LFR_RAI User's Guide

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Abstract

This report describes the Matlab-based toolbox LFR_RAI, which allows to perform robustness analysis of uncertain models in Linear Fractional Representation (LFR), by using several different techniques based on parameter-dependent Lyapunov functions. Details on the techniques and the results obtained within the COFCLUO project are reported in [1]. All the material is available at `http://www.dii.unisi.it/~garulli/lfr_rai`

Contents

1 Introduction

This report describes the software tools developed for two clearance problems: aeroelastic stability of integral models [2] and un-piloted stability of nonlinear models [3]. Both clearance problems have been reformulated as robustness analysis problems for LFR uncertainty models, as described in [1]. Several different robustness analysis techniques based on Lyapunov theory have been implemented. The considered LFR models are those derived in [4, 5] from physical models of the aircraft and of the controller, at different points of the flight envelope and with different values of the uncertain parameters. For all the details about the robustness techniques and the LFR models, the interested reader is referred to [1].

A Graphical User Interface (GUI) has been developed to facilitate the selection of the various options in the clearance problem, and to present the results of the clearance process. The GUI provides a user interactive set-up for the two considered criteria, and for a collection of integral and nonlinear closed-loop LFR models. The software package comprises of a collection of routines coded in Matlab and exploits three publicly available software packages.

The document is organized as follows. Section 2 describes in detail the installation and implementation of the GUI. The step-by-step setup and use of the GUI software for a clearance analysis of a 4 uncertain parameter LFR model is presented in Section 3. An extensive collection of results obtained by applying the developed software tools to the LFR models derived in [4, 5] is included in [1].

2 Software implementation

A graphical user interface has been created to implement the methods discussed so far and to setup the relevant tuning parameters. The interface objective is to reduce the work load for the user in the clearance process of a given model.

2.1 Installation

The GUI software for the analysis of LFR models requires, as a prerequisite, the installation of a 64-bit version of Matlab. Additionally, the aeroelastic stability clearance library routines, on which the GUI software is based, make use of three freely available software packages: YALMIP [6], SDPT3 [7] and LFR Toolbox [8]. These can be downloaded from their corresponding and publicly accessible web-sites.

The following is an outline for the installation and configuration of those toolboxes/packages and the aeroelastic stability clearance library.

2.1.1 YALMIP

- Download the latest release of YALMIP Toolbox from:
  `http://users.isy.liu.se/johanl/yalmip/pmwiki.php?n=Main.Download`
- Guidelines on its installation can be found at:
  `http://users.isy.liu.se/johanl/yalmip/pmwiki.php?n=Tutorials.Installation`

2.1.2 SDPT3 - Semi Definite Programming Solver

- Download `SDPT3-4.0-beta` version of the solver from:
  `http://www.math.nus.edu.sg/~mattohkc/sdpt3.html`

- Instructions for installation can be found on the same web-page under `SDPT3-4.0-beta.zip`.

2.1.3 LFR Toolbox

- Download Version 2.0 LFR Toolbox for Matlab from:
  `http://www.onera.fr/staff-en/jean-marc-biannic/docs/lfrtv20s.zip`.

- Unzip the file. A directory named `LFRTv20pre1` will be created, this should be added to your system's Matlab path.

Installation of the toolboxes and the solver are now completed.

2.1.4 Robust stability analysis GUI

- Download the latest version of the LFR_RAI toolbox from:
  `http://www.dii.unisi.it/~garulli/lfr_rai`

- Unzip the file. Several folders and one function will be extracted. and

Folders

`DATA`: is the folder where a comprehensive set of data from clearance analyses of LFR models are stored. Graphical representation of the clearance results will also be stored within this folder.
`FUNCTIONS`: is the folder which accommodates the library of functions used in the clearance analyses.
`MODELS`: is the folder which hosts, in Linear and NonLinear subfolders, correspondingly the linear and nonlinear closed-loop LFR models to be analysed.
`RESULTS`: is the folder where a file containing particular data from the analysis of a given LFR model is saved.

Functions

`Robust_Stability_Analysis_GUI.m`: is the function which can be run to initiate graphical user interface setup of a stability clearance problem of choice for a given model.

2.2 The GUI panel

- In Matlab your current directory should be $/`Clearance_UniSi`/.

- Run `Robust_Stability_Analysis_GUI.m` to start the graphical user interface.

