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ACOUSTIC ACTIVITIES AT CSTB IN THE 20th CENTURY AND BEYOND

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ABSTRACT

The Acoustic Department was created in the sixties 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 becoming the largest acoustic team in France and worked on 3 main domains : room acoustics, environmental acoustics and building acoustics, in which modelling approaches and calculation tools have been developed.
Work was mainly supported financially by the government (more than 60% of its budget at the beginning).
From the start, CSTB has been involved in standardization at French, European and International levels. The CSTB new European laboratory, LABE, built in the late 90s, proposed a new and faster way to test building components.
Since, the government financial contribution has decreased (from more than 60% to less than 20% of CSTB budget), and furthermore, due to the increased awareness of climate change, the thermal and energy related aspects for buildings have become dominant, shading acoustic research activities.

Keywords: *building acoustics, environmental acoustics, room acoustics, modelling, measurements, research center.*

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1. THE BEGINING

The Center for Building Science and Technology (CSTB) was 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 [1], expresses the need to collect acoustic measurements in buildings and establishes a measurement team within CSTB.
In 1957, the CSTB, headed by Gérard Blachère, decides to bring science into construction, and an acoustic division is created, headed by Robert Josse, a telecommunication engineer, 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. 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 [2], followed by a second one [3], more developed, dealing particularly with environmental acoustics and building acoustics. These books are mainly dedicated to common building. R. Josse also publishes scientific work on sound transmission through walls [4].
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 faucets is then developed, standardized first in France and later at international level. Later on, a temporary building present in Champ sur Marne enabled the study of the effect of the angle of incidence on the sound insulation of different glazings and the effect of balconies.
In the mid-60s, CSTB obtained 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 a research effort 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 Section 2).
The interest in environmental noise corresponds to a global concern linked to the rapid development of transport infrastructure and the associated traffic. A 1/20° scale model chamber is then 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 chamber was equipped with a motorized mast for microphone automatic movement, air absorption corrections were taken into account on the basis of temperature and humidity readings. A large collection of propagation abacus and traffic power laws were created to constitute a forecasting method while a theoretical work exploited the results for a numerical model. That same year, a vast traffic noise measurement campaign [5] was undertaken in Paris and its suburbs (more than a hundred locations). Measurements were performed 2 m from the building façades (see Figure 1) during 48 hours, 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 were associated with each measurement.

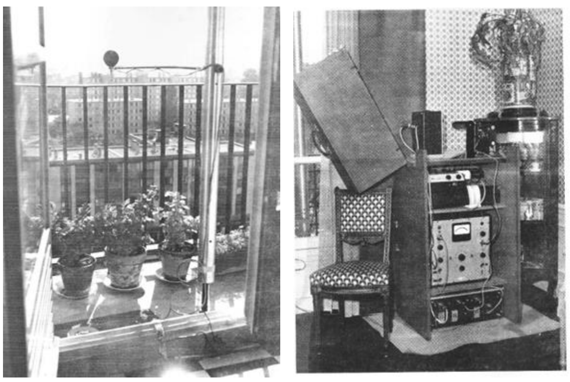

Figure 1. Traffic noise measurements.

The associated sociological survey covered a sample of 500 people living near the measurement points. The study led to annoyance versus road noise curves.
The knowledge of road traffic noise was complemented by that of railway noise. The measurements in open terrain used masts 30 m high and simultaneous recordings on prototype tape recorders. A photographic system made it possible to assess the speed, type and length of the trains [6].
The experience of traffic noise measurement campaigns associated with sociological surveys led CSTB to subsequently participate in the standardization of a European questionnaire. The L_{Aeq} index was again validated against noise annoyance with an excellent correlation.

1.2 International activities

International activities were 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 exchanges between laboratories.
R. Josse then leads an important action at the international level to develop measurement methods and define acoustic descriptors and the associated vocabulary. Supported by sociological surveys, he pled for generalizing the dB(A) use in regulations with limits associated to a single number quantity. In 1968, a congress bringing together all the acoustic laboratories working within the CIB was organized in Paris under the chairmanship of R. Josse. Two major subjects of the time were on the agenda: outdoor noise and floor impact sound.

