Manual for *Theory_1D.py*

a computer program for
predicting reflection coefficients for wave absorbing layers
in (hydro-)acoustic flow simulations

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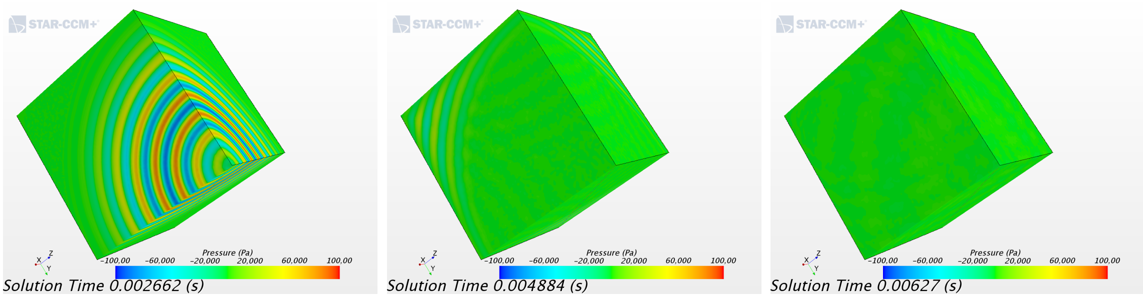


Contents

1 One-minute-explanation of the code

When to use this code?

- You use a flow solver capable of simulating complex non-linear flows (e.g. finite-volume-based solvers for the compressible Navier-Stokes equations, like ANSYS Fluent, Siemens STAR-CCM+, OpenFOAM, etc.)
- You want to simulate pressure wave propagation
- You want to minimize undesired wave reflections at the domain boundaries
- To do so, you want to use an *absorbing-layer-type approach*

When to use absorbing layers?

- You want to quickly implement a simple reflection-reducing boundary treatment or ...
- ... an absorbing-layer-type approach is already implemented in your code (this often is the case)
- You do not have more efficient alternative techniques available (especially for simple flows or simpler governing equations, there exist a variety of alternatives[1])

What does the code do?

- The user can enter wave period, speed of sound, absorbing layer thickness and blending function
- The code calculates reflection coefficient C_R for various forcing strengths γ according to [2] and writes these results to the file $'\mathrm{C_R.csv}'$ in the same folder
- If matplotlib is installed: A window will open with an interactive plot of C_R over γ
- Thus the code can be used to quickly fine-tune the case-dependent absorbing layer parameters

Requirements:

- Check that your absorbing layer can be formulated in terms of Eq. (1)
- Install *python* programming language
- For full functionality, install *matplotlib*
- Operating systems: Linux, macOS, Windows

Tuning absorbing layers:

- Use higher order blending functions such as Eqs. (4) to (6)
- Increasing the layer thickness x_d widens the range of wavelengths which will be damped satisfactorily, and lowers the reflection coefficient for the optimum setting
- Often confidence in reflection absorption is more important than the last few percent efficiency $\Rightarrow$ use slightly thicker layers than necessary
- Typical values for layer thickness are $1\lambda \leq x_\mathrm{d} \leq 4\lambda$
- For irregular waves, tune the layer to the peak period or the longest period (quick approach) or calculate the reflection coefficient for each wave component's period and then tune accordingly (more accurate approach)

Benefits and Limitations:

- The code gave satisfactory predictions for a wide range of flow problems (1D-3D, regular/irregular waves, oblique incidence, different sound pressure levels)
- However, for highly non-linear waves, such as shocks or distorted waves, reflection may be larger than predicted
- Undesired reflections can also be due other mechanisms, e.g. the use of inappropriate grids
- Therefore, tuning the absorbing layer parameters according to this code does NOT guarantee that the actual reflection coefficient in the simulation will equal the prediction

2 Requirements

The programming language python version 2.7 or 3.0 or higher (`https://www.python.org/downloads/`) must be installed.

It is recommended to also have matplotlib (`https://matplotlib.org/users/installing.html`) installed. Then the code will open a window with an interactive plot of the results.

3 Theory and code description

3.1 Motivation and theory behind the code

Absorbing layers (sponge layers, damping zones, forcing zones, ...) can reduce undesired wave reflections at boundaries of the computational domain. However, the absorbing function contains user-defined parameters; these parameters are case-dependent and must be tuned for every simulation. Otherwise strong reflection may occur.

The present code can guide the tuning of these case-dependent parameters. The code is an implementation of the 1D-theory from [2].

In [2], a theory was presented which predicts the reflection coefficient for a given absorbing layer setup. The reflection coefficient C_{R} is the ratio of the reflected wave amplitude to the incidence wave amplitude. Thus the theory can be used to tune the case-dependent parameters *before running the simulation*. The theory preditions were shown to be of satisfactory accuracy for many practical applications (1D-, 2D- and 3D-flow, regular and irregular waves, oblique wave incidence, different sound pressure levels). The theory was given for the 1D-, 2D- and 3D-case; however, for most practical purposes the 1D-theory turned out to be sufficient and easier to use. Thus the 2D- and 3D-theory are not implemented in the present code; implementations can be requested from the author. Please see [2] to find out if and how the theory applies to the absorbing layer implementation that you use.

