Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

# Restoration of Ancient Pipes Organs Aided by Experimental Vibration and Acoustic Modal Analyses

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**PACS:** 43.75.- z ; 43.75.Np

## ABSTRACT

A methodical experimental procedure able to identify on field vibration and acoustic performances of organ pipes has been implemented, tested and discussed in the paper. In particular experimental activities developed during the restoration of the most restored ancient pipes organ in the region of Liguria (Italy) are presented. Experimental approach is oriented to detect and compare vibratory and acoustic frequency responses of single pipes: measurements are implemented in field, using portable multi-channel instrumentation and equipping pipes with external microphones and arrays of micro-accelerometers mounted by means bee wax. Excitation is generated both by impact with instrumented micro-hammer in structural tests and by played note in vibratory and acoustical experiments.

## INTRODUCTION

Ancient organs are unique pieces conceived, designed and crafted within a specific context, to fulfil the needs of the community to which was originally destined. Taking into account their intrinsic value and quality, restoration procedures are not comparable to those of construction of new instruments. The aim of the restorer is to render the instrument a harmonised whole, respecting, as much as possible, original acoustic features and characteristics initially conceived. Theoretical fluid-dynamic modelling and in particular *pipe scaling* (defining the science of measuring and deciding upon pipe diameters) are fundamental references but the actual physical, chemical end mechanical status of surfaces and materials can strongly modify the acoustic responses: consequently mechanical, structural and dynamic performances must be experimentally detected.

Pipes organs are a significative example of high complexity “musical machines”, not only for the internal structure of own mechanical transmission, but also for the interaction between vibratory phenomena typical of the pipe walls and of acoustic propagation within the pipes. Dynamic, vibratory and acoustic phenomena concerning pipes organs can be today studied through modern and innovative experimental analyses allowing to scientifically supporting method and practical procedures usually based on empirical and inductive methods.

In addition, methodological approaches are useful during recover and restoration phases of ancient instruments, allowing acquiring information on the mechanical characteristics of original parts and on the peculiarities of the generated sound.

## THE ORGAN UNDER STUDY

The pipes organ subject of the present experience in the instrument located at the Oratory of N.S. del Suffragio, in S. Margherita Ligure (Genoa, Italy). This organ (Figure 1) goes back ad 1688, built by Tommaso Roccatagliata. In 19th and 20th siecle the organ has been submitted to maintenance works, without modify the original acoustic parts of the instrument.

**Figure 1.** Pipes organ of N.S. del Suffragio, S. Margherita Ligure, Genoa, Italy

In 2009 the organ has been restored and in this rare occasion the present experimental activity has been implemented. The event is particularly rare, both because the restoration interventions of pipes organs aren't particularly frequent, and because usually scientific experimental test aren't developed. As consequence this situation has been considered as particular case study integrative technology, techniques and experimental methods.

The organ of the Oratory N.S. del Suffragio (by G. Giovannini, 1686), located in S. Margherita Ligure, near to Genoa (Italy), includes 50 notes fingerboard, 550 pipes, 15 pedals and 11 stops. Flue pipes have no moving parts and generate their sound by vibrating air in a column like a flute or recorder. Combinations of open pipes and stopped (or closed) pipes built with different materials are involved.

## EXPERIMENTAL SETUP

Experimental approach is oriented to detect and compare vibratory and acoustic frequency responses of single pipes: measurements are implemented in field, using portable multichannel instrumentation and equipping pipes with external microphones and arrays of micro-accelerometers Figure 2 shows the experimental setup: each pipe under test is equipped with an array of micro-accelerometers, assembled by means bee wax on the external surface. The mounting is completely non intrusive. In addition the generated sound is detected by external microphones (Figure 3).

