SOUND FIELD MEASUREMENTS INSIDE A REVERBERANT ROOM BY MEANS OF A NEW 3D METHOD AND COMPARISON WITH FEM MODEL

P. Guidorzi\textsuperscript{a}, F. Pompoli\textsuperscript{b}, P. Bonfiglio\textsuperscript{b}, M. Garai\textsuperscript{a}

\textsuperscript{a}Department of Industrial Engineering (DIN), Viale Risorgimento 2, 40136 Bologna, Italy
\textsuperscript{b}Department of Engineering, Via Saragat 1, 44122 Ferrara, Italy
INTRODUCTION

3D MAPPING FOR ACOUSTIC RESEARCH

- Many different types of **acoustic parameters** and quantities are measured every day by acoustics technicians and researchers

- In many cases, **the position** in which these measurements have been carried out has a **strict meaning in relation to the measurement itself**, for example the measurement of the reverberation time or the analysis of the resonance modes inside a closed space

- In these cases it could be **very useful to know**, with a good degree of accuracy, **the microphone position in the three-dimensional measurement** space, in addition to the specific measured data

- An innovative **three-dimensional positioning system**, based on **acoustic waves**, has been developed and is presented here
INTRODUCTION

3D MAPPING FOR ACOUSTIC RESEARCH

- The system, described in this work, has **low costs** and **good precision**

- Requirements:
  - personal computer
  - multi-channel sound card
  - 4 amplified loudspeakers
  - 1 microphone
PRINCIPLE OF OPERATION

The determination of the position in the 3D space of a target, in principle, is reduced to the measurement of its distance from some other known points.

Let’s start with **2D trilateration** problem:

Problem: find 2D position of **yellow point**

- knowing only the distance of the **target** from “1”, possible solutions are on the **black circumference**

- knowing the distance of the **target** from “1” and “2”, 2 possible solutions: on the 2 crossing points of the black and blue circumferences

- knowing the distance of the **target** from “1”, “2” and “3”, only **one solution** is found, crossing points of black, blue and red circumferences
3D trilateration problem:

Problem: find 3D position in space
Positions of 1, 2, 3, 4 are known

- knowing only the distance of the target from “1”, possible solutions are on the black sphere

- knowing the distance of the target from “1” and “2”, possible solutions are on the circumference intersection of sphere 1 and sphere 2

- knowing the distance of the target from “1”, “2” and “3”, two possible solutions are found (intersection of 3 spheres)

- knowing the distance of the target from “1”, “2”, “3” and “4”, only one possible solution is found: the position of the target is found uniquely
PRINCIPLE OF OPERATION

- The presented system measures the distance between a single microphone and 4 loudspeakers, positioned on a grid of known dimension and position, which fixes the origin of the reference system.
- The 4 loudspeakers could also be positioned in other known locations.

\[(X,Y,Z) = (0,0,0)\]
PRINCIPLE OF OPERATION

- Each loudspeaker emits a **different MLS signal** (of the same order), orthogonal to the others.

- The 4 MLS signals played from the 4 loudspeakers **can be identified** also being **temporally superimposed**.

- The microphone captures the sum of the 4 MLS signals and the software reconstructs the **4 corresponding impulse responses** by means of the Fast Hadamard Transform (FHT).
- From the first peak of each of the impulse responses, the **arrival times** (flight times) of the sound from the 4 loudspeakers to the microphone are determined.

- From the 4 arrival times, computed the 4 **distances** between the microphone and the 4 loudspeakers (considering also the air temperature correction of the sound speed), the **position** in the space of the microphone is determined by **3D trilateration** computations.

\[
\text{Snd\_speed} = 331.6 + 0.6 \cdot \text{Temp}_{\text{air}}
\]

\[
\text{Distance}_{\text{Loudsp-Mic}} = \text{Snd\_speed} \cdot \text{Arrival\_time}
\]
PRINCIPLE OF OPERATION

“manual” mode
(single shot measurements)

“continuous” mode
(measuring continuously points in the space)

Example video
- The **continuous mode** allows to acquire a large number of points and to obtain a **high spatial resolution** of measurements.

- It can lead to incorrect results since the theory underlying MLS involves the measurement of a **stationary linear system**

- If the microphone is **moved too fast** during the MLS signals measurement (in other words if the system is non-stationary), artifacts will appear in the reconstructed impulse responses, specifically noise and low frequency oscillations.
**PRINCIPLE OF OPERATION**

- To validate correct positioning measurements and also to identify the first peak in the 4 impulse responses, **background noise level** is measured in the initial impulse response portion, prior to the arrival of the first peak (or in the final part of the I.R.)

