AVSP_V1.8.3 handbook

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Introduction

AVSP is a tool for acoustic analysis in 3 dimensional configurations. Two kinds of results are provided by this code: eigen frequencies (the number is fixed by user) of the configuration and spatial structure of the corresponding eigenmodes via acoustic pressure and acoustic speed.
This code has been built from the LES code AVBP and borrows some of its characteristics, in particular AVSP is a parallel code. Since the study of low/medium frequency instabilities do not required refined meshes, eigenmodes of large configurations can be computed in a reasonable time thanks to the parallelism of AVSP. The formulation used in AVSP can also take into account the inhomogeneities of mean temperature but influence of active acoustic flames can not be studied with this version. To facilitate the acoustic analysis of LES simulations, the mean field used as input in AVSP can be an AVBP solution file.

The current document deals with the main features of the code.
First, the general principle is described. The formulation of the eigenvalue problem used and some numerical aspects of AVSP are developped.
Second the using of AVSP is detailed. This part includes a description of the input files and the output resulting files.
Finally, two examples of application are described. The input files on this examples are detailed and the results explained.

Contents

Chapter 1

Principle of AVSP

1.1 Governing equations

The acoustic problem in AVSP is modelled with the following assumptions:

- Low Mach number flow.
- Volumic forces neglected.
- Small acoustic fluctuations (linear acoustics).
- Constant mean pressure P_0 in the whole configuration.

In these conditions, a generalized wave equation can be developped:

$$\nabla.(c^2 \nabla p') - \frac{\partial^2 p'}{\partial t^2} = 0 \tag{1.1}$$

In this equation, p' stands for the acoustic pressure and c corresponds to the mean speed of sound.
The relation 1.1 can be obtained by linearizing Euler equation and energy equation in the same way as performed by Poinsot and Veynante in the chapter 8 of their book ([7]). The variations of the mean temperature are taken into account in this equation via the speed of sound. These variations can be generated by a flame but this flame is not considered active in the current version of AVSP.

Assuming harmonic waves, spatial and temporal fluctuations may be decoupled by writing:

$$p' = Re(\hat{p} e^{-i\omega t}) \tag{1.2}$$

The variable ω represents the radial frequency. This formalism used in the relation 1.1 yields to a Helmholtz-like equation:

$$\nabla.(c^2 \nabla \hat{p}) + \omega^2 \hat{p} = 0 \tag{1.3}$$

Finding the eigen frequencies ω and the eigen vectors $\hat{p}$ which verify the relation 1.3 and the boundary conditions chosen is the purpose of the code AVSP.

1.2 Eigenvalue problem

Discretizing the equation 1.3 and taking account of the boundary conditions (numerical aspects of this operation will be detailed in the part 1.4) yield to the following matricial eigenvalue problem:

$$A.\tilde{p} = -\omega^2.\tilde{p} = \lambda.\tilde{p} \tag{1.4}$$

In the relation 1.4, $\tilde{p}$ is a vector and stands for the discretized acoustic pressure. In addition, the operator "$\nabla.(c^2\nabla(\,))$" and the boundary conditions are included in the matrix A. The choice of the method to solve this eigenvalue problem has to consider the two following characteristics:

- The method has to be able to find several eigen frequencies and their corresponding eigen vectors.
- For computing efficiency and space storage reasons, the method must not require the explicit knowledge of the matrix A.

Under these considerations, Arnoldi method has been retained in AVSP. The principle of this method is detailed in the books of Golub and van Loan ([3]) or Lascaux and Theodor ([4]). Several eigen values and their eigen vectors are evaluated from iterations of the matrix A on a vectorial subspace. This subspace is, at the begining, associated with a Krylov basis generated from a given vector (random in AVSP). Thanks to a special algebraic treatment including an orthogonalization of the basis, this subspace can converge to the eigen subspace associated with the smallest eigenvalues or the greatest eigenvalues in magnitude. The number of eigen modes to find and the type of research (greatest eigenvalues or smallest eigenvalues) are fixed by the user. In the thermo-acoustic problem, only the first eigen modes are seeked, as a result Arnoldi method will be mainly used in AVSP to find the smaller eigen values.
A parallel version of the Arnoldi method is implemented in AVSP via the ARPACK/PARPACK library. This tool is a freeware developped by R.B. Lehoucq, D.C. Sorensen, C. Yang ([5]).

