Open Source Combustion Instability Low Order Simulator for Longitudinal Modes (OSCILOS_long)

User guide for version 1.2

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What is OSCILOS?

- The open source combustion instability low-order simulator (OSCILOS) is an open source code for simulating combustion instability. It is written in Matlab® / Simulink® and is very straightforward to run and edit.
- It can simulate both longitudinal and annular combustor geometries. It represents a combustor as a network of connected modules.
- The acoustic waves are modeled as either 1-D plane waves (longitudinal combustors) or 2-D plane/circumferential waves (annular combustors).
- A variety of inlet and exit acoustic boundary conditions are possible, including open, closed, choked and user defined boundary conditions.
- The response of the flame to acoustic waves is captured via a flame model; flame models ranging from linear $n-\tau$ models to non-linear flame describing functions, either prescribed analytically or loaded from experiment / CFD data, can be prescribed.
- The mean flow is calculated simply by assuming 1-D flow conditions, with changes only across module interfaces or flames.
- This current version is for longitudinal modes. This assumes a longitudinal/cannular/can combustor geometry, or an annular geometry but where only plane acoustic waves are known to be of interest.

Who is developing OSCILOS?

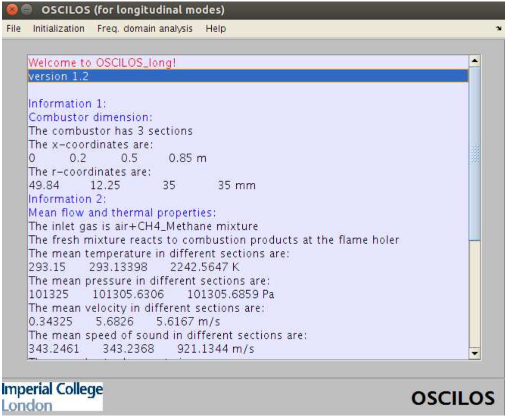
- OSCILOS is being developed by Dr. Aimee Morgans, Dr. Jingxuan Li, Dong Yang and coworkers in the Department of Aeronautics, Imperial College London, UK.
- More details about the development team are available on the website: `http://www.oscilos.com/`.
- Current team members:
  - Dr. Aimee S. Morgans
  - Dr. Jingxuan Li
  - Dong Yang
  - Dr. Xingsi Han
  - Charles Luzzato

Required Matlab toolboxes

- Control System Toolbox
- Matlab
- Optimization Toolbox
- Robust Control Toolbox
- Simulink
- Symbolic Math Toolbox

Menu Bar

- File
  - New case
  - Load
  - Save
- Initialization
  - Chamber dimensions
  - Thermal properties
  - Flame model
  - Boundary conditions
- Frequency domain analysis
  - Eigenmode calculation
- Help
  - About
  - User guide



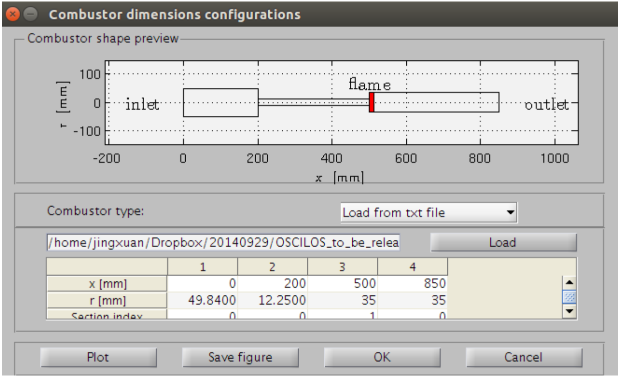
```
Welcome to OSCILOS_long!
version 1.2

Information 1:
Combustor dimension:
The combustor has 3 sections
The x-coordinates are:
0       0.2       0.5       0.85 m
The r-coordinates are:
49.84       12.25       35       35 mm
Information 2:
Mean flow and thermal properties:
The inlet gas is air+CH4_Methane mixture
The fresh mixture reacts to combustion products at the flame holer
The mean temperature in different sections are:
293.15      293.13398      2242.5647 K
The mean pressure in different sections are:
101325      101305.6306      101305.6859 Pa
The mean velocity in different sections are:
0.34325      5.6826      5.6167 m/s
The mean speed of sound in different sections are:
343.2461      343.2368      921.1344 m/s
```

File

- New case: This menu option is used to clear current calculation results and create a new calculation.
- Load...: This menu option is used to load data from existing Mat file. The current calculation results will be deleted once the user clicks "Yes".
- Save...: This menu option is used to save the current calculation results as a Mat file.

