe that practicing INP requires little knowledge in acoustics. In fact, it is exactly the other way round. Modelling a real practical industrial situation is a difficult job that requires a very high expertise. Input data to an INP calculation play the major role. If their accuracy is low, then the accuracy of the computed values is low too, however precise the calculation itself may be. Potential users of INP based on ray-tracing often ask about the precision of predicted data. It is not possible to answer this necessary question easily with a single figure. For given values of input data and if the calculation parameters (number of rays shot from each source, number of reflections for each ray, size of reception cells) are correctly chosen, the calculation itself is very precise (tenths of decibels) but, as stated above, the inaccuracy of input data or inappropriate modelling of machines as sources of sound and of walls and other obstacles as sound reflectors will strongly influence the accuracy of the prediction.

## 4. THE REALITY

Time and effort proved that researching in noise prediction in workshops was not irrealistic. Noise prediction methods have developed very successfully indeed. The myth has become reality. Most consultants in acoustics and private or public laboratories use an INP technique as a current tool for planning and find it quite helpful. INP is not a magic flute but a valuable scientifically-based practical tool. Ray-tracing is the most commonly used INP technique in FRANCE nowadays. It is proved now via current practice that INP is a powerful decision-aid tool that allows right decisions to be made regarding the technical means to be implemented in order to design acceptably noisy workshops or correct existing noisy situations with the highest "decibel gained/cost" ratio. It turns out that the main field of application of INP is still the correction of existing situations. This is a pity because INP is also applicable to planned workrooms. This is not INP's fault. The situation will only improve when acousticians are considered as design partners which is unfortunately not often enough the case.

## 5. PERSPECTIVES

On the research side, the story is not over. There is still a lot to discover regarding INP at low frequencies, INP in the vicinity of the machines or of big obstacles (which involve directivity and interference effects), in situ estimation of the diffusion frequency of a fitted zone in a workroom, simultaneous consideration of reflection, diffusion and diffraction by boundaries etc. INP would also strongly benefit from research in the field of modelling of machines as sources of sound and of materials as reflecting and diffusing boundaries.
INP methods proved themselves a useful tool for carrying out research in areas such as architectural acoustics (30) and source modelling (31).

On the development side, no doubt that improved INP products will be produced in the future to enlarge the present field of application and to help with the modelling of practical industrial situations for INP purposes (introduction of source directivity as input parameter, consideration of some interference or diffraction effects, understanding of some in situ sound propagation features that INP methods do not describe yet, allowance of more friendly data input and more elaborated data output, development of routines for machine, material and fitting modelling for INP purposes etc.).

The proof that INP is now in France a routine concept can be found in a regulation (32) issued in 1990 by the French Ministry of Labor. This regulation relates to the acoustical correction of workrooms and specifies a criteria to be met by the slope per distance doubling of the decay curve determined using a method given in an annex to the regulation. If the reverberation of the workroom is likely to cause at the work places a sound pressure level increase of at least 3 dB, then the specified criteria must be fulfilled. The regulation specifies the use of an INP method to determine whether this 3 dB increase is likely to be met or not.

Another proof that INP is now widely recognized can be found in the standardization area. Under the frame of the application of the so-called "noise at work" EEC-Directive (33), European countries agreed to prepare standards in the field of noise reduction in work places. This decision was welcomed by countries outside Europe and consequently three Working Groups were created in ISO to deal with various aspects of this topic (34). One of them was given the task to prepare a three-part standard devoted to the recommended practice in the design of low-noise workrooms. Part 3 is entitled "sound propagation and noise prediction in workshops" (35). A first draft of it is being commented at national levels till March 1993. The experts in charge of preparing this standard are from 9 countries and agreed fairly easily on the fact that INP is a very necessary and effective tool for noise abatement in industry and that standardization is a good way to promote INP. The standard will offer an internationally recognized methodology for INP (see Fig.2) and give a list of presently available INP methods. Whether or not it is appropriate to standardize specific INP methods is an open question. Future will tell.

## ACKNOWLEDGEMENTS

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| INP method | | Contributors | Type of rooms | Noise control measures that can be simulated | Comments |
|---|---|---|---|---|---|
| DIFFUSE FIELD | | Sabine | CR<br>ER<br>with little absorption | NRS<br>SD<br>WL<br>E | Easy and quick.<br>Systematic overestimation of sound pressure levels when the sound field is not diffuse.<br>First step calculation method. Fittings are not considered but the sound field in a fitted room may be diffuse. |
| GEOMETRICAL ACOUSTICS | Image method | Jovicic | ER<br>UFR<br>fR, lR | NRS<br>SD<br>E<br>WL (ceiling of a fR)<br>WL (4 main surfaces of a lR) | Quick.<br>Computer required |
| GEOMETRICAL ACOUSTICS | Image method | Lindquist | ER<br>UFR<br>PR | NRS, SD<br>E<br>WL (any surface) | Computer required.<br>Complex calculation of integrals. |
| GEOMETRICAL ACOUSTICS | Ray tracing | Ondet-Barbry | ER<br>UFR, NUFR<br>ASR (planar surfaces) | NRS, SD<br>E<br>WL, pWL<br>S | Computer required.<br>Possible division of the room volume in zones with different fitting density and absorption. |

NOTE : These methods apply above 250 Hz, assume point sources and do not take account of interference and diffraction effects.