1.3 Boundary conditions

Three kinds of boundary condition are available in this version of AVSP:

- Null acoustic pressure: $\hat{p} = 0$.
- Null acoustic speed relatively to the normal $\vec{n}$ of the face where the boundary condition is applied: $\vec{\hat{u}}.\vec{n} = 0$.
- Admittance: $\frac{1}{Z} = \frac{\rho c \vec{\hat{u}}.\vec{n}}{\hat{p}}$

Because of the "pressure formulation" chosen in the fundamental equation 1.3, the first boundary condition ($\hat{p} = 0$) can be considered as a Dirichlet condition and the second boundary condition ($\vec{\hat{u}}.\vec{n} = 0$) can be seen as a von Neumann condition. Indeed, by using the linearized Euler equation (equation 1.5), it can be proved that a null acoustic speed is equivalent to a null acoustic pressure gradient (equation 1.6).

$$i\omega\rho_0\vec{\hat{u}} = \nabla\hat{p} \tag{1.5}$$

$$\vec{u}.\vec{n} = 0 \Longleftrightarrow \nabla\hat{p}.\vec{n} = 0 \tag{1.6}$$

The admittance boundary condition requires a specific treatment. By using equation 1.5 it yields:

$$\nabla\hat{p}.\vec{n} = \frac{i\omega\hat{p}}{cZ} \tag{1.7}$$

As a consequence, this boundary condition type is dependent from the frequency which is the eigenvalue of the problem. The formulation used in equation 1.4 has then to be modified, the new eigenvalue problem obtained is now:

$$A.\tilde{p} + \omega C_Z.\tilde{p} + \omega^2 I.\tilde{p} = 0 \tag{1.8}$$

In equation 1.8, $A.\tilde{p}$ represents the part of “$\nabla.(c^2\nabla(\tilde{p}))''$ calculated from the interior domain and from the dirichlet or von Neumann boundaries whereas $\omega C_Z.\tilde{p}$ represents the part calculated from the admittance type boundaries. The eigenvalue problem is not anymore linear but still polynomial so the following treatment can be applied (see [1]):

$$M.y = \omega y \tag{1.9}$$

Where y vector and matrix M size are twice the size of respectively $\tilde{p}$ and A and are defined as follows:

$$M = \begin{pmatrix} -C_Z & -A \\ I & 0 \end{pmatrix} \tag{1.10}$$

$$y = \begin{pmatrix} \omega\tilde{p} \\ \tilde{p} \end{pmatrix} \tag{1.11}$$

This means that the time to evaluate eigenmodes of a configuration with admittance type boundary conditions will be at least the double of the time required for the same geometry but without admittance type boundary conditions.

1.4 Numerical method

1.4.1 Interior nodes

This part deals with the numerical formulation of the operator “$\nabla.(c^2\nabla(\ ))$”. The numerical method used in AVSP is inherited from AVBP methods. It is a cell-vertex finite volume method of order 2. In 2D on triangular cells and, in 3D on tetrahedradric cells, it can be proved (see [2]) that this method is equivalent to a finite element approach.

As it was explained in the part 1.2, Arnoldi method requires iterations of the numerical operator from which eigenmodes are searched. As a result, the basic operation in AVSP is the numerical evaluation (at the nodes) of $\nabla.(c^2\nabla(\tilde{p}))$ with a given acoustic pressure field $\tilde{p}$ and a speed of sound field c calculated from the input files. In order to only calculate physical eigenmodes and suppress “wiggle” modes, the numerical method uses a 4-δ stencil. To help the understanding, the operations implied in this approach are detailed on a given group of adjacent cells.

