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SIDLAB: NEW 1D SOUND PROPAGATION SIMULATION SOFTWARE FOR COMPLEX DUCT NETWORKS

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Abstract

Low frequency sound generation and propagation in duct and pipe systems is important in many applications. The examples range from ventilation systems to IC-engine exhaust and inlet systems. Plane wave two-port theory can be used to describe the sound transmission along the system. Based on a long experience of different applications, a new user-friendly software (SIDLAB) has been developed to meet today's engineering needs. The new software is MATLAB based and allows access to the source code. This gives the user a flexibility to do other calculations than those already defined and further post-process the data. SIDLAB includes typical two-port elements for many applications but also unique elements, e.g., for modelling devices for exhaust gas cleaning. It is also unique that the two-port elements are allowed to be active, i.e., contain sources. There is no limitation to the number of elements and they can be connected together in any arbitrary scheme. By introducing one-port elements, the network can handle several inlets and outlets. SIDLAB can simulate passive results, such as transmission loss and transfer matrices between arbitrary nodes (points) in the network. It can also simulate active results, such as pressure and sound power at each node in the network. In this paper an overview of the new software is presented together with an example of the analysis of a complex muffler.

INTRODUCTION

In many applications where acoustic waves propagate inside ducts, the duct cross-sectional dimensions are small compared to the frequency of interest. These applications range from ventilation systems, hearing aids, to IC-engine exhaust and inlet systems. This fact leads to the assumption of the propagation of plane waves inside the duct system, which offers a good simplification of the problem. During the course of the design of such systems, there is a need to simulate sound generation and propagation along different paths inside the system. Several codes were developed by universities to simulate this problem. Some examples are: Davies [1], LAMPS [2], and SID [3].

Based on the experience of using two-port codes for many years, a new user-friendly software was developed to meet today's engineering needs. The new code is based on the old SID 3.0 developed at MWL/KTH [3]. It is MATLAB based with available access to the source code.

THEORETICAL METHODOLOGY AND ELEMENTS DESCRIPTION

Duct systems or networks are often too complicated to enable direct solution of the governing equations. One method to describe the sound transmission along the system is called the building block method or two-port transfer matrix method. This method splits the system into several smaller duct parts, acoustic elements, in which the sound propagation is well defined. Plane waves are assumed to propagate between different elements and the sound field can be characterized by two state variables. One convenient choice is to use pressure and volume velocity. The sound propagation inside each element is analyzed separately and higher order modes can exist inside the element.

There exists a complex 2 x 2 matrix **T**, one for each frequency, which completely describes the sound transmission within this element. The pressure and volume velocity on each side of the element can be related with the following expression

$$\begin{bmatrix} p_1 \\ q_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \cdot \begin{bmatrix} p_2 \\ U_2 \end{bmatrix} + \begin{bmatrix} p^s \\ q^s \end{bmatrix} \tag{1}$$

where p and q are the pressure and volume velocity, 1 refers to the inlet side and 2 refers to the outlet side, T_{ii} are the elements of the two-port transfer matrix, p^s is the source pressure and q^s is the source volume velocity.

The definition of a one-port element is that it can only affect the network through one opening (port). It is usually connected to a single node, i.e., a connection point between two elements (two-ports) in a network. A one-port connected to a node can be completely described by the source acoustic impedance and the source strength (constant pressure source). The pressure over the node can be written as

$$p = p^s - z_s q \tag{2}$$

where p^s is the source strength and z_s is the source impedance. If no one-port element is connected to a node, it is supposed to be an ideal node with zero source strength and infinite impedance.

After all the elements in a network are generated, they are connected to each other as defined by the network structure and the sound propagation in the complete duct system can be analyzed. If the elements are connected in cascade ("a chain"), the problem is simple and the transfer matrix for the system is the result of the successive multiplication of the transfer matrices of all elements. If the elements are connected in an arbitrary fashion, the analysis developed by Glav & Åbom [4] is used to set up a global network matrix.

There are a number of elements which are included as standard elements within SIDLAB. Standard elements can be one- or two-ports. The available elements in the present version are described below:

Standard Two-Port Elements

Pipe: The hard-walled pipe can be found in many applications. It is defined by its length and cross-sectional area. The transfer matrix can be easily deduced for this element using basic equations. The effects of viscous and turbulent damping are taken according to Allam & Åbom [5]. It can be filled with porous material whose properties are calculated based on Delany and Bazley [6].

Horn: This is a smooth expansion or contraction in a flow duct where any effects of flow separation are assumed negligible. The model is based on dividing the horn into a number of small straight pipes whose cross-sectional areas vary from the inlet area to the outlet area.