- The importance and topicality of the outdoor noise subject were recognized. Results from the CSTB Paris demonstrated the validity of the L_{10} (level reached and exceeded 10 percent of the time), which was adopted in England by the BRE. Judith Lang (Austria) presented the results of a Vienna survey validating a new index: the equivalent sound level, which was then used by CSTB in its own measuring campaigns and validated.
- The work presented on impact noise included research work on a reference source: a walking shoe for France (see Figure 2) [7] and a tapping machine for Germany and the Netherlands, which was used afterwards at CSTB to develop the impact sound evaluation method and related descriptors. Note that the first description of a tapping machine was already included in 1938 in DIN 4110.

1.3 Concorde sonic boom investigations

In 1969, Concorde aircraft flights were launched with the hope of exploiting it at supersonic speed above inhabited zones. Many studies were then initiated to estimate the reactions of the populations flown over, to the sonic bang emitted throughout its trajectory, as well as to evaluate the possible disorders and damages on light constructions and

old heritage buildings.
CSTB was 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 on (see section 2), measurements on structural elements were performed in laboratory.
An experimental house was built in Istres (close to Marseille) and subjected to Mystère IV military jets passages at different altitudes in supersonic flight (see Figure 3). The last tests were carried out with flights at 600 m altitude, planned to be destructive, which was actually verified. Furthermore, cathedral stained glass windows subjected to supersonic flights of military jets were equipped with vibration sensors. A paper synthesized the different investigations carried out on this subject [8].
The overflight of inhabited areas at supersonic speed was then prohibited.

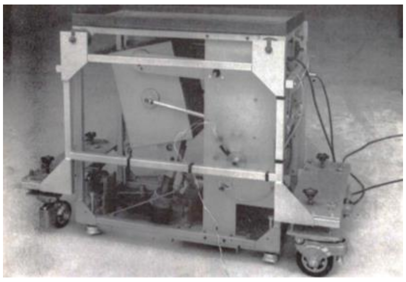

Figure 2. CSTB walking machine.

Figure 3. Experimental house subjected to aircraft passages in supersonic flight.

2. DEVELOPMENT

In 1970, Robert Josse accompanied by 6 other acousticians moved to Grenoble; the team quickly increased by 4 more persons. The acoustic division became the acoustic department, the testing laboratories still being in Champs sur Marne and three other divisions were created in Grenoble, mainly for applied research in the three domains: building acoustics, environmental acoustics and room acoustics. New acoustic laboratories were constructed on the Grenoble site in 1973, mainly for research. All this corresponded to the CSTB research effort in developing models, either calculation models based on physics and/or scale models, which also allowed validating calculation models.

2.1 Environmental acoustics

2.1.1 Metrology

The first test facilities build in Grenoble was a lightweight ceiling fatigue test bench, build to study the potential damages of sonic booms, using a huge piston to produce the necessary overpressure impulse (see section 1.3).

2.1.2 Scale modelling

Since the 1/20 scale model had been validated with the construction of the first sound barrier, a 1/100 scale model, suitable for urban planning, was considered technically possible on 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) were not very sensitive and required powerful sources. Sources based on air jets were developed. Inaugurated in 1975, the “maquette” laboratory (see Figure 4, [9]), equipped with significant automation, was quickly monopolized by major transport infrastructure projects.

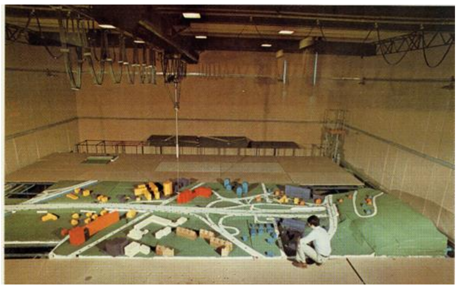

Figure 4. the “Maquette” laboratory for environmental noise evaluation.

