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Topical Issue – Development of European Acoustics in 20th Century

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Acoustic activities at CSTB in the 20th century

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Abstract – This paper is about the history of the acoustic activities at CSTB, French Center for building Science and Technology. It is an improved and extended version of a paper presented in a structured session on the history of acoustic activities in Europe, at Forum Acusticum 2023 in Torino, Italy. The CSTB Acoustic Department was created in the 1960s around an acoustic test laboratory. From the beginning CSTB has been involved in improving acoustic performance for building occupants. It played an important role in technically supporting the French acoustic regulation (first one in 1968 and last one in 1995) and in developing solutions to reach mandatory building performances in cooperation with the industry. The acoustic department grew fast, mainly supported financially by the government (more than 60% of its budget at the beginning), thus becoming the largest acoustic team in France and worked on 3 main domains: room acoustics, environmental acoustics and building acoustics, in which physical models and calculation tools have been developed to bring science to construction. From the start, CSTB has been involved in standardization at French, European and International levels.

Keywords. Acoustics, Building acoustics, Environmental acoustics, Room acoustics

Foreword

This paper is about the history of the acoustic activities at CSTB, French Center for building Science and Technology. It is an improved and extended version of a paper [1] presented in a structured session on the history of acoustic activities in Europe at Forum Acusticum 2023 in Torino, Italy. The extended paper particularly identifies other centers (and their research domain), with whom CSTB has cooperated or from whom CSTB has got its knowledge, and gives the corresponding references.

1 The beginning

CSTB, French Center for Building Science and Technology, is created in Paris in 1947 to bring together construction specialists in order to draft building rules after the second world war. Jacques Brillouin, French acoustician [2], expresses the need to collect acoustic measurements in buildings and establishes a measurement team within CSTB.

In 1957, CSTB, headed by Gérard Blachère, decides to bring science into construction, and an acoustic division is created, headed by Robert Josse a telecommunication engineer; the acoustic division is associated with a human sciences division. The goal is to develop acoustic comfort rules, validated by the social sciences, predictable by calculation and controllable by measurements. Right at the beginning, R. Josse spends two weeks at T.U. Berlin to get some advanced knowledge in building acoustics from professor L. Cremer, head of the Acoustic Institute. Soon, the first rules regarding sound insulation in buildings are instituted.

1.1 National activities

In 1962, R. Josse publishes his first (small) book on building acoustics, followed by a second one [3], more developed, dealing particularly with environmental acoustics and building acoustics. These books are mainly dedicated to common residential buildings. R. Josse also publishes scientific work on sound transmission through walls [4], a wave-based calculation, which will lead to applications such as acoustical holography, many years later (see Sect. 2.2.6).

An acoustic performance evaluation laboratory for walls, floors and windows is built in Champs sur Marne (Paris area) while the acoustic team grows. A new laboratory method for characterizing water taps is then developed, standardized first in France and later at international level. Later, a temporary and unused building on

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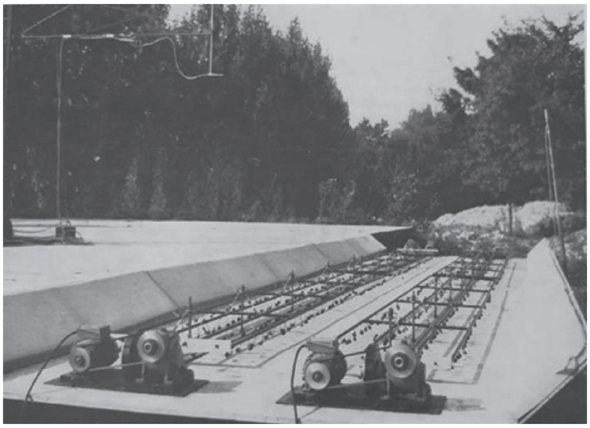


Figure 1. CSTB 1/20 scale model to study environmental sound propagation and the effects of screens.

the CSTB Champ sur Marne site, enabled the study of the effect of the angle of incidence on sound insulation for glazing and the presence of balconies.

In the mid-1960s, CSTB obtained governmental financial support for major development. New acoustic laboratories are built in Champs sur Marne, and a computing center is also created. The development plan involved an effort for research with new resources in personnel and equipment, a link with universities and the development of models, either scale models or calculation models based on physics (see Sect. 2).

The interest in environmental noise corresponds to a global concern linked to the rapid development of transport infrastructures and the associated traffic. In the mid-1960s, formulas for calculating sound propagation from a line of un-correlated sources are known, but considering the width of the line of sources is a research topic and the way of performing any calculation in general is still very limited (no computers!); usually, abacuses are used, set of hand-calculated curves, from which results of complex formulas can be read. Estimating diffraction at the edge of a screen by calculation is also solved using abacuses, first in the 1960s by considering a point source and propagation in a vertical section perpendicular to the screen [5]. First experimental validations are performed in Japan in an anechoic chamber on absorbing ground [6].

