TEACHING ACOUSTICS USING IHA’s OPEN-SOURCE TLM-PACKAGE “LAMBDA”

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Abstract

Numerical methods such as FEM/BEM have become standard tools in predicting acoustical quantities in research and development. In education, their use is much less common, mainly because these methods imply a steep learning curve (even before using them) and generally don’t lend themselves to be used as a tool to explore acoustics off-class. On the other hand, no one doubts that the visualization of acoustical wave phenomena can strongly facilitate the understanding of acoustics. In this paper, the use of the 2D open-source Package ”Lambda”, which is based on the Transmission Line Matrix (TLM) method, in teaching acoustics is proposed. Among the advantages of using this package is that (1) the underlying principle, i.e. the TLM method as a special case of the Finite Difference Time Domain (FDTD) method, is (fairly) easy to understand, (2) there are ready-made simulation examples available for many topics that may be covered in an introductory course on acoustics (multipoles, reflection, scattering, enclosed spaces, hearing, ...), (3) it is easy to generate new simulation examples, (4) it works on both Windows and Linux platforms.

1 INTRODUCTION

Numerical methods such as FEM/BEM have become standard tools in predicting acoustical quantities in research and development. In education, their use is much less common, mainly because these methods imply a steep learning curve (even before using them) and generally don’t lend themselves to be used as a tool to explore acoustics off-class, for a variety of reasons, such as the need of pre- and postprocessors, license management and costs in general.

On the other hand, no one doubts that the visualization of acoustical wave phenomena can strongly facilitate the understanding of acoustics. It appears that this gap can well be filled in using the Transmission Line Matrix (TLM) method (which in acoustics is sometimes also referred to as Digital Waveguide Mesh).

One TLM package that already offers a lot of what one might be interested in is VWT [1]. Unfortunately, VWT is closed-source (although available at no cost) and appears to be no longer actively developed, such that one is left with the status quo. Above all, this means that there is no option of extending its features or porting it to other platforms.

Thus the motivation to develop an own code at IHA was to get a flexible, extendable code, the 2D-version of which should be released open-source. The result is called “Lambda” and was first released in September 2006.
2 THE “LAMBDA” PACKAGE

2.1 Background
Lambda uses the Transmission Line Matrix (TLM) method [2] on a rectilinear grid to simulate sound propagation in 2 dimensions. As this method basically is a finite-difference approximation of the wave equation, it will suffer from numerical dispersion at higher frequencies [3]. As a rule of thumb, one should use at least 10 nodes per wavelength, in order for dispersion effects to become negligible.

In the free field, Lambda uses the recursive relation

\[ p_{ij}(k + 1) = \frac{1}{2} \sum \text{adjacent nodes}(k) - p_{ij}(k - 1) \]  

(1)

to update the node pressures \( p_{ij} \) at position \((i, j)\) every new time step \( k + 1 \), which is a very efficient and fast implementation of the TLM scheme in acoustics [4]. This formulation allows to take pressure sources into account, by simply prescribing \( p(k) \) at the source position.

At boundaries, the update scheme for the node pressures is more complicated and involves incident (from direction \( \text{dir} \)) waves \( I_{ij}^{\text{dir}} \). The boundary node pressures result from the sum of all \( I \)'s at the respective boundary node,

\[ p_{ij}(k + 1) = \frac{1}{2} \sum I_{ij}^{\text{all dirs}}(k + 1), \]  

(2)

where the \( I \)'s in turn are updated according to

\[ I_{ij}^{\text{dir}}(k + 1) = r p_{ij}(k) - r I_{ij}^{\text{dir}}(k) \]  

(3)

for the direction pointing to the boundary and according to

\[ I_{ij}^{\text{dir}}(k + 1) = p_{\text{neighbor in dir}}(k) - p_{ij}(k - 1) + I_{ij}^{\text{dir}}(k - 1) \]  

(4)

for all other directions. Eqn. 3 allows the inclusion of plane wave reflection coefficients \( r \) to model the boundary. It should be noted that while rigid boundaries \( (r = 1) \) are well modeled using this approach, \( r = 0 \) will cause spurious reflections for waves impinging non-perpendicularly onto the boundary and thus ideally absorbing boundaries are difficult to implement. (This is true for TLM in general, and a field of ongoing research).

2.2 Getting it
Lambda is available for download at www.hoertechnik-audiologie.de/Lambda. There are prebuilt binaries for Win32 and Linux, as well as the source code. Lambda uses QT4 for its GUI, so in order to compile from source, users must have QT4 installed on their systems.

