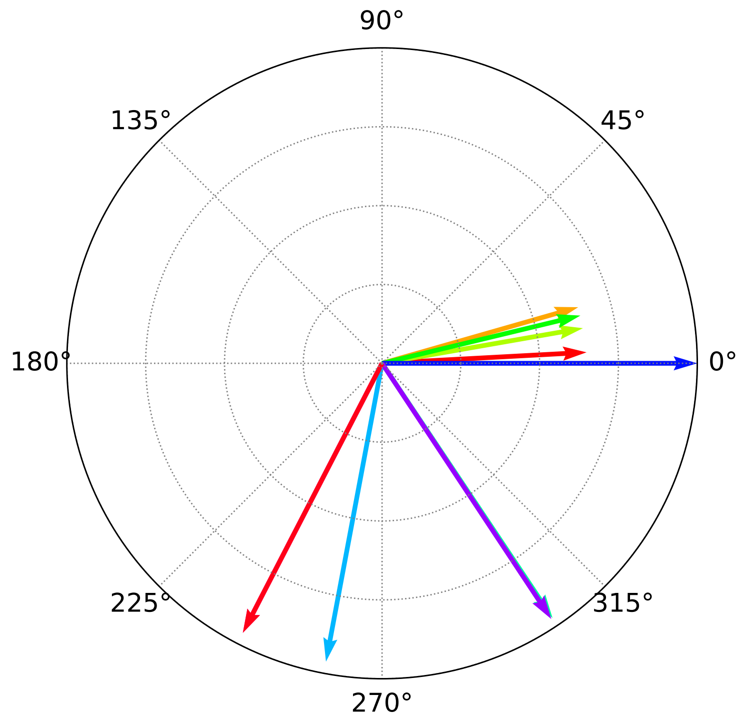

Ringdown Oscillations' Monitoring and Analytics (ROMA)

Web Application User Guide

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Wide-Area Monitoring System
http://148.216.38.78/cict/roma/

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Chapter 1

Linear Ringdown Analysis Methods

1.1 Prony analysis

The Prony method is described as a sum of exponentially damped sinusoidal signals, whose signal model is given by [1]:

$$\hat{y}(k) = \sum_{i=1}^{n} A_i e^{\sigma_i * n\Delta t} \cos(2\pi f_i n\Delta t + \theta_i), \tag{1.1}$$

where modal parameters A_i, σ_i, f_i, θ_i respectively stand for amplitude, damping factor, frequency, and phase. Δt is a sample time for N samples in $\hat{y}(t)$. Likewise, the model in (1.1) can be represented by

$$\hat{y}(k) = \sum_{i=1}^{n} B_i z_i^k \tag{1.2}$$

where n is the number of the estimated eigenvalues corresponding to the Prony's model order and $z_i = e^{\lambda_i \Delta t}$ denotes the roots of the n-th characteristic polynomial function of the system.

1.1.1 Prony analysis for single channels

Given the time-series data of recorded signal $y(k)$ with N samples, the procedure begins to construct a Toeplitz matrix $\mathbf{T}$ using the elements of the recorded signal, to fit the data with a discrete linear prediction model (LPM) of order N. It must be considered that $n \leq N$, which is the subset of modes to be determined.

$$\mathbf{Y} = \mathbf{Ta} \tag{1.3}$$

where $\mathbf{Y}$ is:

$$\mathbf{Y} = [y(n) \quad y(n+1) \quad \cdots \quad y(N-1)]^T \tag{1.4}$$

To find the polynomial coefficients

$$\mathbf{a} = (\mathbf{T}^T\mathbf{T})^{-1}\mathbf{T}^T\mathbf{Y} \tag{1.5}$$

And to find the z_i roots of the polynomial

$$z^n - (a_1 z^{n-1} + a_2 z^{n-2} + \cdots + a_{n-1} z^0) = 0 \tag{1.6}$$

1.1.2 Prony analysis for multiple channels

Considering a set of M signals $\mathbf{Y}^{(m)}$, $m = 1, ..., M$ that share a common set of eigenvalues obtained from the same system, same event, and the same sampling time. Toeplitz matrix $\mathbf{T}$ as in (1.3) and vector $\mathbf{Y}$ in (1.4) can be formulated for every channel and notated as $\mathbf{T}^{(m)}$ and $\mathbf{Y}^{(m)}$ [2]. Thus, the LPM can be extended as follows:

$$[\mathbf{Y}^{(1)}\ \mathbf{Y}^{(2)}\ \cdots\ \mathbf{Y}^{(m)}] = [\mathbf{T}^{(1)}\ \mathbf{T}^{(2)}\ \cdots\ \mathbf{T}^{(m)}]\mathbf{a}. \tag{1.7}$$

and the next steps are the same to estimate the roots z_i using multiple channels.

