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# Aeroelastic application of AES=V=

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# Contents

## Nomenclature

| | |
|---|---|
| $\dot{q}$,dq/dt | Generalized velocity |
| ABCD | Quadruple system: $\frac{dx}{dt} = Ax + Bu; y = Cx + Du$<br>$x^{n+1} = Ax^n + Bu^n; y^{n+1} = Cx^n + Du^n$ |
| AES=2= | General two-dimensional unsteady lifting surface method |
| AES=3= | General three-dimensional unsteady lifting surface method |
| AES=O= | General three-dimensional steady and unsteady body method in bounded and unbounded flows |
| AES=V= | Aeroelastic multipurpose method |
| CFD | Computational Fluid Dynamics |
| EAS | Equivalent Air Speed |
| ESM | Exponential Sine Method |
| FCS | Flight Control Systems |
| FFT | Fast Fourier Transform |
| FSI | Fluid Structure Interaction |
| GAC | Generalised Coordinate |
| GAF | Generalised Air Force |
| GAF_g | Generalised Air Force due to gust |
| GAF_q | Generalised Air Force due to generalized coordinate |
| GAF(k) | Generalised Air Force in reduced frequency domain |
| GAF(t) | Generalised Air Force in (reduced) time domain |
| GLUI | User Interface Library |
| GSF | Generalised Servo Force |
| H | Harmonic Interpolation |
| HH | HH method, flutter tracking along altitude based on damping dependent aerodynamics using Harmonic interpolation |
| HK | HK method, flutter tracking along speed based on damping dependent aerodynamics using Harmonic interpolation |
| HKM | HKM method, flutter tracking along speed based on damping dependent aerodynamics using Harmonic interpolation and consistent Mach number |
| k | Reduced frequency |
| K | K method, flutter tracking along reduced frequency |
| M | Mach number |
| MIMO | Multi Input Multi Output |
| MCK | Generalised mass, damping and stiffness |
| OSM | One Shot Method |
| PH | PH method, flutter tracking along altitude based on damping free aerodynamics |
| PK | PK method, flutter tracking along speed based on damping free aerodynamics |
| PKM | PKM method, flutter tracking along speed based on damping free aerodynamics and consistent Mach number |
| q | Generalized coordinate |

| | |
|---|---|
| SH | SH method, flutter tracking along altitude based on damping dependent aerodynamics using state space ABCD quadruples from MIMO identification |
| SK | SK method, flutter tracking along speed based on damping dependent aerodynamics using state space ABCD quadruples from MIMO identification |
| SKM | SKM method, flutter tracking along speed based on damping dependent aerodynamics using state space ABCD quadruples from MIMO identification and consistent Mach number |
| SRV | Generalised Servo Force |
| TAS | True Air Speed |
| u | Inputs quadruple system |
| y | Outputs quadruple system |

## Introduction

**AES=V=** is a tool directed to the analysis, the preprocessing and postprocessing involved in aeroelasticity. The app is easy to use and applies the GLUI user interface library (Version 2.36). It consists of a number of modules: A 2D and 3D visualization module, a warping module (representation of mode shapes on aerodynamic grid from the structural grid), a mollifier module (data enhancing), a surface grid generation module, a volume grid generation module, a time analysis module and a modal flutter analysis module. The time analysis module deals with the analysis (damping, frequencies, transfer functions, Fourier transforms) of time traces (e.g. obtained from CFD simulations or Flight Tests ), generates MIMO (Multi Input Multi Output) models and ABCD quadruples, frequency tabular models of the time traces and simulates compositions of ABCD quadruple models in order to investigate effects of the flight control system , effectors, gusts et cetera. The modal flutter analysis module deals with stability analysis applying a multitude of methods (K, P and state space) and also generates MIMO models and ABCD quadruple models of the unsteady aerodynamic forces, gusts and servo forces from tabular frequency data.

In combination with AES4AC's aerodynamic tools (**AES=2=, AES=W=, AES=O=** & **AES=3=**[1]) or alien aerodynamic tools it is straightforward to perform flutter analysis and obtain a global flutter diagram in a few clicks and seconds for a required Mach number, altitude, speed range of an A/C. As a consequence, it is easy to perform design &sensitivity/ uncertainty/optimization analysis.

The objective of this report is to demonstrate mainly the modal flutter analysis of **AES=V=** and in lesser detail the time analysis.

[1] AES=3= and AES=O= are one of the very rare programs that calculate generalized aerodynamic forces for diverging oscillating motions. Also, they both contain the H method which automatically extends the aerodynamic data obtained for purely oscillatory motions to damped and diverging oscillatory motions by means of the direct harmonic interpolation method.

## Flutter Analysis

The objective of the flutter analysis example is to demonstrate the modal flutter analysis of **AES=V=** for AGARD wing 445.6. **AES=V=** can perform the flutter analysis with the following methods (using common abbreviations):

- Frequency domain based using tabular GAF's at discrete Mach number, reduced frequencies:
    - The first is the K method, which predicts flutter points at the crossings of the artificial damping curves with the zero-damping ordinate. Only the crossing is valid! The damping and frequency trends of the K method are known to be false. Moreover, the applied Mach number is in general not consistent with the speed of sound at the selected altitude. GSF's cannot be applied with the K method. The method is non-iterative.
    - The second is the PK method, which predicts flutter at the crossings of the approximate damping curves with the zero-damping ordinate. Contrary to the K method, the damping and frequency trends are fairly correctly predicted near zero damping. Again, the applied Mach number is in general not consistent with the speed of sound at the selected altitude.
    - The third is the Mach number matched PKM method, which predicts flutter at the crossings of the approximate damping curves with the zero damping ordinate and at each velocity, the applied Mach number is consistent with the speed of sound at the selected altitude.
    - The fourth is the velocity matched PH method, which predicts flutter at the crossings of the approximate damping curves with the zero damping ordinate and at each altitude, the applied Mach number is consistent with the speed of sound and the dynamic pressure.

- Time domain based:
    - The fifth to seven methods are the SK, SKM and SH method. These are state space methods which improves the damping and frequency trends by taking into account the effect of nonzero damping by means of generalized aerodynamic forces that are approximately valid for the damping-frequency range under consideration. Our S methods apply ABCD quadruple sets of the generalized aerodynamics forces using an analytical continuation of the GAF's tables with a state space model based on MIMO identification. This requires the selection of a number of states and a reduced time step. For that purpose, one can inspect the quality of the GAF's MIMO identification by comparing the original data with the continued data table. These ABCD GAF(t) models can be applied in time simulations.

The PK and PH methods apply cubic spline interpolation along the reduced frequency assuming aerodynamic forces are invariant to damping. By so-called H (harmonic) interpolation the aerodynamic forces are depending on damping and augment the predictions. The H-interpolation flutter methods are named HK, HKM and HH methods, respectively and are especially of value for lowly damped structures.

The Mach number matched methods apply cubic spline interpolation along the Mach number and linear extrapolation beyond the lowest and highest Mach number.

All the aforementioned methods should provide the correct flutter speed at zero damping, however the dampings and frequencies trends can be different and the altitude, speeds might not be consistent with the applied Mach number.

For the purpose of time simulation, it is embedded to obtain analytical continuation of FCS induced GSF tables with a state space ABCD quadruple model based on MIMO identification.

Similarly, for the purpose of time simulation it is embedded to obtain analytical continuation of gust induced tables with a state space ABCD quadruple model based on MIMO identification.

## Running AES=V='s Flutter Analysis

The flutter analysis requires the preparation of two files: a file containing generalized mass and stiffness and a file containing generalized forces for a set of reduced frequencies (the latter assumes that the set is invariant for airspeed!) and Mach numbers. Both files have the ***AES=V=*** format. A speed and/or altitude distribution might be specified on a separate file. The latter is not required because speeds and altitudes can be specified interactively.

**AES=3=** is applied to calculate the Generalized Aerodynamic Forces (GAF's) for a range of 7 Mach numbers (0.5 ... 1.4) and 21 reduced frequencies (0.0 ... 2.0) which are saved on file. Reference length is set to ONE. The generation is fairly easy. Just create a paneling by entering the four vertices and select a distribution, apply the warping of the vibration modes set the Mach numbers and reduced frequencies, and run the code. This will take you just a few minutes (see page 31 ). **AES=V=** easily generates a reduced time domain MIMO model and ABCD quadruple of the reduced frequency domain tabular GAFs that can be applied in state space analysis using the time analysis module and in state space flutter analysis.

Effects of the flight control system on the flutter analysis can be modelled by providing Generalized Servo Forces (GSF's) for a range of Mach numbers and frequencies.
The GSF's model the effect of the mode shapes, sensors, control channels, control logic, gains, scheduling and actuators on the effectors. The GSF's are added to the GAFs.
**AES=V=** can easily generate a time domain MIMO model and ABCD quadruple of the frequency domain GSF's that can be applied in state space analysis using the time analysis module.