- Ideally there should be no signal in this time interval, since the sound wave has not yet reached the microphone

- background noise level in the measured impulse responses is used also to help the software to **find the first peak**
- The first peak finding is **not a trivial task**. In real conditions, many problems could confuse the peak search algorithm:

- **Noise overlapped** on the IR with higher peak value than the real first peak

- **More peaks** are present if the microphone is placed near a *highly sound reflecting surface* and the first peak falls between 2 discrete sampling time instants (picket fence effect in time domain), or phase interferences between the first and the reflected peak are present

- **Ratio** between the (supposed) main peak and the background noise level is used as discriminating factor, together with the fact that the main peak must be the first peak in temporal order
THE MEASUREMENT SYSTEM - HARDWARE
THE MEASUREMENT SYSTEM - HARDWARE

Paolo Guidorzi
SOUND FIELD MEASUREMENTS INSIDE A REVERBERANT ROOM BY MEANS OF A NEW 3D METHOD AND COMPARISON WITH FEM MODEL
THE MEASUREMENT SYSTEM - SOFTWARE

SOUND FIELD MEASUREMENTS INSIDE A REVERBERANT ROOM BY MEANS OF A NEW 3D METHOD AND COMPARISON WITH FEM MODEL
MEASUREMENT ACCURACY

Factors that most affect measurement accuracy:

- size and geometry of the speaker grid
- frequency response of speakers and microphone
- sample rate of the measurement system
- distance of the microphone from the grid
MEASUREMENT ACCURACY

Not considering advanced processing techniques:

- discrete time between two samples $\Delta t \leftrightarrow$ resolution in measured distance

- at **sample rate of 44.1 kHz** the time between 2 samples is 0.01041667 ms: (single) distance **resolution** is around **7.8 mm** (343 m/s as sound speed)

- at **96 kHz sample rate**, (single) distance resolution is around **3.6 mm**

Mentioned theoretical spatial resolutions are relative to a **single distance**
MEASUREMENT ACCURACY

- 4 distances between the microphone and the 4 loudspeakers on the grid → trilateration algorithm

- actual resolution of the measurement is not simple to calculate

- statistical analysis on measurement accuracy was performed using a square 1 m x 1 m grid on which the 4 loudspeakers were mounted and with different combinations of sample rates and distances microphone-grid
MEASUREMENT ACCURACY

Measurements placing the microphone at the two ends of a rigid meter, **sample rate 96 kHz**

**Average value measured**: 1,0045 m  
**Standard deviation**: 0,0234 m (2,34 cm)  
**Average error**: 1,99%

Experimentally it has been found that the **area covered** by the 3D positioning system with a **grid 1 m x 1 m** extends for at least **10 meters in every spatial direction**

**Increasing the grid size, most likely the covered area can be increased**

**Similar measurements, same boundary conditions, sample rate 44.1 kHz**:  
**Average error**: 3.5%

**Increasing sample rate or oversampling data in time domain, most likely the precision can be further increased**
EXPERIMENTAL RESULTS

- A series of measurements were carried out in the reverberating chamber of the University of Ferrara.

- The 3D positioning system was used to sample the sound field inside the chamber in 109 points, at a fixed height of 2 meters from the ground, placing the microphone on a stand, moved manually to cover the entire area of the chamber. Single shot measurement mode.

\[ V \approx 252 \, \text{m}^3 \quad A \approx 50 \, \text{m}^2 \]

Side walls lengths between 6,42 and 8,53 m
Ceiling height between 4,26 and 6,02 m
- Distance between measurement points ≈ 50 cm (frequencies analyzed in this study < 100 Hz, wavelengths longer than 3.4 m)
- No particular care for exact positioning, since the exact position was calculated by the 3D positioning system and associated with each corresponding acoustic measurement
- A fifth MLS signal, different from the other 4 was emitted by a dodecahedron placed inside the chamber

- For each measurement point, an impulse response of the chamber was measured, using the MLS signal emitted by the dodecahedron

- MLS signals of order 18, 262143 points (time length about 6 seconds, 44.1 kHz)

- The chamber has reverberation times of less than 6 seconds above 315 Hz and a maximum of 7 seconds at 100 Hz

- Compromise between (too) long measurement times and slight "contamination" from tail of the IRs
- Grid with the 4 loudspeakers: in the middle of the back wall of the camera
- At the foot of the line joining the two left speakers is the **origin** of the three-dimensional cartesian reference system
- The 109 measurements covered the whole area of the reverberation chamber, detecting for each point the **position in space** and the **impulse response** of the chamber
- The dodecahedron was left in a fixed position
- Only measurements at a fixed height of 2 m have been taken
EXPERIMENTAL RESULTS

- A "cloud" of **georeferenced points** was measured, each of which is associated with an **Impulse Response** measured at that point.