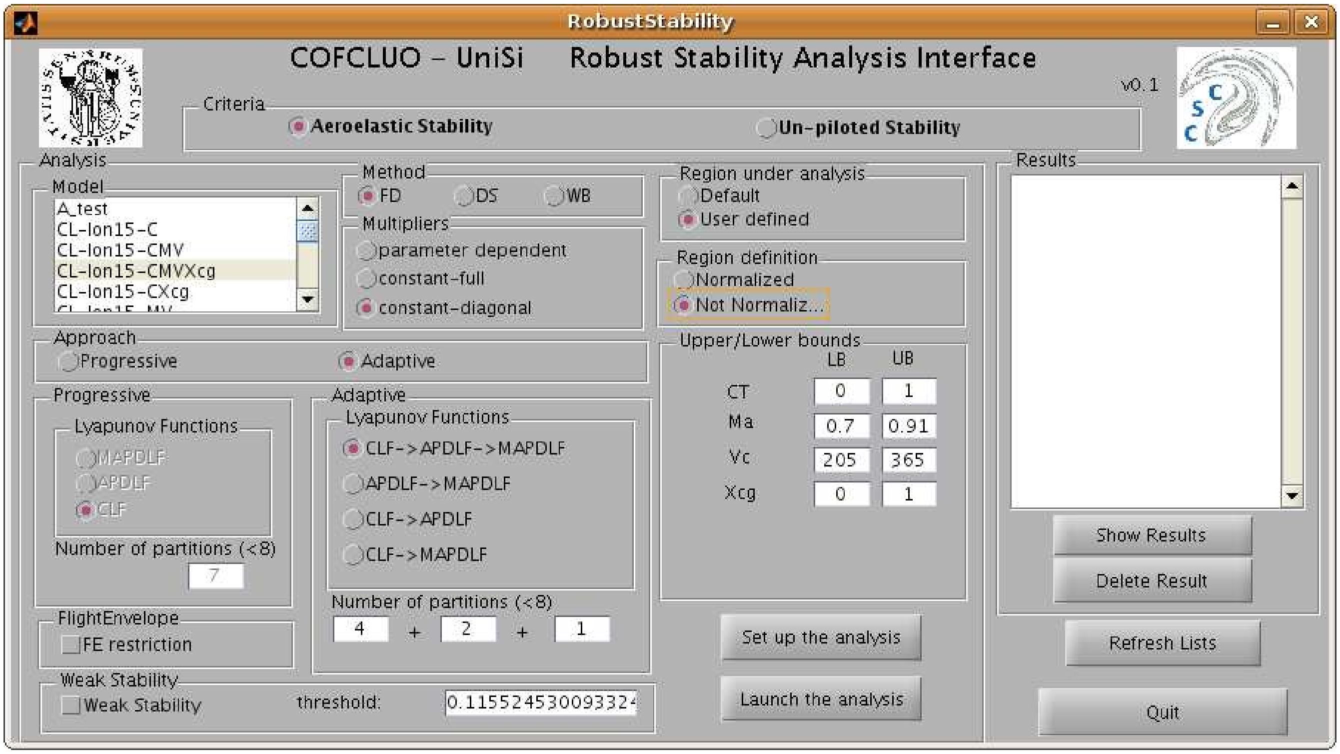


Figure 1: COFCLUO GUI panel.

Figure 1 is a screenshot of the Graphical User Interface panel for the Robust Stability Analysis of LFR models.

The GUI panel is divided into three (sub)panels:

- Criteria
- Analysis
- Results.

which are described in the following.

2.3 Criteria selection

Figure 2: COFCLUO GUI panel.

The graphical interface allows for the selection of two criteria on which the robust stability analysis of the LFR models will be based, namely: the aeroelastic stability criterion [2] for the integral models, and the un-piloted stability criterion [3] for the nonlinear models.

2.4 Analysis subpanel

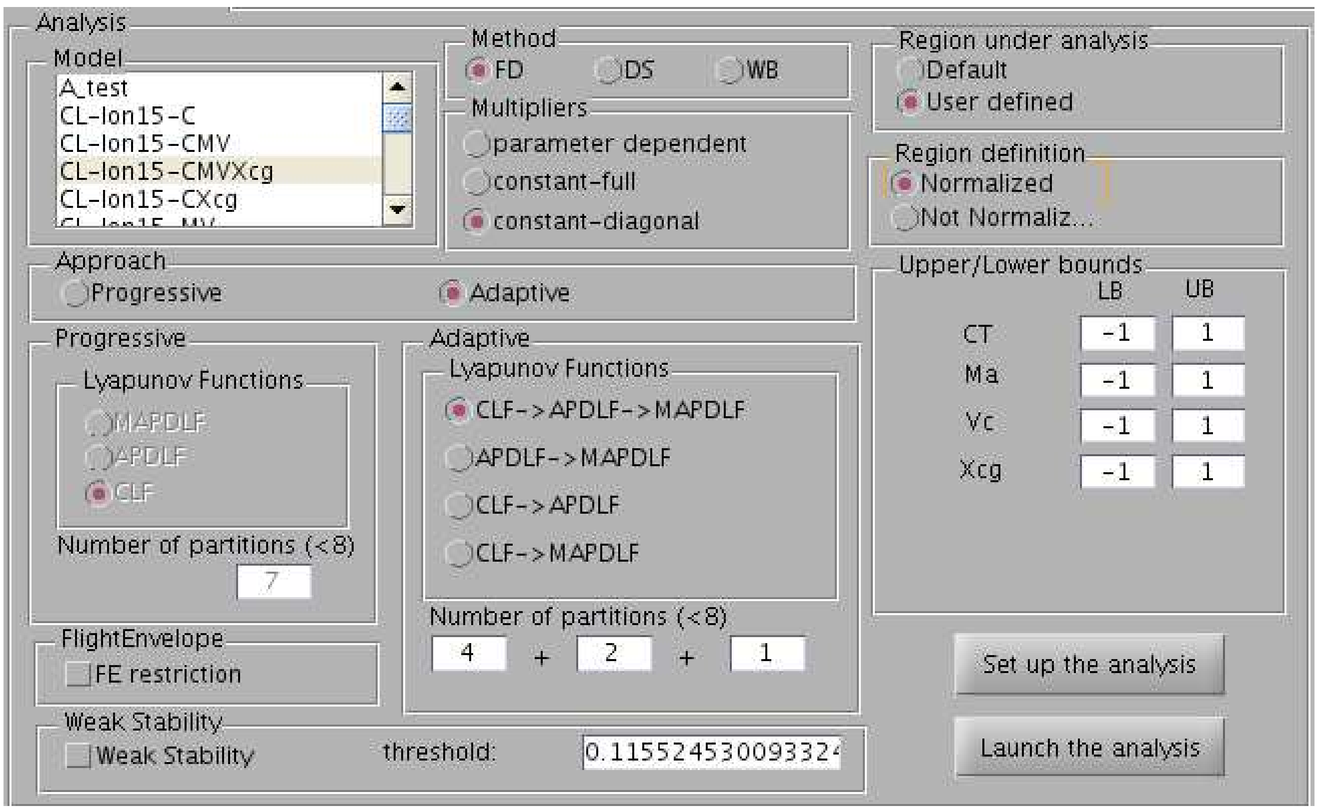


Figure 3: GUI Analysis panel.

The analysis panel, in Figure 3, is comprised of a collection of categories and tuning “knobs” which the user is expected to select, in order to setup the analysis of an LFR model, before initiating the clearance procedure.