Running **AES=V=** ab initio will generate automatically the preferences file *.prefs_aes=v =* in your home directory and the configuration file *aes=v=.cnf* in your specified working directory. These files might serve as templates for your own applications. The files containing the bulky data should be listed on the *aes=v=.cnf file.*

First specify the name of the file folder on the *.prefs_aes=v=* file in your home directory.

Next prepare a very simple aes*=v=.cnf* file just containing names of the files containing the structural data and the aerodynamic data in the file folder. The files should reside in the file folder.

Then execute **AES=V=** in any other directory however, resulting analysis files are saved in the aforementioned file folder. The **AES=V=** workbench screen will then show up, see figure 1.

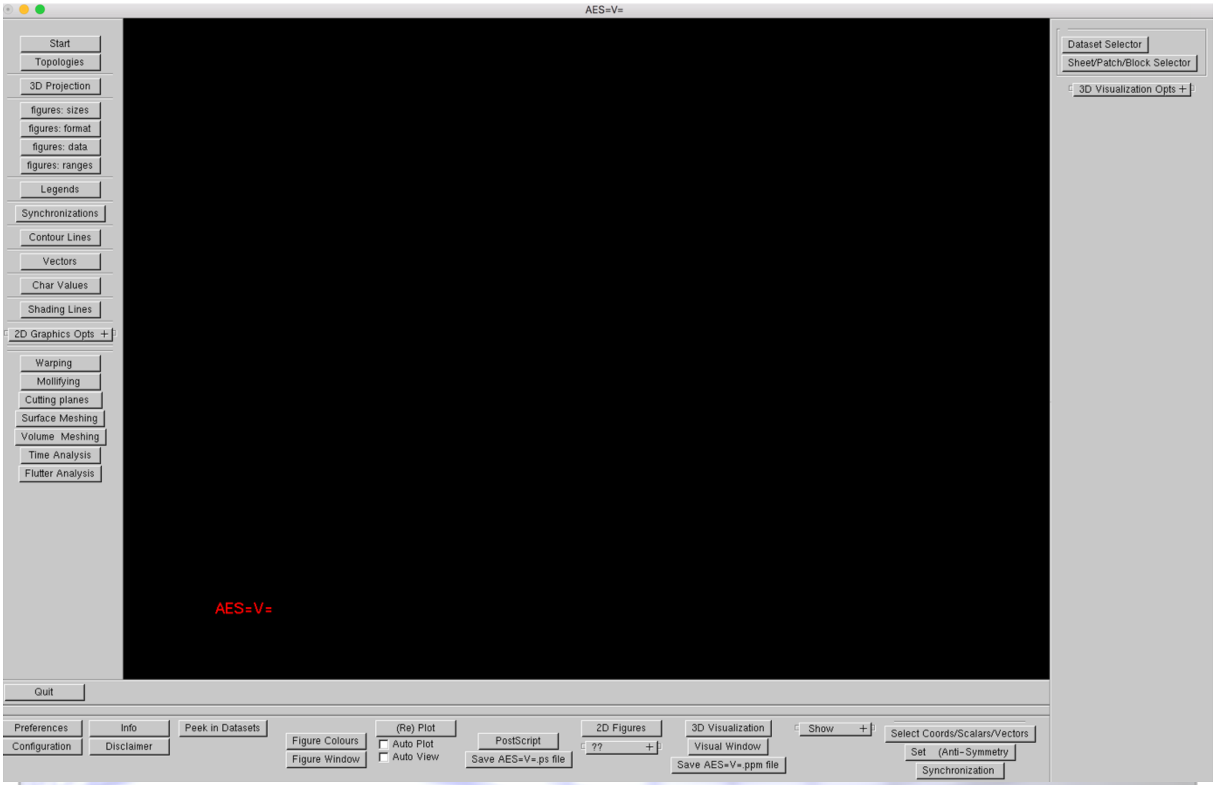


Figure 1 The startup screen of AES=V=: the AES=V= workbench

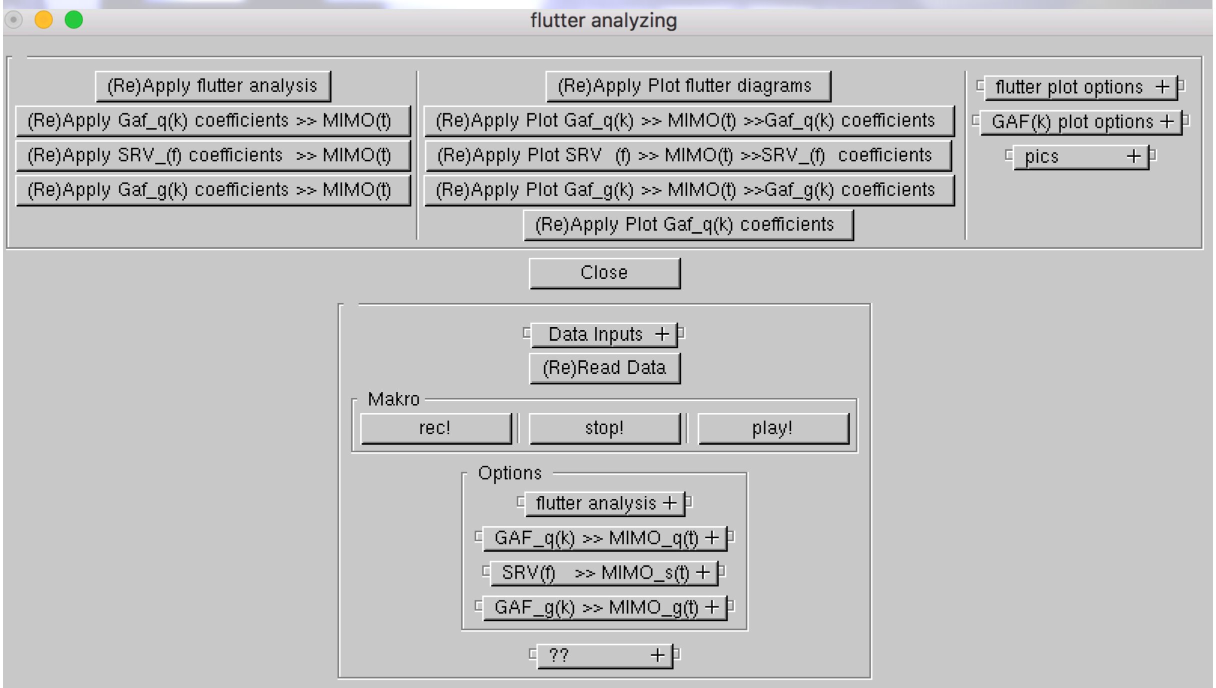


Figure 2 The Flutter Analysis Window

## AES=V='s Flutter Analysis

You enter the flutter analysis module by pressing the flutter analysis button and the Flutter Analysis Window will show up (see figure 2). You can perform the actions by pressing associated buttons:

- Flutter Analysis and inspection,
- ABCD quadruple model generation and inspection of tabular Generalized Air forces in reduced frequency domain.
- ABCD three-dimensional model generation and inspection of tabular Generalized Servo forces in frequency domain.
- ABCD three-dimensional model generation and inspection of tabular Generalized Gust forces in reduced frequency domain.
- Inspection of Generalized Air forces.
- Plot control.
- File import.
- Makro save and play of all inputs and actions.
- Operation control parameters of the models et cetera.

Then you have to press the data inputs button to select the files containing the generalized aerodynamic forces (GAF_q(k)) and the structural data (MCK) from the list defined in *aes=v=.cnf*.   After the selection by checking the associated box the data will be loaded (see figure 3).