1.2 Eigensystem Realization Algorithm

The eigensystem realization algorithm is a system identification technique that is widely used to identify and reduce linear systems. The ERA is based on the singular value decomposition (SVD) of the Hankel matrix $\mathbf{H}_0$ associated with the ringdown behavior of a linear system [3, 4].

1.2.1 Eigensystem Realization Algorithm for single-channel

Given the time-series data of recorded signal $y(k)$ with N samples, establish r which is the size of the Hankel matrix $\mathbf{H}$ and ensure that $r = \frac{N}{2} - 1$, this choice assumes that the number of data points is sufficient such that $r > n$, and hold $\mathbf{H}_0$ and $\mathbf{H}_1$.

To construct the Hankel matrix $\mathbf{H}_0$ and its shifted Hankel matrix $\mathbf{H}_1$ using the elements of the recorded data signal $y(k)$, such as:

$$\mathbf{H}_0 = \begin{bmatrix} y_0 & y_1 & \cdots & y_r \\ y_1 & y_2 & \cdots & y_{r+1} \\ \vdots & \vdots & \ddots & \vdots \\ y_r & y_{r+1} & \cdots & y_{N-1} \end{bmatrix} \tag{1.8}$$

$$\mathbf{H}_1 = \begin{bmatrix} y_1 & y_2 & \cdots & y_{r+1} \\ y_2 & y_3 & \cdots & y_{r+2} \\ \vdots & \vdots & \ddots & \vdots \\ y_{r+1} & y_{r+2} & \cdots & y_N \end{bmatrix} \tag{1.9}$$

Then apply SVD to $\mathbf{H}_0$:

$$\mathbf{H}_0 = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^T \tag{1.10}$$

To separate $\mathbf{H}_0$ into two components, a n large (nonzero in the case of noiseless measurements) and s small (zero in the case of noiseless measurements) singular values. This is to extract singular values with the higher energy.

$$\mathbf{H}_0 = \begin{bmatrix}\mathbf{U}_n & \mathbf{U}_s\end{bmatrix} \begin{bmatrix}\boldsymbol{\Sigma}_n & 0 \\ 0 & \boldsymbol{\Sigma}_s\end{bmatrix} \begin{bmatrix}\mathbf{V}_n^T \\ \mathbf{V}_s^T\end{bmatrix} \tag{1.11}$$

this way it can be considered the approximate high-rank Hankel matrix $\mathbf{H}_0$ by a reduced-rank n matrix:

$$\mathbf{H}_0 \approx \mathbf{U}_n \boldsymbol{\Sigma}_n \mathbf{V}_n^T \tag{1.12}$$

Compute the discrete system matrix $\mathbf{A}$

$$\mathbf{A} = \mathbf{\Sigma}_n^{-\frac{1}{2}} \mathbf{U}_n \mathbf{H}_1 \mathbf{V}_n^T \mathbf{\Sigma}_n^{-\frac{1}{2}} \tag{1.13}$$

Then z_i roots are obtained from $z_i = eig(\mathbf{A})$

1.2.2 Eigensystem Realization Algorithm for multiple-channel

For multiple outputs channels, a set of M signals is shaped in matrix form such that $\mathbf{Y}_m \in \Re^{N\times m}$, that is m-column arrays corresponding to single channels, as follows:

$$\mathbf{Y}_m = [\mathbf{y}^{\{1\}}\ \mathbf{y}^{\{2\}}\ \cdots\ \mathbf{y}^{\{q\}}\ \cdots\ \mathbf{y}^{\{m\}}] \tag{1.14}$$

with $\mathbf{y}^{\{q\}} = [y(0)\ y(1)\ \cdots\ y(N-1)]^T$.

The Hankel matrix $\mathbf{H}_0$ can be also derived for multiple output channels by using submatrices that are constructed by each signal. This is called a block Hankel matrix and is given by

$$\tilde{\mathbf{H}}_0 = [\mathbf{H}^1 \quad \mathbf{H}^2 \quad \cdots \quad \mathbf{H}^m]^T \tag{1.15}$$

Thus, this block Hankel matrix and its shifted Hankel matrix $\tilde{\mathbf{H}}_1$ are replaced such as in (1.16), enabling to extend for multiple channels. Hence, the next steps are the same to estimate the roots z_i using multiple channels.

1.3 Matrix Pencil

The matrix pencil (MP) method produces a matrix whose roots (z_i) facilitate the extraction of the eigenvalues. The number of significant modes (n) in the system is determined from the SVD of the Hankel matrix $\mathbf{H}$. The basic process of the MP is similar to that of the ERA method [4–7].