Quarter Wave-Length Resonator: The resonant behaviour is generated by the incident wave reflected at the closed end of the resonator which generate a "zero" impedance condition at the resonator inlet at certain frequencies. At these frequencies the resonator "blocks" sound propagation in the duct to which it is connected by "total" reflection. The resonator is defined by its length, cross-sectional area, and the impedance of the closed end. It can be filled with a porous material.

Helmholtz Resonator: A popular device due to its compactness. It is the acoustical counterpart of the mechanical mass-spring system. It is defined by its volume ("spring"), and neck properties ("mass"), length, area, and resistance.

Catalytic Converter: A catalytic converter is used to decrease the contents of harmful exhaust gases, mainly CO, HC, and NO_x, from internal combustion engines. The key element in a typical catalytic converter is the honeycomb structure which comprises a large amount of parallel coated capillary pipes. It is defined by its length, diameter, wall thickness and the cells per square inch which gives an indication of the porosity. This model is based on [17].

Diesel Particulate Filter (DPF): DPFs are used in the exhaust system of diesel engines in order to reduce the harmful emission of soot particles. The model is based on Allam & Åbom [8]

Lined Duct: This is a duct lined with a porous material. The parameters are length of the duct, the inner area of the empty duct, and the area of the outer hard envelope enclosing the porous material. The model is based on Aurégon [9].

Area Expansion and Area Contraction: These elements represent a sudden change in the cross section area of a flow duct. The analysis is rather complicated in the case of superimposed mean flow. They are defined by the inlet area, outlet area, and the length of the extended smaller pipe. The effects of higher modes are taken care of by using Karal's end correction [10].

Expansion Chamber: This is a conventional expansion chamber with concentric extended inlet and outlet. All walls but the end plates, which can be given a wall impedance, are assumed to be hard. The effects of mean flow are neglected whereas higher order modes are included. The model is based on Ref. [11]

Area Constriction: This simulates the acoustic losses resulting from an area constriction in the flow duct.
Lumped Elements (Inline or shunted): These elements introduce impedance to the flow duct. Example of an inline element is flow through a perforated plate, and a shunted element is Helmholtz resonator.
Perforate: This is a special case of a lumped element. The lumped impedance is calculated based on the dimensions of the perforate: thickness, porosity, hole diameter, grazing and through flow, and total area. The used model is based on the expressions developed by Elnady and Bodén [12]. A number of perforated elements can be grouped together to model a four-port perforated pipe. The details of such techniques are described by Elnady and Åbom in Ref. [13].
User Defined: This is an element where the user can specify the four elements of the transfer matrix as a function of frequency and store it in a file with a supported format.

Standard One-Port Elements

Reflection Free: This is a termination with no reflections (impedance is equal to $\rho_0 c/A$).
Free Space: This is an open end of an unflanged pipe termination to free space. The impedance is calculated using the expressions proposed by Levine & Schwinger [14] for the no flow case. When there is flow going out of the system, the impedance is modified by Hofmans [15].
Baffle: This is the same as the last element but the open pipe is flanged. The impedance is calculated by expressions given by Pierce [16].
Constant: This is a one-port with constant impedance at all frequencies. A chosen real and imaginary, normalised, number is given.
User Defined: This is an element where the user can specify an impedance as a function of frequency and store it in a file with a supported format.

Active Sources [17]

For each element, one- or two-port, you can define a source strength to be applied at the node connected to the element. For one-port elements, the source strength is applied to the node to which the element is connected. For two-port elements, you can define inlet source strength to be applied at the inlet node, or outlet source strength to be applied at the outlet node, or both. The sources in a network can be either correlated or uncorrelated. They are arranged in correlation groups, each containing a number of sources, all correlated within the group, but uncorrelated with other elements in other groups. Both two-ports and one-ports can belong to the same correlation group. For two-port elements, it is assumed that the inlet and outlet are always correlated with each other. A correlation group contains at least one element.

Non-Standard Elements

If you have a new element that you want to include in the calculations, you can do it in one of two ways:

1. If you are using this element once, you can use include it as a User Defined Element in one of the supported formats. These are MATLAB function (.m), MATLAB file (.mat), or ascii file.
2. If you plan to use this element frequently, you can add a standard element to SIDLAB.

The process of adding a new standard element is done on two steps. The first is to add the element in Element Edit (***Figure 1***). This includes defining the element name, type, properties, default values, and the pictures it uses. The second is to write the code which calculates the properties of this element and save it in a (.m) file. The format of this file depends on the type of this element, either one- or two-port element. This file is called by the main program; therefore, it should follow certain guidelines in order to be successfully integrated.