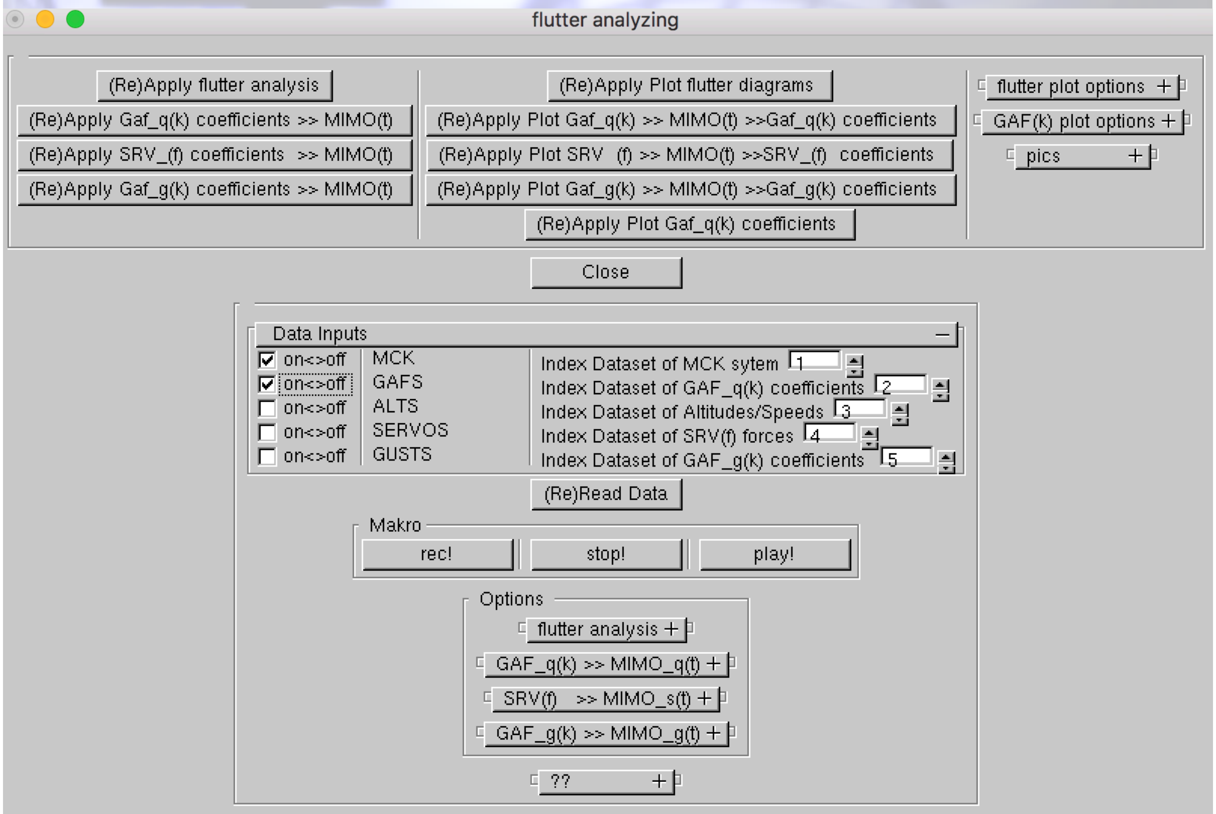

Figure 3 Selection of structural and aerodynamic files

## Inspection of Generalized Air Forces

You can inspect the GAF's (see figure 4) by pressing the (Re)Apply GAF plot button and or fit the GAF's (MIMO and Padé). Open the GAF plot options rollout to change plots and various options can be set:

- Minimum and Maximum of |GAF's|.
- (reduced) frequency range.
- Rows and Columns of the GAF Matrices.
- Full diagonal or full matrices.
- Real, Imaginary or Nyquist plots.
- Padé fitting.

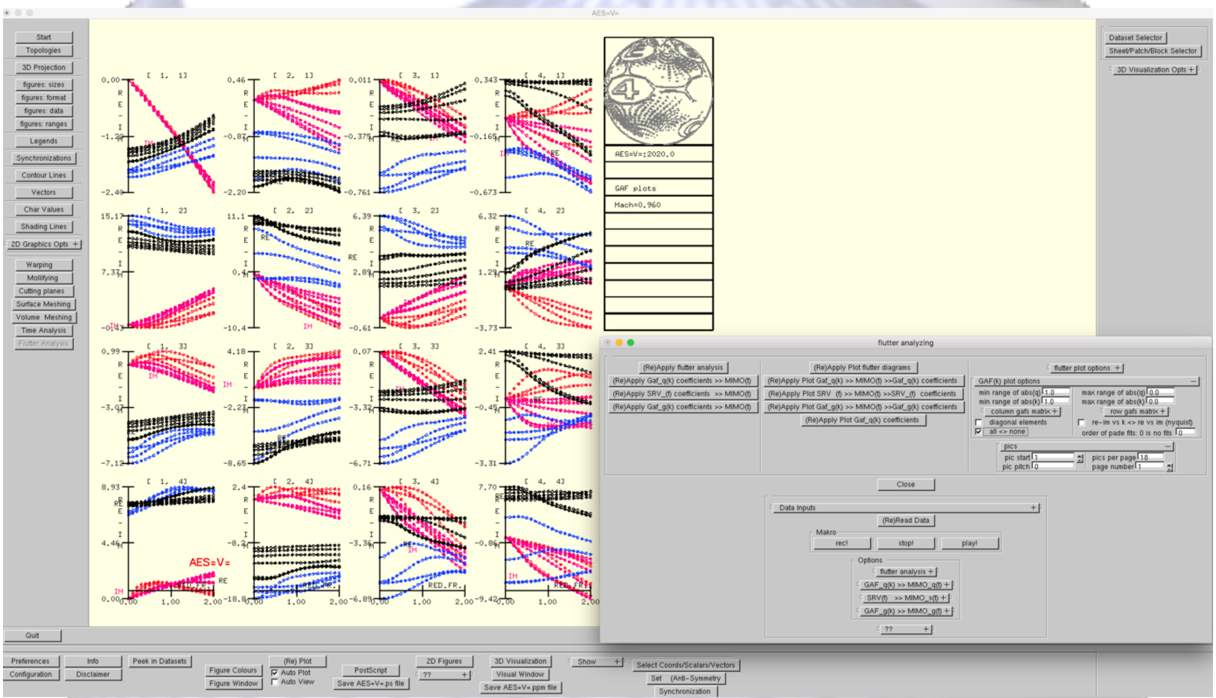

**Figure 4 Inspection of GAF, real and imaginary parts versus reduced frequency and Mach number (0.5 ... 1.4)**

## Single point flutter application

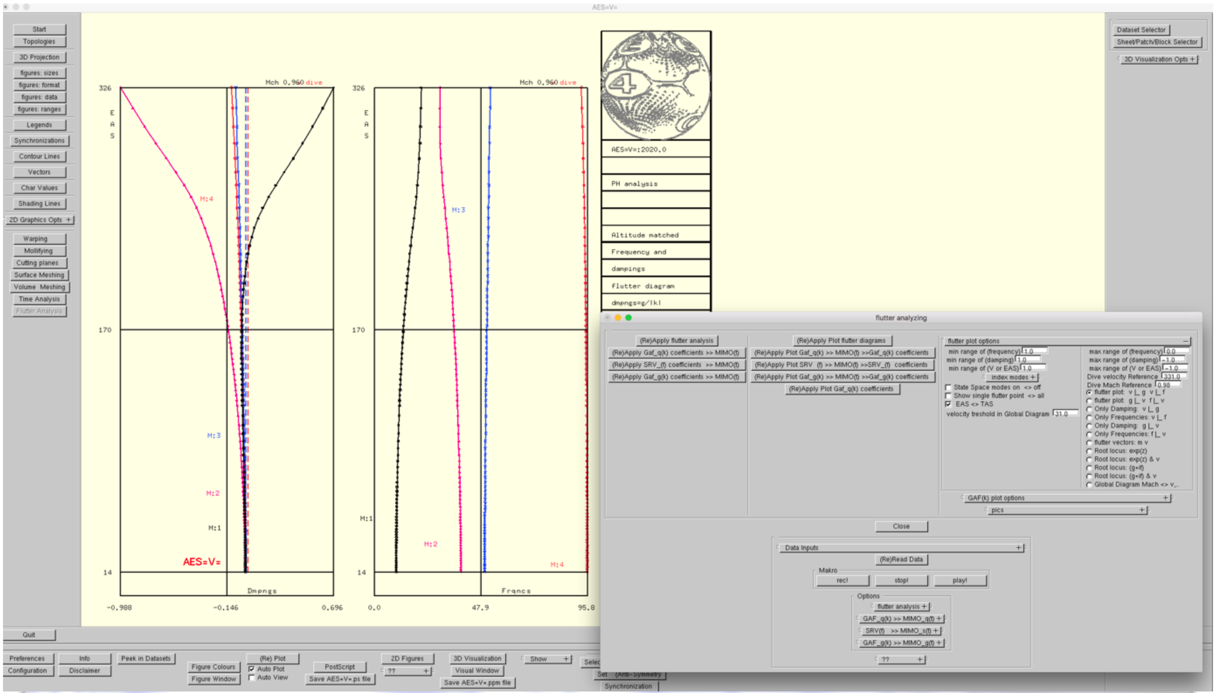


**Figure 5 PH flutter analysis diagram at Mach 0.96 (EAS vertically plotted)**

By pressing the (Re)Apply flutter analysis button a single Mach number (Mach=0.96) PH flutter analysis is performed with default parameters and immediately a default damping/frequency versus equivalent airspeed plot is depicted (see figure 5). The results (dampings, frequencies and flutter points) can be extensively analyzed. Also, the analysis can be stored in data files, ppm files and postscript files. Prior to pressing the (Re)Apply flutter analysis button one could set/select parameters (Mach number, analysis et cetera) by opening the flutter analysis options rollout (see Figure 11).