It should be noted that the West German Ministry of the Environment launched then a project to compare prediction methods and in situ measurements. The predictions by the CSTB scale model were validated, which subsequently led to work on German infrastructure projects.

2.1.3 Calculation models

At the same time, prediction algorithms [10] based on ray tracing, precursor of noise mapping current tools, were developed, a constant comparison between in situ measurements, scale-modeling and calculation models allowing a permanent improvement of the calculation models (see Figure 5). This work leaded to an acoustic simulation software based on a GIS, MithraSIG, co-developed by CSTB and GEOMOD.

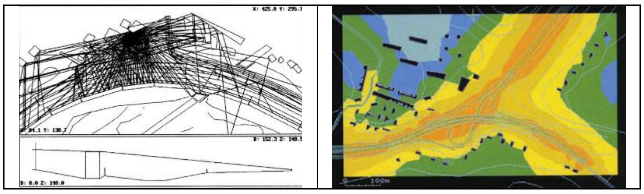

Figure 5. Ray tracing tool toward noise mapping.

An extension of the ray tracing approach was dedicated to electromagnetism ; MithraREM software co-developed by CSTB allows simulating at city scale electromagnetic fields of antennas (mobile, telephony, radio, TV…).
Furthermore, the ray acoustic solver ICARE from CSTB is integrated to Siemens Simcenter simulation and testing solutions. ICARE allows simulation of acoustic propagation in complex 3D environments.

2.1.4 Use of finite/boundary element models

The optimization of road screens required in the 90s the fine modeling of diffraction phenomena using boundary elements [11]. A software has been developed internally (MICADO software). This approach allowed in particular the study of screens at the edge of railway tracks taking into account the acoustic interaction of the train with the screen (Figure 6).

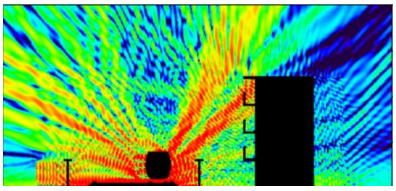

Figure 6. Acoustic field generated near a building by a railway track with screen.

2.1.5 Creation of "ACOUSTB" subsidiary in 1995

A significant number of operational studies were 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 of operational work in order to feed research work was found essential but led to two difficulties within CSTB structure: (i) the urgency associated with operational studies required skills from research teams disorganizing them; (ii), the suspicion of using research funds to make attractive commercial offers existed.
For this reason, the CSTB management decided in 1995 to create a private acoustic subsidiary, with about fifteen persons including part of the staff of the CSTB acoustics team. The ACOUSTB subsidiary was established in partnership with a large engineering company in transport infrastructure. The synergy between research and operational investigations was then preserved through scientific assistance contracts.
Furthermore, in the late 80s, spin-off acoustic firms were started by some of CSTB personnel.

2.2 Building acoustics

From the 1970s, CSTB decided 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, have been studied and used. Some approaches and models have been the subject of PhD work supervised by different universities.

2.2.1 The SEA contribution

This method, developed in the early 1970s by Richard Lyon, USA MIT, makes it possible to estimate the sound and vibration energy of rooms and structural elements (walls, beams …) in broadbands (1/3 octave or octave), for a given sound or vibration excitation. At first simple, this method requires a good physical knowledge of the couplings between structural elements or between structures and rooms, and was only mastered at the end of the 90s.
CSTB adopted the method and worked for many years to develop it; an operational software (CATRAS software) was developed in the mid-1980s, taking into account the different types of waves in structures [12]. CATRAS has been used for studying the propagation of structural noise in assemblies of structures (see Figure 7), and in particular in a Parisian project where the railway tracks near Gare d'Austerlitz were covered with residential and office buildings (late 90s).
CATRAS was also used for the French Navy: (i) in the mid-1980s, in a study of the propagation of impact noise generated by aircraft catapults in the structure of aircraft carriers, with experimental validation on the aircraft carrier Foch, then (ii) at the end of the 1980s, in a study of the structural noise generated by a heel compensation system (by mass displacement) of an aircraft carrier (see Figure 8).