1.3.1 Matrix Pencil for single channel

Given the time-series data of recorded signal $y(k)$ with N samples, determine r such as $r = \frac{N}{2} - 1$, where r is the size of the Hankel matrix $\mathbf{H}$, this choice assumes that the number of data points is sufficient such that $r > n$. Construct $\mathbf{H}$ using the elements of the recorded data signal. Then apply SVD:

$$\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^T \tag{1.16}$$

Then define matrices $\mathbf{V}_1$ and $\mathbf{V}_2$

$$\begin{aligned} \mathbf{V}_1 &= [\mathbf{v}_1 \quad \mathbf{v}_2 \quad \cdots \quad \mathbf{v}_{n-1}] \\ \mathbf{V}_2 &= [\mathbf{v}_2 \quad \mathbf{v}_3 \quad \dots \quad \mathbf{v}_n] \end{aligned} \tag{1.17}$$

matrix $\mathbf{Y}_1$ and $\mathbf{Y}_2$ come from:

$$\begin{aligned} \mathbf{Y}_1 &= \mathbf{V}_1^T \mathbf{V}_1 \\ \mathbf{Y}_2 &= \mathbf{V}_2^T \mathbf{V}_1 \end{aligned} \tag{1.18}$$

finally get roots $z_i = eig(\mathbf{Y}_1^\dagger \mathbf{Y}_2)$.

1.3.2 Matrix Pencil for multiple-channel

For each channel, two shifted Hankel matrices are formed. Consider $\mathbf{H}_1^{(m)}$ and $\mathbf{H}_2^{(m)}$ are the Hankel matrices for the m-th channel. The aggregated Hankel matrices are, as follows:

$$\begin{aligned} \mathbf{H}_1 &= [\mathbf{H}_1^{(1)}, \mathbf{H}_1^{(2)}, ..., \mathbf{H}_1^{(m)}] \\ \mathbf{H}_2 &= [\mathbf{H}_2^{(1)}, \mathbf{H}_2^{(2)}, ..., \mathbf{H}_2^{(m)}] \end{aligned} \tag{1.19}$$

These Hankel matrices in (1.19) are decomposed in the same way as in (1.16). The complete process to get z_i, it is the same as the single-channel from (1.17)-(1.18).

1.4 Estimation of modal parameters

Once the roots z_i are computed by all three methods according to the pseudo-codes, the eigenvalues of the discrete system z_i can be found as $\lambda_i = \frac{\ln(z_i)}{\Delta t}$ and the modal parameters can be estimated by:

$$\hat{f}_i = \mathrm{Im}\left(\frac{\lambda_i}{2\pi}\right) \tag{1.20}$$

$$\hat{\sigma}_i = \mathrm{Re}(\lambda_i) \tag{1.21}$$

The damping ratio is obtained as

$$\hat{\zeta}_i = \frac{\hat{\sigma}_i}{\hat{\omega}_i} \tag{1.22}$$

where $\hat{\omega}_i = 2\pi \hat{f}_i$. Likewise, the modal energy can be estimated by

$$\hat{E}_i = \frac{1}{2} \hat{\omega}_i^2 \hat{A}_i^2 \tag{1.23}$$

where $\hat{A}_i$ corresponds to the amplitude estimates, $\hat{A}_i = 2|B_i|$. The residues B_i are calculated solving the Vandermonde problem using the z_i roots as

$$\mathbf{B} = (\mathbf{Z}^H \mathbf{Z})^{-1} \mathbf{Z}^H \mathbf{y} \tag{1.24}$$

where the complex matrix $\mathbf{Z}$ is formed using the roots z_i, and $\mathbf{y}$ is the recorded signal of size N.

Chapter 2

Web Application

2.1 Introduction

The goal of this application is the analysis of a single signal or a set of signals obtained from events measured in electrical power systems, which can be synchrophasor data containing the same time-stamp. When a set of signals is considered, this must be obtained from the same event in the same system. The analysis methods embedded in this web platform are: Prony, Matrix Pencil, and Eigensystem Realization. These are integrated into the application allowing their execution in a simple way, enabling the provision of graphical and numerical results.

2.2 Web development

This application is developed in Python3 [8, 9] and contains two main classes: main window and preview window. In turn, these classes correspond to the application's two windows (objects): the main window and the preview Window, respectively. Classes exchange information between them, but the main window manages the data reception, settings, analysis, and results. This app is developed using mainly the Django library [10, 11] for the Model–view–controller, Numpy [12] and Scipy [13] are employed as mathematical tools, and Matplotlib [14] is used to plot all results. The first step is to read the file with data samples from PMU or other devices providing the same time-stamp for all samples. These files must meet certain criteria in order to be read. Then, the configuration according to the criteria of each user needs to be established; if some errors or inconsistencies appear, then the application notifies the error necessary to correct them to continue with the execution of the app by clicking the RUN button. Afterwards, the app will collect all data verifying that everything is correct and it will show all numerical results in the results section.

2.2.1 Settings

Starting the application, the main window is displayed, shown in figure 2.1, which contains the following:

A) *Examinar* (*Button*) is the browser, allows files with extensions **.csv* or **.xlsx*.