The first stage consists in evaluating the quantity $\nabla\tilde{p}$ at the center of the cells. To reach this goal, a numerical Gauss integration is performed on the mesh, in particulary on the cell Ω_1 of the figure 1.1 as:

$$(\nabla\tilde{p})_{\Omega_1} = \frac{1}{N_d V_{\Omega_1}} \sum_{i\in\Omega_1} \tilde{p}.\vec{dS_i} \tag{1.12}$$

In the relation 1.12, N_d represents the number of space dimensions and V_{Ω_1} stands for the volume of the cell Ω_1. As it is explained in the AVBP handbook [8], in this formulation the geometrical information has been factored into terms $\vec{dS_i}$ that are associated with individual nodes of the cell, and not faces i.e. $\vec{dS_i}$ is merely the average of the area-weighted normals for triangulated faces with a common node $i \in \Omega_1$.
Since the operator's expression implies the sound speed c, the value of this variable at the centre of the cell is also needed hence:

$$c_{\Omega_1} = \frac{1}{n_{\Omega_1}} \sum_{i\in\Omega_1}^{n_{\Omega_1}} c_i \tag{1.13}$$

With n_{Ω_1} the number of nodes in the cell Ω_1.

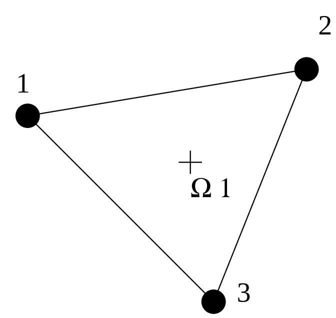

Figure 1.1: Cell on which $\nabla\tilde{p}$ is calculated.

Once these stages are achieved, the evaluation of $\nabla.(c^2\nabla(\tilde{p}))$ is possible. To get this value at the node 1 of the example, the operation is performed on a sort of "virtual" cell Ω'_1 as shown by the figure 1.2. The vertices of this cell are the centre of the cells surrounding the node 1 and its volume corresponds to the sum of the third of each surrounding cell. Consequently, the node 1 is the centre of the cell Ω'_1 and the value of $\nabla.(c^2\nabla(\tilde{p}))$ at this point can be deduced from a Gauss integration on the "virtual" cell:

$$(\nabla.(c^2\nabla\tilde{p}))_1 = \frac{1}{N_d V_{\Omega'_1}} \sum_{i\in\Omega'_1} (c^2\nabla\tilde{p})_{\Omega_i}.\vec{dS'}_i \tag{1.14}$$

Again, in the relation 1.14, $\vec{dS'}_i$ represents the normals at the vertices of the cell Ω'_1.

1.4.2 Boundary nodes

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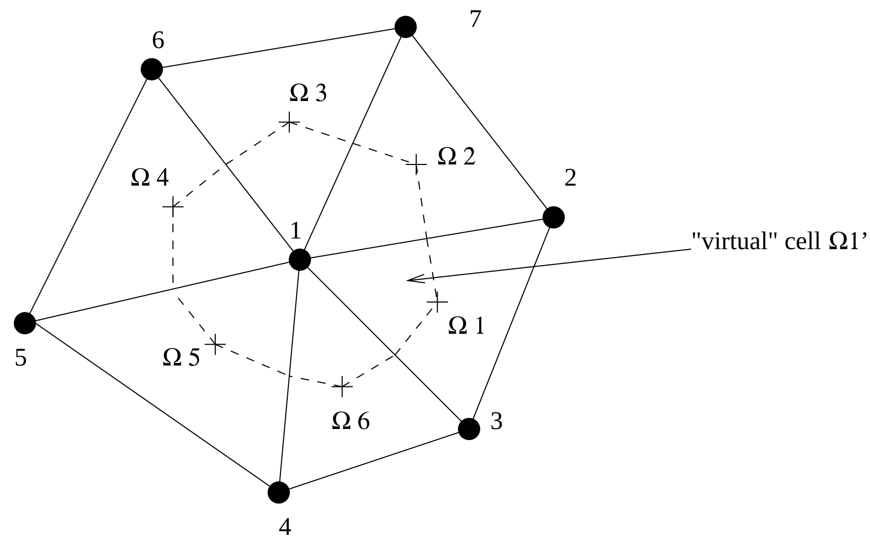

Figure 1.2: Cells on which $\nabla.(c^2\nabla(\tilde{p}))$ is calculated.

