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2pED5. Black box measurements – Using a family of electrical circuits as a tool for self-guided learning in acoustical engineering

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A partnership between Brazil’s first undergraduate program in Acoustical Engineering and the Institute of Technical Acoustics of RWTH Aachen University yielded a didactic project that uses the engineering software MATLAB with the ITA-Toolbox to teach acoustic measurements. Simple electrical circuits are used to mimic typical behavior of acoustical systems. This low-cost solution has proven to be didactically very effective since it helps students to identify themselves with the measurement tasks. Two hardware solutions were developed—a simple oscillator circuit integrated into connectors of audio cables and a desktop box containing seven different transfer characteristics ranging from ideal linear and time-invariant to nonlinear and time-varying behavior. Undergraduate students of Acoustical Engineering used both devices in classroom experiments for self-guided learning by comparing their results to published results. Students were able to learn the fundamental concepts of acoustical measurements and to handle measurement tasks. Besides the practical experiences and the learning effect, the students were also encouraged to step into the open source routines of the software, understand the signal processing steps, adapt routines and even write their own ones, e.g. a GUI that provides effective control of the measurement via touch-screens.

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INTRODUCTION

Acoustical measurement equipment is usually very sensitive and very expensive. Incorrect usage may easily cause permanent damage. Thus, teaching practical acoustics to a large number of students is usually quite unfeasible, as measurement equipment is often unavailable in sufficient number. Especially in developing countries or BRIC countries such as Brazil the problem is even more accentuated. Nevertheless, practical measurements are an important part of learning and measurements carried out directly by the students cause higher learning impact than measurements carried out just in front of them. Thus, within Brazil’s first undergraduate program in Acoustical Engineering at Federal University of Santa Maria (EAC) practical measurements play an important role and didactic projects, classes and experiments were elaborated in this way. As high cost equipment would be a barrier to the implementation of such activities, less expensive solutions were required.

A partnership between EAC and the Institute of Technical Acoustics (ITA) of RWTH Aachen University yielded a didactic project that uses the engineering software MATLAB together with the open-source ITA-Toolbox measurement software solution. In order to emulate acoustical transfer paths low-cost solutions were developed, aiming to mimic the typical behavior of acoustical systems by simple low-cost electrical circuits. Additionally, the fact that the source code is available and students are able to follow and comprehend all parts of the signal processing chain [1] is considered very useful for learning process. Furthermore, students are also able to adapt routines and are encouraged to write their own functions to develop their programming and algorithmic skills.

On the hardware side, two simple hardware solutions were developed by the ITA to mimic acoustical transfer paths and used by EAC for the first measurement tasks and its evaluation. The first solution consists of a simple oscillator circuit connected to standard audio plugs, called herein the Special Black-Box-Cable. Secondly, the so called BlackBox was developed, a desktop box containing seven different circuits with different transfer characteristics ranging from ideal linear and time-invariant to nonlinear and also time-varying behavior. Details can be found in [1, 2].

This paper discusses the application of this tools in an Acoustics Engineering undergraduate program. In the first part of this article, the technical tools that originated this work will be presented, as well as its main functions. In the second part, the experiments will be detailed, including the measurement setups and parameters. Finally, the results of these experiments will be presented, with priority on the didactic results.

MEASUREMENT EQUIPMENT FOR CLASS ROOMS

The focus of this paper is to present an efficient and powerful didactic solution to teach acoustic transfer function measurements in detail. The low-cost equipment developed and used for the class is present in the following. An editable open-source measurement software is preferred as it allows the students to understand the task from an acoustical, from a signal-processing and from a programming point of view at the same time.

PC Hardware and Software

A personal computer running either Windows, Linux or Mac OS with MATLAB R2010a or higher installed is required. A simple soundcard with at least one input and one output channel is sufficient for the measurements in the course as the ITA-Toolbox realizes communication with the soundcard via PortAudio and runs therefore on all operating systems mentioned. The ITA-Toolbox is freely available online at www.ita-toolbox.org.
Soundcards and computers

Measurements of the Special Black-Box-Cable were realized with affordable commercial soundcards, such as Presonus Firebox with FireWire connection, M-Audio Fast Track Pro USB and even the computer’s onboard soundcard. During these measurements different types of soundcards were evaluated according to the flowchart in Figure 4.

Desktop BlackBox

A small desktop device that contains seven different circuits in order to mimic seven different transfer characteristics such as bandpass filtering, non-linearities, amplitude modulation, noise and also a simple bypass has proposed for didactic measurement purposes by Fingerhuth et al. [2]. This device is simply called BlackBox in the following. Until the start of the course only one copy of this BlackBox was available. The advantage of this electric solution compared to an electro-acoustic solution using a loudspeaker, a small chamber and an microphone are the cost and the flexibility. Line levels allow for direct connection to various sound cards by using e.g. cheap jack to XLR connectors.