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

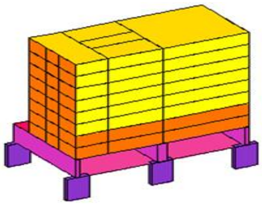

Figure 7. Building and covering structure for railway tracks (Parisian ATM project).

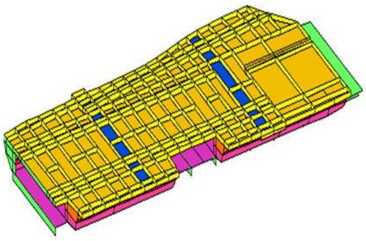

Figure 8. Example of modeled aircraft carrier structure.

2.2.2 European standardization (of SEA in particular)

In 1985, a new approach was formulated to support the CE marking of products and allow their free circulation in the different European union countries. The method consisted of drafting essential requirements in the form of directives to be transposed into national law, 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 was attributed to France, and with one exception, ensured 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 and the German tradition, ending with the adoption of a complicated index.
The SEA model, simplified in the early 1980s (TNO [13]) in its building application and reduced to transmissions between neighboring rooms was discussed within CEN TC126 from the 90s with the active participation of CSTB and led to the EN 12354 series for predicting building acoustic performance from the building components. This standard series shows that working together at European level has been very fruitful. Recent revisions take into account low frequencies (down to 50 Hz), lightweight structures and structural noise sources (building service equipment).
The above European standards have been progressively implemented at CSTB in the ACOUBAT software (see Figure 9); in France, the ACOUBAT distribution reached about 400 licenses in the 2000s. It should be noted that the ACOUBAT software was also sold in Spain and used, once a specific database of Spanish building products was created in the software.

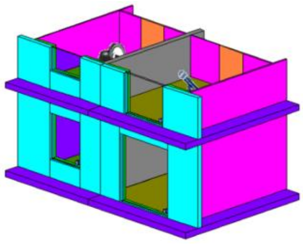

Figure 9. Example of horizontal noise transmission configuration between rooms (ACOUBAT software).

2.2.3 CSTB design tools and solutions for the French acoustic regulation in 1995

The French acoustic regulations concerning new housing dated from June 1969. The progress made in construction materials and techniques, in particular the use of lightweight structures and thermal insulation, required both setting the level of new requirements and review the design guides to achieve them. In this context, CSTB played the role of 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.
Appropriate design tools had been developed in the 80s and made available, such as the ACOUBAT software (see above). ACOUBAT was used for the acoustic predictions, which contributed to the development of examples of acoustic solutions (ESA) satisfying the 1995 French acoustic regulations. The document presents building configurations for each regulatory section (for example impact noise) using products belonging to performance classes (Figure 10).

2.2.4 Modelling multilayered building elements

The increasingly frequent use of double-glazing, double-walls and light multi-layer walls required, for their optimization, the development of multi-layer physical models at the beginning of the 90s, first with the modal approach, quite heavy, then with a simpler wave approach:

the calculations are carried out wave by wave, for a given frequency, in the wavenumber domain and the method is applied to layers of infinite surface, the finite dimension effects of the element being approximated by rectangular spatial windowing of the acoustic waves radiated on the reception side [14]. Originally developed to model the performance of elements in airborne transmission, the wave approach was then extended to impact noise transmission performance in the early 2000s [15]. The calculation software was marketed in 2010 (ACOUSYS software).