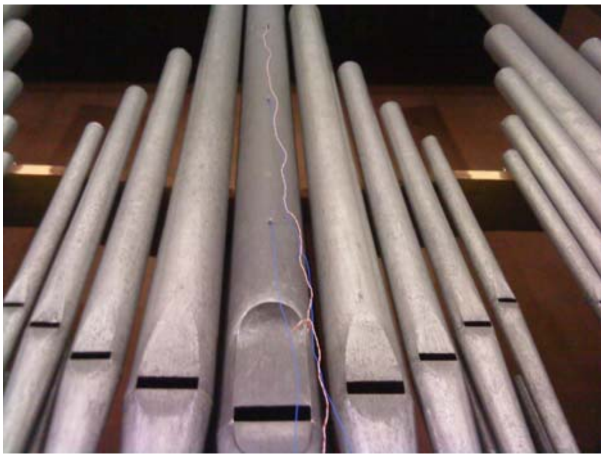


**Figure 2.** Vibratory acquisition

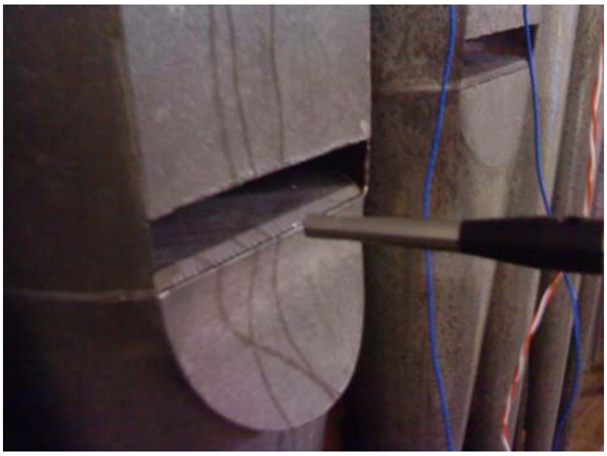


**Figure 3.** Acoustic acquisition

Signals from transducers are acquired and elaborated by SCADAS III portable unit (by LMS, Figure 4). Tests are implemented on different pipes: in particular C pipes are tested, as described hereafter.

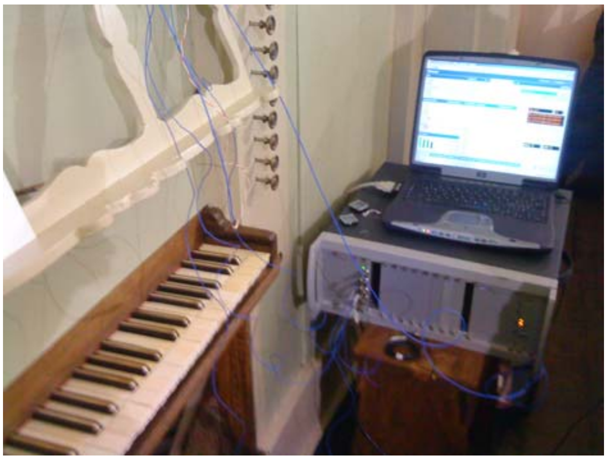


**Figure 4.** SCADA III portable acquisition and elaboration unit (by LMS)

## VIBRATORY TESTS

Some significative reference pipes are chosen: in particular C pipes are considered. Fundamental frequencies of C pipes are 66, 131, 262, 523 and 1046 Hz: three variants present on the instrument are considered: pipes in lead-tin alloy, in lead and in "flute" tonality.

Structural vibratory analysis is oriented to compare the response of all possible mode shapes (free motion analysis) with modes related to the forcing function generated by played notes. Each pipe is equipped with 4 micro-accelerometers (with seismic mass of 0.4 g), positioned on the pipe (Figure 2)

Vibration mode shapes are deduced exciting each pipe with micro-hammer instrumented by load cell. Responses on C5 are used in order to describe this type of results (Figure 5).

Sum FRFs and vibratory operative spectrum are compared in 0÷ 1000 Hz frequency range: as previously cited the operative spectrum (accelerometer measurement, corresponding to the green line) the harmonic components are identified by very narrow peaks, related to the forced response of the played note. Peaks corresponding to resonance conditions are less narrow, influenced by structural damping of the pipe.