The diagram can be adapted by opening of the flutter plot options rollout. A variety of flutter plot adaptations can be selected:

- Frequency range.
- Damping range.
- Velocity and Speed range.
- Select the modes.
- State Space modes (SH, SK, SKM).
- Single (lowest) or multiple flutter points.
- Equivalent or True Airspeed.
- Dive velocity and Dive Mach number.
- Combined or separate damping and frequency plots, horizontal or vertical.
- Flutter vectors.
- Root locus plots.
- Global flutter plots versus Mach numbers.
- Plot per page selections to reduce the number of plots when a multipoint flutter analysis is performed.

Figure 6..10 shows various examples of flutter plots resulting from various selections.

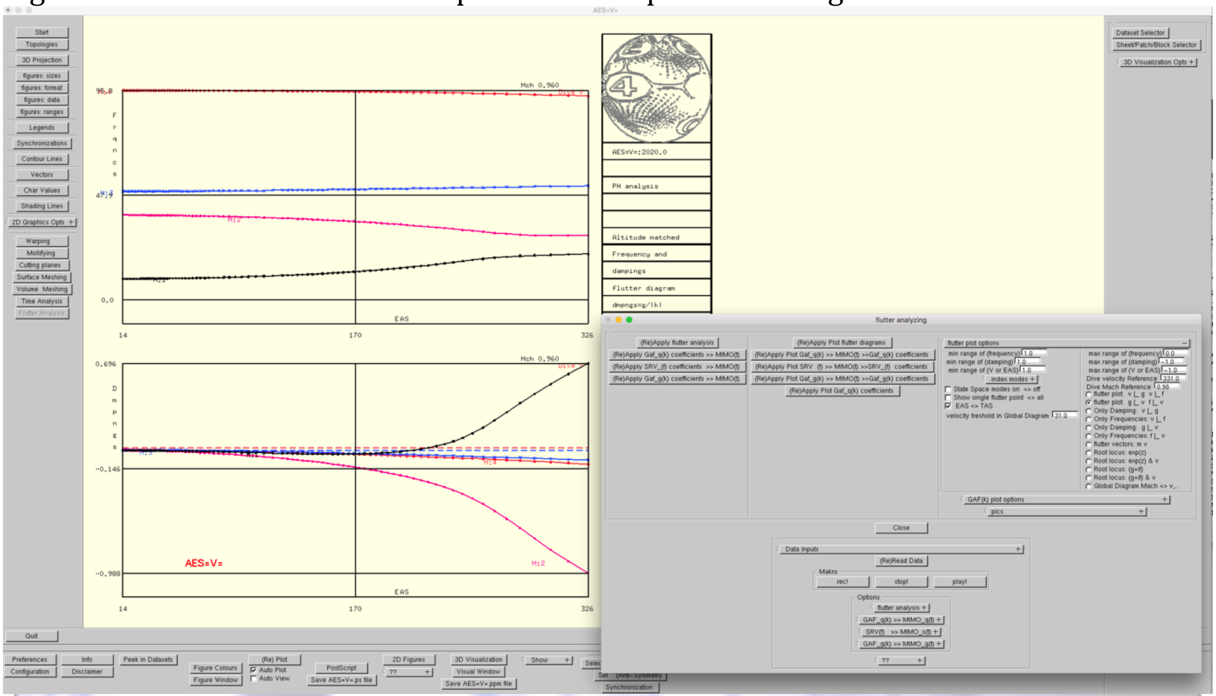

Figure 6 PH flutter analysis diagram at Mach 0.96 (EAS horizontally)