2.4.1 Models

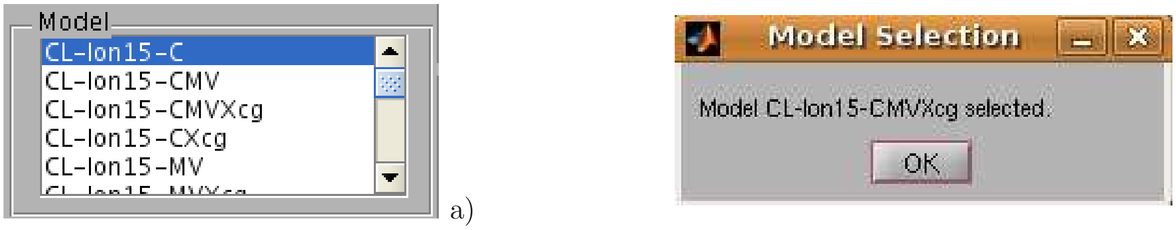


Figure 4: a) Models box. b) Model selection confirmation.

Select a model by *double clicking* onto a desired model, Figure 4(a). A dialogue box, as shown in Figure 4(b), “Model Selection” will prompt for confirmation of the the selection.

2.4.2 Methods and Multipliers

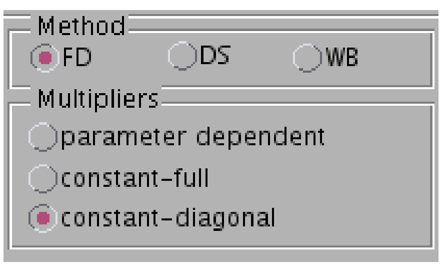


Figure 5: Methods and Multipliers box.

Select one of the methods:

- FD,
- DS or
- WB.

and one of the three structures of multipliers:

- parameter-dependent,
- constant-full,
- constant diagonal.

The methods are described in [1]. Note that, the parameter-dependent multiplier structure is supported only by FD method. Experience accumulated in employing the sufficient conditions to the clearance criterion on a collection of closed-loop integral models indicates that FD-cμ relaxation offers a good trade-off between computational complexity and conservatism, i.e. the power of the relaxation to successfully clear the clearable uncertainty domain.

2.4.3 Region under analysis and Region definition

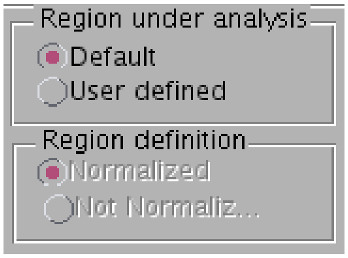
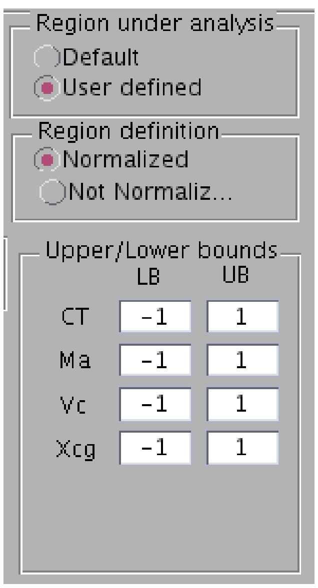


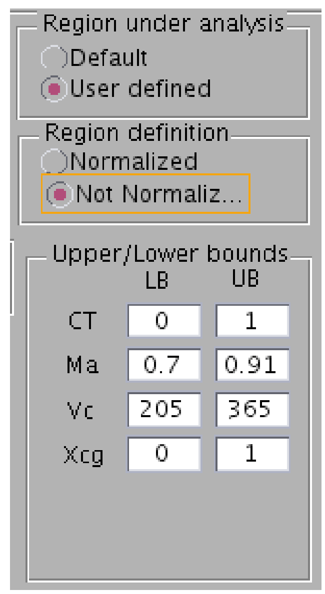
Figure 6: Region under analysis and Region definition's box.

In the *Region under analysis* box a user can select a *Default* region (corresponding to the whole flight/uncertainty domain), or define a new (smaller) region, within the boundaries of the uncertain parameter domain, where the model is going to be assessed for robust stability. In the *Region definition* box, the user can choose whether the uncertain parameters are "normalised" between -1 and 1 (default values), or if their physical values are considered.

2.4.4 Bounds: normalised and physical



a)



b)

Figure 7: a) Bounds: normalised. b) Bounds: physical values.

The region under analysis is defined by lower and upper bounds (LB/UB). Values delimiting the uncertainty domain vary in the range $[-1, 1]$ if the range is normalised, Figure 7(a). Otherwise, and in view of the considered uncertain parameters, they must be chosen as physically meaningful values, Figure 7(b). In both options the user can redefine the boundaries of the analysis region providing that the default (normalised and physical) values of the lower and upper bounds are not exceeded.

2.4.5 Progressive tiling approach

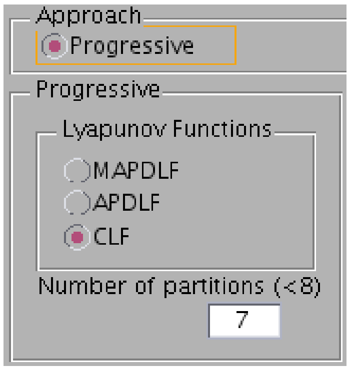


Figure 8: Progressive approach box.

This selection employs the progressive partitioning presented in [1]. Select a structure of the Lyapunov Function (LF) to be used:

- Common Lyapunov Function (CLF),
- Affine Parameter Dependent Lyapunov Function (APDLF) or
- Multi-Affine Parameter-Dependent Lyapunov Function (MAPDLF),

and, the number of partitions signifying the maximum number of times the uncertainty domain is going to be bisected. If the number is set (for example) to 7, for a model with two uncertain parameters, this will result in an uncertainty domain meshed with $2^7 \times 2^7$ tiles.