2.3 Using it
Once installed, the use of Lambda is rather straightforward. When launched (multiple instances possible), a GUI opens which lets the user open simulation *.sim files (which can easily be created, see below), control contrast, zoom, and other visualization parameters, and start/pause/stop/quit the simulation. The simulation output can be either visualized on screen, written to an *.avi file (currently on Linux only) or the sound pressure time history for all or previously chosen receiver nodes can be recorded. One thing to note is that the visualization window opens only after the “Vis” button has been checked. In visualization mode, screen shots can be taken any time, they will be saved as *.bmp files.
### 2.4 How to create new simulations

New simulations are made by creating a binary *.sim* file which contains information on the problem geometry, boundary reflection coefficients and source properties. As an example, the following piece of code generates the simulation of the right panel in fig. 3 using Scilab (www.scilab.org):

```plaintext
1 ysize=600; xsize=600; steps=0; c=343; w=0.01;
2 env=zeros(ysize,xsize); env(320:600,300)=1; env(1:280,300)=1;
3 sources=[]; for q=1:ysize, sources=[sources q 1 1 1 1500 0]; end
5 filename='example.sim'; simFile = mopen(filename,'wb');
6 mput([ysize xsize steps c w],'dl',simFile);
7 mput(env.','dl',simFile);
8 mput(sources,'dl',simFile);
9 mclose(simFile);
```

In line 1, the key parameters for the simulation are defined: the size of the region to be modeled, the number of time steps (0 for infinite), the speed of sound in m/s and the distance between the nodes in m. In line 2, the simulation region is initialized as an array (env) which contains zeros for the free field, positive numbers between 0 and 1 for boundaries (taken as reflection coefficients) and negative numbers (not shown in the above listing) for receiver positions. In line 3, the sources are defined as a sequence of 6 numbers per source, containing (in this order): the y-position of the source, the x-position of the source, the source type (1 for sine, 2 for rectangular), the amplitude, the frequency (in Hz) and the phase angle in degrees. In lines 5 to 9, this information is written to the *.sim* file as double little-endian numbers. All of the above can of course as well be done with any other software the user has access to.

### 3 SIMPLE EXAMPLES

#### 3.1 Multipoles

Multipoles are a key concept of every course on acoustics. Usually, the discussion starts with monopoles and dipoles, the directional characteristics of which are readily established. One may ask whether a visualization of these simple source models is of great value besides an unquestioned entertaining effect, but it actually appears that for instance in the case of the dipole, a visualization (fig. 1) helps to distinguish between the concepts of wave propagation (which is spherical) and directivity (which is figure-of-eight).

Line arrays of point sources (equal volume velocity) exhibit a directivity which depends on the ratio of the distance $d$ between the point sources and the wavelength and the number $N$ of sources. In fig. 2, two line arrays of 6 point sources (one with $d/\lambda = 0.25$ and another one with $d/\lambda = 1.5$) are simulated and show the expected directivity factor of $\Gamma(\vartheta) = (1/N)\left(\sin\left(N\pi d/\lambda \sin \vartheta\right)\right)/\left(\sin \left(\pi d/\lambda \sin \vartheta\right)\right)$.

#### 3.2 Scattering and diffraction

In introductory courses on acoustics, scattering and diffraction are usually discussed in a qualitative manner. This can very well be supported by numerical simulation: In fig. 3 for instance, a plane wave impinging onto an orifice is simulated, showing the expected effects for low and high frequencies.

#### 3.3 Enclosed spaces

The constraints imposed onto the sound field by (rigid) boundaries yield special types of sound fields. One widely discussed example are plane waves in ducts, see fig. 4. It can
Figure 1: Screen shots from the simulation of a monopole (left) and a dipole (right). Both emit spherical waves, although the directivity factor for the monopole is a sphere, whereas for the dipole it is a figure-of-eight. In all pictures, gray represents zero, white positive and black negative instantaneous sound pressure.

Figure 2: Simulation of line arrays made up of 6 point sources. Left: $d/\lambda = 0.25$, right: $d/\lambda = 1.5$.

Figure 3: Screen shots from the simulation of a plane wave impinging onto an orifice. Left: low frequencies, right: high frequencies.
4 MORE ADVANCED EXAMPLES

The real power of numerical simulation is in its capability to tackle problems with complicated geometry. Below, Lamda’s capabilities are illustrated with two just slightly more advanced examples.

4.1 Radiation from an unvented loudspeaker box
In one experiment, students at IHA are requested to measure the directivity of a loudspeaker in an unvented cubic box (20 cm side length). In order to aid the interpretation of the measured results, a Lambda simulation is used to visualize the diffraction around the box, see fig. 6, which corresponds well to the measured results.

4.2 Head scattering
As another example, the acoustics of directional hearing is illustrated in the simulation in fig. 7. A point source in the vicinity of the head produces a complicated scattering field around the head. The shadowing effect of the head can be observed as well as ear canal resonance effects.

5 CONCLUDING REMARKS

In this paper, IHA’s open-source 2D TLM package Lambda is presented, along with examples covering some of the topics of an introductory course on acoustics. The *.sim
Figure 6: Simulation of sound radiation (at 1 kHz) from an unvented loudspeaker box (0.2 × 0.2 × 0.2 m$^3$). The waves diffracted around the box interfere in the rear of the box.

Figure 7: Screen shot of a simulation of a point source (3 kHz) in the vicinity of a listener’s head. Both the $\lambda/4$-resonance of the ear canals and the shadowing effect of the head are clearly seen.

Files of all simulation examples shown here can be obtained by sending an email to the author. Further work is needed to provide better absorbing boundaries, or impedance boundaries in general, and to provide velocity sources.

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References