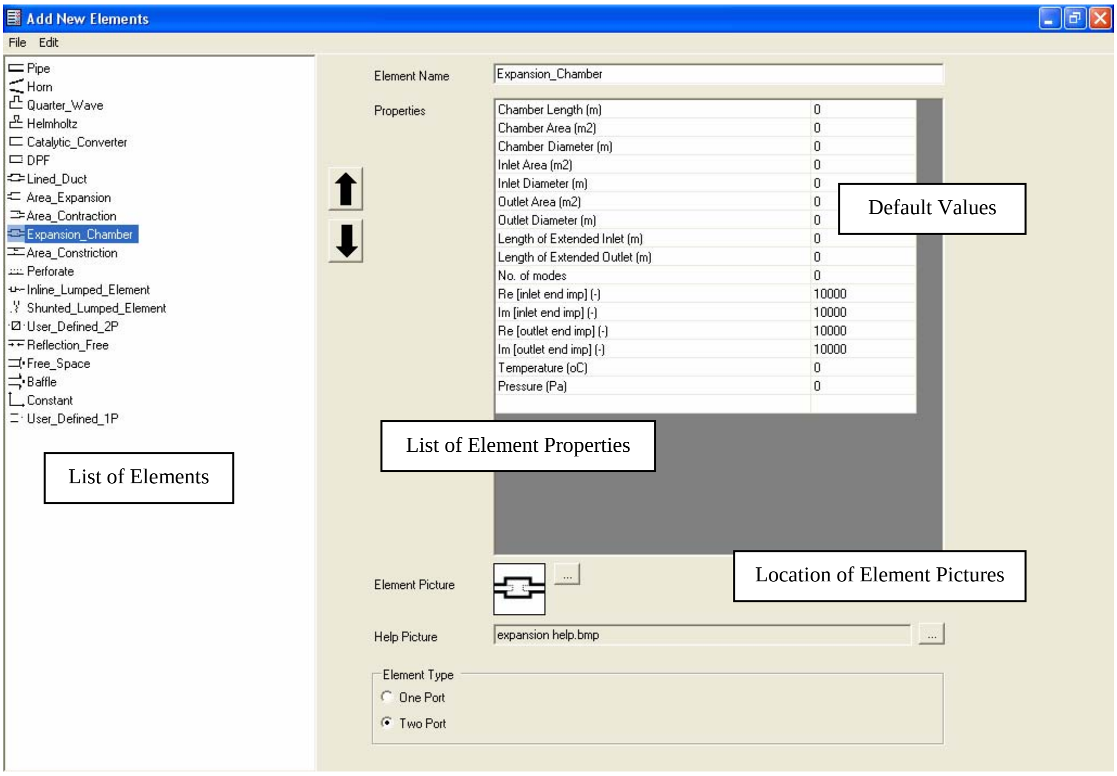

Figure 1 – The Elements Window

DESCRIPTION OF THE SOFTWARE

SIDLAB is based on the idea of project files. When you start a new project, all variables and results are saved in a single (.sid) file which is compatible with MATLAB. This file can be later opened in MATLAB for any non-standard post processing. You can re-open this file in SIDLAB and you restore your working environment with all variables set, exactly as you saved it the last time.

In the main SIDLAB window (***Figure 2***), the user starts by defining the global variables of the system such as frequency range, step, temperature, static pressure, and inlet mass flow. The temperature, static pressure, and mass flow can be later changed for any element in the network if necessary. The second step is to build the network from the available elements in the Layout window (***Figure 3***).