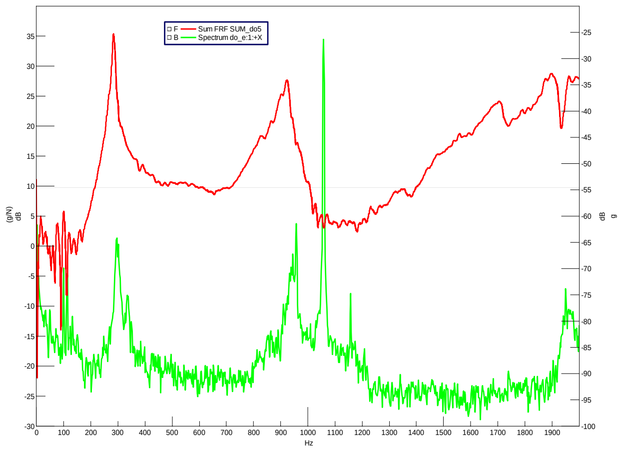



**Figure 5.** Response of C5 pipe

Red curves correspond to free frequency response functions (obtained with excitation by micro-hammer) and green curves show the corresponding forced responses, generated playing the pipe. Collection of results from C1 to C4 is reported in Figure 6.

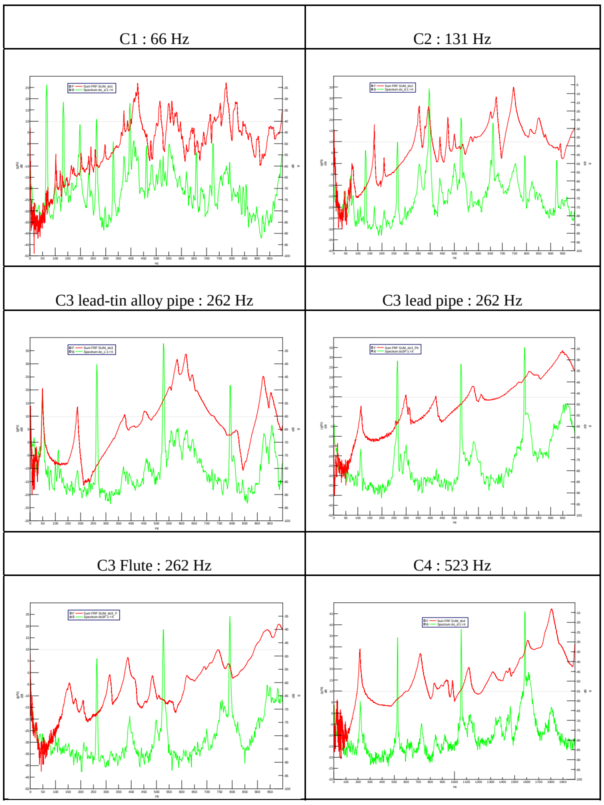



**Figure 6.** Comparisons between free and forced response functions

Specific analysis has been implemented on pipes built to play the same note but with different richness of harmonics: Figure 7 shows the frequency response functions of three C3 pipes: in red lead-tin alloy pipe, in green lead pipe and in blue flute tonality pipe.

Peaks of structural frequencies are differently distributed in 0÷3000 Hz range: pipe in alloy and flute pipe show a fundamental frequency around 1050 Hz, while lead pipe shows this peak at 800 Hz. Flute pipe shows a well distributed series of harmonics.

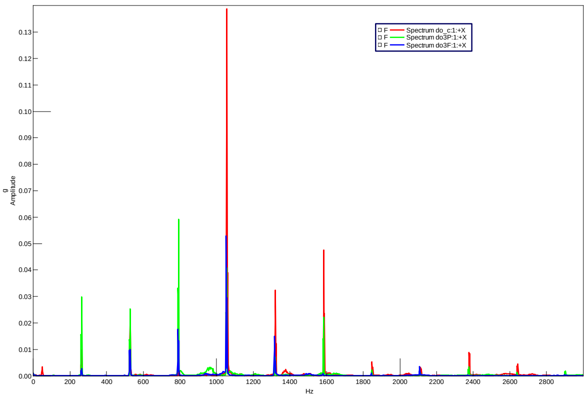



**Figure 7**. Comparison on C3 pipes frequency response functions

Interesting is the also the comparison between this frequency response and the corresponding acoustic frequency distribution, reminded in Table 1.