Initialization/Chamber dimensions

- This menu option is used to set the geometric dimensions of the combustor.



Combustor dimensions configurations

Combustor type: Load from txt file

/home/jingxuan/Dropbox/20140929/OSCILOS_to_be_relea

	1	2	3	4
x [mm]	0	200	500	850
r [mm]	49.8400	12.2500	35	35
Section index	0	0	1	0

Initialization/Chamber dimensions

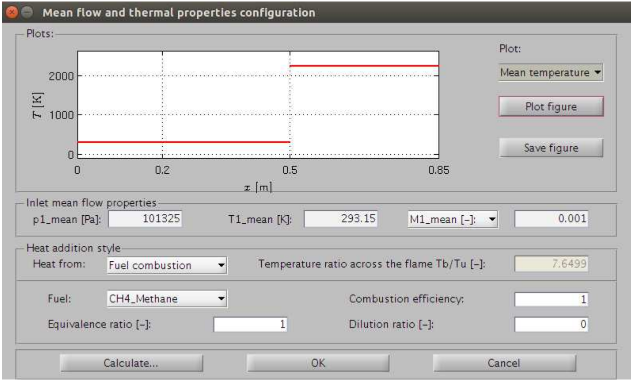
- The length and radius of the combustor can be quickly configured for the case of a Rijke tube.
- For complicated combustor geometries, users can load the information from an external txt file by clicking "load". It is better to create the txt file as the form of "CD_example.txt" in the "subProgram" folder. The format of data is shown in the following table:

x [m]	r [m]	Section index [-]
0	0.04984	0
0.2	0.01225	0
0.5	0.03500	1
0.85	0.03500	0

  where,
  - x means axial position of each sectional interface;
  - r indicates the radius of each section;
  - "section index" represents the type of sectional interface: '0': only sectional surface area change; '1': with heat addition; '$2, 3 \ldots n$': for further developments.
- A schematic of the combustor can be previewed by clicking "Plot".
- The figure can be saved by clicking "save figure".
- The current configuration is saved by clicking "OK". The key information will be printed in the information window.

Initialization /Thermal properties

- This menu is used to set the inlet mean flow properties and the mean heat addition.



Mean flow and thermal properties configuration

Plots:

Plot: Mean temperature

Inlet mean flow properties

p1_mean [Pa]: 101325

T1_mean [K]: 293.15

M1_mean [-]: 0.001

Heat addition style

Heat from: Fuel combustion

Temperature ratio across the flame Tb/Tu [-]: 7.6499

Fuel: CH4_Methane

Combustion efficiency: 1

Equivalence ratio [-]: 1

Dilution ratio [-]: 0

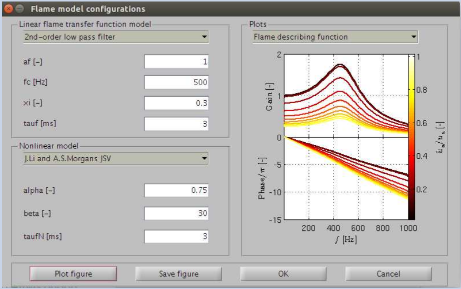
Initialization /Thermal properties

- The mean flow and thermal properties within each combustor section are considered uniform.
- The mean properties in different sections can be calculated by clicking “Calculate” once all the inputs have been completed.
- Users can choose a model for the (mean) heat addition from the pop-up menu.
  1. Heat from a heating grid (T_b/T_u is given), where T_u represents the temperature before the heating grid, and Tb indicates that after the grid. This is often used for the case of a Rijke tube.
  2. Heat from fuel combustion.
     - Users can choose the fuel from the pop-up menu, including CH_4, C_2H_4, C_2H_6, C_3H_8, C_4H_8, C_4H_{10} (n-butane), C_4H_{10} (isobutane) and $C_{12}H_{23}$ (Jet-A).
     - User can also set: (1) Equivalence ratio ϕ; (2) Combustion efficiency η; (3) Dilution ratio, which is used when a bias flow is accounted for.
- The distribution of mean temperature and mean flow velocity can be previewed by clicking “Plot figure”.
- The figures can be saved by clicking “Save figure”.
- The current configuration is saved by clicking “OK”. The key information will be printed in the information window.