At the same time, a 1/20 scale model is built at CSTB to study environmental sound propagation and the effects of screens, where cat bells are used as sound sources to simulate the 500 and 1000 Hz octave bands on a scale model. The scale model (Fig. 1) is equipped with a motorized mast for microphone automatic movement, and air absorption corrections are considered, based on temperature and humidity readings. Measurements on the scale model led to a large collection of sound propagation abacuses.

That same year, a vast traffic noise measurement campaign [7] is undertaken in Paris and its suburbs (more than a hundred locations). Measurements are performed at 2 m from the building façades (Fig. 2) during 48 h, the sound levels being recorded in 5 dB increments on statistical counters and collected hour by hour on silver film to be converted into punched cards processed at the CSTB computer center. Traffic counts are associated with each measurement. The associated sociological survey covers a sample of 500 people living near the measurement points, leading to annoyance versus road noise curves. The field data measured also contributes to a better knowledge of the road traffic source powers and of sound propagation in U-shaped streets.

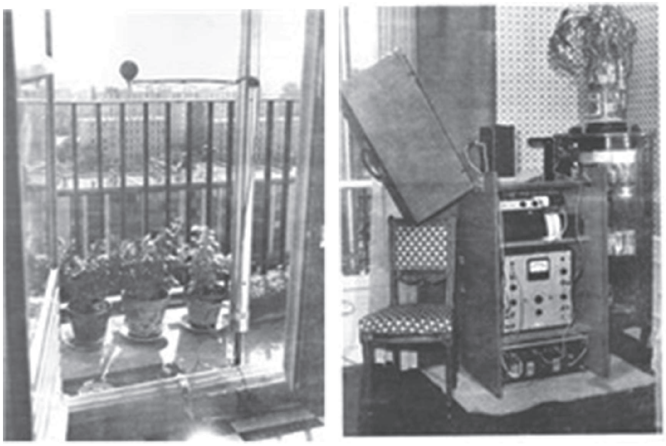


Figure 2. Traffic noise measurements: microphone location (left); measurement setup (right).

The knowledge of road traffic noise is soon complemented by that of railway noise. Measurements in open terrain use masts 30 m high and simultaneous recordings on (prototype) tape recorders. A photographic system makes it possible to assess the speed, type, and length of the trains [8].

The experience of traffic noise measurement campaigns associated with sociological surveys leads CSTB to subsequently participate in the standardization of a European questionnaire and allows a French validation of the L_{Aeq} index against noise annoyance with an excellent correlation.

1.2 International activities

International activities are developed early by Gerard Blachère who created the “Conseil international du bâtiment” (CIB), bringing together the research centers of the main European countries, North America, Brazil and the USSR. This council defines common research themes and promotes exchanges between laboratories. R. Josse leads an important action at international level to develop measurement methods and define acoustic descriptors and the associated vocabulary. Supported by sociological surveys, he pleads for generalizing the dB(A) in regulations with limits associated to a single number quantity. In 1968, a congress bringing together all the laboratories working in acoustics within the CIB is organized in Paris under the chairmanship of R. Josse. Two major subjects of the time are on the agenda: outdoor noise and floor impact sound.

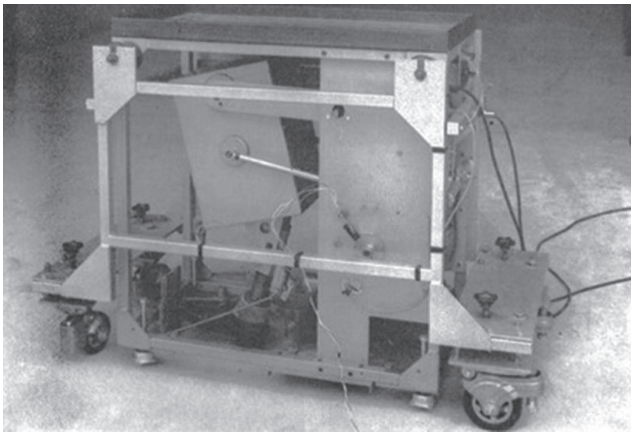


Figure 3. CSTB walking machine.

- The importance of outdoor noise is recognized. Results from the CSTB Paris measurement campaign (i) demonstrate the validity of the L_{10} index (level reached and exceeded 10 percent of the time), which is adopted in England by the British Research Establishment and (ii) confirm the validity of a new index (the equivalent sound level) validated in Vienna first and presented at the conference by Judith Lang.
- The work presented on impact noise includes research work on a reference source: a walking shoe for France (see Fig. 3) [9] and a tapping machine for Germany and the Netherlands, which is used afterwards at CSTB to develop the impact sound evaluation method and related descriptors. Note that the first description of a tapping machine is published in standard DIN 4110 [10] in 1938!

1.3 Concorde sonic boom

In 1969, Concorde aircraft flights are launched with the hope of flying at supersonic speed above inhabited zones. Many studies are then initiated to estimate people's reactions to the sonic boom emitted along Concorde trajectory, as well as to evaluate the possible disorders and damages on light constructions and old heritage buildings (churches with stained-glass windows in particular).

CSTB is requested to study these potential disorders and damages both theoretically, by estimating the overpressures generated inside the buildings, and experimentally by in situ measurements. Later, laboratory measurements on lightweight structural elements will be performed (Sect. 2).