Remark 2.1 *It is advised that the number of partitions is selected to be always greater than 0. Assuming that there are no unstable models within the domain of uncertainty, i.e. the domain is clearable, partitioning set to 0 indicates no partitioning of the uncertainty domain. Hence, the entire uncertainty domain (or the flight envelope) will undergo an attempt to be cleared at once, and only once. While clearance with this setting may be possible for some simple models, it is extremely unlikely to be sufficient and effective for the clearance in the majority of more complex models analysis. Increasing the number of partitions, while it may facilitate more areas to be cleared, it is likely to adversely affect the computational overhead. The selection of the structure of the Lyapunov function will also affect the accuracy and the computational burden. Starting with APDLF has been found to be a plausible choice.*

2.4.6 Adaptive tiling approach

The approach still exploits the partitioning of the domain and the number of partitions has to be selected for each of the LF in the adaptive steps. The sum of the number of partitions has to be ≤ 7. For example, the choice in Figure 9 means that one will perform 4 partitions with CLF, 2 with APDLF and the last one with MAPDLF. A combination of CLF with APDLF has been found to be an effective combination in this approach.

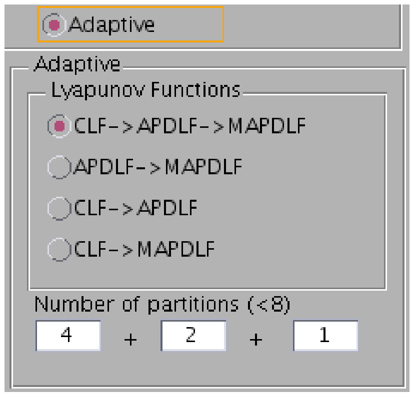


Figure 9: Adaptive approach box.

This selection initiates the adaptive approach presented in [1]. Consider the approach as a multi stage progressive tiling. Because the approach is adaptive, and the adaptation is performed on the structure of the Lyapunov Function, a sequence of two or three types of LFs have to be selected from one of the following:

- CLF,
- APDLF,
- MAPDLF.

2.4.7 Flight Envelope (FE)

Figure 10: Flight Envelope restriction.

Selecting the Flight Envelope (FE) restriction is appropriate only for models with (M) Mach and (V) Conventional air speed in the uncertainty Δ-block. This selection will force the analysis to take place only in the actual flight envelope, defined as the convex hull of a set of matrices.

2.5 Robust weak stability

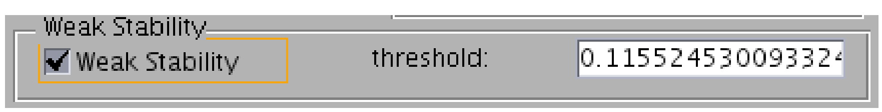


Figure 11: COFCLUO GUI panel.

The user can check the box "Weak stability" and define the "threshold" corresponding to the maximum value allowed for the real part of the system eigenvalues (the default value of the threshold is set to log(2)/6, corresponding to a time of doubling of 6 sec, as required in [3]).

2.5.1 Setup and launch

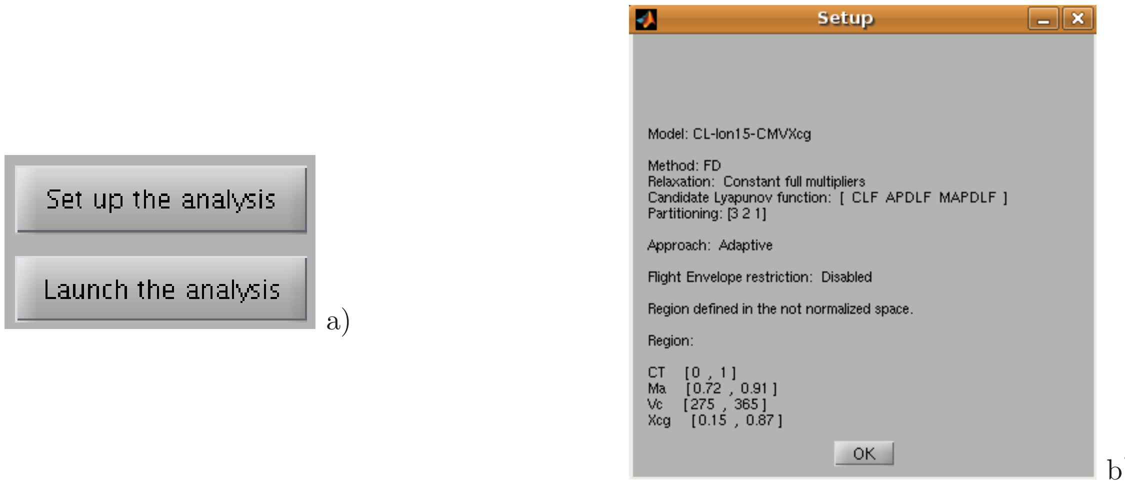


Figure 12: a) Setup and launch. b) Confirmation of the clearance analysis setup.

Press *Set up the analysis* to confirm the formulation of the clearance procedure, Figure 12(a). The selection of all the parameters is confirmed with a dialogue-box, Figure 12(b), and then the analysis can be initiated. Press the *Launch the analysis* to start the clearance process, Figure 12(a).