Initialization /Flame model

- This menu option is used to set the flame model, which describes how the (normalized) unsteady heat release rate $\hat{\dot{q}}/\bar{\dot{q}}$ of the flame responds to (normalized) velocity fluctuations $\hat{u}/\bar{u}$.
- Users can choose between prescribing a flame transfer function model (with non-linearity options) or loading and fitting experimental / CFD data.

1.Analytically flame describing function setting panel



Flame model configurations

Linear flame transfer function model: 2nd–order low pass filter

af [–] 1

fc [Hz] 500

xi [–] 0.3

tauf [ms] 3

Nonlinear model: J.Li and A.S.Morgans JSV

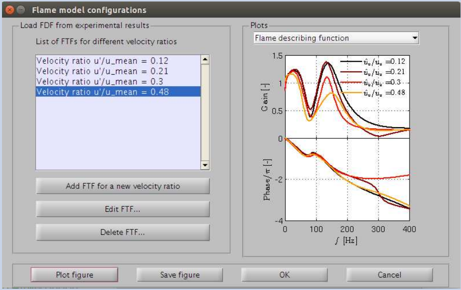
alpha [–] 0.75

beta [–] 30

taufN [ms] 3

Plots: Flame describing function

2.Flame describing function from Loading and fitting experimental / CFD data panel



Flame model configurations

Load FDF from experimental results

List of FTFs for different velocity ratios

Velocity ratio u'/u_mean = 0.12
Velocity ratio u'/u_mean = 0.21
Velocity ratio u'/u_mean = 0.3
Velocity ratio u'/u_mean = 0.48

Plots: Flame describing function

Add FTF for a new velocity ratio
Edit FTF...
Delete FTF...
Gain [-]
Phase/π [-]
1.5
1
0.5
0
-2
-4
0
100
200
300
400
f [Hz]
$\hat{u}_u/\bar{u}_u$ =0.12
$\hat{u}_u/\bar{u}_u$ =0.21
$\hat{u}_u/\bar{u}_u$ =0.3
$\hat{u}_u/\bar{u}_u$ =0.48
Plot figure
Save figure
OK
Cancel

Flame transfer function

Four kinds of flame transfer function models ($\mathcal{T}_u(s) = \hat{\dot{q}}(s)/\bar{\dot{q}} \Big/ \hat{u}(s)/\bar{u}$) can be prescribed: the first three involve:

1. Crocco's famous $n-\tau$ model:

$$\mathcal{T}_u(s) = a_f e^{-\tau_f s}$$

2. the $n-\tau$ model filtered by a first order filter:

$$\mathcal{T}_u(s) = \frac{\omega_c}{s+\omega_c} a_f e^{-\tau_f s}$$

3. the $n-\tau$ model filtered by a second order filters:

$$\mathcal{T}_u(s) = \frac{\omega_c^2}{s^2 + 2\xi\omega_c s + \omega_c^2} a_f e^{-\tau_f s}$$

- s: the Laplace variable
- a_f: gain
- τ_f: time delay
- $f_c = \omega_c \big/ 2\pi$: cut-off frequency
- ξ: damping ratio

The fourth option is a user-defined FTF model using a polynomial transfer function by inputting the numerator coefficients $\mathbf{b}$ and denominator coefficients $\mathbf{a}$. The order of the numerator should not be larger than that of denominator $n \leqslant m$.

$$\mathcal{T}_u(s) = \frac{b_1 s^{n-1} + b_2 s^{n-2} + \cdots + b_{n-1} s + b_n}{a_1 s^{m-1} + a_2 s^{m-2} + \cdots + a_{m-1} s + a_m}$$