Chapter 2

Using of AVSP

2.1 Input files

This section deals with the input files required to use AVSP. Many of them are similar to AVBP input files since many aspects of AVSP are inherited from AVBP. These files can be ordered in different categories: files characterizing the mesh used, files related to parallelism, files describing the mean field, files concerning the boundary condition and finally a command file which recaps on all the features of the run.

2.1.1 Mesh files

These files give the information concerning the mesh used by AVSP. They are completely identical to the mesh files of AVBP so more details are available in the AVBP help guide [8]. As for AVBP, it means that these files are generated by HIP software from the file created by the meshing software. An important feature of the mesh used in AVSP concerned the type of cell: because of the numerical method used in AVSP, **cells must be triangular in 2D and cells must be tetrahedric in 3D**. All the characteristics of the mesh needed by AVSP are contained in the following files:

- The mesh coordinates file “file.coor”.
- The connectivity file “file.conn”.
- The external boundary data file “file.exBound”.
- The internal boundary data file “file.inBound”.

All these files are unformatted.

2.1.2 Partition file

This formatted file is always named “partiton.dat”. It gives the type of partitonning to be used by AVSP and concerns the parallelism of the code. Basic user of AVSP may not modify this file and a standard file will be available in the examples of application.

2.1.3 Mean field files

In AVSP, the mean field is needed to evaluate the speed of sound c in the Helmholtz equation 1.3. In addition, the mean density ρ is required to calculate the corresponding acoustic speed of a given mode with linearized Euler equation (eq. 1.5). This mean field is contained in a file written following the instantaneous solution AVBP_V4.8 file format. The different variables are stored as follows:

- ρ
- ρu
- ρv
- ρw (if 3D configuration)
- ρe
- c (the mean speed of sound)

As it can be seen, the mean speed of sound is stored as an additional variable following the instantaneous solution AVBP_V4.8 file format.

To generate this AVSP mean field file, two ways are possible:
Firstly, this file can be built from an AVBP_V5.x solution by using the preprocessing tool “AVBP2AVSP”. The AVBP_V5.x file can be an instantaneous file or an average file (from AVBP point of view).
Secondly, without AVBP solution file, the AVBP mean field file can be created by the preprocessing tool “AVBP4AVSP_INITSOLUT”. This tool is actually similar to the AVBP preprocessing tool “INITSOLUT”, the only slightly difference between these two tools is the creation of the mean speed of sound as an additionnal variable.

2.1.4 Boundary condition file

The name of this file is of the form: “file.asciiBound”. It specifies for each patch of the configuration the type of boundary condition. The three kinds of boundary condition are selected by keyword:

- “AC_PRESS_NULL” is the keyword associated with the Dirichlet boundary condition:

$$\hat{p} = 0$$

- “AC_SPEED_NULL” is the keyword associated with the von Neumann condition:

$$\vec{\hat{u}}.\vec{n} = \nabla \hat{p}.\vec{n} = 0$$

  Where $\vec{n}$ is the normal to the patch face.

- "AC_ADMITTANCE" is the keyword associated with the admittance condition :

$$\frac{1}{Z} = \frac{\alpha}{\omega} + \frac{1}{Z_0} + \beta\omega \tag{2.1}$$

The keyword "AC_ADMITTANCE" has to be followed by the values of the six parameters introduced in equation 2.1:
Re(α) (must be set to 0.0 in this version of AVSP)
Im(α) (must be set to 0.0 in this version of AVSP)
Re($1/Z_0$)
Im($1/Z_0$)
Re(β) (must be set to 0.0 in this version of AVSP)
Im(β) (must be set to 0.0 in this version of AVSP)

2.1.5 Command file "run.dat"

This file contains the path of all the files needed or produced by AVSP (excepted the "partiton.dat") and specifies the number of eigen modes to find, the type of eigen frequencies to find and the value of the eventual frequencial shift. An example of "run.dat" is available at the part **??**.