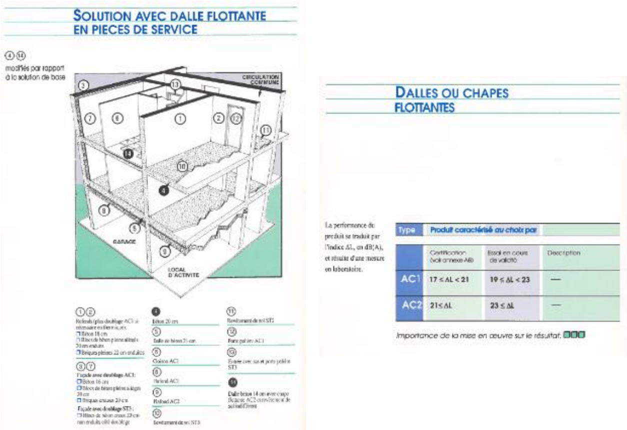

Figure 10. Examples of Acoustic Solutions (1995): solution with floating slab in service rooms and associated classes.

2.2.5 Finite element (FEM / BEM) contribution

In the 90s, the need to know the vibrational soil-structure interaction (at the level of building foundations in particular) to study and predict the transmission of railway vibrations from the ground to buildings, led to the development of a numerical model. [16]. First in 2D, the model was developed in 2.5 D (structures infinite in one direction), thus lighter than in 3D and well suited to line sources [17]. This software makes it possible to obtain maps of vibratory fields (Figure 11). The software was marketed in the mid-2000s (MEFISSTO software).

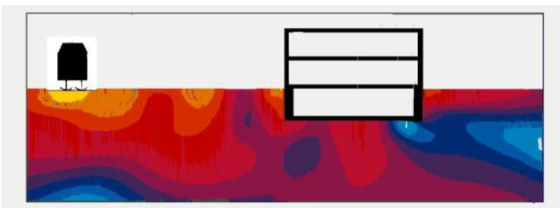

Figure 11. Ground vibration levels by trains.

2.2.6 Metrology

In the 70s, CSTB worked on developing a new method for sound insulation measurements [18]; the method was based on using pistol shots as the sound source, and had the advantages of speed and economy in comparison with classical measurements.
Like many European centers, CSTB gained knowledge on acoustic intensity during the 1980s and used this technique in particular in building acoustics [19]. A few years later, CSTB became interested in acoustic imaging and acoustic holography [20], a technique allowing the visualization not only of the acoustic field emitted by a wall but also of the vibratory field of this wall and the resulting sound power. A measuring testing bench was built on the Grenoble site (Figure 12). The decomposition of the sound field into plane waves for a given frequency makes it possible to visualize the isotropy (or orthotropy) of building walls.

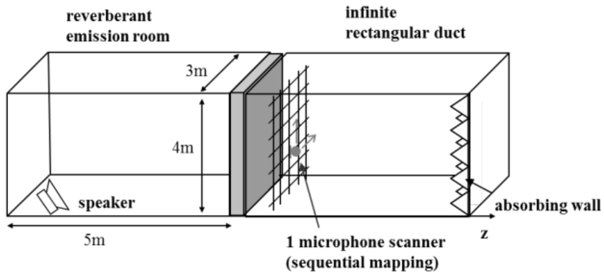

Figure 12. Acoustic holography test bench built at CSTB.

2.3 Room acoustics

The skills acquired at CSTB regarding scale models as well as computer modeling found an outcome in room acoustics. One of the most prestigious applications was undoubtedly the design of the great hall of the Opéra Bastille (architect Carlos Ott, acoustic design Helmut Mùller, Mùller BBM and Jean Paul Vian CSTB). A 1/20 scale model made it possible to draw the geometry of the hall to meet the request of a “popular” opera house where each of the 2700 seats had to have good acoustics (see Figure 13).
The ICARE software, successor of CSTB Epidaure software [21] based on ray tracing has been used for the study of the acoustics of the Beijing Opera (Architect Paul Andreu, with J.-P.Vian from CSTB as the acoustician at the start of the project). In order to satisfy both the architect and the acoustician, the visual shape of the room and its acoustic geometry have been decoupled by the use of a metallic mesh curtain, opaque for the eyes but transparent to the acoustic waves.