Nonlinear model — 1

Users can choose between prescribing an analytically nonlinear flame describing function or loading and fitting experimental / CFD data. The first nonlinear model is an abrupt heat release rate ratio $\hat{\dot{q}}/\bar{\dot{q}}$ saturation model proposed by Dowling (JFM:1997), which can be mathematically expressed as:

$$\frac{\dot{q}'}{\bar{\dot{q}}} = \begin{cases} \left(\dfrac{\dot{q}'}{\bar{\dot{q}}}\right)_L & \text{for } \left|\dfrac{\dot{q}'}{\bar{\dot{q}}}\right| \leqslant \alpha \\[2ex] \alpha \operatorname{sgn}\left(\dfrac{\dot{q}'}{\bar{\dot{q}}}\right) & \text{else} \end{cases}$$

where α is a constant associated with the saturation $(0 \leqslant \alpha \leqslant 1)$ and $\left(\dot{q}'\middle/\bar{\dot{q}}\right)_L$ denotes the heat release rate ratio for weak perturbations, which can be calculated from the linear flame transfer function.

Nonlinear model — 2

The second nonlinear model is recently proposed by the authors. The nonlinear flame describing function depends on s and velocity ratio $\hat{u}_1/\bar{u}_1$ and it is assumed here can be decoupled as:

$$\widetilde{G}(\hat{u}_1/\bar{u}_1, s) = \mathcal{L}(\hat{u}_1/\bar{u}_1)\widetilde{\mathcal{T}}_u(s)$$

where the superscript $\hat{}$ indicates the signal amplitude. The nonlinear function $\mathcal{L}(\hat{u}_1/\bar{u}_1)$ describes the saturation of heat release rate with velocity perturbations $\hat{u}_1/\bar{u}_1$, and $\mathcal{L}(\hat{u}_1/\bar{u}_1) = \widetilde{G}(\hat{u}_1/\bar{u}_1, 0)$. The mathematical link is:

$$\frac{\widehat{\dot{q}}(\hat{u}_1/\bar{u}_1, 0)}{\bar{\dot{q}}} = \mathcal{L}(\hat{u}_1/\bar{u}_1)\frac{\hat{u}_1}{\bar{u}_1} = \int_0^{\hat{u}_1/\bar{u}_1} \frac{1}{1 + \left(\xi + \alpha\right)^{\beta}} \mathrm{d}\xi$$

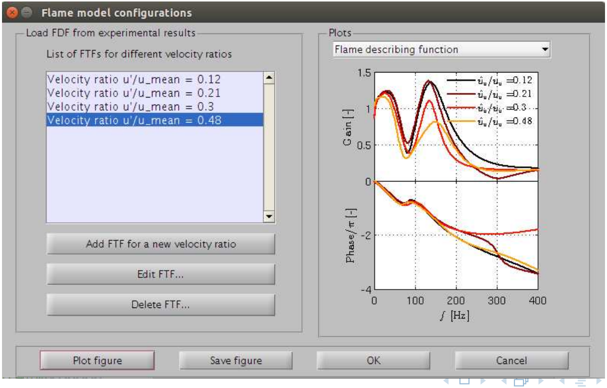
where α and β are two coefficients which determine the shape of the nonlinear model. One may also introduce a simple nonlinear model of the time delay, using the mathematical description:

$$\tau_f = \tau_f^0 + \tau_f^N\left(1 - \mathcal{L}(\hat{u}_1/\bar{u}_1)\right)$$

where τ_f^0 means the time delay when $\hat{u}_1/\bar{u}_1 = 0$ and τ_f^N is a time delay to describe the change of τ_f as $\mathcal{L}$ changes.

Load and fit FDF from experiment / CFD

- The flame describing function can be loaded from experimental / CFD frequency response data.
- The user can add a set of flame transfer functions measured at different velocity ratios, by clicking “Add FTF for a new velocity ratio”.