Structural characterization of original pipes has been significant during the restoration phases, also to detect possible structural damages able to modify the dynamic response of the pipe. As well know chemical modifications of the material (e.g. tin pest) correspond to different crystal structures under varying conditions of temperature and pressure and are responsible of strong acoustic modifications of organ pipes.

**Table 1**. C frequencies

| *No. of harmonics* | *Frequency [Hz]* | *Description* |
|---|---|---|
| 1st | 262 | fundamental |
| 2nd | 524 | octave |
| 3rd | 786 | decima seconda |
| 4th | 1048 | decima quinta |
| 5th | 1310 | decima nona |
| 6th | 1572 | vigesima seconda |
| 7th | 1834 | vigesima sesta |
| 8th | 2096 | vigesima nona |
| 9th | 2358 | trigesima terza |
| 10th | 2620 | trigesima sesta |

## ACOUSTIC TESTS

Sum FRFs (red curves) and acoustic operative spectra (green curves) are analysed in detail for each C pipes: Figures from 8 to 14 report structural and acoustic spectra in 0÷1000 Hz range of frequency for C1, C2, C3 (lead-tin alloy), C3 (lead), C3 (flute), C4 and C5 pipes. Structural response is acquired by micro-accelerometers and acoustic signals by external microphones: in both cases the excitation is generated playing the pipe.