An experimental house is built in Istres (close to Marseille) and subjected to Mystères 3 aircraft flyover events at different altitudes in supersonic flights (Fig. 4). The last tests, carried out with flights at 600 m altitude planned to be destructive, are effectively destructive. A paper synthesizing the different investigations carried out by CSTB is then published [11]. Flying over inhabited areas at supersonic speed is at the end prohibited.

Figure 4. Experimental house, subjected to supersonic flyover events.

Figure 5. CSTB acoustic leading team (from left to right: J. Roland, R. Josse, J.-P. Vian, J.-M. Rapin).

2 Development

In 1970, Robert Josse and 6 other acousticians move to Grenoble; the team quickly increased by 4 more people. The former acoustic division becomes the acoustic department, the testing laboratories still being in Champs sur Marne. Three other divisions are created in Grenoble, mainly for applied research in the three following domains: building acoustics (leader J. Roland), environmental acoustics (leader J.M. Rapin), and room acoustics (leader J.P. Vian). Figure 5 shows the leading team. New acoustic laboratories are constructed on the Grenoble site in 1973, mainly for research. All this corresponds to the CSTB research effort in developing models, either calculation models based on physics and/or scale models, which also allow the validation of calculation models. About 20 years later, R. Josse will retire and J. Roland become head of the acoustic department.

2.1 Environmental acoustics

2.1.1 Metrology

The first test facility build in Grenoble is a lightweight wall fatigue test bench, constructed to study the potential damages of sonic booms, using a huge piston (Fig. 6) to produce similar overpressure impulses (Sect. 1.3).

2.1.2 Scale modeling

Once the 1/20 scale model validated with the construction of the first sound barrier, a 1/100 scale model,

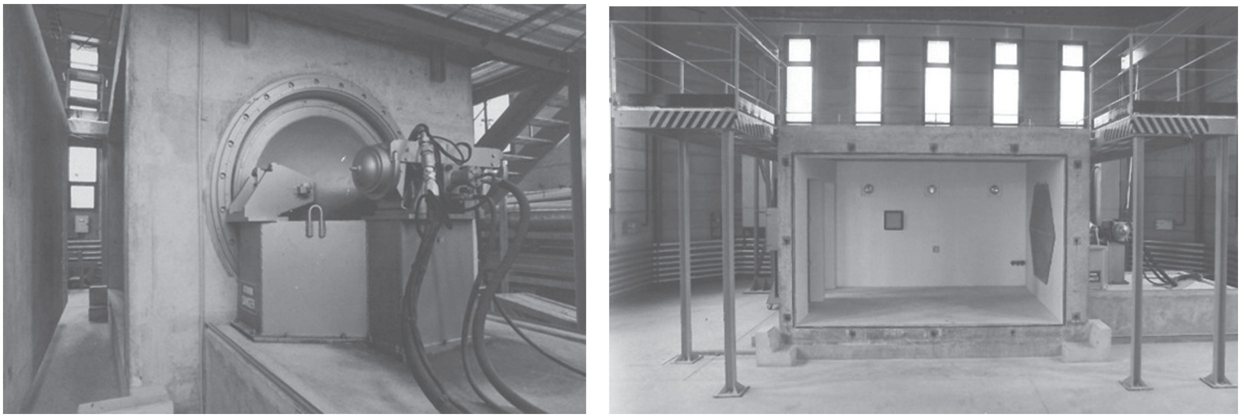


Figure 6. View of the sonic boom generator (left) and of the testing room of the fatigue test bench with lightweight wall removed (right).

suitable for urban planning, is considered technically possible with the condition of working in dehydrated air (3% humidity at 20°) in order to compensate for the growth of conventional absorption by reducing molecular absorption. Suitable microphones (1/8° inch) are not very sensitive and require powerful sources. Sources based on air jets are then developed. Inaugurated in 1975, the "Maquette" laboratory (Fig. 7, [12]), equipped with significant automation, is quickly monopolized by major transport infrastructure projects.

This new lab gives the opportunity to update the abacuses obtained using the former CSTB 1/20 scale model. Moreover, at that time, the West German Ministry of the Environment launches a project to compare prediction methods and in situ measurements; the German data are then successfully used to validate the CSTB new scale model measurement results, thus subsequently leading CSTB to work on German infrastructure projects.

2.1.3 Calculation models

In the early 1970s, calculation models for screens consider both ground sound absorption [13] and lines of uncorrelated sources – thus including oblique incidence [14]. Measurements in real scale in the UK is an opportunity for experimentally validating these models. Computers were still missing but cooperation between all the above cited institutions leads to useful experimentally validated prediction tools (abacuses and corresponding calculation methods).

In the late 1970s, when computers allow faster and more sophisticated calculations, all the necessary calculation methods are ready to be implemented in prediction algorithms [15] based on ray tracing (Mithra software), precursor of noise mapping current tools (Fig. 8). Later in the 1990s, this work will lead to an environmental acoustic simulation software (MithraSIG, co-developed by CSTB and GEOMOD), working from a GIS (ground information system).