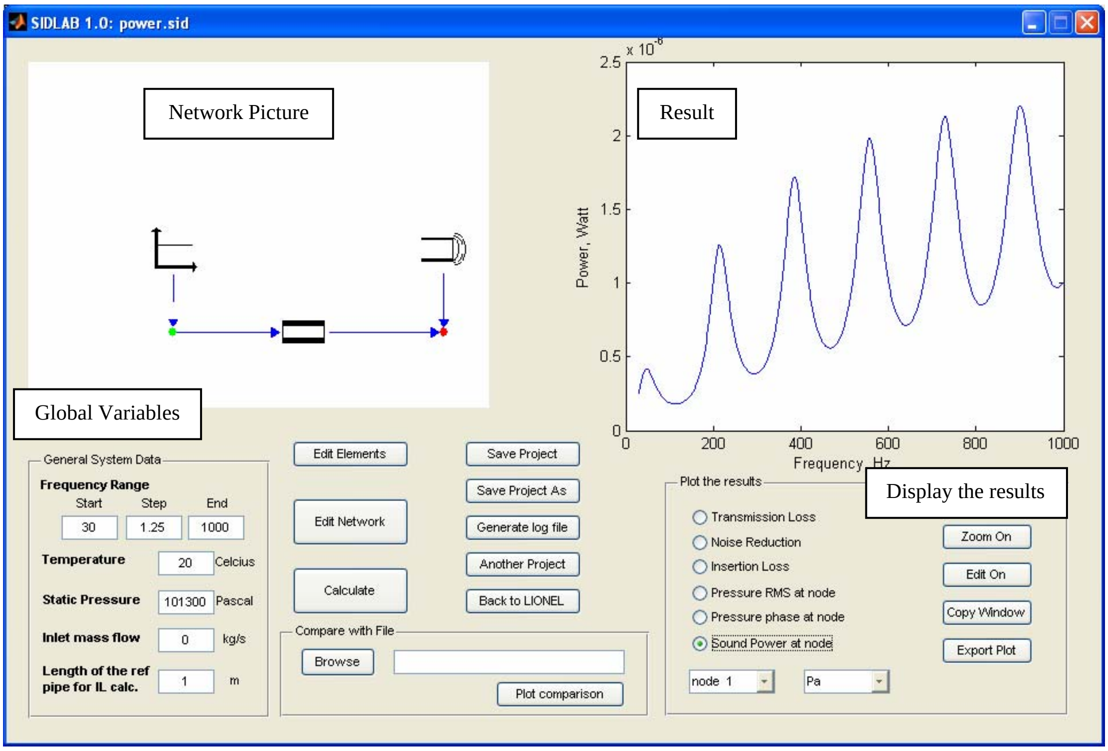

Figure 2 – Main window of SIDLAB

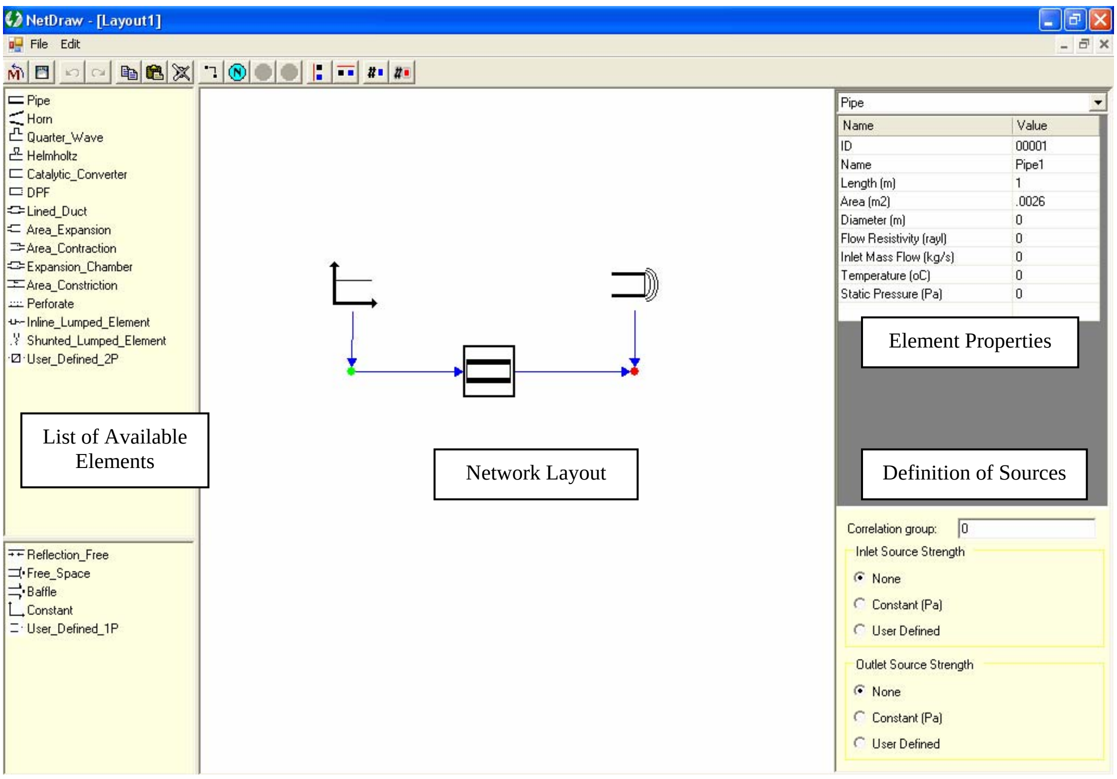

Figure 3 – Window for drawing or editing a network

The user simply drags and drops the required element in the network layout area. The properties of each element are defined in the right upper pane. The active sources are defined in the right lower pane. A number of useful viewing tools are available: zoom, pan, and element alignment.