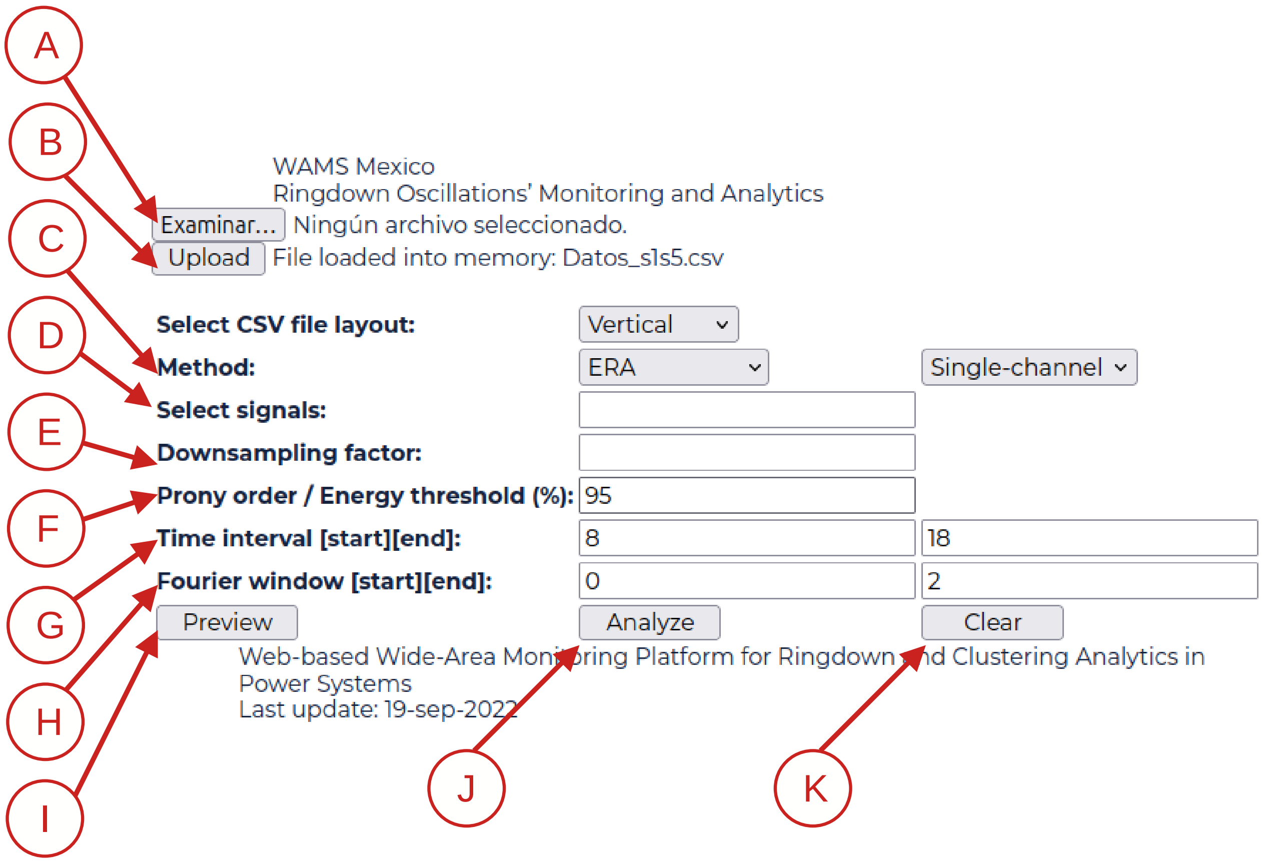


Figure 2.1: Main window.

B) *Upload* (*Button*) is to upload temporarily to the application the file previously selected.

C) *Method* (*Menu buttons*), it allows to choose the solution method: Prony, MP or ERA, and also single-channel or multi-channel.

D) *Select signals* (*string entry*), it allows to write manually the signals' names to be analyzed.

E) *Downsampling factor* (*integer entry*), it enables to provide a downsampling factor.

F) *Method Prony order/Energy threshold* (*integer/float*), this has two options depending on the selection of the analysis method *Prony* or any of *ERA* or *MP*.

- If *Prony* (*integer*) is selected, this leads to ask for the number of *Modes*.
- If *ERA or MP* (*float*) are selected, this lead to ask for the *Energy threshold (%)* to get the singular values.

G) *Time interval* (*float entry*), it enables to provide the initial and final time of the analysis window.

H) *Fourier window* (*float entry*), it enables to provide the initial and final time of the Fourier spectrum window.

I) *Preview* (*Button*), displays graphical and numerical input data previews for analysis.

J) *Analyze* (*Button*), it executes the analysis of the signal(s).

K) *Clear* (*Button*), it clears all data and graphics of the main window.