![Figure 1: Opened BlackBox circuits detail](image)

Special Black-Box-Cable

Based on the more complex BlackBox a simpler, alternative approach is used additionally to allow several groups to measure at the same time. The Special Black-Box-Cable is a simple oscillator circuit according to Figure 2 with audio connectors to be connected to the input and output of commercial soundcards [3].

Experiments and Measurement Parameters

Undergraduate students of Acoustical Engineering used both the Cable and the Blackbox in classroom experiments for self-guided learning aiming to understand the functionality of the software and basic concepts of measurements, also by comparing their results to published results [2].

The principal behaviour of electro-acoustic measurements was studied beforehand in MATLAB with the ITA-Toolbox by using "virtual" measurement routines that simulate real measurement behaviour as e.g. nonlinearities, quantization, aliasing and noise. The advantage is that this does not require a sound card as it emulates the entire chain as illustrated in
Figure 3. As in the real measurements conducted later on the students could specify the type of excitation signal and its length, the time to wait for the system decay (stop margin), number of averages, the stop margin and of course the frequency range of interest and regularization to suppress noise outside the frequency range of interest. The background information given to the students is based on [4] and [5].

The ADC adds quantization artefacts according to the number of bits specified and add latency in the same way as a real sound card. The quantization artefacts have to be added although we want to go to the analog domain as the representation in MATLAB with floating point numbers does not carry this quantization. Then the discrete quantized signal is fed to a simple non-linear simulator. This simulator uses a Taylor expansion around a working point with specified coefficients up to an arbitrary order. The ITA-Toolbox routines are based on the model introduced by NOVAK [6]. The coefficients are frequency independent in this simple model. This nonlinear simulator takes care about the the Nyquist theorem and therefore suppresses aliasing. Then this distorted signal arrives at the DUT where the transfer function \( H(f) \) is multiplied. Finally we add measurement noise with arbitrary shape and level before the signal arrives at the ADC where it is quantized and limited to a specified magnitude to emulate clipping. Clipping at the ADC after the low pass filter results in aliasing which is emulated accordingly.

**Figure 2:** Special Black-Box-Cable’s FRF and circuit detail

**Figure 3:** The virtual measurement chain with quantization, sampling and nonlinearites as simulated by the ITA-Toolbox routines
The first measurements were carried out using the Special Black-Box-Cable together with four different computers and two sound cards according to Figure 4. Different configurations of measurement parameters, such as signal length, excitation level or stop margin\(^1\) were investigated by the students separately. They are fixed to a standard configuration to allow for direct comparison of the hardware and to evaluate its influence on the result of the measurement e.g. in the plots for this paper. Using a fixed parameter combination for the measurement the results obtained with different hardware combinations can be compared also with nominal results sent by the developers. This stage of measurement was used also to check software and hardware compatibility.

**Figure 4:** Hardware combinations flowchart, DUT may represent a cable or a channel of the BlackBox.

After using the Special Black-Box-Cable and learning the basics of measurements and some important concepts in acoustics, such as the ability to compare and interpret graphs, impulse response, transfer function, hardware delay and stop margin relation and linear limits due to signal amplification, students used the BlackBox to measure its seven different transfer characteristics. To identify the transfer characteristics each channel was analysed by means of different responses (FRF, IR) and different types of signals (expswep, white noise, pure tone) in order to identify clearly each transfer characteristic. Results were compared to each other and also compared to results published in [2].

**DISCUSSION OF RESULTS AND DIDACTIC APPROACH**

The students conducted measurements with the virtual measurement chain, the Black-Box-Cable and the desktop BlackBox on their own but could ask the supervisors’ help any time throughout the course. They were encouraged to discuss the results in groups to apply the theoretical knowledge on practical problems.

**Special Black-Box-Cable**

After some measurements, students get used with ITA-Toolbox features and obtained the transfer function of the Special Black-Box-Cable and of the direct input-output connection. The software was stable in all hardware setups tested, although not much reliable with the onboard AD/DA converter due to low frequency distortions. It was detected that external soundcards, due to better driver and component qualities, presented lower latency than the onboard one as shown in Table 1. Consequently short signals may not be correctly measured with onboard soundcards. Also, low frequency distortion were not detected with extenal soundcards. Results obtained using set-ups with external soundcards agreed well with the standard transfer function sent by developers.

\(^1\)stop margin: time that the system keeps recording after the end of excitation signal to cover hardware delay
**TABLE 1:** Measured latencies for each hardware combination setup

<table>
<thead>
<tr>
<th>Setup</th>
<th>Obtained latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compaq Windows 7 + PreSonus</td>
<td>0.0129 s</td>
</tr>
<tr>
<td>Compaq Windows 7 + M-Audio</td>
<td>0.0169 s</td>
</tr>
<tr>
<td>Compaq Windows 7 + Onboard</td>
<td>0.2942 s</td>
</tr>
<tr>
<td>Mac OSX Snow Leopard 10.6.8 + PreSonus</td>
<td>0.0218 s</td>
</tr>
<tr>
<td>Mac OSX Snow Leopard 10.6.8 + M-Audio</td>
<td>0.0232 s</td>
</tr>
</tbody>
</table>

**BlackBox**

As the BlackBox has seven unknown circuits, the analysis of each circuit is to be done stepwise. First, the signal levels arriving at the PC must be checked. Then, the spectral shape in the frequency domain is analysed and the first guess of what might be inside is possible. More information is to be retrieved by looking into the time domain and analyzing decay, delay, distortions and non-linearities. Also, active processes such as time-windowing of the signals might be required to show fundamental characteristics of certain channels.