The ray tracing approach will later be extended to electromagnetic waves; MithraREM software co-developed by CSTB allows simulating at city scale the electromagnetic field of antennas (mobile phones, radio, TV…).

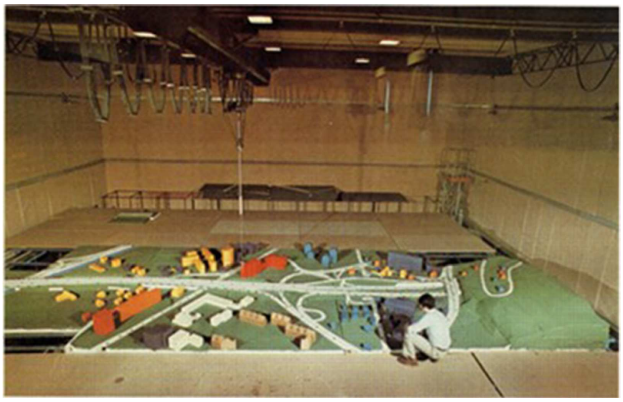


Figure 7. The "Maquette" laboratory for environmental noise evaluations in 1/100 scale models.

2.1.4 Use of finite element models

The optimization of road screens requires in the 1990s fine modeling of diffraction phenomena using finite elements [16]. From the beginning of the 1990s, all the finite element models required at CSTB, not only for environmental acoustics but also in building acoustics (Sect. 2.2), are home-developed by Philippe Jean, based on a Boundary Element Method and using an efficient variational formalism. The software MICADO is developed, first in 2D, thanks to the financial contribution of Europe (ERRI program), then in 2.5D (structures infinite in one direction) approach developed at the French Ecole Nationale des Ponts et Chaussées [17], lighter than in 3D and well suited to line sources. MICADO allows for example the study of screens at the edge of railway tracks, considering the acoustic interaction of the train with the screen (Fig. 9). The finite element models are also used as reference calculation methods to numerically validate the ray tracing models mentioned above.

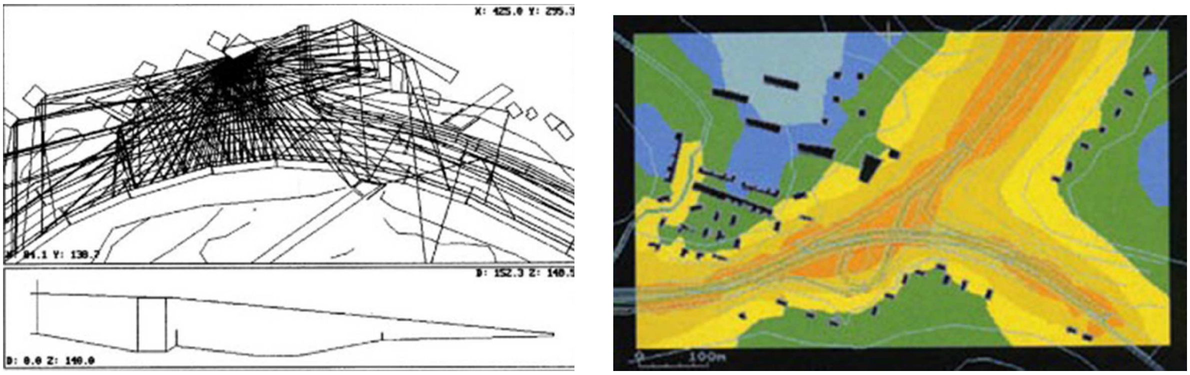


Figure 8. From ray tracing tool (left) to noise mapping (right).

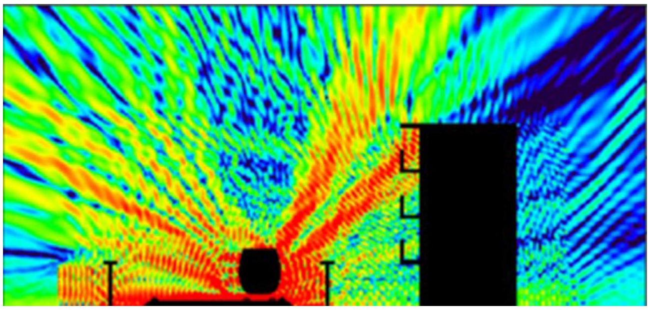


Figure 9. Acoustic field generated near a building by a railway track with screen.

2.1.5 *ACOUSTB subsidiary*

A significant number of operational studies are now performed not only at the CSTB "Maquette" laboratory, but also using the CSTB ray tracing calculation model, first used by CSTB only, but then marketed (MITHRA software) and used by other consultant companies. The contribution to operational work in order to feed research work is found essential but leads to two difficulties within CSTB: (i) the emergency associated with operational studies requires new skills from research teams and disorganizes them; (ii) the suspicion of using research funds to make commercial offers attractive, exists. For this reason, the CSTB management decides in 1995 to create a private acoustic subsidiary, with about fifteen people including part of the CSTB acoustics team staff. The ACOUSTB subsidiary is created in partnership with a large engineering company dealing with transport infrastructure. The synergy between research and operational investigations is then preserved through scientific assistance contracts. Furthermore, in the late 1980s, spin-off acoustic firms will be created by some of the CSTB staff.