The third step is to view the results of the simulation. There is a number of standard calculated parameters that the user can choose from: Transmission Loss, Noise Reduction, Insertion Loss, amplitude and phase of the acoustic pressure at each node, and the acoustic net power flow through a certain node.

There is a possibility to generate a log file which stores all input parameters and variables of the project in a text file for easy access. A (.bmp) picture of the network is also available in the project directory to be included in reports. You can easily manipulate plots the same way you are used to in MATLAB. You can easily export any plot to any other Windows application. You can compare the results of this project to any simulation or measurement result you have earlier.

TEST CASE

An example of a complicated muffler system is presented here. *Figure 5* shows the sample resistive reactive multi-chambered muffler under test. *Figure 4* shows the breakdown of the muffler into two-port elements.

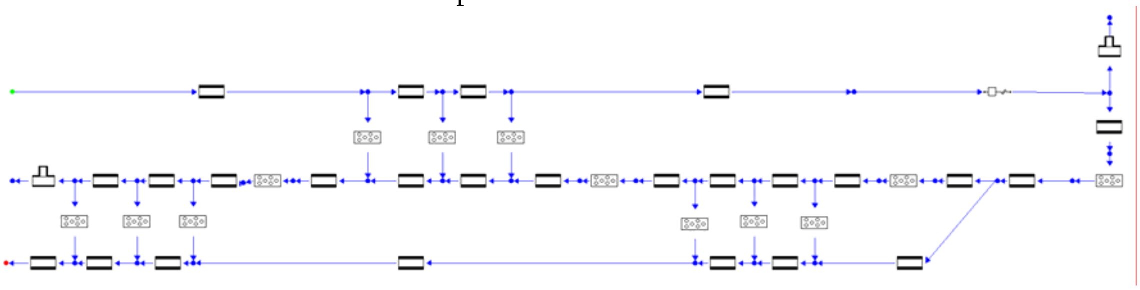

Figure 4 – The SIDLAB network for the test muffler.

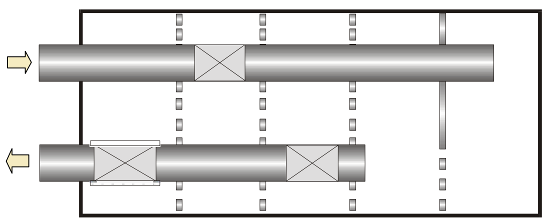

Figure 5 – The test muffler

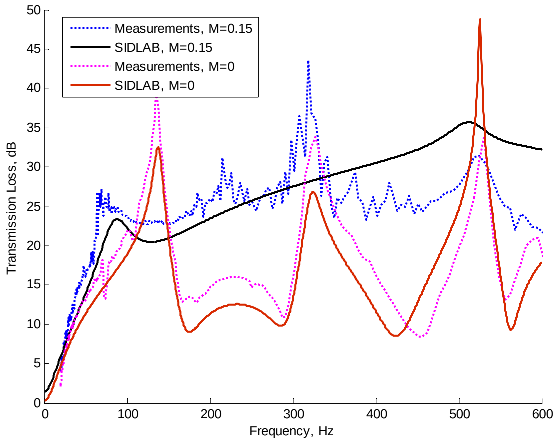

Figure 6 – Comparison of the TL

Figure 6 shows a comparison between the measurements and the SIDLAB simulation. The agreement is good for the no flow case. The main reason for the less good agreement with flow above 330 Hz is that the magnitude and spatial distribution of the flow related losses are not modelled with sufficient accuracy. The flow distribution was only estimated using a simple 1D flow model which is probably not sufficient.

CONCLUSION

A new 1D sound propagation simulation software for complex duct networks was developed. It is based on the tow-port theory and compiles the experience and knowledge of using similar codes for years. It is MATLAB based with possible access to the source code. Building the network is easy by simply dragging and dropping different elements. Definition of active sources is possible and easy to implement. A number of the most common one- and two-port elements are included using the latest models that are available in the literature. The user has the possibility to add his own standard models. Calculation time is typically a few seconds on a normal PC. Post-processing within SIDLAB is simple and straightforward, with the possibility to save the results in different formats.

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