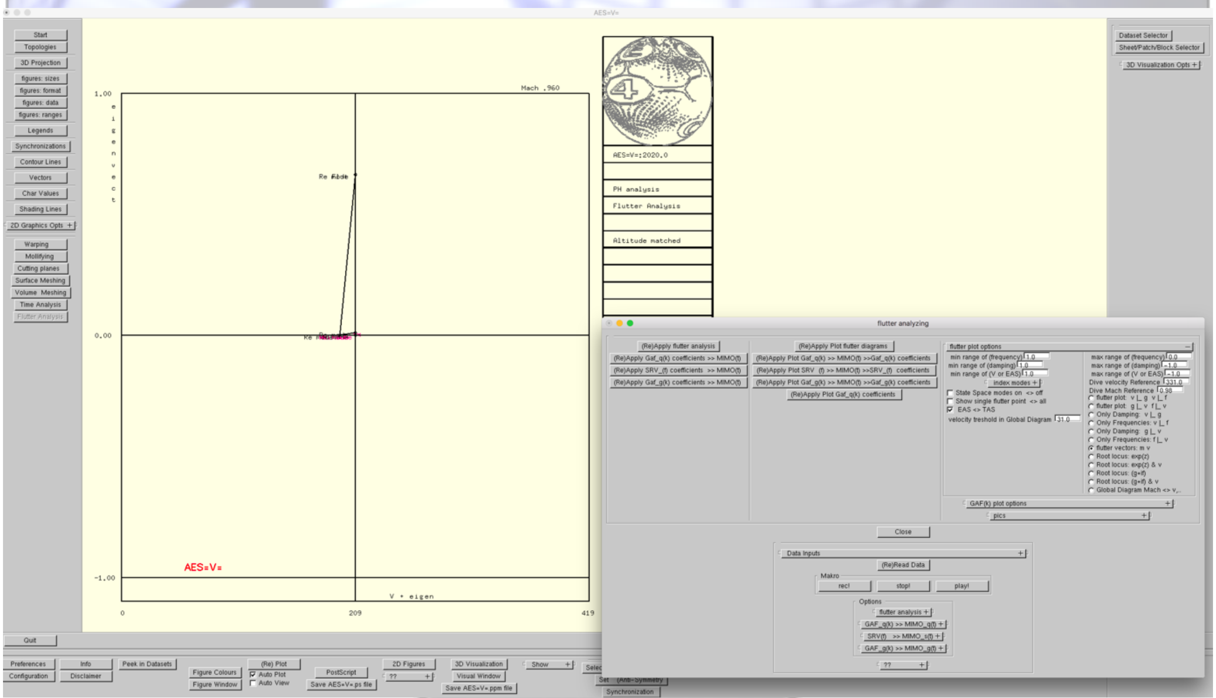

Figure 7 PH eigenvector distribution at flutter speed

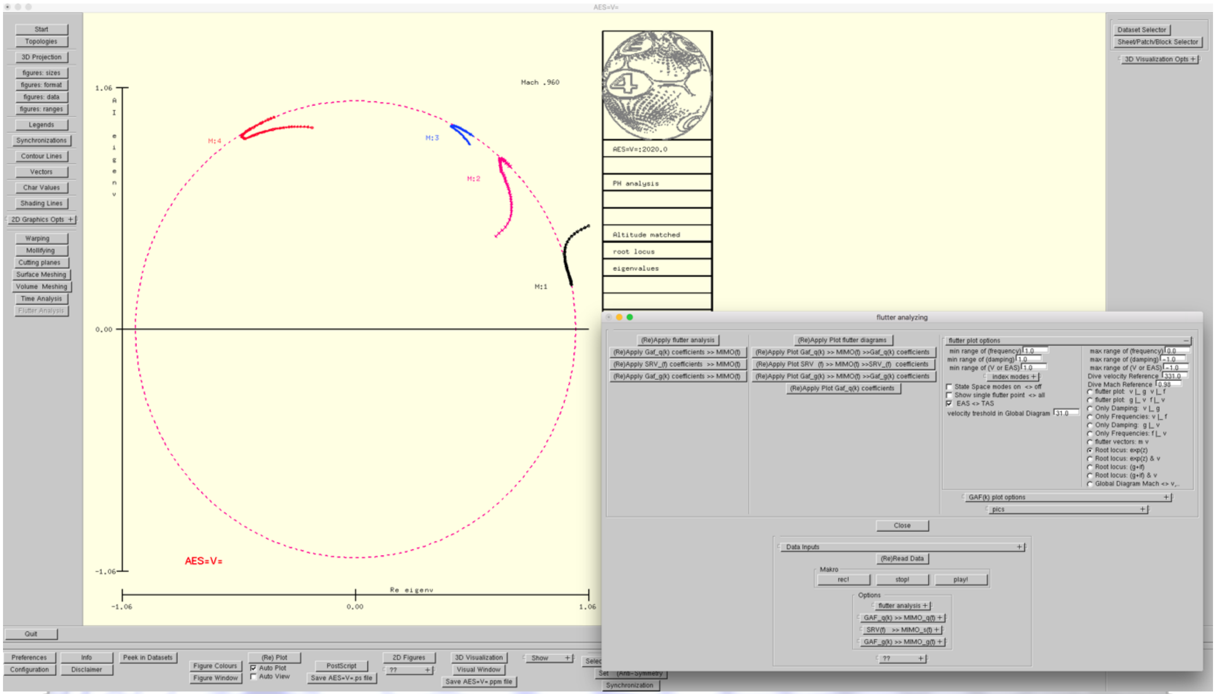


Figure 8 PH root locus plot

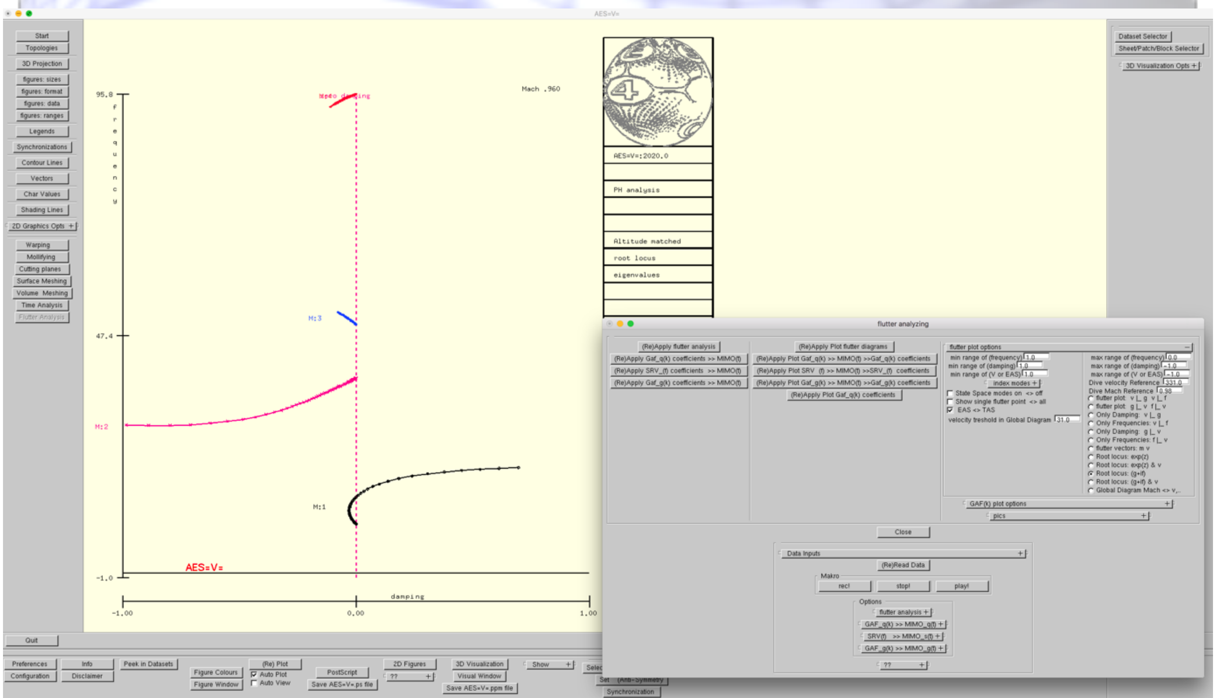


Figure 9 PH eigenvalues plot

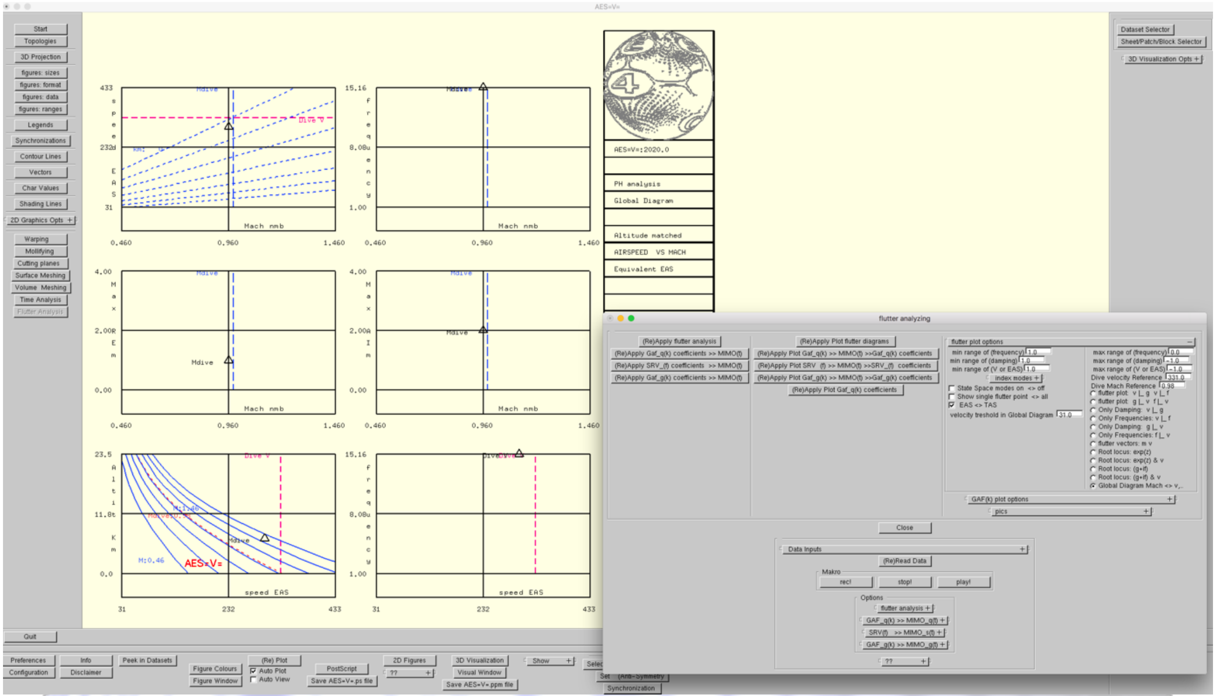

Figure 10 PH Global flutter analysis plots

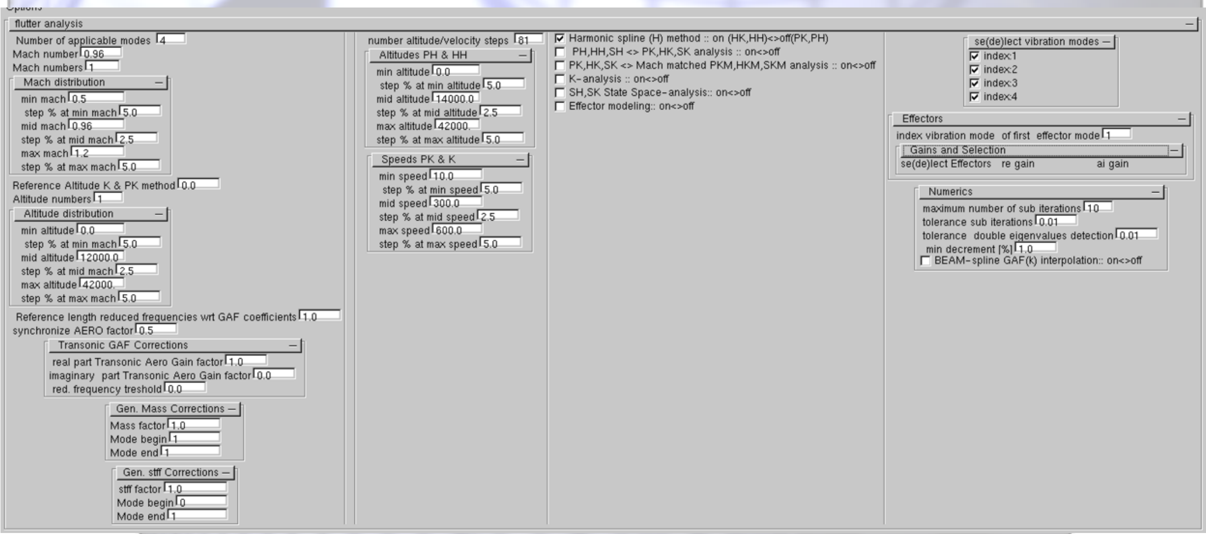


Figure 11 Flutter analysis Rollout

Various analysis options can be selected to accommodate accuracy and/or efficiency. You can enter the flutter analysis options rollout presenting many options (see Figure 11) you might set:

- Number of Mach numbers.
- The Mach number distribution or a single Mach number.
- Number of Altitude numbers.
- Number of reference Altitudes (PK & K).
- The Altitude distribution or a single Altitude in USSA standard atmosphere (PK & K).
- The reference length (the reduced frequency is based on the reference length).

- The synchronization factors which accounts for scale difference between the structural and aerodynamic data (symmetry, signs et cetera).
- Number of modes.
- Transonic gains and phase delays (sensitivity, uncertainty).
- Generalized mass variations (sensitivity, uncertainty).
- Generalized stiffness variations (sensitivity, uncertainty).
- Number of analysis steps.
- Altitudes and Speeds in analysis steps.
- Flutter Analysis options: PH, HH, SH, PK, HK, SK, PKM, HKM, SKM and K.
- Effector modelling.
- Vibration mode activation.
- Effector mode activation.
- Numerics.

## Single point HH, PK, PKM, K and State Space flutter applications

Figure 12..Figure 16 shows various examples of flutter analysis diagrams resulting from HH, PK, PKM, K and State Space (SH) analysis selections.