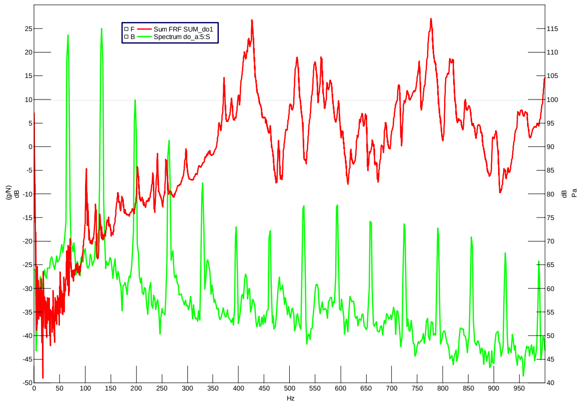



**Figure 8**. Sum FRFs and acoustic operating spectrum (C1)

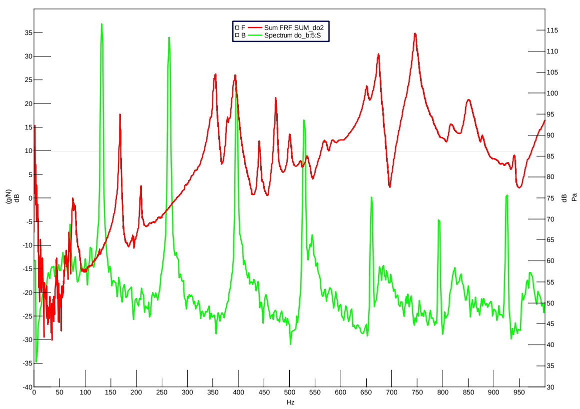



**Figure 9**. Sum FRFs and acoustic operating spectrum (C2)

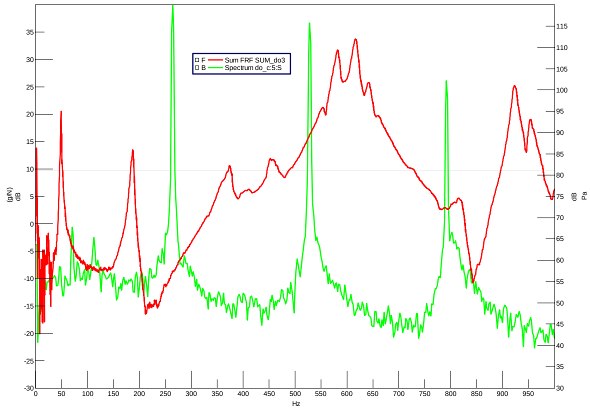


**Figure 10**. Sum FRFs and acoustic operating spectrum (C3, lead-tin alloy)

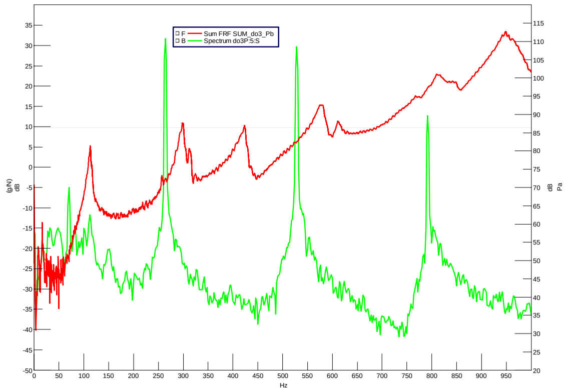


**Figure 11**. Sum FRFs and acoustic operating spectrum (C3, tin)

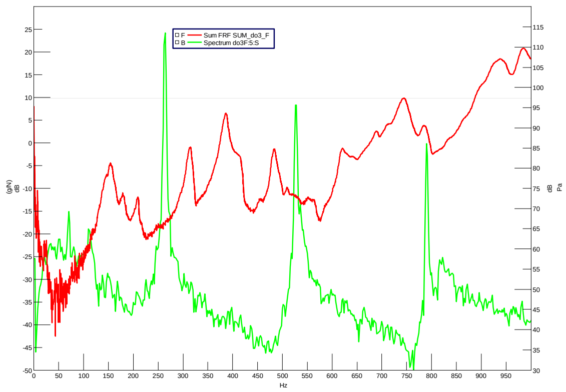


**Figure 12**. Sum FRFs and acoustic operating spectrum (C3, flute)

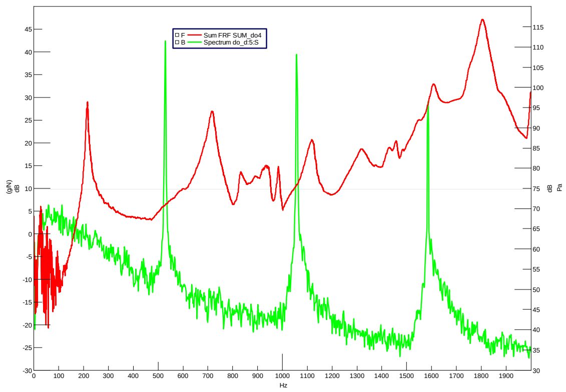


**Figure 13**. Sum FRFs and acoustic operating spectrum (C4)

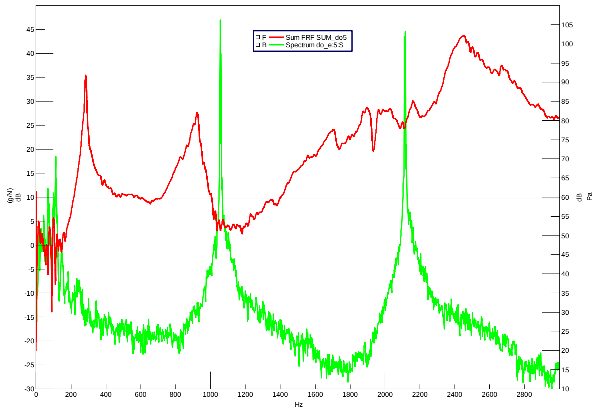


**Figure 14**. Sum FRFs and acoustic operating spectrum (C5)

Acoustic and structural spectra show significant differences: the generated sound is related to the coupling between acoustic stationary waves, moving longitudinally, and the wall vibration of the pipe, detected in orthogonal direction.

## LABORATORY TESTS

In addition to field tests compared analyses on new pipes geometrically and acoustically corresponding to original pipes installed in the organ under study are implemented. Sound quality of specific pipes is related to the frequency coupling of structural and acoustic response. In particular, further comparisons with experiments performed in laboratory of corresponding pipes submitted to acoustic holography approaches are developed. Figure 15 shows a laboratory setup for modal analysis on an F# pipe and Figure 15 reports the corresponding result.