2.1.6 *European projects and standardization*

In the late 1990s, the CSTB environmental acoustics division participates successively in two major European projects: HARMONOISE [18] (road and railway noise) and IMAGINE [19] (road, railway, industrial and aircraft noise), which allow harmonizing and improving methods for environmental noise prediction and assessment in Europe. These projects will lead later to a European common framework for noise assessment methods (CNOSSOS-EU), for the main sources of noise (road, railway, aircraft and industrial noise sources) to be applied for strategic noise mapping. Moreover, improvements to the 2012 CNOSSOS-EU method proposed by CSTB are accepted and integrated into the European Directive adopted in December 2020, which becomes the official European method starting in 2021; the method is integrated in the MithraSIG software.

2.2 Building acoustics

From the 1970s, CSTB decides to develop the modeling of acoustic and vibration phenomena (scale-models and calculation models) in order to understand and predict the acoustic performance of the building and its components. Different approaches, described below, are studied and used; some approaches and models are the subject of PhD work co-supervised by different universities and CSTB.

2.2.1 *Contribution to SEA*

Statistical Energy Analysis (SEA), developed in the early 1970s by Richard Lyon, USA MIT [20] makes it possible to estimate the sound and vibration energy of rooms and structural elements (walls, beams ...) in broadbands (one-third octave or octave bands), for a given sound or vibration random excitation. At first simple, this method requires, if used for prediction, a good physical knowledge of the couplings between structural elements or between structures and rooms; as a result, SEA is only mastered at the end of the 1990s, the physical knowledge coming in the 1970s from Germany, thanks to the English translation of Cremer and Heckl's book [21] and the mastering of random signals coming from the US [22].

CSTB adopts the method and works for many years to develop it; an operational prediction software (CATRAS software) is developed in the mid-1980s, considering the different types of waves in the building structures [23].

CATRAS is first used for the French Navy: (i) in the mid-1980s, in a study predicting the propagation of

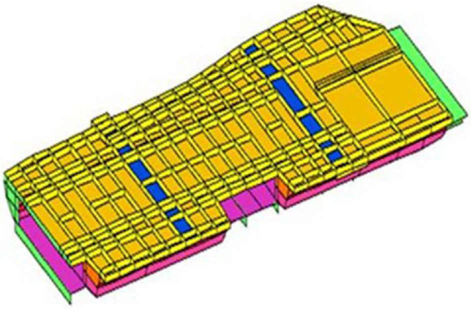


Figure 10. Example of modeled aircraft carrier structure.

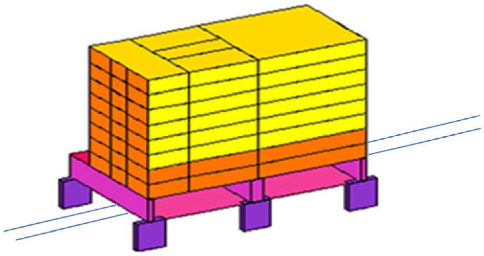


Figure 11. Building and supporting structure covering railway tracks near Gare d'Austerlitz (Parisian ATM project).

impact sound generated by aircraft catapults in the structure of aircraft carriers; an experimental validation of the model is performed on the French aircraft carrier Foch; (ii) at the end of the 1980s, in a study of structure-borne sound generated by a heeling compensation system (by mass displacement) in a new French aircraft carrier (Fig. 10).

The financial support brought by the contracts with the French Navy contributes to more R&D at CSTB in the domain of structure-borne sound transmission.

CATRAS is then mainly used for studying structure-borne sound transmissions in building structures; a typical application can be this Parisian project in the late 1990s, where railway tracks near Gare d'Austerlitz are covered with residential and office buildings (Fig. 11).

2.2.2 European standardization

In 1985, a new approach is formulated to support the CE marking of products and allows their free circulation in the different European Union countries. The method consists of drafting essential requirements in the form of directives to be transposed into national laws, while the technical specifications used to meet these requirements refer to harmonized European standards prepared by a European Committee for Standardization (CEN). The chairmanship of the building acoustic technical committee CEN/TC126 is attributed to France, and with one exception, held by CSTB.

Among the work of this commission, it should be mentioned the definition of single number quantities which gave rise to memorable clashes between the French approach (quantities in dB(A)) and the German tradition (w weighting), leading to a complicated index.

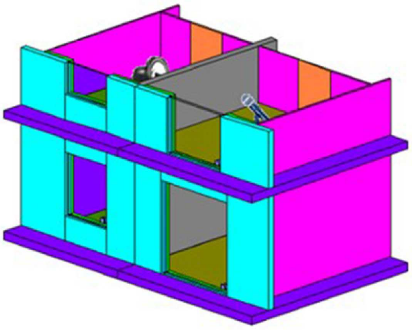


Figure 12. Geometry and building elements for horizontal sound transmission between rooms (ACOUBAT software).