2.6 Results subpanel

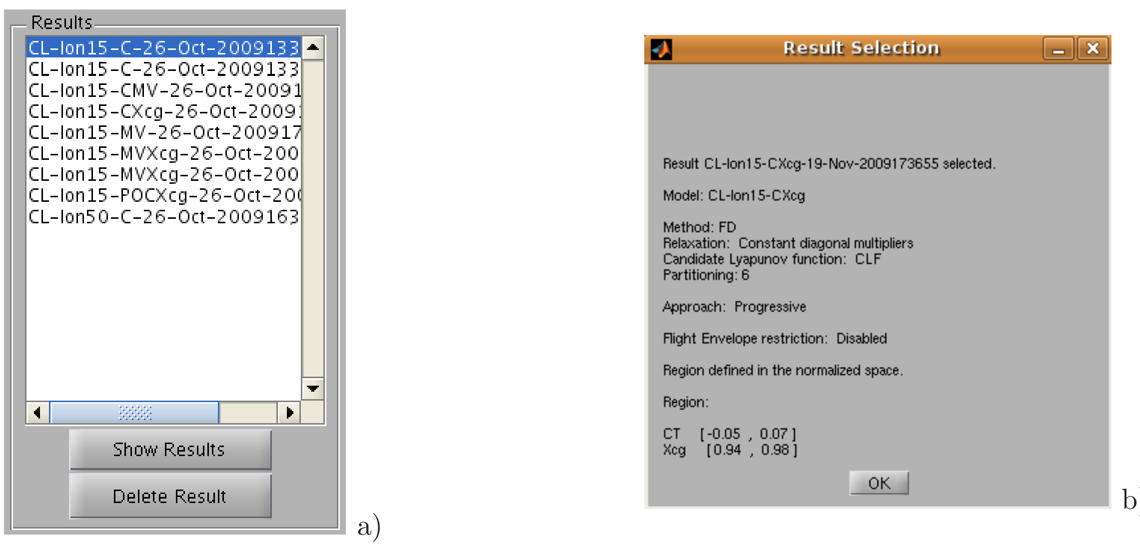


Figure 13: a) Performed clearance analyses. b) Confirmation of the selected analysis.

The results from the performed clearance analysis are stored in a newly created subfolder: `CL-lon`[interval]-[model]-[DateTime], e.g. `CL-lon15-OC-01-Aug-2009183510`, located under $/`Clearance_UniSi/DATA/`.

The subfolder contains:

- Four ∗.mat files which are used by the analysis library routines.
- Results.txt file which hosts, in a table format, some performance indicators.
- /IMAGES/ subfolder with pictorial representations of the clearance analysis results.

Another mat file, CL-lon[interval]-[model]-[DateTime].mat, is created and saved in $/⋯/RESULTS/ subfolder. This file, utilised in the generation of numerical and graphical representation of clearance analysis, constitute the summary of the results from the analysis.

From the on-display list within the *Results* subpanel, in Figure 13(a), double click to select a model for which analysis results are desired to be displayed. A dialogue-box, as shown in Figure 13(b), will appear showing the parameters (model, method, relaxation etc.) characterising the clearance problem set-up for the desired model. This step allows the user to confirm that the selected model (with configuration of set-up parameters) is indeed the one for which clearance analysis results are of interest. To display the results press *Show Results*; results

from the analysis will be presented in two formats: numerical and graphical.

2.7 Presentation of numerical results

The numerical presentation of the clearance results produces, in the Matlab command window, the following summary of both the clearance problem setup and the clearance analysis:

```
Model:
Method:
Relaxation:
Candidate Lyapunov function:
Partitioning:
Approach:
Flight Envelope restriction:
Region defined in the ⋯ space[1].
```

```
Region:
```

[Lower bound , Upper bound]

$\delta_1 \in [\quad lb_1 \quad , \quad ub_1 \;]$

$\delta_2 \in [\quad lb_2 \quad , \quad ub_2 \;]$

$\vdots$

$\delta_{n_\theta} \in [\quad lb_{n_\theta} \quad , \quad ub_{n_\theta} \;]$

```
Results
```

NOPs	Time (h:m:s)	Time/OP (h:m:s)	Time (Gridding) (h:m:s)	Time/OP (Gridding) (h:m:s)
-	-	-	-	-

[1] *Normalized* or *not normalized* replaces "⋯".

Cleared (%)	Unstable (%)	Unknown (%)	Rate (%)
-	-	-	-

The analysis summary can be divided into three parts. The first part, before the continuous line, and the second part, the `Region`, contain the same information as in Figure 12(b). The last part, the `Results`, contains a table reporting the performance indicators of the robust stability analysis (the table is also stored in `CL-lon`[interval]-[model]-[DateTime]/`Results.txt` file).

The `Results` table is divided, for convenience, into two parts. The first part presents information for the computational times, whereas the second part gives quantitative information about the clearance success. In the first part of the `Results` table, the first (NOPs) column denotes the number of optimisation problems that have been solved (and this, corresponds to the number of tiles attempted to be cleared), the second column (Time) provides the time elapsed in the course of the clearance procedure, whereas the third column (Time/OP), shows the average time elapsed per optimisation problem. Time (Gridding) column offers information about the time elapsed in the gridding of the uncertain parameter domain, and finally Time/OP (Gridding) column presents the average time elapsed per optimisation problem. All times are shown in h:m:s format.

In the second part of the `Results` table: the ratio (in %) of the cleared domain to the whole uncertainty domain is given in column *Cleared*; whereas, the percentage of the whole uncertain parameter domain, which, after gridding (see [1]), was found to host closed-loop unstable models, is given in column *Unstable*. The column *Unknown* indicates the percentage of the whole uncertainty domain, which could not be defined as unstable after gridding, yet, with the tested method it could not be certified as cleared either. The final column, *Rate*, provides the rate of cleared uncertainty region which refers only to the clearable domain, i.e the domain that did not contain closed-loop unstable models found by gridding.

2.8 Presentation of graphical results

Graphical presentation of the aeroelastic stability clearance analysis accompanies the numerical presentation of the results and is generated automatically for models with 2 uncertain parameters. Plots are displayed on the screen and stored in two different graphics formats (Fig and Tif), in $/$\cdots$/`IMAGES/FIG/` and $/$\cdots$/`IMAGES/TIF/` subfolders, respectively.

Dimension of the figure

2-D format. For LFR models with only 1 uncertain parameter in the Δ uncertainty block, clearance results constitute segments within the interval $[0, 1]$. The dimension of a pictorial representation of a clearance result depends on the number of uncertain parameters within the analysed LFR model. Accordingly, for LFR models with

- 1 uncertain parameter: the clearance result is comprised of segments within the interval $[0, 1]$, or the whole interval
  - no plot is generated, the numerical result is saved within `Results.txt` file in the subfolder
    $/$\cdots$/`CL-lon`[interval]-[model]-[DataTime]/;

- 2 uncertain parameters: the clearance result is presented on a 2-D figure
  - the figure is saved in the subfolder $/$··· /`IMAGES`/ ;
- $n_\theta \geq 3$ uncertain parameters: n_θ-dimensional hypervolumes are "sliced" by fixing $n_\theta - 2$ uncertain parameters from the uncertain parameter space of the analysed LFR. Given the intervals of the uncertain parameters, the user has a choice to select the uncertain parameters and assign a value to each one of them. As a result, a 2-D plot is generated.
  - the resulting figure is saved in the subfolder $/$··· /`IMAGES`/.