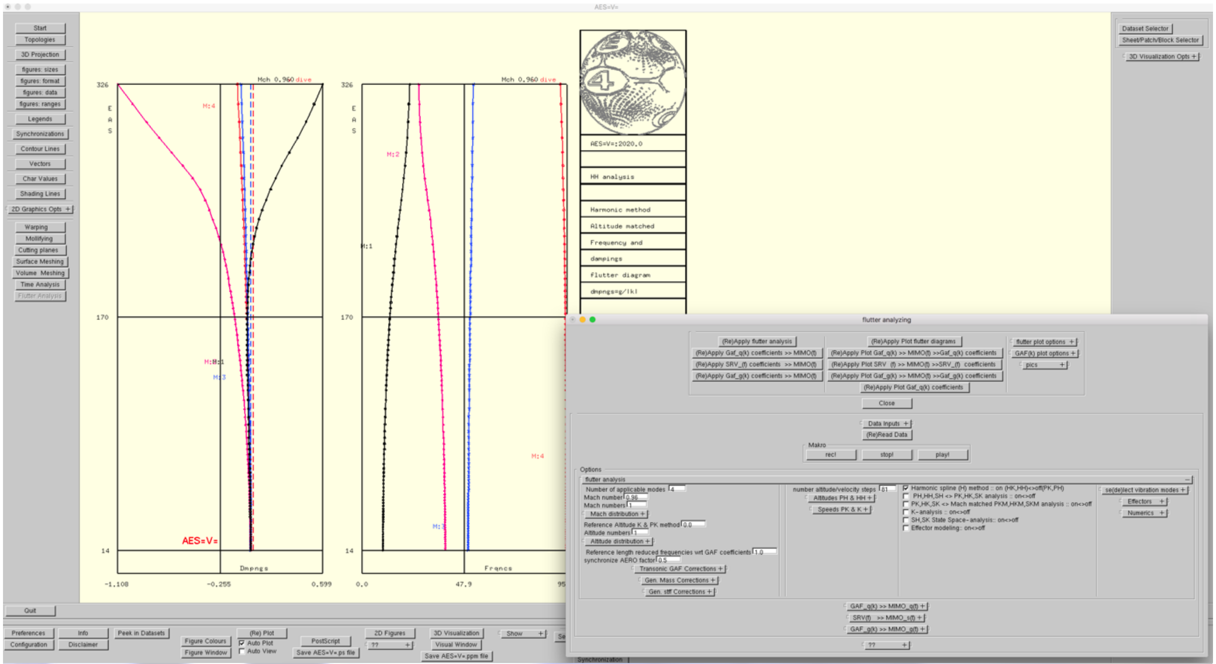


Figure 12 HH analysis at Mach=0.96

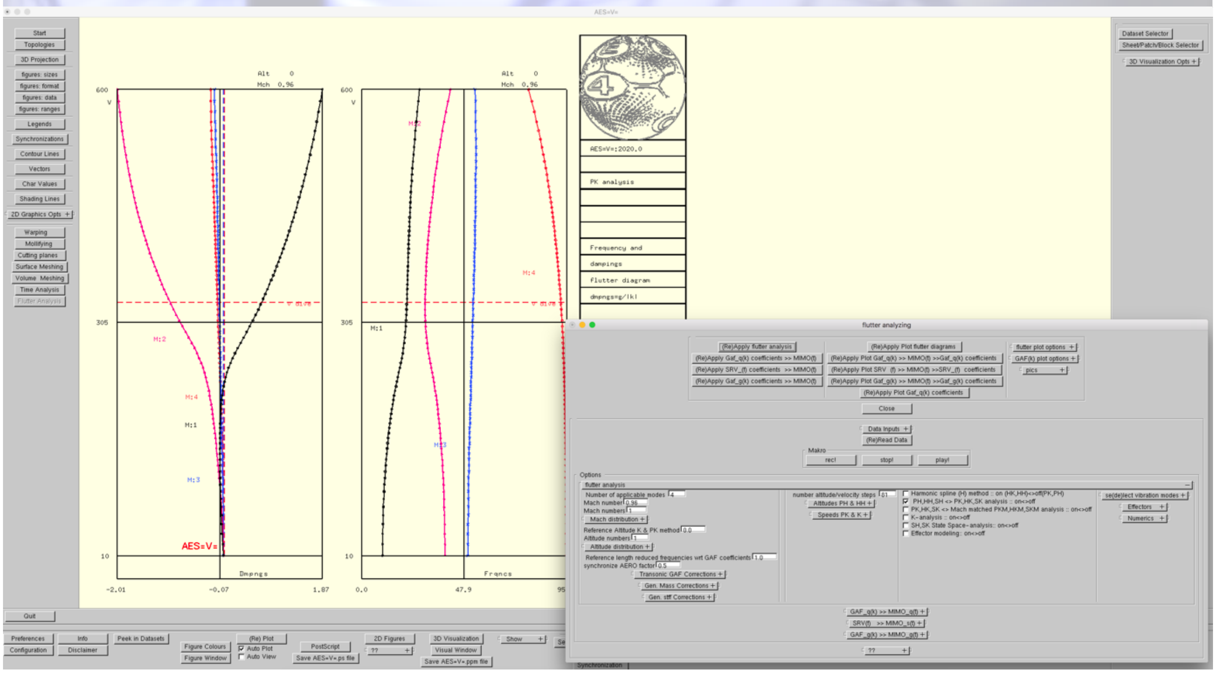


Figure 13 PK analysis at Mach=0.96 and altitude zero

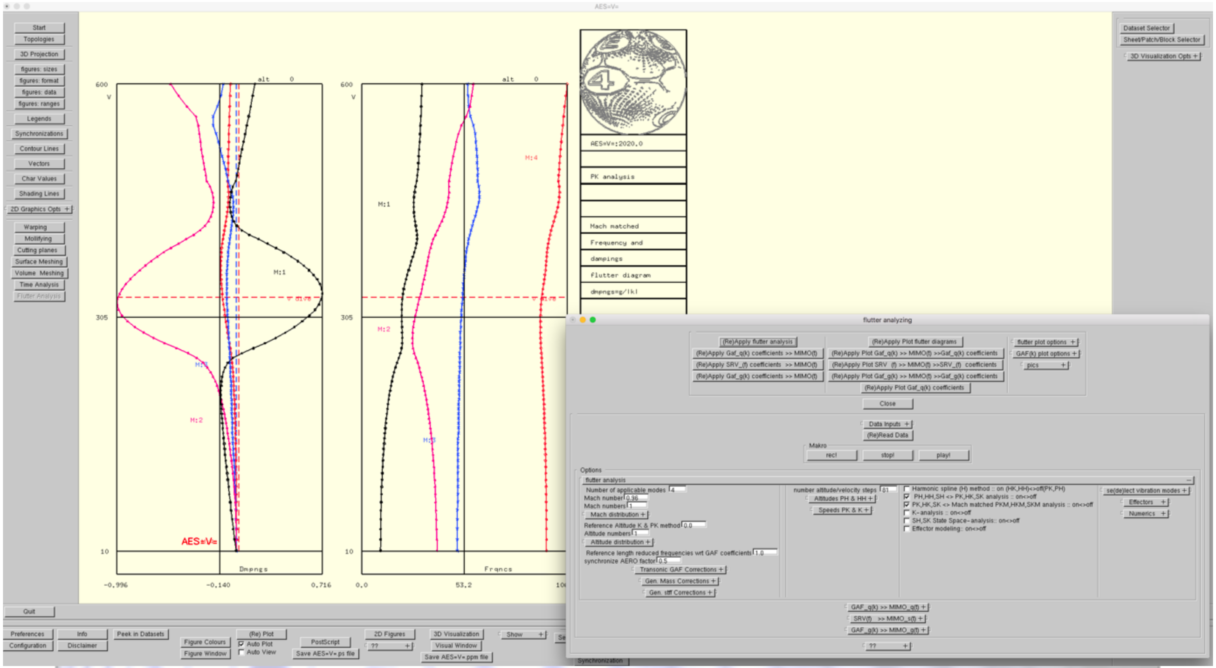

Figure 14 Mach number matched PKM analysis at altitude zero

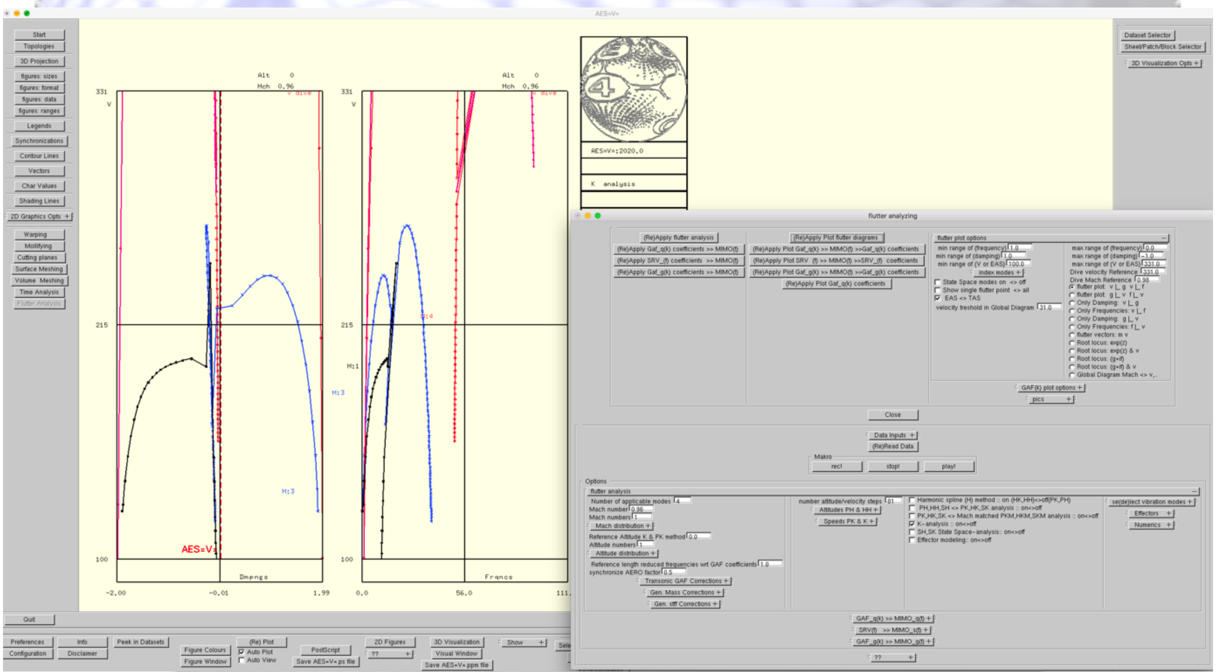

Figure 15 K analysis at Mach=0.96 at altitude zero

## State space flutter analysis

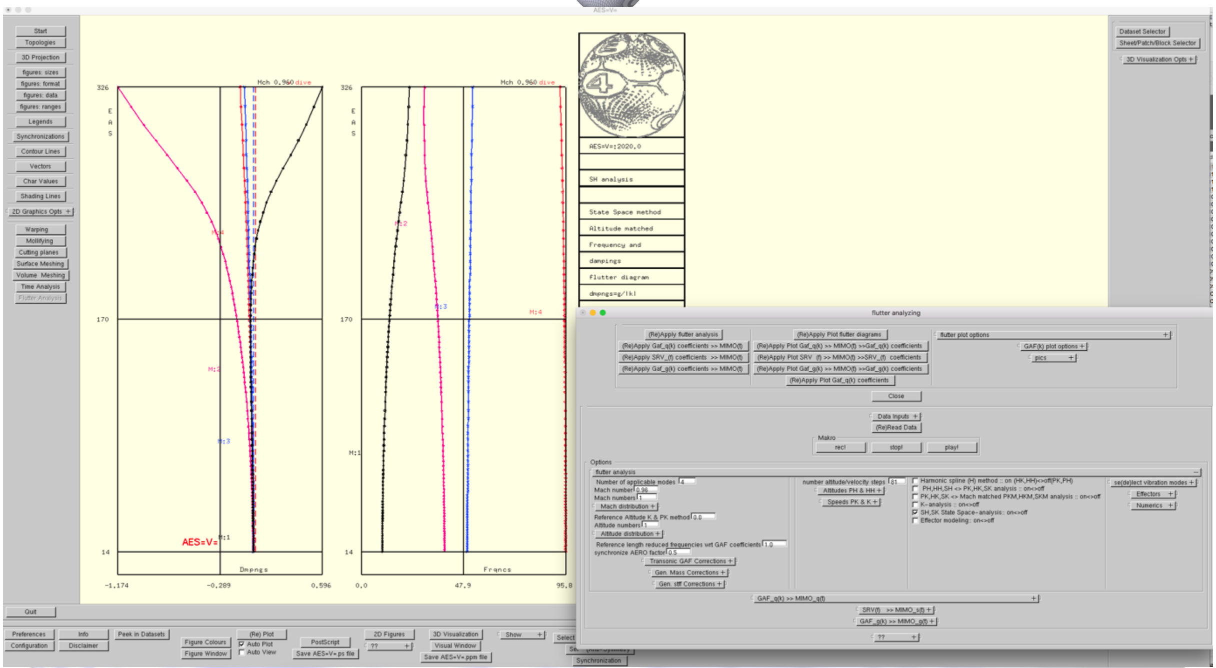


Figure 16 State Space Flutter Analysis at Mach=0.96

The state space flutter analysis transforms the discrete GAF_q table to an equivalent ABCD quadruple obtained from the MIMO fit using the operation control parameters which can be set when opening the GAF_q(k)>> MIMO_q(t) rollout. It should be noted that the PH (see Figure 5), the HH(see Figure 12) and the SH (see Figure 16) analysis show the same flutter point. The damping and frequency behavior of the HH and SH are close while the difference with the PH is larger. The flutterpoint preduction of the K (see Figure 15) and the PK(see Figure 13) method are in agreement.