**FIGURE 5:** Didactic approach used to evaluate transfer function measurement methods in the classroom using different measurement parameters, plots, post-processing and discussion.

All circuits could be correctly measured and classified according to its main characteristic, their analysis was supported by different methods, as shown in Table 2. Band-pass filtering and noises were detected by their respective transfer functions. Non-linear influences appear clearly in its impulse response, they may also be filtered by a time-windowing process as shown in Figure 5. In channels 5 and 6, the identified random noise was classified as blue noise due to greater energy levels at higher frequencies. Channel 7 presents a bypass connection, so it was used as reference for the comparisons.

**TABLE 2:** BlackBox channel classification

<table>
<thead>
<tr>
<th>Channel</th>
<th>Analyzed response</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FRF</td>
<td>2 band-pass filters (approx. 100 Hz e 2,4 kHz)</td>
</tr>
<tr>
<td>2</td>
<td>FRF + IR</td>
<td>Non-linear influences</td>
</tr>
<tr>
<td>3</td>
<td>Y(t)</td>
<td>Modulation</td>
</tr>
<tr>
<td>4</td>
<td>FRF + IR</td>
<td>Non-linear influences</td>
</tr>
<tr>
<td>5</td>
<td>FRF</td>
<td>Blue noise</td>
</tr>
<tr>
<td>6</td>
<td>FRF</td>
<td>chan 1 + chan 5</td>
</tr>
<tr>
<td>7</td>
<td>FRF</td>
<td>By pass</td>
</tr>
</tbody>
</table>

Experiments using the BlackBox were repeated in classroom, also helping students not involved in the project. Students were required to have basic knowledge on MATLAB and general measurement chain only. Basic knowledge of signal processing and acoustical...
FIGURE 6: Measured frequency response of channel 6 of the Blackbox (Band-pass time-invariant filter + Blue noise) measured with exponential sweep.

Measurements were incorporated into the learning process, as well as students learned to handle MATLAB and acoustical concepts better.

FIGURE 7: Impulse response of channel 2 of the desktop black box (non-linear, time invariant behavior) measured with exponential sweep.
User Manual and Documentation

Parallel to the measurements and accompanying the learning curve, students developed an illustrated manual in Portuguese language to guide other new users in their first contact with the software and acoustical measurements. The manual describes different ways of measuring the transfer function of simple systems considering hardware setups, settings, etc. It also gives a basic parameters description and has a FAQ section, containing FAQ based on the many difficulties that appeared in first measurements such as questions regarding software’s functions and commands, correct connections, terminology and even figure formatting. Thus, the manual is especially interesting to new users that are still learning to use MATLAB and having their first contact with ITA-Toolbox.

Implementation and Investigation of Specific Routines

The open structure of the software and the academic project with ITA Aachen is also intended to encourage students to step more thoroughly into the open source routines of the software and to adapt routines and even writing their own. One of the new functions developed is a GUI for measurement configuration and execution via touch-screen devices such as smartphones and tablets. This GUI was optimized especially to be used on such small screens and will be described in a later publication. The idea behind the development of the GUI for remote control was to avoid interference of the physical presence of the experimenter in the room which, in case of acoustical measurements, presents part of the device under test.

![FIGURE 8: Screenshot of the graphical user interface (GUI) on a tablet PC designed by the students during the course in MATLAB.](image)
CONCLUSION

The work with the ITA-Toolbox for MATLAB, a simple Special Black-Box Cable, the desktop BlackBox and an external converter showed that the solution provides a reliable and easy to use measurement system for classroom use and also research. Onboard sound cards were identified to sometimes present distortions in some cases. Students were able to learn the fundamental concepts of acoustical measurements and to handle measurement tasks. Topics of digital signal processing, such as relation between frequency responses and impulse responses, hardware latency, time-windowing, magnitude and phase, non-linearities and amplitude modulation were investigated and explored in the laboratory and classroom using standard audio devices.

Despite the initial difficulties, after some measurements the software could be effectively controlled by the students in order to obtain the expected results. Different from the manual developed by the ITA-Toolbox developers, a portuguese manual and video tutorial were developed intended for absolute beginners not only in ITA-Toolbox and MATLAB but also in acoustical measurements.

Bugs, problems or improvements detected by students or supervisors were reported to the software developers to contribute to its evolution, giving a small contribution to the development and the user experience of the ITA-Toolbox and its applicability for didactic purposes. Easy of use, compatibility, flexibilty and operational readiness make that ITA-Toolbox and MATLAB is being used in several other projects carried out in the laboratory of EAC not only by students.

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