**Figure 15**. Laboratory setup for modal analysis and pipe F#4 under test

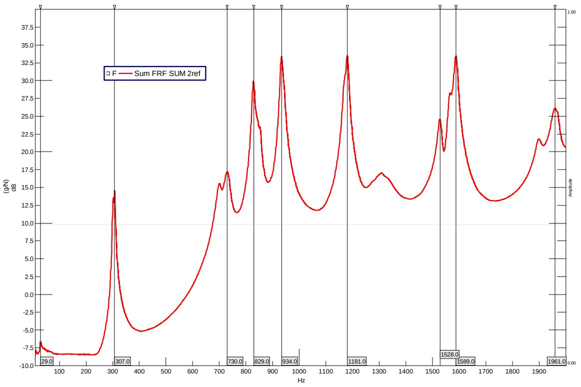
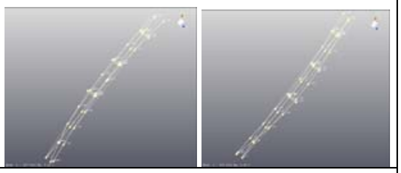
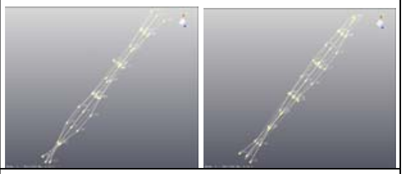
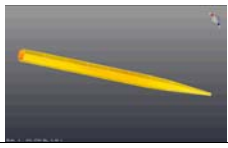
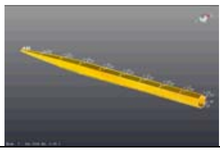


**Figure 16**. Modal analysis of F# pipe

Frequencies corresponding to nine experimental extracted modes are collected in Table 2.

**Table 2.** Extracted modes F#4 pipe (370 Hz)

| *Mode* | *Frequency [Hz]* | *Mode shape* |
|---|---|---|
| 1 | 301.134 |  |
| 2 | 307.331 |  |
| 3 | 704.274 |  |
| 4 | 731.684 |  |
| 5 | 828.210 |  |
| 6 | 933.375 |  |
| 7 | 941.936 |  |
| 8 | 1169.632 |  |
| 9 | 1180.993 |  |

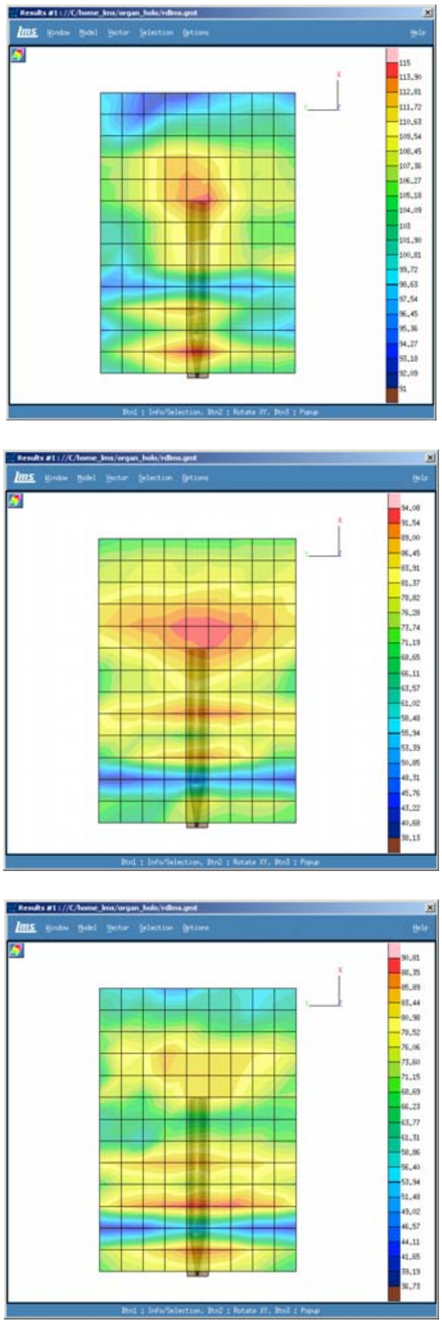
Graphical elaboration based on VirtualLab software (by LMS) allows to make available mode shapes, animations, 3d modelling of pipes, starting from the geometrical mesh defined for experimental acquisition. In Table 2 some graphical facilities are proposed.