**Fig. 1 : Main INP methods - Fields of application.**

Captions :

Room types :

- CR : cubic rooms ;
- PR : parallelepipedic rooms ;
- ASR : rooms of any shape ;
- lR : long rooms ;
- fR : flat rooms ;
- ER : empty rooms ;
- UFR : uniformly fitted rooms ;
- NUFR : non uniformly fitted rooms.

Noise control measures :

- NRS : noise reduction at source (reduction of sound power) ;
- SD : displacement of sources in the room ;
- E : machine enclosures ;
- WL : absorbing lining on the total area of one or more room surfaces ;
- pWL : absorbing lining on parts of one or more room surfaces ;
- S : screen.

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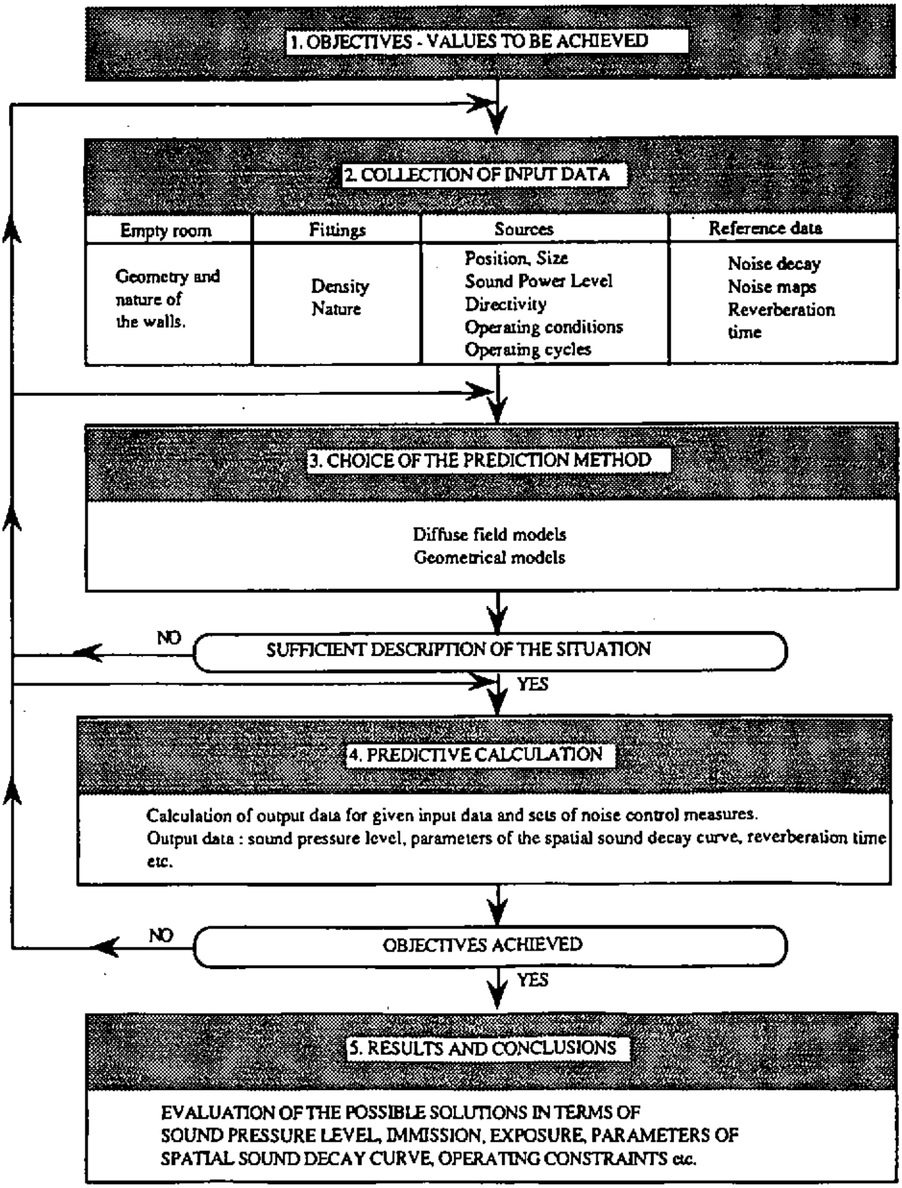


**Fig. 2 :** General INP methodology. Excerpt from the draft standard ISO 11690 - Part 3 (35).