Line by line, the meaning of the different entry parameters is the following:
Line 1: file.coor name
Line 2: file.conn name
Line 3: file.exBound name
Line 4: file.inBound name
Line 5: file.asciiBound name (boundary conditions file)
Line 6: mean field file (written in AVBP_V4.7 format)
Line 7: initial acoustic pressure field (always set to "random")
Line 8: eigen file name and also prefix of the eigenmode files name
Line 9: number of eigenmodes to find
Line 10: Type of eigenvalue research (usually set to "SM" which means that the smallest eigen values in magnitude will be searched)
Line 11: Reference length (scales coordinates X by X/reflen)

The remaining lines must not be changed by the user.

2.2 Output files

Two kinds of results are provided by AVSP: the value of the eigen frequencies and the eigen vectors.

The eigen frequencies are contained in the corresponding file specified in the "run.dat".

For each eigen vector, an output file is created. If the name of the file containing the eigen frequencies values is “eigenfile” then the name of j^{th} eigen mode will be of the following form “eigenfile_000000j”. This file contains:

- The mean mass density field.
- The mean speed field.
- The mean total energy field.
- The acoustic pressure modulus field $|\hat{p}|$ of the corresponding eigen mode.
- The acoustic pressure argument field $arg(\hat{p})$ of the corresponding eigen mode.
- The acoustic speed (x component) modulus field $|\hat{u}_x|$ of the corresponding eigen mode.
- The acoustic speed (x component) argument field $arg(\hat{u}_x)$ of the corresponding eigen mode.
- The acoustic speed (y component) modulus field $|\hat{u}_y|$ of the corresponding eigen mode.
- The acoustic speed (y component) argument field $arg(\hat{u}_y)$ of the corresponding eigen mode.
- The acoustic speed (z component) modulus field $|\hat{u}_z|$ of the corresponding eigen mode (if 3D configuration).
- The acoustic speed (z component) argument field $arg(\hat{u}_z)$ of the corresponding eigen mode (if 3D configuration).
- The speed of sound c .

The acoustic pressure field is normalized and consequently its modulus value is comprised between 0 and 1. The acoustic speed field is calculated with the normalized acoustic pressure field so the values of the acoustic speed modulus field for the different components are comprised between 0 and 1.

The classic AVBP postprocessing tools “a2e” and “a2t” for visualization with ENSIGHT or TECPLOT softwares can be used with a slightly modified “visu.choices” to take into account acoustic variables (as additionnal variables).

2.3 Important remarks

Remark 1

As already mentioned, the type of cell used in an AVSP mesh is crucial:

- In 2D, cells must be triangular.
- In 3D, cells must be tetrahedric.

Remark 2

Sometimes the number of eigen frequencies computed by AVSP is less than the number wanted by user. It means that the backward error of these eigen frequencies is too important although the maximum iterations has been reached. If the user changes this number of eigen frequencies, the problem can disappear.

Remark 3

With this version of AVSP, the mesh must be relatively homogeneous. More precisely, the quotient between the greatest cell volume and the smallest cell volume must not be too important (typically less than 20000).

Chapter 3

Tutorial and examples of application of AVSP

3.1 Uniform 3D tube with a temperature jump and an admittance type boundary condition

3.1.1 Geometry and mesh of the configuration

This configuration corresponds to a tube with an open outlet and an inlet with a non trivial admittance. The characteristics of this configuration are given in the figure 3.1. The figure **??** represents the speed of sound field used as input in AVSP.