Flame model configurations

Load FDF from experimental results

List of FTFs for different velocity ratios

Velocity ratio u'/u_mean = 0.12
Velocity ratio u'/u_mean = 0.21
Velocity ratio u'/u_mean = 0.3
Velocity ratio u'/u_mean = 0.48

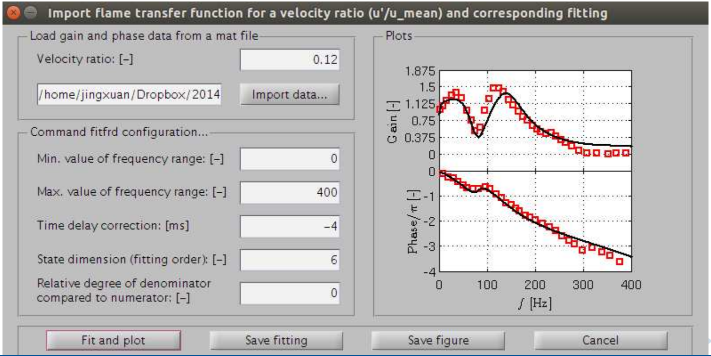
Plots

Flame describing function

Add FTF for a new velocity ratio
Edit FTF...
Delete FTF...
1.5
1
0.5
0
Gain [-]
$\hat{u}_u/\bar{u}_u$ =0.12
$\hat{u}_u/\bar{u}_u$ =0.21
$\hat{u}_u/\bar{u}_u$ =0.3
$\hat{u}_u/\bar{u}_u$ =0.48
-2
-4
Phase/π [-]
0
100
200
300
400
f [Hz]
Plot figure
Save figure
OK
Cancel

Load and fit FDF from experiment / CFD

- Once the button "Add FTF for a new velocity ratio" is clicked, a window for displaying the experimental FTF and fitting will appear.
- The user can set the velocity ratio and then import experimental FTF from an external Mat file. (It is better to save the data in a Mat file prior to running OSCILOS).
- The user needs to set the fitting frequency range, time delay correction and fitting order, relative degree of denominator compared to numerator, which are used for fitting.
- The fitting process is operated on clicking "Fit and plot".



Import flame transfer function for a velocity ratio (u'/u_mean) and corresponding fitting

Load gain and phase data from a mat file

Velocity ratio: [–] 0.12

/home/jingxuan/Dropbox/2014

Command fitfrd configuration...

Min. value of frequency range: [–] 0

Max. value of frequency range: [–] 400

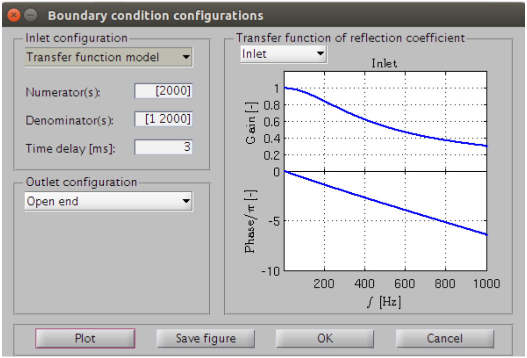
Time delay correction: [ms] -4

State dimension (fitting order): [–] 6

Relative degree of denominator compared to numerator: [–] 0

Initialization / Boundary conditions

The link between the outward and inward propagating waves at the end of the combustor can be described by the reflection coefficients. When the indirect noise induced by the entropy waves can be neglected, the pressure reflection coefficients at the inlet and outlet are characterized by R_1 and R_2 respectively.


Boundary condition configurations

Inlet configuration

Transfer function model

Numerator(s): [2000]

Denominator(s): [1 2000]

Time delay [ms]: 3

Outlet configuration

Open end

Transfer function of reflection coefficient

Inlet

Initialization / Boundary conditions

Six kinds of boundary conditions are provided:

1. Open end ($R = -1$).
2. Closed end ($R = 1$).
3. Choked end.
4. User defined (Amplitude and time delay)...
5. User defined (Amplitude and phase)...
6. User-defined model using a polynomial transfer function by inputting the numerator coefficients $\mathbf{b}$ and denominator coefficients $\mathbf{a}$. The order of the numerator should not be larger than that of denominator $n \leqslant m$.

Boundary conditions/Include indirect noise from entropy waves —1

When the user choose the choked outlet boundary, there is an option to include the indirect noise from the entropy or not. Two models accounting for the advection of entropy waves are prescribed in this work.