2.3 Example for a real system event

2.3.1 Mexican electrical system

In Mexico four electrical systems operate in isolation, Muleje, Baja California (BCA), Baja California Sur (BCS), and the National Interconnected System (NIS) which is the largest one. The total installed capacity is approximately 91,050MW with a maximum demand of about 53GW in 2024. The BCA system is interconnected to the California ISO (CAISO) through two synchronous 230kV transmission lines.

The NIS is a mesh system with radial connections towards the northwest and southeast. Its transmission level is mainly composed of TLs with operating voltages of 400kV, 230 kV and 130-69kV. This system covers from Quintana Roo to Sonora state, making up the main electrical power grid in Mexico, and it is split into 7 regions: Central, Eastern, Western, Northwestern, North, Northeastern, and Peninsular. It also has six trade international interconnections: (*i*) there are four asynchronous connections in the Northeastern region with the Electric Reliability Council of Texas (ERCOT) in USA by four tie-lines with 436MW capacity; (*ii*) there is one synchronous connection in the Eastern region with Guatemala via one tie-line with 240MW capacity; and (*iii*) there is also one synchronous connection in the Peninsular region with Belize by one tie-line with 55MW capacity. For the sake of brevity, public official documents are available at [15].

2.3.2 Real case in Mexico, December 28, 2020

On Dec 28^{th}, 2020 two of the main TLs that interconnect the Northwestern, North and Northeastern regions with the Central, Eastern, Western and Peninsular regions were tripped provoking a cascade event that tripped other TLs, such as the interconnection with Guatemala. Due to the loading capacity of TLs and the presence of power oscillations, the Northwestern, North and Northeastern regions remained connected with the Central, Eastern, Western and Peninsular by one TL. Thus, this sequence of events yielded that the power generation surpassed the load demand in the Northwestern, North and Northeastern, causing a frequency excursion up to 61.14Hz that activated the stages of remedial action schemes to trip generation derived from high frequency. Meanwhile the load demand surpassed the power generation in the Central, Eastern, Western, and Peninsular regions, dropping down the frequency up to 58.76Hz and activating the load shedding stages as a consequence of the low frequency. As a result, the total affectation of power generation and load reached 8,696MW, representing 26% of the demand [15].

This case comprises the recorded measurements in the mentioned event, which are collected by five time-synchronize frequency disturbance recorders (FDRs) and a PMU installed in the following

	A	B	C	D	E	F
1	time	s1	s2	s3	s4	s5
2	200	59.9836	59.9996	60.0029	60.0022	60.0005
3	200.1	60.0042	60.0035	60.0038	60.0017	60.0006
4	200.2	60.0032	60.0020	59.9989	60.0015	59.9996
5	200.3	60.0076	60.0021	59.9983	60.0025	60.0011
6	200.4	59.9861	60.0022	60.0000	60.0012	60.0020
7	200.5	60.0014	60.0020	60.0025	60.0011	60.0016

a)

	A	B	C	D	E	F	G	H
1	time	200	200.1	200.2	200.3	200.4	200.5	200.6
2	s1	59.9836	60.0042	60.0032	60.0076	59.9861	60.0014	60.0138
3	s2	59.9996	60.0035	60.0020	60.0021	60.0022	60.0020	60.0034
4	s3	60.0029	60.0038	59.9989	59.9983	60.0000	60.0025	60.0033
5	s4	60.0022	60.0017	60.0015	60.0025	60.0012	60.0011	60.0016
6	s5	60.0005	60.0006	59.9996	60.0011	60.0020	60.0016	60.0013

b)

Figure 2.2: CSV file layout. (a) Vertical format. (b) Horizontal format.

locations: 1389-Monterrey (Northeastern), 1422-Mazatlan (Northwestern), 1378-Guadalajara and 1408-Morelia (both Western), and 1424-Chetumal (Peninsular), and PMU-Chiapas (Eastern). Numbers denote the ID code for FDRs in the FNET/GridEye project [1].