- The **FFTs** of the **IRs** were performed and imported in an excel sheet.

- “**Fingerprint**” of the chamber: each row represents a measurement point (in measurement chronological order), each column is a single discrete frequency, from 20 Hz to 100 Hz, in steps of 0.67 Hz. The color scale indicates the levels in dB. Dynamic range is about 50 dB.

- The presence of **vertical red lines** allows to discover and highlight specific **frequencies** at which **modal resonances in many points of the room** can be observed.
- The spectra corresponding to each measurement point were associated with their position.

- All the measurements (at the same height of 2 m) were projected on a 2D plane.

- Spectrum values, at each frequency and measurement point, were spatially interpolated: colored maps, were red color means high sound level and blue color low sound level.

Maps 32 to 56 Hz (amplitude scale normalized)
EXPERIMENTAL RESULTS

- The spectra corresponding to each measurement point were associated with their position.
- All the measurements (at the same height of 2 m) were projected on a 2D plane.
- Spectrum values, at each frequency and measurement point, were spatially interpolated: colored maps, were red color means high sound level and blue color low sound level.

Maps 57 to 80 Hz (amplitude scale normalized)
EXPERIMENTAL RESULTS

- The spectra corresponding to each measurement point were associated with their position.
- All the measurements (at the same height of 2 m) were projected on a 2D plane.
- Spectrum values, at each frequency and measurement point, were spatially interpolated: colored maps, were red color means high sound level and blue color low sound level.
EXPERIMENTAL RESULTS

- The **spectra** corresponding to each measurement point were associated with their position.
- All the measurements (at the same height of 2 m) were projected on a 2D plane.
- **Spectrum values**, at each frequency and measurement point, were **spatially interpolated**: colored maps, were red color means high sound level and blue color low sound level.
EXPERIMENTAL RESULTS

Modal analysis at **54 Hz**

- **FEM model**
- **Measurement (interpolated)**
EXPERIMENTAL RESULTS

Modal analysis at 71 Hz

FEM model

Measurement (interpolated)
EXPERIMENTAL RESULTS

Reverberation times RT15

- From the impulse responses measured in the 109 points, decay curves were calculated by means of Schroeder’s backward integration.

- Maps similar to the previous ones have been obtained; each point represents a value of reverberation time RT15, filtered in a 1/3 octave band.

- Here is the distribution of RT15 filtered in 63 Hz 1/3 octave band.

1/3 octave band 63 Hz
ExperimenTal results

Reverberation times \textbf{RT15}

- From the impulse responses measured in the 109 points, decay curves were calculated by means of \textit{Schroeder’s backward integration}.

- Maps similar to the previous ones have been obtained; each point represents a value of \textit{reverberation time RT15}, filtered in a 1/3 octave band.

- Here is the distribution of RT15 filtered in \textit{80 Hz 1/3 octave} band.

1/3 octave band 80 Hz
CONCLUSIONS

- The described 3D positioning system has good precision and can be used to measure acoustical parameters associated with the position in space, such as sound pressure levels or impulse responses but also temperature, humidity or data from various types of sensors, fixed together with the microphone.

- The acoustic field inside a reverberation chamber has been studied.

- The measurements were compared with results from FEM simulation at some frequencies, obtaining excellent concordance.

- This system allows analysis of the sound field with sufficient degree of detail and is useful when a simulation is difficult to perform or when a quick investigation in real conditions is required.
P. GUIDORZI\textsuperscript{a}, F. POMPOLI\textsuperscript{b}, P. BONFIGLIO\textsuperscript{b}, M. GARAI\textsuperscript{a}

\textsuperscript{a}DEPARTMENT OF INDUSTRIAL ENGINEERING (DIN), UNIV. OF BOLOGNA, ITALY
\textsuperscript{b}DEPARTMENT OF ENGINEERING, UNIV. OF FERRARA, ITALY

\textsuperscript{a}paolo.guidorzi@unibo.it \quad \textsuperscript{b}pmpfnc@unife.it \quad \textsuperscript{b}bnfpsb@unife.it \quad \textsuperscript{a}massimo.garai@unibo.it

THANK YOU FOR YOUR ATTENTION

www.unibo.it
acustica.ing.unibo.it

The presented system has been patented and deposited by University of Bologna: “Method for the calculation of a position and the mapping of one space-related variable through the use of acoustic signals and corresponding apparatus for the implementation of the method”
Deposit nr. 102017000066160

Contact for the use of the patent:
kto@unibo.it
(+39)0512098833