The theory in [2] was derived so that it works for any continuous or discontinuous blending function. A few common blending functions are already implemented. Custom blending functions can be entered at the location indicated in the source code.

3.2 Introduction to absorbing layers

The theory in [2] is based on the following general absorbing layer formulation, which applies to many existing absorbing-layer-type approaches. Set in the right-hand side of the (compressible) Navier-Stokes equations as source term

$$q_{\mathrm{i}} = \gamma b(x) \left(u_{i,\mathrm{ref}} - u_i\right) \quad , \tag{1}$$

with reference velocity component $u_{i,\mathrm{ref}}$, velocity component u_i, forcing strength γ and blending function $b(x)$. Outside the absorbing layer holds $q_{\mathrm{i}} = 0$. Let the reference solution be the medium at rest, so $u_{i,\mathrm{ref}} = 0\,\frac{\mathrm{m}}{\mathrm{s}}$.

The forcing strength γ with unit $\left[\frac{1}{\mathrm{s}}\right]$ regulates how strong the solution at a given cell is forced against the reference solution.

The blending term $b(x)$ regulates the distribution of the source term over the domain, where x is the wave propagation direction. Many different types of blending functions can be applied. The following common choices are implemented in the code: Constant blending

$$b(x) = 1 \quad , \tag{2}$$

linear blending

$$b(x) = \frac{x - x_{\mathrm{sd}}}{x_{\mathrm{ed}} - x_{\mathrm{sd}}} \quad , \tag{3}$$

quadratic blending

$$b(x) = \left(\frac{x - x_{\mathrm{sd}}}{x_{\mathrm{ed}} - x_{\mathrm{sd}}}\right)^2 \quad , \tag{4}$$

cosine-square blending

$$b(x) = \cos^2\left(\frac{\pi}{2} + \frac{\pi}{2}\frac{x - x_{\mathrm{sd}}}{x_{\mathrm{ed}} - x_{\mathrm{sd}}}\right) \quad , \tag{5}$$

or exponential blending such as

$$b(x) = \left(\frac{e^{\left(\frac{x - x_{\mathrm{sd}}}{x_{\mathrm{ed}} - x_{\mathrm{sd}}}\right)^2} - 1}{e^1 - 1}\right) \quad , \tag{6}$$

with start coordinate x_{sd}, end coordinate x_{ed}, and thickness $x_{\mathrm{d}} = |x_{\mathrm{ed}} - x_{\mathrm{sd}}|$ of the absorbing layer. These blending functions are illustrated in Fig. 1. Though so far the optimum blending function is not known, several investigations showed that higher order blending functions are more effective than constant or linear blending.

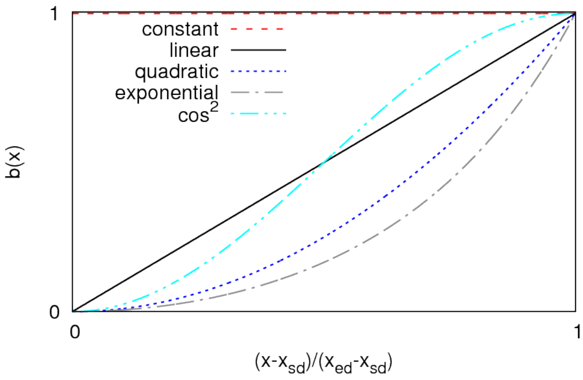


Figure 1: Different blending functions $b(x)$ over location in absorbing layer

As shown in [3], parameters γ and x_d scale with angular wave frequency ω and wavelength λ as

$$\gamma \propto \omega \quad , \quad x_\mathrm{d} \propto \lambda \quad . \tag{7}$$

Therefore these parameters must be tuned for every simulation; as [2] shows, there is not one configuration that fits all wave problems.

3.3 Benefits and limitations

The code gave satisfactory predictions for a wide range of flow problems (1D-3D, regular/irregular waves, oblique waves, different sound pressure levels). It is easy to use and requires low computational effort; even on older computers, predictions are calculated within seconds.

Although the code's predictions are often quite accurate [2], please keep in mind that every theory has its limitations! For highly non-linear waves, such as shocks or distorted waves, reflection may be larger than predicted. This can also be the case when the wave source is positioned very close to the absorbing layer and if the emitted sound intensity varies substantially with propagation direction. Further, undesired reflections can be due other mechanisms as well, e.g. the use of inappropriate grids. Therefore, tuning the absorbing layer parameters according to the present theory does NOT guarantee that the actual reflection coefficient in the simulation will equal the prediction. See [2] for a detailed discussion.