2.3.3 Analysis in web application (ROMA)

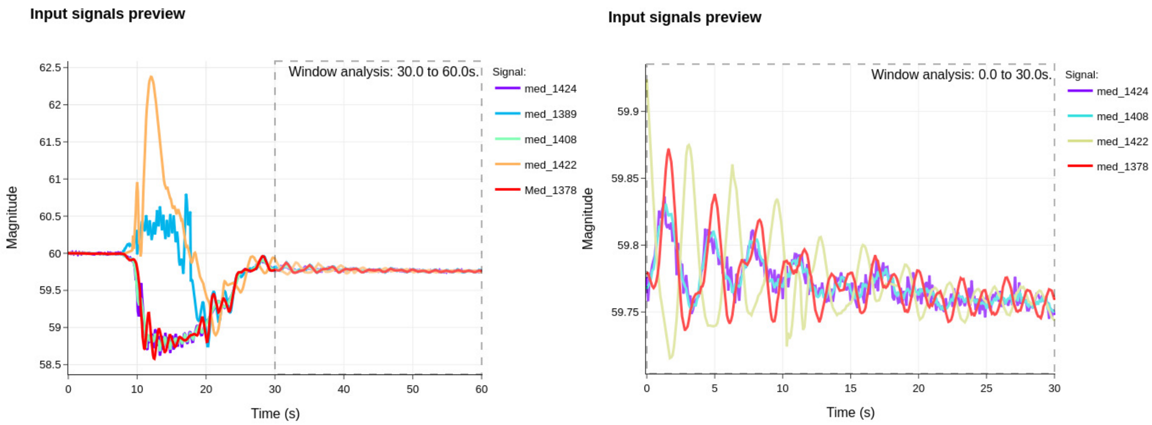
To use the ROMA web tool we must first have information in a certain format in a CSV file. The layout format can be vertical or horizontal. In its vertical form, the information of each channel is arranged in the form of columns, where the first column is the time vector and the subsequent ones are the information of the channels. The first row is the title of the modes. See Figure 2.2(a). In its horizontal form, the information of each channel is arranged in the form of rows where the first row is the time vector and the subsequent ones are the information of the channels. The first column is the title of the modes. See Figure 2.2(b). In both cases the program reads continuous data, the moment it detects a blank space, the program stops and assumes the end of the data, this is why it is important to avoid empty cells, columns, or rows.

For this example, the csv file is available in [16] for both horizontal and vertical layouts with name *mex28dic_wams_h.csv* and *mex28dic_wams_v.csv* respectively.

Once the measurement file is ready, click on the *Examinar* button, it is to select the local file and then load it using the *Upload* button, this is to temporarily upload it to the server. Before to analyze data, it is possible to make a pre-visualization with the *Preview* button, to adjust the analysis window of the signal(s) to be studied.

In this example, all signals will be analyzed with the ERA method and an energy threshold of 60% to obtain a low number of modes, but with the higher energy. Once the study window has been selected, as well as the method, type of study, order for Prony or energy threshold for ERA

[1] http://fnetpublic.utk.edu/index.html



a) b)

Figure 2.3: Preview of the signals under study. a) Full view of the measurements. b) Time window under study of the ringdown response.

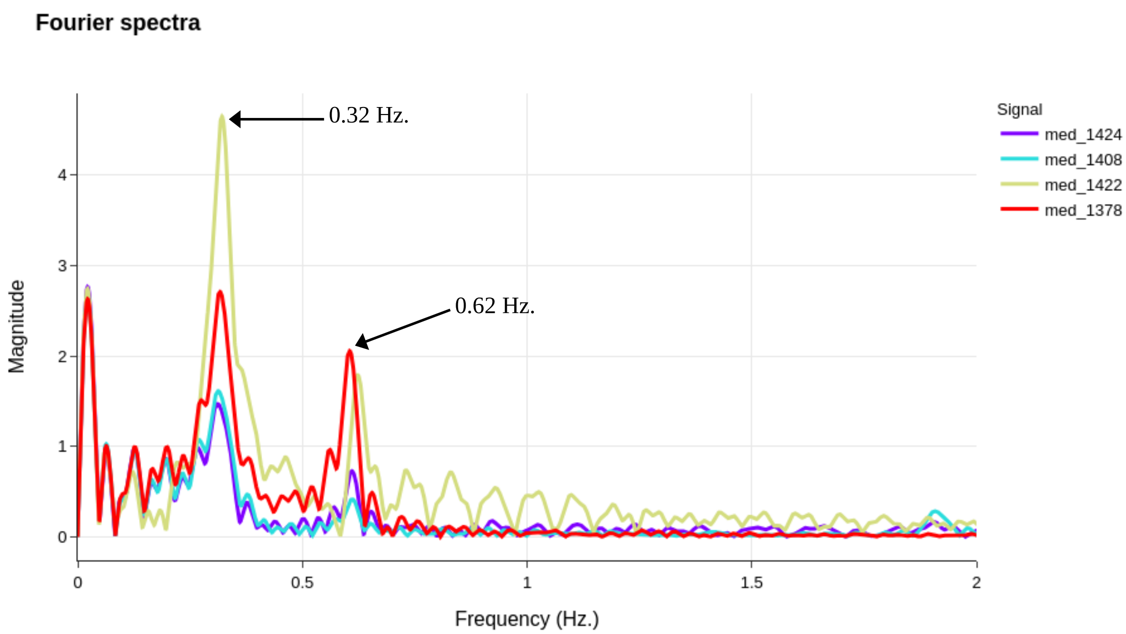


Figure 2.4: Fourier spectra, with two main modes with frequencies 0.32 and 0.62 Hz.

or MP, then press the *Analyze* button: this will initially show a Fourier analysis to see the modes immersed in the signal as depicted in Figure 2.4. Here you can set the number of modes you want to obtain.