## *State space ABCD modeling of GAF(k) and GSF(k)*

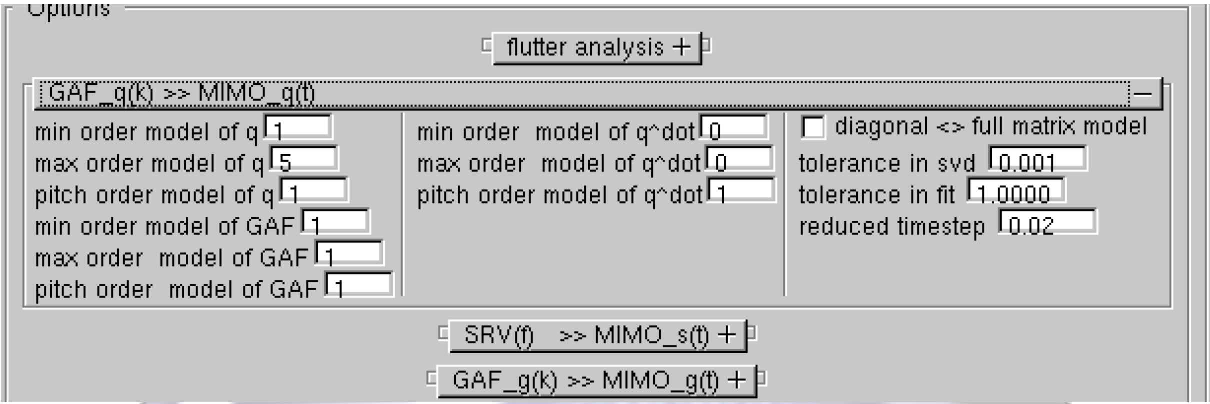


**Figure 17 MIMO Rollout**

In order to develop seriously good ABCD state space models one can specify in the respectively option rollouts:

- A minimum and a maximum of the degree of freedom associated with the inputs (q and/or dq/dt).
- A minimum and a maximum of the degree of freedom associated with the outputs (GAF_q, GAF_g and GSF(SRV)).
- Pitch (skip)order used in the optimization procedure.
- A diagonal or full model of the output matrix.
- Tolerances.
- The (reduced) time step.

When activating the generation the GAF(GSF) versus (reduced) frequency will show up comparing the original (reduced) frequency data with the generated (reduced) frequency data obtained from the developed ABCD model and the error will be depicted (see Figure 18). Open the GAF plot options rollout to change plots and various options are depicted and selectable.