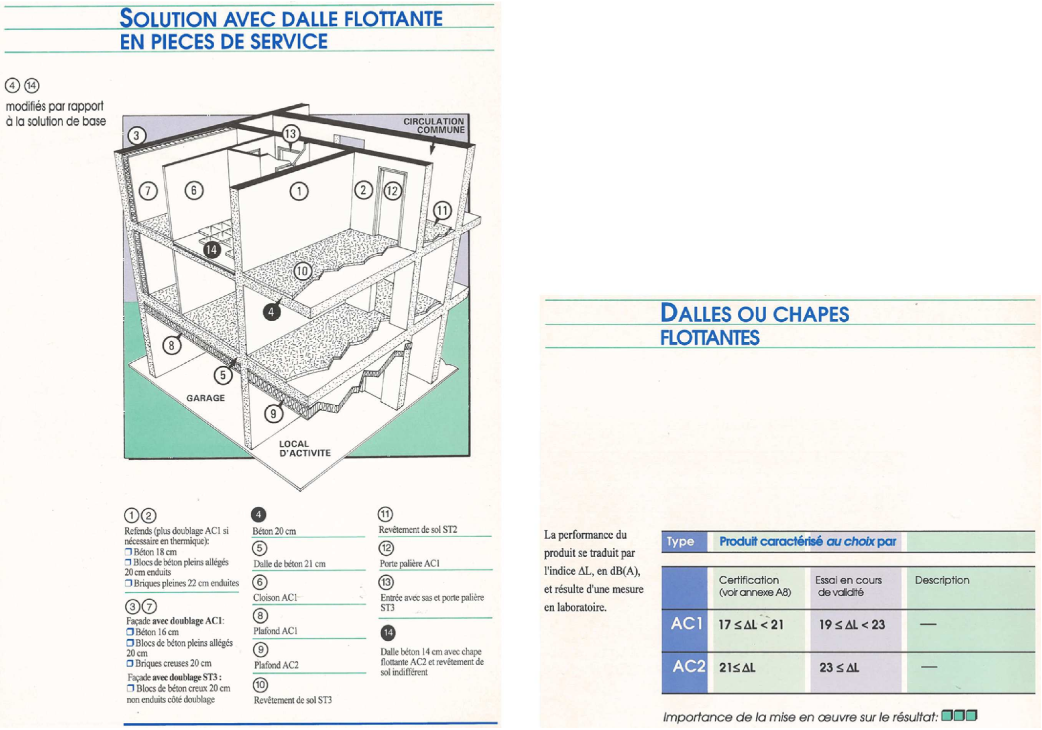
The SEA method, simplified in the early 1980s (TNO [24]) in its application to buildings and reduced to transmissions between neighboring rooms is discussed within CEN TC126 WG2 (led by TNO) from the 1990s with the active participation of CSTB, leading to the series of standards EN 12354 for predicting building acoustic performances from the performance of building components [25]. This standard series shows that working together at European level is very fruitful. Recent revisions consider low frequencies (down to 50 Hz), lightweight structures and structure-borne sound sources (building service equipment).

The above European standards are progressively implemented at CSTB in a software (ACOUBAT software, Fig. 12) distributed in France and reaching about 400 licenses in the 2000s. The ACOUBAT software is then also sold in Spain, once a specific database of Spanish building products is created.

2.2.3 The 1995 French acoustic regulation

Since the first French acoustic regulation in June 1969, the progress made in construction materials and techniques, in particular the use of lightweight structures and thermal insulation, requires both setting higher levels of requirements and reviewing the design guides to achieve them. In this context, CSTB becomes the main technical support for the ministry concerned, in the dialogue between manufacturers of construction products, social construction organizations, and the demand for quality by the inhabitants.

The appropriate design tools, already developed and made available, such as the ACOUBAT software (see above) are then used for acoustic predictions, which contributed to the development of a design guide "Exemples de Solutions Acoustiques" (ESA, i.e. Examples of Acoustic Solutions) for building according to the 1995 French acoustic regulations. The document presents building configurations for each regulatory section (for example impact noise) using products belonging to performance categories, as shown in Figure 13. The latest version of this acoustic design guide dates from 2014 [26].



SOLUTION AVEC DALLE FLOTTANTE EN PIECES DE SERVICE

④ ⓮
modifiés par rapport
à la solution de base

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Refends (plus doublage AC1 si nécessaire en thermique):
☐ Béton 18 cm
☐ Blocs de béton pleins allégés 20 cm enduits
☐ Briques pleines 22 cm enduites

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Façade **avec doublage AC1**:
☐ Béton 16 cm
☐ Blocs de béton pleins allégés 20 cm
☐ Briques creuses 20 cm
Façade **avec doublage ST3 :**
☐ Blocs de béton creux 20 cm non enduits côté doublage

❹
Béton 20 cm

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Dalle de béton 21 cm

⑥
Cloison AC1

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Plafond AC1

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Plafond AC2

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Revêtement de sol ST3

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Revêtement de sol ST2

⑫
Porte palière AC1

⑬
Entrée avec sas et porte palière ST3

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Dalle béton 14 cm avec chape flottante AC2 et revêtement de sol indifférent

DALLES OU CHAPES FLOTTANTES

La performance du produit se traduit par l'indice ΔL, en dB(A), et résulte d'une mesure en laboratoire.