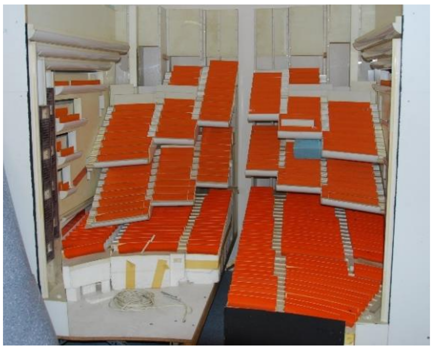

Figure 13. CSTB scale model of Opéra Bastille.

In the 90s, the CSTB acousticians were also concerned with improving the natural acoustics of concert halls without requiring any architectural modifications (materials or geometry). They developed the electroacoustic “Carmen” system to control the reverberation time. Consisting of active cells composed of a microphone and a loudspeaker, and hidden in the room's walls and ceiling, sound is captured and replicated in real time, as if naturally reflected by the walls [22]. The Carmen system has been installed in several concert halls in France and abroad.

2.4 Commissioning of a large innovative acoustic measurement laboratory 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 a resilient underlay, windows intended for noisy areas... A new laboratory was therefore designed and built to meet this demand. One of the problems encountered by traditional laboratories is that the construction of the tested element, and the drying in the case of concrete elements, for example, neutralizes a test station for a period which can go up to one month, seriously limiting the number of tests that can be carried out. Hence, the idea of designing transmission test chambers with a fixed noise reception room and a mobile noise emission room that can move apart to make space for a frame in which the tested element had been previously built in a different laboratory zone. This laboratory, called "Laboratoire Acoustique du Bâtiment Européen", LABE, which was inaugurated in July 1998, has six testing stations, three of which are equipped with mobile rooms, one dedicated to lateral transmissions, a reverberation room for sound absorption and acoustic power measurements as well as a station dedicated to measuring the hydraulic components (see Figure 14). More than a thousand tests are carried out each year on building elements.

Figure 14. CSTB acoustic laboratory, LABE.

3. NOWADAYS

Concerning environmental acoustics, CSTB has participated to important European projects, Harmonoise and Imagine, that allowed improved methods for noise assessment in the environment. Finally, a common framework for noise assessment methods (CNOSSOS-EU) from the main sources of noise (road traffic, railway traffic, aircraft and industrial), was developed to be applied for strategic noise mapping. In 2020, CSTB proposed improvements to the 2012 CNOSSOS-EU method; this new method was integrated into the modification of the Annex II of the European Directive which was adopted in December 2020, becoming the official method starting in 2021; it has been integrated in the MithraSIG software. Furthermore, much work has been dedicated to sound models simulating urban noise through auralization (MithraSound software). Indeed, such tools are essential for assessing the sound impact of a development project by listening to a simulation.

Concerning buildings acoustics, lightweight buildings have been a major subject in the past two decades, at the French and European level, especially due to promotion of carbon storing renewable materials. The use of biobased and geobased materials in buildings has also been investigated. CSTB also remains dedicated to improve and optimize products for industrial partners, in terms of acoustics but also with a broader analysis. Indeed, multidisciplinary projects have become more and more common, such as coupling acoustic and thermal renovation, global comfort approach, etc…The CSTB participation in the RIVAS European project allowed more activities in railway induced vibration and structure-borne noise in buildings, subject of a soon coming regulation in France.

Concerning room acoustics, a new system dedicated to the acoustic variability of small and medium-sized venues has been developed : CarmenCita.

The acoustic activities still continue, in spite of limited government financial contribution compared to the 70s, also related to the now dominant concerns about thermal and energy related problems in buildings. CSTB has been switching towards research partnerships with major focus for developing and supporting innovation and improving usability, while tackling the socio-economic challenges of safety, health and comfort and the environment and energy, as they apply to buildings, neighborhoods, and cities.

4. ACKNOWLEDGMENTS

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