Figure 14 is an exemplar graphical presentation of an aeroelastic clearance analysis result. The green areas represent regions where the corresponding model has been cleared; areas coloured in red denote areas where the LFR model could not be cleared (due to the presence of unstable models found by gridding within those areas); white-coloured areas represent areas where, no unstable models were found by gridding, but stability of the model could not be certified with the chosen sufficient robust stability conditions.

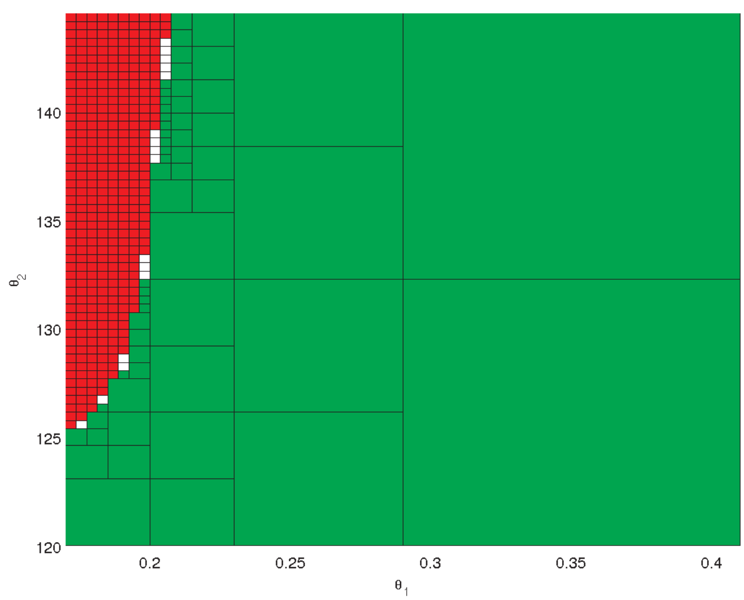


Figure 14: Clearance result: cleared (green), unstable (red), unknown (white).

2.9 Models with dead-zones

When addressing un-piloted stability of nonlinear models, the considered LFRs may contain not only uncertain parameters, but also dead-zones. In such a case, each dead-zone is treated as a sector-bounded time-varying uncertainty between 0 and 1, and this is independent from the setting of the uncertainty region as "Normalized" or "Not Normalized".

The bounds of the sector-bounded uncertainty can be modified (e.g., to consider bounded signals as inputs of the dead-zones). When a model with dead-zones is selected, all the features on the GUI panel concerning parameter-dependent Lyapunov functions (APDLF, MAPDLF) or multipliers are disabled, because the dead-zones are treated as time-varying uncertainties. The partitioning of the uncertainty domain is performed only with respect to the time-invariant uncertain parameters (if there are any in the selected model). When the "Show results" button is pushed, if the model has $n_\theta \geq 3$ parameters (including dead-zones) the user is asked to select 2 of them and provide values for the remaining $n_\theta - 2$. If the latter include dead-zones, any value between 0 and 1 can be chosen for the dead-zone parameter and this will not affect the plot. Clearly, there will be no partitioning (i.e. no tiles) in the resulting 2-D plot with respect to the plot axes associated with dead-zones.

3 Example of GUI use

In this section, as an example of the use of GUI software, we present steps followed in the setup of clearance analysis problems and corresponding results for the aeroelastic stability of LFR models MV and POCXcg with the following characteristics.

Model	n	d	θ_1, $s1$	θ_2, $s2$	θ_3, $s3$	θ_{s4}, $s4$
MV	20	54	M, 26	V, 28	-	-
POCXcg	20	83	C, 42	O, 24	P, 13	Xcg, 4

Table 1: MV and POCXcg closed-loop LFR models: uncertainty structure.

3.1 MV model

The FD method with constant-diagonal multiplers (cdμ) and common Lyapunov function (CLF) has been used in the clearance of the MV model. Progressive tiling approach has been employed in the clearance analysis, where the number of partitions was set to 7. The entire uncertain parameter domain, with bounds given in Table 2, will be subjected to clearance.

Uncertain parameter	*Lower bound*	*Upper bound*
Ma	-1	1
Vc	-1	1

Table 2: Uncertainty region: normalised bounds.

3.1.1 Setup of the clearance problem

Figure 15 shows the GUI panel with the methods and tuned values of parameters used in the clearance of the MV model in a given region of interest within the uncertainty domain.