Type	Produit caractérisé *au choix* par		
	Certification (voir annexe A8)	Essai en cours de validité	Description
AC1	17 ≤ ΔL < 21	19 ≤ ΔL < 23	—
AC2	21≤ ΔL	23 ≤ ΔL	—

Importance de la mise en œuvre sur le résultat: 🟩🟩🟩

Figure 13. Design guide "Exemples de Solutions Acoustiques" (1995 first version): solutions with floating slab in service rooms (left) and corresponding performance categories (right).

2.2.4 Modeling multilayered building elements

The increasingly frequent use of double-glazing, double-walls and light multi-layer walls requires at the beginning of the 1990s the development of multi-layer physical models to better understand and optimize the products. The book by F. Fahy on sound and structural vibration [27] then greatly helps understand structure-borne sound radiation. First a modal approach, quite heavy, is used to simulate sound transmission through a building element between two rooms [28]; then a simpler wave approach, in which calculations are carried out wave by wave for a given frequency in the wavenumber domain and the method applied to layers of infinite surface, the element finite dimension being approximated by spatially windowing (rectangular aperture) the transmitted acoustic field [29].

Originally developed to model the performance of elements in airborne sound transmission, the wave approach is extended to mechanical excitation in the early 2000s [30]. The corresponding calculation software is marketed in 2010 (ACOUSYS software).

2.2.5 Use of finite element (FEM/BEM) models

The ability of the home-developed numerical models to deal with multi-domain and multi-approach problems, makes possible to couple for example a BEM model of the sound field exciting a façade with balconies to a modal approach representing the window and room behind. Moreover, the need to know in the 1990s vibrational soil-structure interaction (at building foundations in particular) to study and predict the transmission of railway vibration from ground to buildings (Fig. 14), leads to developing a numerical model (MEFISSTO software, [31] from the work of the French Laboratoire Central des Ponts et Chaussées [32] and others; the French Agency for Environment (ADEME) financially helps for this development. Like MICADO (Sect. 2.1.4), the software is later developed in 2.5D [33].

Figure 14. Ground vibration field generated near a building by a railway track on ground surface.

2.2.6 Metrology

In the 1970s, CSTB works on developing a new method for sound insulation measurements [34]; the method is based on using pistol shots as sound source, thus fast and cheap compared to using stationary signals and loudspeakers. And, like many other European centers, CSTB is interested in the acoustic intensity technique during the 1980s, applies it to building acoustics

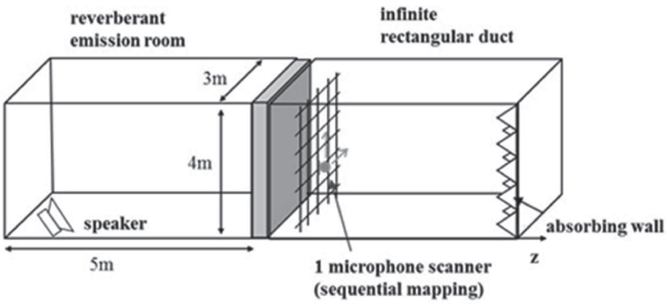

Figure 15. Schematic drawing of the CSTB Acoustical holography test bench.

Figure 16. CSTB Acoustic test laboratory (LABE); moving (therefore slightly blurred) room in red; fixed rooms behind.

and actively participates in conferences on this subject [35]. A few years later, CSTB learns about acoustic imaging and acoustical holography [36], a technique based on wave analysis of sound pressure measurement surfaces, using FFT algorithms in the space domain. The CSTB original application of holography to enclosed spaces [37] leads to the construction of a measuring test bench on the Grenoble site (Fig. 15), which allows to get not only the acoustic field transmitted by a wall but also the vibration field of this wall and the resulting sound power radiated. Moreover, the decomposition of the wall vibration field into plane waves for a given frequency makes it possible to show the isotropy (or orthotropy) of this wall.

2.3 New laboratory (CSTB site in Champs-sur-Marne)

In the 1990s, the demand from manufacturers to test construction elements grew rapidly due to the emergence of new products: lightweight structures, thermal-acoustic insulation, floor coverings on resilient layers, windows intended for noisy areas… A new laboratory is designed and built to meet this demand. The problems of the time consuming construction of the elements to be tested and drying (case of concrete elements), which can stop the activity for up to one month, is solved by designing transmission test chambers with a fixed noise reception room and a mobile noise emission room. The mobile room can be moved apart to make space for a frame in which the tested element is previously built in a different laboratory zone. This laboratory, called “Laboratoire Acoustique du Bâtiment Européen” (LABE), is operational in 1998, with six testing stations, including three equipped with mobile rooms (Fig. 16). More than a thousand tests are carried out each year on building elements.