Then Figure 2.5 (in the case of analysis with ERA and MP) will show the single value numbers and their energy for each signal in the single-channel option, or just one single value number and its energy for the set of signals, to see the modes ordered by energy and how many represent a certain percentage of the signal.

Figure 2.6 then shows the function under analysis in the continue line, and the reconstruction in a dotted line with the estimates obtained with the method used. The reconstruction will depend

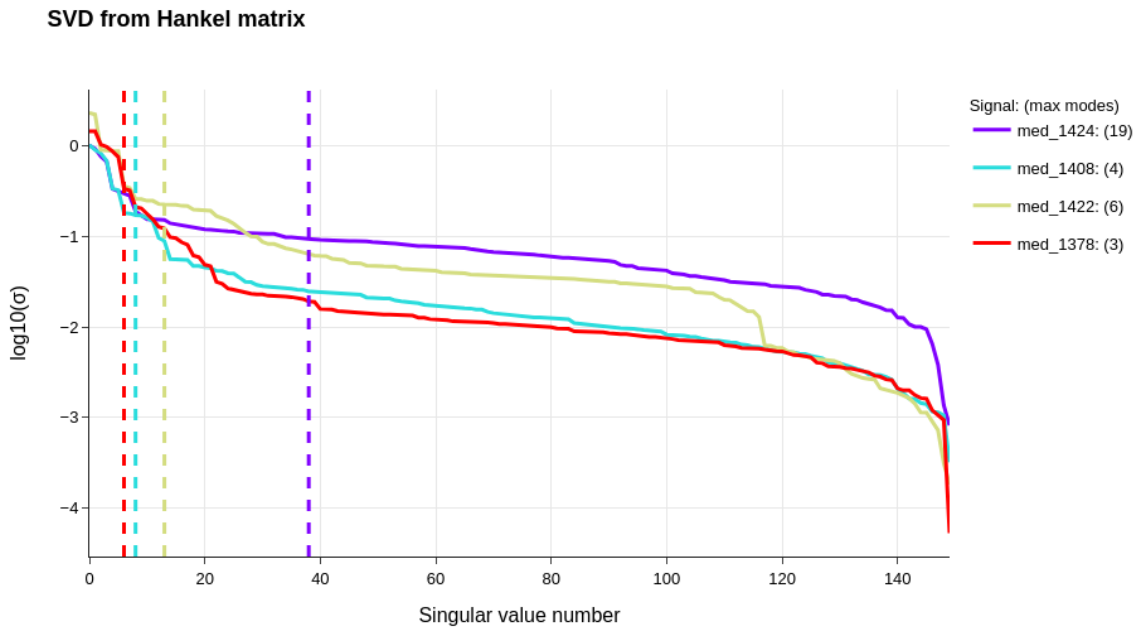


Figure 2.5: Singular value number for each signal ordered by energy and how many modes are needed to cover the energy threshold previously established.

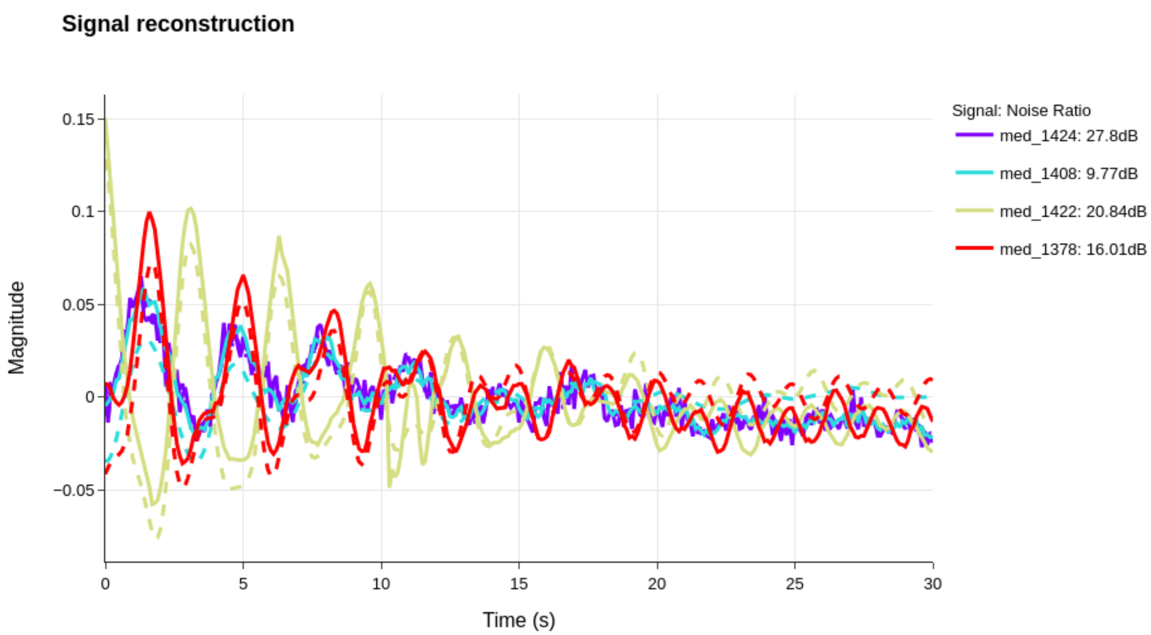


Figure 2.6: Signals under study (continuous line) and their reconstruction with the estimates (dashed line).

greatly on the energy threshold for ERA or MP and the modes selected for Prony.