1. Select Aeroelastic stability criteria, because POCXcg LFR model is integral.

2. To select MV: double click on MV LFR model from the "Model" box of the "Analysis" subpanel.

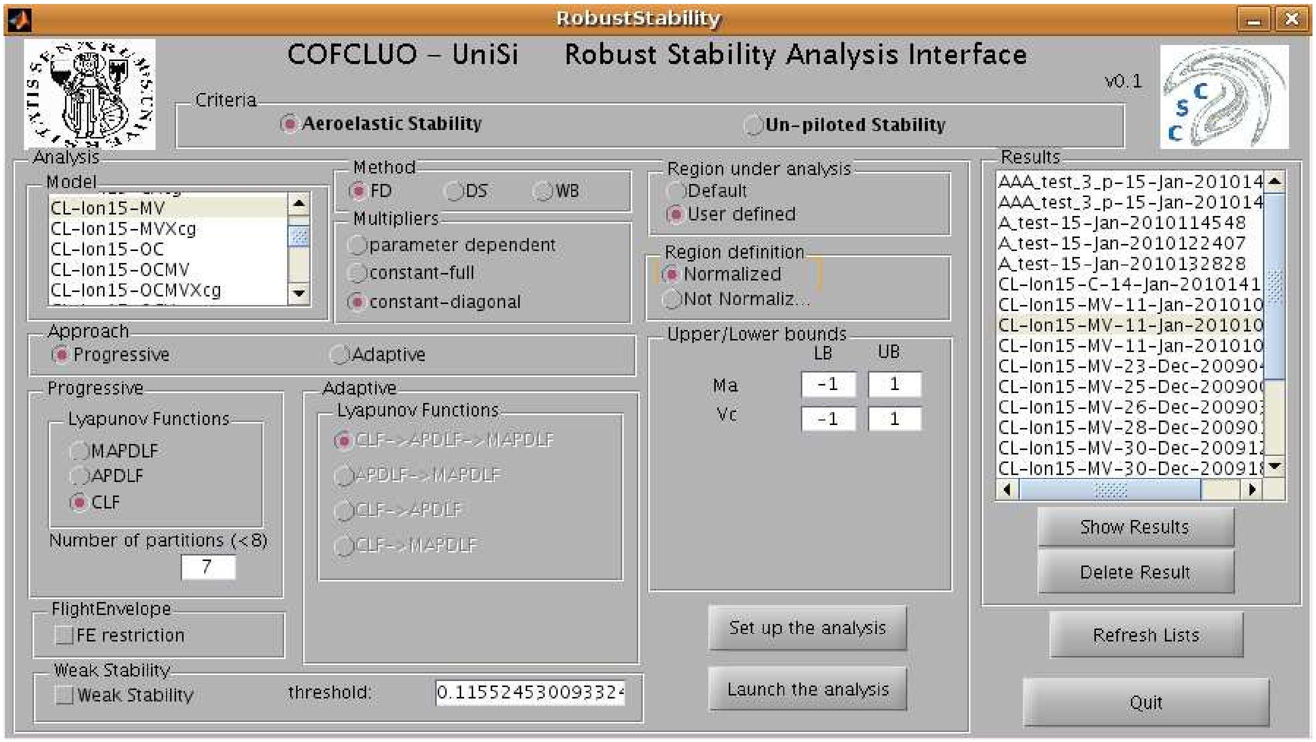


Figure 15: GUI panel: MV model clearance setup.

3. Select a method from the “Methods” box: FD.

4. Select the type of multipliers: *constant-diagonal multipliers*; the resulting method is FD-cdμ.

5. Choose an approach: *Progressive* tiling.

6. Choose the structure of the candidate Lyapunov function: CLF.

7. Select the number of maximum possible partitions, to be performed on each uncleared tile: 7.

8. “Region under analysis”: *User defined*.

9. “Region definition”: refer to Table 2 for bounds on the relevant uncertain parameters.

10. Press “Setup the analysis” to load the selection. A dialogue box will appear for confirmation.

11. Press “Launch the analysis” to start the clearance process.

12. The optimisation process initiates with iterations shown on the command window.

Once the analysis is completed the results are automatically generated and presented both numerically, in a Table, and graphically, in a Figure, as outlined in Subsection 2.7 and 2.8, respectively.

3.1.2 Results

Clearance results of the MV model can be viewed by following the steps below:

1. Select MV model from the "Results" panel: double click on the model MV.
2. Confirm that the clearance analysis problem setup (method, multipliers, LF, Approach), from the "Result Selection" dialogue box, corresponds to the correct MV model.
3. Press "Show Results" to regenerate the numerical and graphical results from the conducted analysis.

The following analysis history appears in the Matlab command window.

```
Model:  CL-lon15-MV
Method:  FD
Relaxation:  Constant diagonal multipliers
Candidate Lyapunov function:  CLF
Partitioning:  7
Approach:  Progressive
Flight Envelope restriction:  Disabled
Region defined in the normalized space.
```

`Region:`
[Lower bound , Upper bound]
`Ma`∈ [-1 , 1]
`Vc`∈ [-1 , 1]

NOPs	Time (h:m:s)	Time/OP (h:m:s)	Time (Gridding) (h:m:s)	Time/OP (Gridding) (h:m:s)
1346	8:28:3	0:0:22	0:4:25	0:0:0

Cleared (%)	Unstable (%)	Unknown (%)	Rate (%)
86.79199	12.29248	0.91553	98.95616

Figure 16 illustrates the graphical representation of the clearance analysis. The green, red and white colours within the uncertain parameter domain denote, correspondingly: areas which have been cleared, areas which contain unstable models and areas which were neither cleared nor they contained unstable models found by gridding- this is mainly because of the stability conditions being only sufficient.

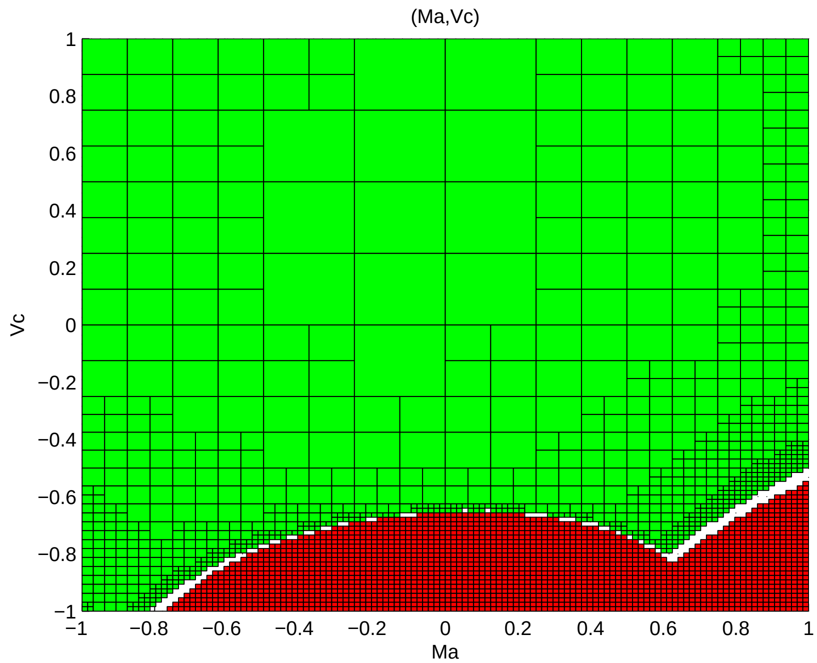


Figure 16: Clearance result (MV model): cleared (green), unstable (red), white (unknown).