Another laboratory test useful to compare original pipe to accurate copies concerns the acoustic holography. An acoustic setup reproducing in laboratory flows and pressures available on the organ has been assembled. An array of microphones is used to detect acoustic response on the pipe under test and these experimental results are used to simulate holography maps at different distance from the pipe.

Hereafter results concerning test on the F# pipe shown in Figure 17 are collected.

**Figure 17**. F# pipe

Figure 18 (a, b and c) reports the acoustic holography at frequencies of 769 Hz, 1538 Hz and 2308 Hz respectively.



a) b) c)

**Figure 18**. Acoustic holography

Experimental acoustic holography allows simulating predictions of the behaviour of the pipe, defining acoustic distributions in different spatial locations. Figure 19 reports a holographic prevision at distance of 120 mm from the pipe, while Figure 20 simulates the acoustic effect on an ideal plane including the mouth.

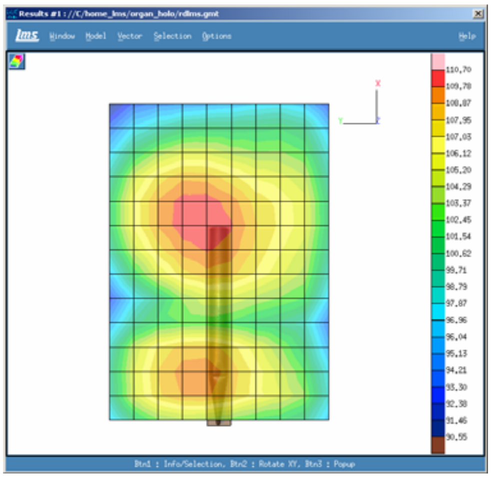


**Figure 19.** Holographic prediction at 120 mm

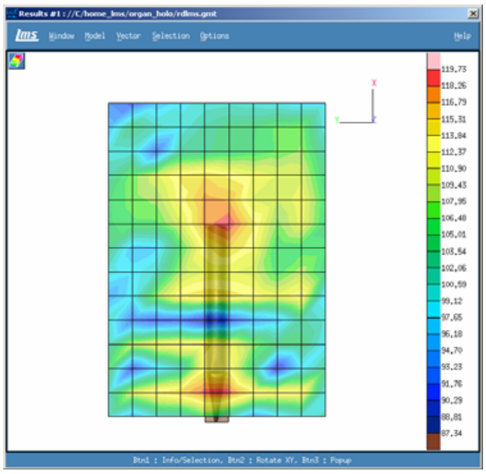


**Figure 20.** Holographic prediction on the mouth

## CONCLUDING REMARKS

An original experience of experimental vibration and acoustic modal analysis applied to restoration of an ancient pipes organ has been developed. During restoration of original pipes the organ-maker is interested to acquire data on the actual vibratory and acoustic performance of damaged pipes and to correlate dynamic responses of ancient and new components.

Vibratory and acoustic analyses have been performed on specific pipes (C and F) particular interesting for the peculiarities of the organ under restoration. The implemented methodological approach is general and could be applied in similar experimental tests.

Particular exciting seems to be the comparison between acoustic and structural spectra, influenced also by the surfaces condition: compared laboratory tests have completed the experimental approach on field. An oriented setup of acoustic holography has been assembled and samples of pipes have been submitted to tests.

The research activity is still under development, through the monitoring of the restored organ: a periodic comparison of vibratory and acoustic performances seems to be a significant test on the efficiency of the restoration process.

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