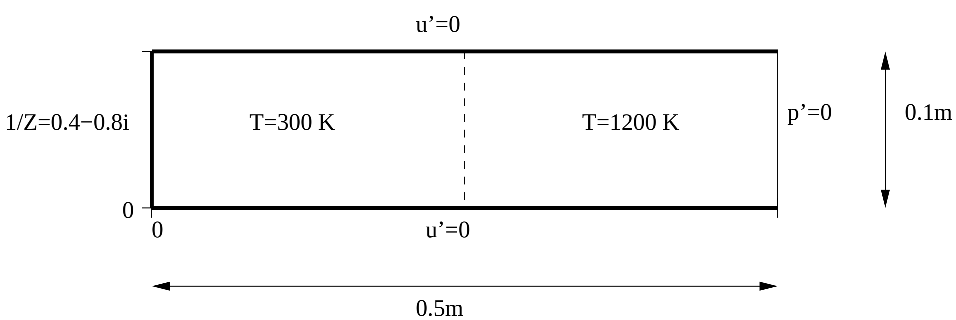

Figure 3.1: Geometry and general features of the 3D tube with a jump of temperature and an admittance type boundary inlet.

The mesh used in this example contains 1941 nodes (figure 3.3).

3.1.2 Input files

The following input files have been used for this example:

input_thermo.dat for AVBP4AVSP_INITSOLUT tool

```
PRE_CH4_AIR_GRI2.11_PHIvar_P=1atm_T=680K          ! Identifier for chemistry
```

Figure 3.2: 2D cut of the mean temperature field used in AVSP in the 3D tube with a jump temperature and an admittance type boundary inlet.

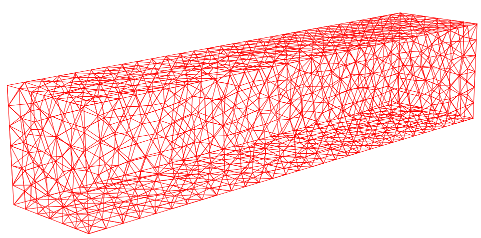

Figure 3.3: Mesh used in AVSP in the example of the the 3D tube with a jump temperature and an admittance type boundary inlet.

```
3.27d-5     ! mu0 [Kg/m/s] - reference viscosity for power law or First Sutherland Con
300d0       ! Tref [K] - Reference temperature for power or Sutherland law
-0.76d0      ! < 0: exponent for power law, > 0: Second Sutherland Constant, = 0: visc
0.71d0       ! Prandtl number
0.02897d0     ! Mean molecular mass [kg/mole]
1004.5d0      ! Cp [J/Kg K] - specific heat capacity at constant pressure
```

asciiBound file

```
  Grid processing by hip version 1.14.7.
  3 boundary patches.
---------------------------------------------
  Patch: 1
  Wall
  AC_SPEED_NULL
---------------------------------------------
  Patch: 2
  Outlet
  AC_PRESS_NULL
---------------------------------------------
  Patch: 3
  Inlet
 AC_ADMITTANCE
0.0
0.0
0.4
-0.8
0.0
0.0
```

run.dat

```
'./MESH/jumpT3d.coor'     ! Mesh file
'./MESH/jumpT3d.conn'     ! Connectivity
'./MESH/jumpT3d.exBound'  ! Boundary
'./MESH/jumpT3d.inBound'  ! Interface
'./jumpT3d_admitt.asciiBound'    ! Ascii file
'./initfield.sol' ! AVBP initial file for temperature field
'random'     ! initial solution for pressure field
'./jumpT3d_adm_sol'     ! Output solution file
10        ! number of eigen values/vectors to find
'SM'      ! which eigen values to find
1.0d0     ! Reference length  | scales coordinates X by X/reflen

100      ! Number of elements per group (typically of order 100)
1        ! Initial values: free stream data (0) or restart file (1)
1         ! Preprocessor: skip (0), use (1) & write (2) & stop (3)
0         ! PGS convergence acceleration (1) or not (0)



1 0 0 0 0        ! Scheme specification                 |
```