2.4 Room acoustics

The skills acquired at CSTB in the 1970s and 1980s regarding scale models as well as computer modeling (ray tracing) find an outcome in room acoustics. Part of the room acoustics knowledge comes once again from Germany [38]. One of the most prestigious applications is undoubtedly the design of the great hall of the Opéra Bastille in Paris, performed in collaboration with the Germans: architect Carlos Ott, acoustic design Helmut Müller, Müller BBM Germany, and Jean Paul Vian CSTB. The EPIDAURE software [39], developed at CSTB, helps in designing the acoustics of the opera house (Fig. 17).

This tool deals with plane facets and point sources using cone-shaped beam tracing method derived from ray tracing. The cone-shaped tracing method proposed by van Maercke [40] is an efficient algorithm allowing to find all the image sources up to a high order; each beam is represented by a single ray standing for the cone axis and one scalar value corresponding to the top angle of the cone. The challenge related to overlapping cone-shape beams is then handled by weighting the contributions of the different rays falling inside the cone (normal distribution). EPIDAURE is soon marketed, CSTB becoming at the time the first company in the world to put a software based on geometrical acoustics on the market.

At the same time, the geometry of the Opéra Bastille is experimentally tested at CSTB on a 1/20 scale model to meet the request of a “popular” opera house, where each of the 2700 seats must be acoustically good (Fig. 18).

Later, EPIDAURE leads to EBINAUR, a software which includes diffusion. EBINAUR is dedicated to auralization of closed volumes such as concert halls, but also introduces new fields of applications such as car cabin acoustics. Finally in the 2000s, ICARE replaces EBINAUR with a totally new solver. ICARE is a sound pressure prediction tool based on an adaptative hybrid ray-beam (for early reflections) as well as particle tracing method (diffuse field and late reflections). It considers all types of facets (planes and curves, [41]), reflection and diffraction in an indoor or outdoor environment, as well as moving sources. The geometric solver being totally independent from its acoustics counterpart, it can be used for other physical quantities, such as electromagnetic fields.

A prestigious application of ICARE is the study of the acoustics of the National Centre for the Performing Arts in Beijing: Architect Paul Andreu, with J.-P. Vian from CSTB as the acoustician (J.-P. Vian will die in May 2006 before the NCPA completion).

In the 1990s, CSTB is also concerned with improving the natural acoustics of concert halls without requiring

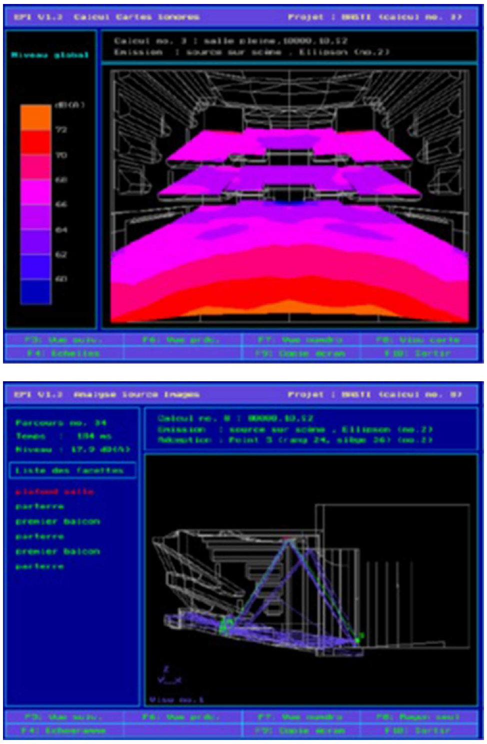

Figure 17. EPIDAURE modeling of the Opera Bastille, Paris.

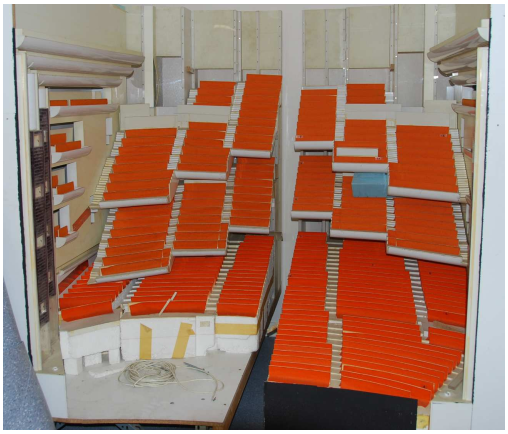

Figure 18. 1/20 scale model of the Opera Bastille, Paris.

any architectural modifications (materials or geometry). The electroacoustic "CARMEN" system is then developed to control reverberation time, based on active control of the walls. Active cells composed of a microphone and a loudspeaker, hidden in the room's walls and ceiling, capture, control and feed back sound in real time, as if naturally reflected by the walls [42]. The Carmen system is installed in several concert halls in France and abroad.

3 Concluding remarks

Nowadays, the CSTB acoustic R&D activities continue, but have decreased in relation to a very limited government financial contribution compared to the 1970s, and the dominant concerns about thermal and energy related problems in buildings; accordingly, the team has been reduced in size. Building acoustic is now often part of more global projects involving safety, health and comfort.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

No new data were created or analysed in this study.

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