Figure 2.7(a) shows the unit circle with the poles and zeros of the analysis, they are stable modes since are within the unit circle, unstable modes are symbolized by X.

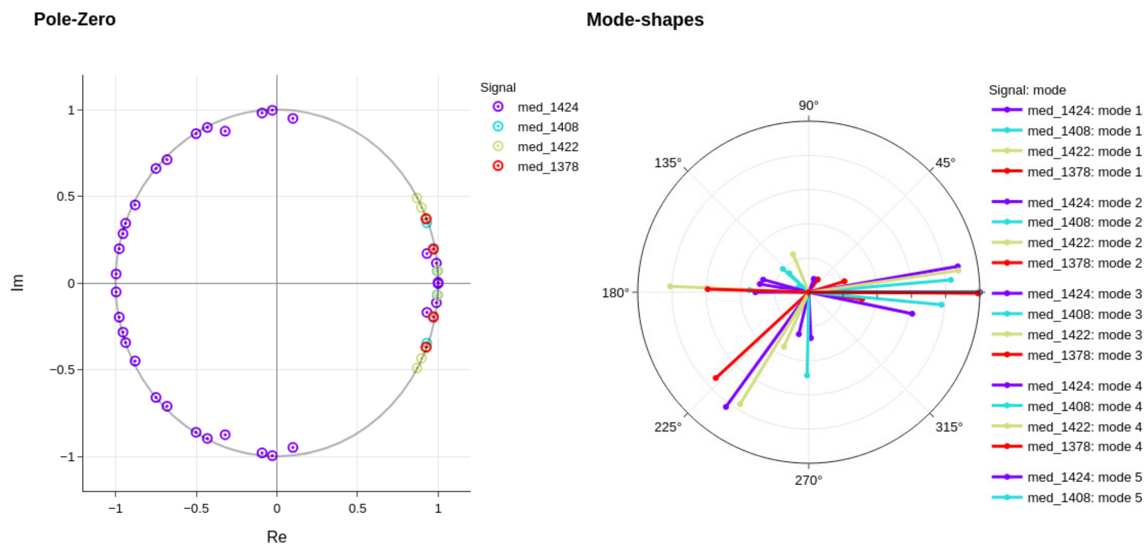


Figure 2.7: a) Pole Zero in the z-plane. b) Mode shape representation of all estimates.

Table 2.1: Numerical results - Dynamic parameters by ROMA

Signal (Name)	Mode m	Type (-)	Freq. (Hz.)	Amp. (-)	Damp. (1/s)	Damp.Rat. (%)	Phase (rad)	Energy (%)
med_1422	1	Inter-Area	0.72	0.004	-0.043	-0.953	0.472	0.0207
med_1422	2	Inter-Area	0.617	0.021	-0.042	-1.074	0.595	0.3195
med_1422	3	Inter-Area	0.317	0.1	-0.106	-5.336	-0.036	1.9808

The Figure 2.7(b) is the mode shape. To plot this feature, it is necessary to select Multi-channel analysis since the computation of the mode shapes works with several signals at a time. This chart shows the forms of the calculated modes which are the vectors for all signals in the i-th mode. Mode shapes are typically exhibited in a polar plane, considering the signal with the higher magnitude as a reference in magnitude and angle to normalize between 0 and 1.

The numerical results of the calculation in Table 2.1 based on the algorithm and the established configuration are shown. In the Table, it can be observed that 5 modes are obtained, of which two have greater energy with frequencies of 0.317 and 0.617 Hz. These are the ones that we had previously observed using FFT.

The export of the attained numerical results is done through the Export links $ExportCSVFile$ and $ExportLatexcode$ at the bottom of the main window. These links create a CSV format file or txt format file with Latex code respectively with the latest solution information obtained from the application. The CSV and txt files are created in the download file address, being named as results $ddmmyyyy\_hhmmss.xlsx$, substituting day, month, year, hour, minute, and second, respectively, in which the file was generated. The results file shows the numerical information of the analysis of the signal(s), where the first part indicates the settings and criteria for the analysis; whereas the second part exhibits all dynamic parameters. Table 2.1 depicts the numerical results for the NIS real event, this can be exported in CSV or Latex format; meanwhile graphical results can be saved in several formats (eps, pdf, png, etc).

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