- A "Rectangular" model (proposed by Sattelmayer (2003)): The p.d.f. or impulse response is modelled as a rectangular pulse of length $2\Delta\tau_C^s$ and height $1/2\Delta\tau_C^s$ centred about the mean residence time τ_C^s:

$$E_C^{\text{inlet}}(t) = \delta(t)$$

$$E_C^{\text{outlet}}(t) = \begin{cases} \dfrac{1}{2\Delta\tau_C^s} & \text{for } \tau_C^s - \Delta\tau_C^s \leqslant t \leqslant \tau_C^s + \Delta\tau_C^s \\ 0 & \text{else} \end{cases}$$

The corresponding Laplace transform of the transfer function between the entropy waves at the outlet and inlet can be expressed as:

$$\frac{\widetilde{E}_C^{\text{outlet}}(s)}{\widetilde{E}_C^{\text{inlet}}(s)} = \widetilde{\mathcal{E}}(s)\exp\left(-\tau_C^s\ s\right) = \frac{\exp\left(\Delta\tau_C^s\ s\right) - \exp\left(-\Delta\tau_C^s\ s\right)}{2\Delta\tau_C^s\ s}\exp\left(-\tau_C^s\ s\right)$$

Boundary conditions/Include indirect noise from entropy waves —2

- A “Gaussian” model (proposed by Morgans et al.(2013)): Shear dispersion is assumed to be predominantly caused by spatial variations in the time-mean velocity profile, rather than by turbulent eddies. The impulse response is modelled as a Gaussian distribution:

$$\begin{aligned} E_C^{\mathrm{inlet}}(t) &= \delta(t) \\ E_C^{\mathrm{outlet}}(t) &= \frac{1}{\sqrt{\pi}\Delta\tau_C^s} \exp\left(- \left(\frac{t - \tau_C^s}{\Delta\tau_C^s} \right)^2 \right) \end{aligned}$$

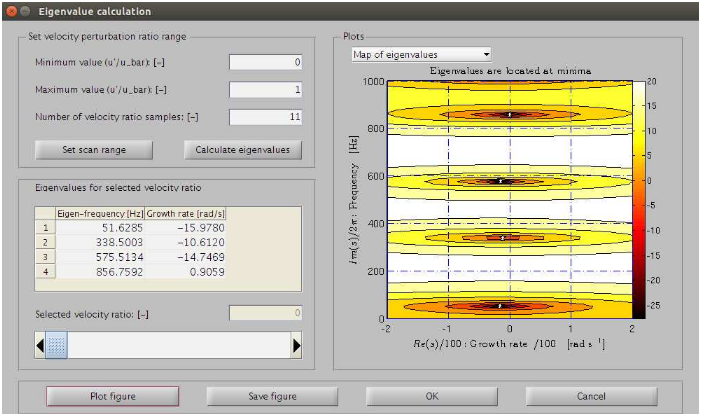
with the Laplace transforms of the transfer function:

$$\widetilde{\mathcal{E}}(s) = \exp\left(\frac{\left(\Delta\tau_C^s \ s\right)^2}{4} \right)$$

where time delay $\Delta\tau_C^s$ is proposed to describe the dispersion of resident time.

Freq. domain analysis / Eigenmode calculation

Once all initializations are complete, the user can then progress to the "Eigenmode calculation" panel.



Eigenvalue calculation

Set velocity perturbation ratio range

Minimum value (u'/u_bar): [-] 0

Maximum value (u'/u_bar): [-] 1

Number of velocity ratio samples: [-] 11

Eigenvalues for selected velocity ratio

	Eigen-frequency [Hz]	Growth rate [rad/s]
1	51.6285	−15.9780
2	338.5003	−10.6120
3	575.5134	−14.7469
4	856.7592	0.9059

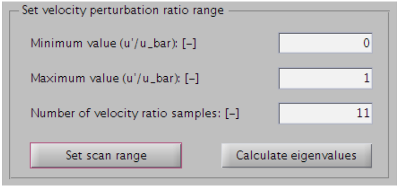
Selected velocity ratio: [-] 0

Plots

Map of eigenvalues

Freq. domain analysis / Eigenmode calculation

If the user previously chose the flame describing function model in the "Flame model" panel, the minimum and maximum velocity ratios ($(\hat{u}/\bar{u})_{min}$ and $(\hat{u}/\bar{u})_{max}$) now need to be set. The number of velocity ratio samples is also needed to equally space the velocity ratio range.