3.1.3 Results

The eigen frequencies found by AVSP in this example are stored in the file "jumpT3d_adm_sol" as follows:

```
 AVSP Version V1.8.3

Eigen frequencies:
eigen_freq1=         (391.868207379900,36.2967813956106)
eigen_freq2=         (776.224889650430,28.3873305242941)
eigen_freq3=         (1257.21060357274,42.2781736398951)
eigen_freq4=         (1784.40881038452,34.4785948266512)
eigen_freq5=         (1824.68318713004,9.71503244356384)
eigen_freq6=         (1826.30202691323,9.59027961110213)
eigen_freq7=         (2158.10954992422,29.8480317622942)
```

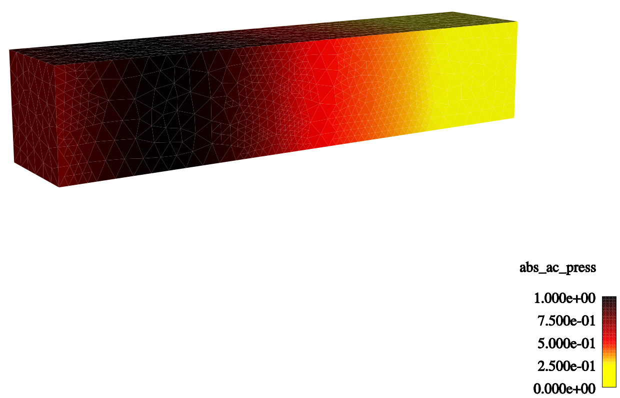

Figure 3.4: First eigenmode (1L) of the 3D tube with a jump temperature and an admittance type boundary inlet ($|\hat{p}|$ normalized)

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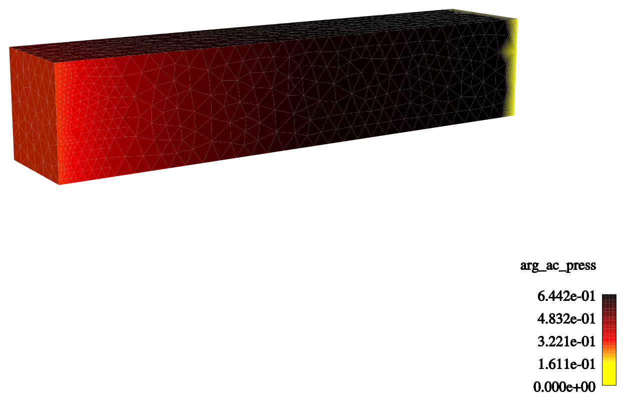

Figure 3.5: First eigenmode (1L) of the 3D tube with a jump temperature and an admittance type boundary inlet ($arg(\hat{p})$)

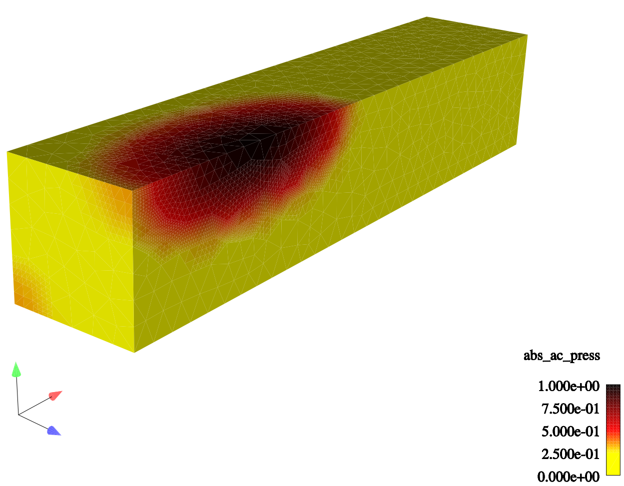

Figure 3.6: First transverse eigenmode (mode 5 in “jumpT3d_adm_sol”) of the 3D tube with a jump temperature and an admittance type boundary inlet ($|\hat{p}|$ normalized)

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