3.4 Recommendations for tuning absorbing layers

The use of higher order blending functions such as Eqs. (4) to (6) is recommended. Constant or linear blending, i.e. Eqs. (2) to (3), are generally less efficient, meaning that to obtain the same reflection coefficient they require greater layer thickness and thus also greater computational effort. Currently it is not clear which blending function is the best choice: Although blending functions in Eqs. (4) to (6) look different, the differences in wave absorption between them was comparatively small, with perhaps a slight preference towards exponential blending[2].

Increasing the layer thickness x_d widens the range of wavelengths which will be damped satisfactorily, and lowers the reflection coefficient for the optimum setting; thus if the wave absorption is not satisfactory, then layer thickness x_d should be increased.

Although for regular waves it may be possible to achieve satisfactory damping with layers as thin as $x_{\mathrm{d}} \approx 0.5\lambda$, such thin layers should be avoided or at least used with caution, since then the reflection coefficient is very sensitive to the wave parameters.

In engineering practice, usually confidence in wave absorption is more important than the last few percent efficiency. Therefore it is recommended to use layer thicknesses x_{d} slightly larger than possibly necessary. Typical values are $1\lambda \leq x_{\mathrm{d}} \leq 2\lambda$.

For irregular waves, a quick approach is to tune the layer to the peak period or the longest period[3]. A more accurate approach is to calculate the reflection coefficient for each wave component's period and in this manner tune the layer parameters accordingly.

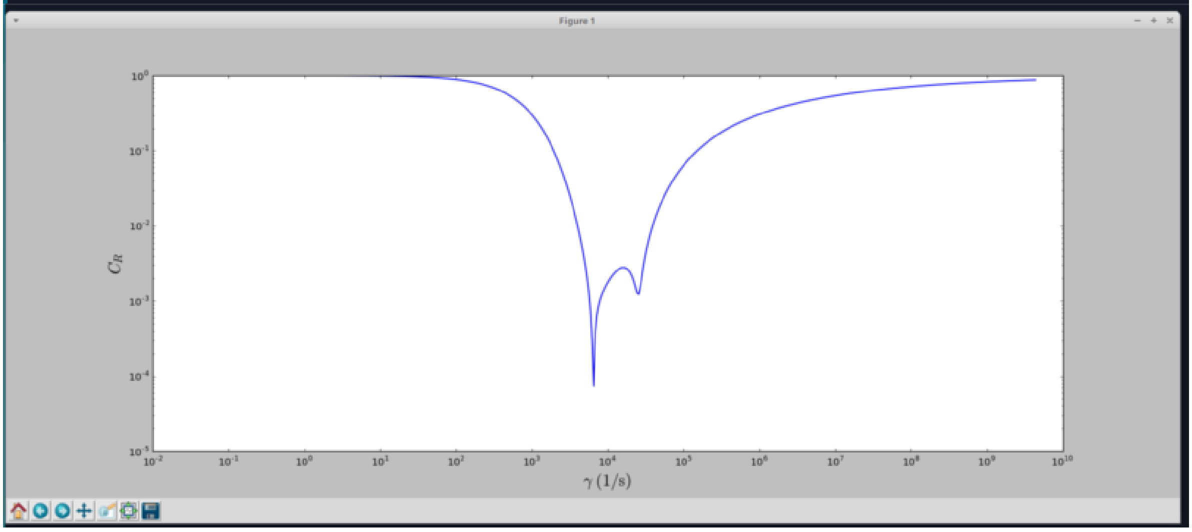
4 How to run the code

In windows, double click on the executable file *Theory_1D.py*.

In Linux and macOS, open a terminal and type:
python Theory_1D.py

Example output:

```
python Theory_1D.py


Please enter wave period (s):
0.002272727

Please enter speed of sound (m/s):
340

Please enter layer thickness per wavelength (enter 2 if thickness = 2 * wavelength):
2

Available blending functions are:
Constant blending: 1
Linear blending: 2
Quadratic blending: 3
Cosine**2 blending: 4
Exponential blending: 5
Custom blending: 6

Please enter number of desired blending function:
5
```



5 Reporting bugs

So far, no bugs are known.

If you find bugs, or if you have questions or suggestions, please contact the author:

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The code is available at
`https://github.com/wave-absorbing-layers/pressure-wave-absorption`
Updates and further useful information will be posted there as well.

6 Copyright

7 References

[1] T. Colonius and S. K. Lele. "Computational aeroacoustics: progress on nonlinear problems of sound generation." Progress in Aerospace sciences, 40, 345-416 (2004).

[2] R. Perić. "Analytical Prediction of Reflection Coefficients for Wave Absorbing Layers." Preprint, arXiv:1705.06937 [physics.flu-dyn], (2017).

[3] R. Perić and M. Abdel-Maksoud. "Reliable damping of free-surface waves in numerical simulations." Ship Technology Research, 63, 1, 1-13 (2016).