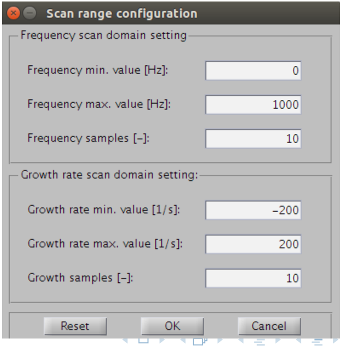
Set velocity perturbation ratio range

Minimum value (u'/u_bar): [–] 0

Maximum value (u'/u_bar): [–] 1

Number of velocity ratio samples: [–] 11

The user needs to define a scan range (including frequency and growth rate) to search for eigenvalues within this range. This can be done by clicking "Set scan range".



Scan range configuration

Frequency scan domain setting

Frequency min. value [Hz]: 0

Frequency max. value [Hz]: 1000

Frequency samples [–]: 10

Growth rate scan domain setting:

Growth rate min. value [1/s]: –200

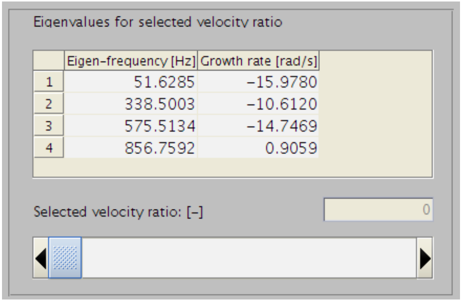
Growth rate max. value [1/s]: 200

Growth samples [–]: 10

When all the sets have been done, the user can calculate the eigenvalues for a set of velocity ratios.

Freq. domain analysis / Eigenmode calculation

- The eigenvalues for a selected velocity ratio appears in the table (as shown in the bottom figure).
- The user can change the slider to switch the velocity ratio. The values in the table will automatically change with the velocity ratio.



Eigenvalues for selected velocity ratio

	Eigen-frequency [Hz]	Growth rate [rad/s]
1	51.6285	-15.9780
2	338.5003	-10.6120
3	575.5134	-14.7469
4	856.7592	0.9059

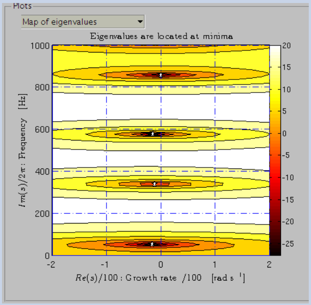
Selected velocity ratio: [-] 0

Freq. domain analysis / Eigenmode calculation

The user can plot three kinds of figures from the choices of the popup menu:

- A contour map showing the eigenvalue locations (growth rate and frequency).
- The mode shape.
- The evolution of eigenvalues with increasing velocity ratio.

1.A contour map showing the eigenvalue locations (growth rate and frequency)

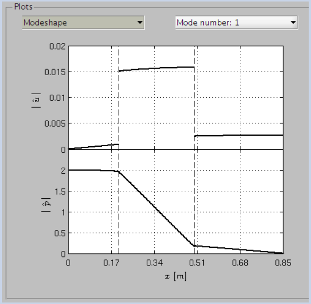


Plots

Map of eigenvalues

Eigenvalues are located at minima
1000
800
600
400
200
0
$Im(s)/2\pi$: Frequency [Hz]
-2
-1
0
1
2
$Re(s)/100$: Growth rate /100 [rad s^{-1}]
20
15
10
5
0
-5
-10
-15
-20
-25

2.The mode shape

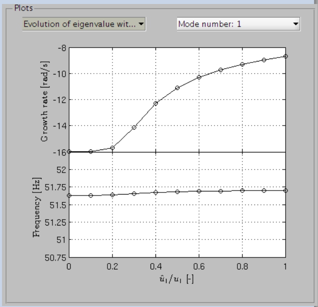


Plots

Modeshape

Mode number: 1

3.The evolution of eigenvalues with increasing velocity ratio



Plots

Evolution of eigenvalue wit...

Mode number: 1