3.2 POCXcg model

Set up for the analysis of POCXcg model and corresponding analysis results in numerical and graphical formats are presented in the following.

3.2.1 Set up of the clearance problem

The setup for aeroelastic stability analysis of POCXcg model has been completed by following steps similar to those described in Section 3.1.1.

In the clearance the FD method with constant-diagonal multiplers (cdμ) and common Lyapunov function (CLF) have been used. Progressive tiling approach has been employed, where the number of partitions was set to 6. Only a portion of the uncertainty hyperspace has been subjected to clearance. The physically meaningful bounds defining the region of our interest are given in Table 3.

Uncertain parameter	*Lower bound*	*Upper bound*
CT	0	0.05
Vc	0.9	0.95
PL	0.5	0.55
Xcg	0.5	0.6

Table 3: Uncertainty region: physical bounds.

3.2.2 Results

Clearance results of the POCXcg model can be viewed by following the steps below:

1. Select POCXcg model from the "Results" panel: double click on the model POCXcg.
2. Confirm that the clearance analysis problem setup (method, multipliers, LF, Approach), from the "Result Selection" dialogue box, corresponds to the correct POCXcg model.
3. Press "Show Results" to regenerate the numerical and graphical results from the conducted analysis.

The following analysis history appears in the Matlab command window.

```
Model:  CL-lon15-POCXcg
Method:  FD
Relaxation:  Constant diagonal multipliers
Candidate Lyapunov function:  CLF
Partitioning:  6
Approach:  Progressive
Flight Envelope restriction:  Disabled
Region defined in the not normalized space.
```

`Region:`
[Lower bound , Upper bound]
`CT`$\in$ [0 , 0.05]
`OT`$\in$ [0.9 , 0.95]
`PL`$\in$ [0.5 , 0.55]
`Xcg`$\in$ [0.5 , 0.6]

NOPs	Time (h:m:s)	Time/OP (h:m:s)	Time (Gridding) (h:m:s)	Time/OP (Gridding) (h:m:s)
1	0:2:24	0:2:24	0:0:12	0:0:12

Cleared (%)	Unstable (%)	Unknown (%)	Rate (%)
100.00	0.000	0.000	100.00

In order to generate a 2-D plot we have to select $n_\theta-2$ uncertain parameters and assign a value to each one of them. These values have to be chosen from within the lower and upper bounds of the corresponding uncertain parameters used to define the uncertainty region. Here, n_θ=4 is the number of uncertain parameters: P=PL, O=OT, C=CT and Xcg. The following text appears in the Matlab command window, immediately after "`Region`":

`Parameters to fix`:

1. : [`CT OT`]

2. : [`CT PL`]

3. : [`OT PL`]

4. : [`CT Xcg`]

5. : [`OT Xcg`]

6. : [`PL Xcg`]

`Enter a number`: 2
`Fix the parameters`:
`-> CT defined in` [0 , 0.05]
`-> PL defined in` [0.5 , 0.55]

`Enter the value`:

`CT` = 0.04
`PL` = 0.53

`CT` = [0.03999 , 0.040039], `PL` = [0.52998 , 0.53003]

`Results`

Cleared (%)	Unstable (%)	Unknown (%)	Rate (%)
100.00	0.0	0.0	100.00

`Analysis completed`, `data in` ··· `/Data/CL-lon15-POCXcg-16-Oct-2010050329`

At the same time, a figure is generated to provide a graphical presentation of the results.

Figure 17 illustrates the aeroelastic clearance result of the model within the specified uncertainty region. The area coloured in green represents the region where the POCXcg model has been cleared, i.e. certified as stable. By checking the bounds of the uncertainty region, defined in Table 3, it can be concluded that the whole selected slice has been cleared (as one could expect, from the `Results` table).

References

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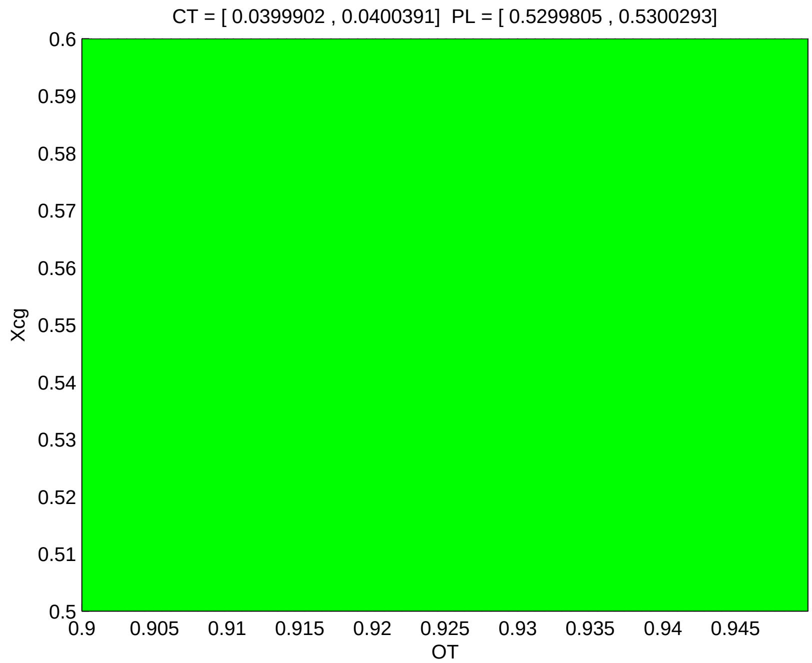

Figure 17: Clearance result (POCXcg model): cleared (green).

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