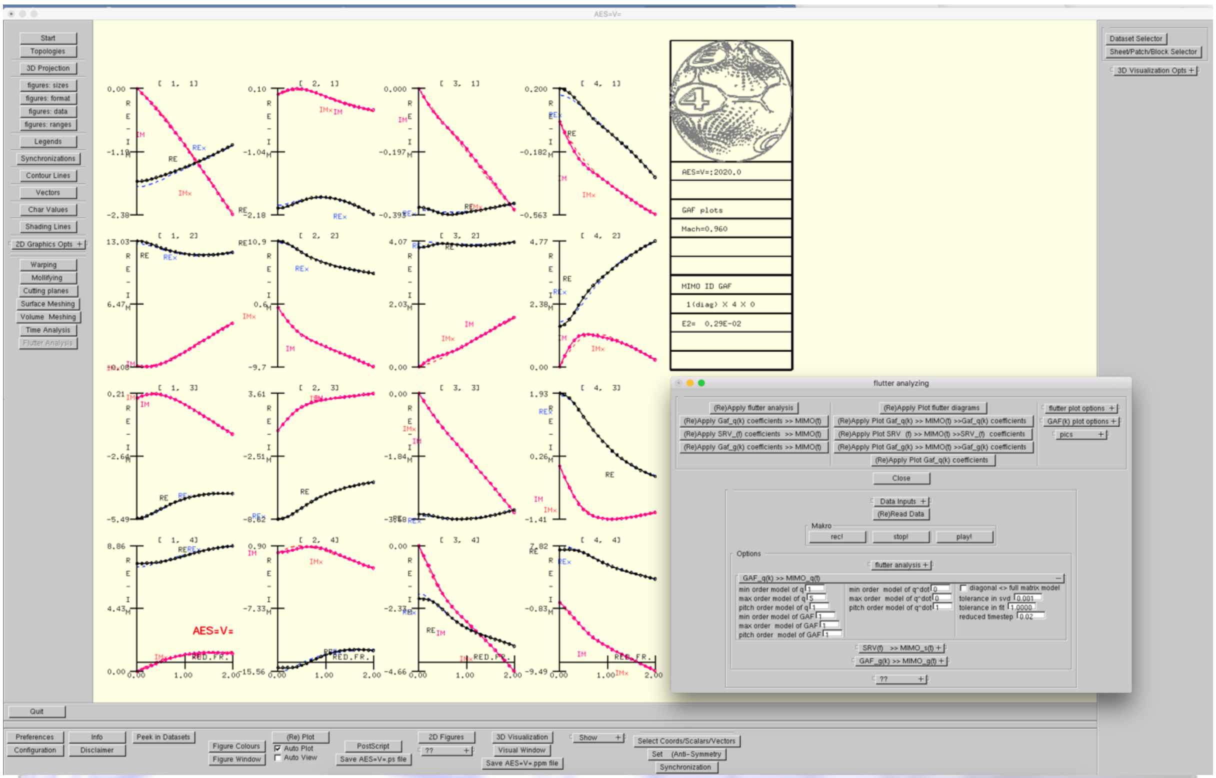


Figure 18 Comparison of original GAF's and MIMO fitted GAF's at Mach=0.96

## Multiple point flutter analysis

By selecting a Mach altitude grid the PK flutter analysis is performed for the cases and depicted in the various plots. Figure 19 presents the dampings for 8 Mach numbers at three altitudes versus speeds. Moreover Figure 20 depicts global flutter analysis diagrams:

- Flutter airspeed versus Mach number.
- Flutter frequency versus Mach number.
- Mode indexes of flutter eigenvector with maximum real part contribution, maximum imaginary part contribution, respectively.
- Flutter altitude versus airspeed.
- Flutter frequency versus airspeed.

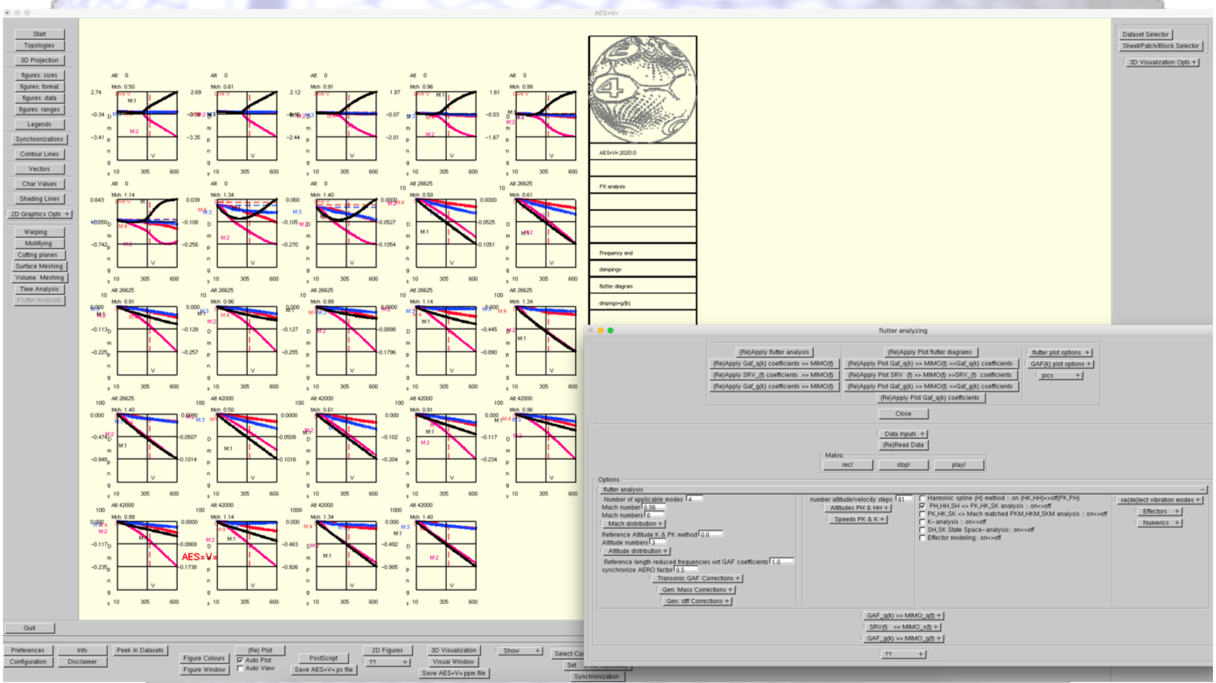

Figure 19 PK damping analysis at Various Mach numbers (0.5 .. 1.4) and Altitudes (0.0 .. 42000 m)

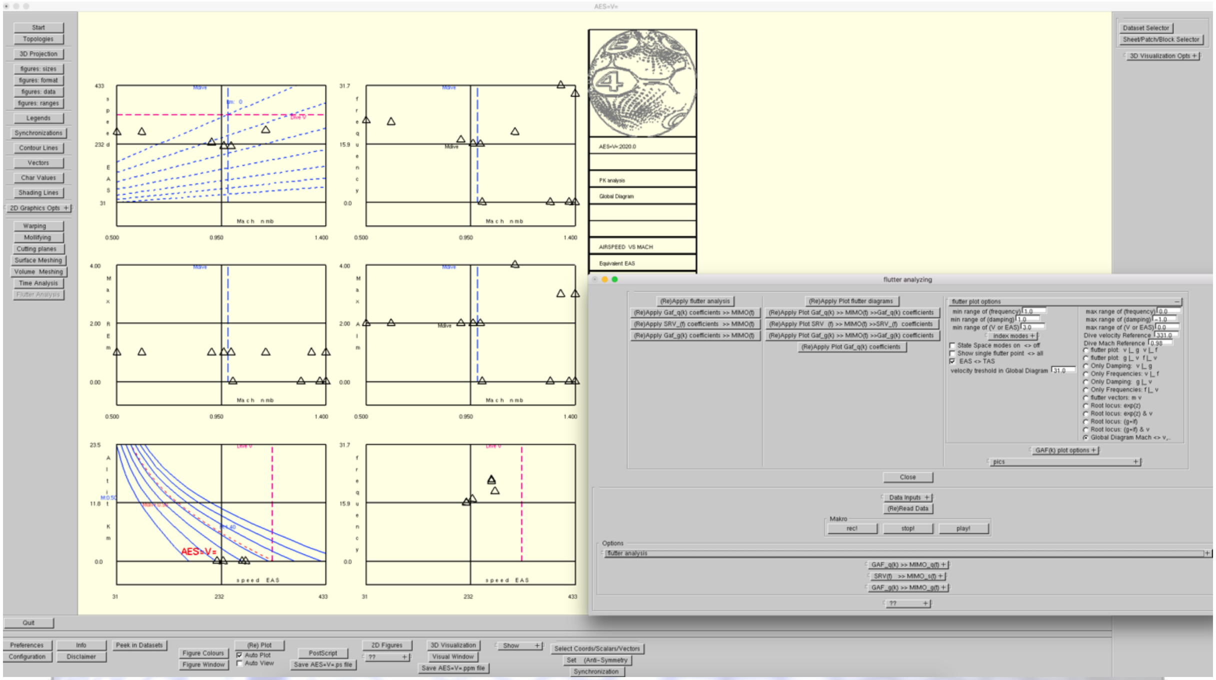


Figure 20 Global flutter diagram from PK analysis at Various Mach numbers (0.5 .. 1.4) and Altitudes (0.0 .. 42000 m)

## Running AES=V='s Time Analysis

The objective of this section is to demonstrate in a nutshell the time analysis modeling of **AES=V=**. You enter the time analysis module by pressing the time analysis button and the Time Analysis Window will show up (Figure 21). You can perform the actions by pressing associated buttons. **AES=V=** contains the following techniques for analyzing input and output of provided time traces and simulations of ABCD quadruples:

- Methods to derive dampings and frequencies of the time traces generated by CFD or flight experimental data.
- Creates transfer functions of the time traces.
- Create a MIMO model and ABCD quadruples of the time output signals (GAF's).
- Creates a frequency table model of the MIMO output model which could be used in modal flutter analysis.
- Time simulation of coupled ABCD time-continuous and time-discrete quadruple models.

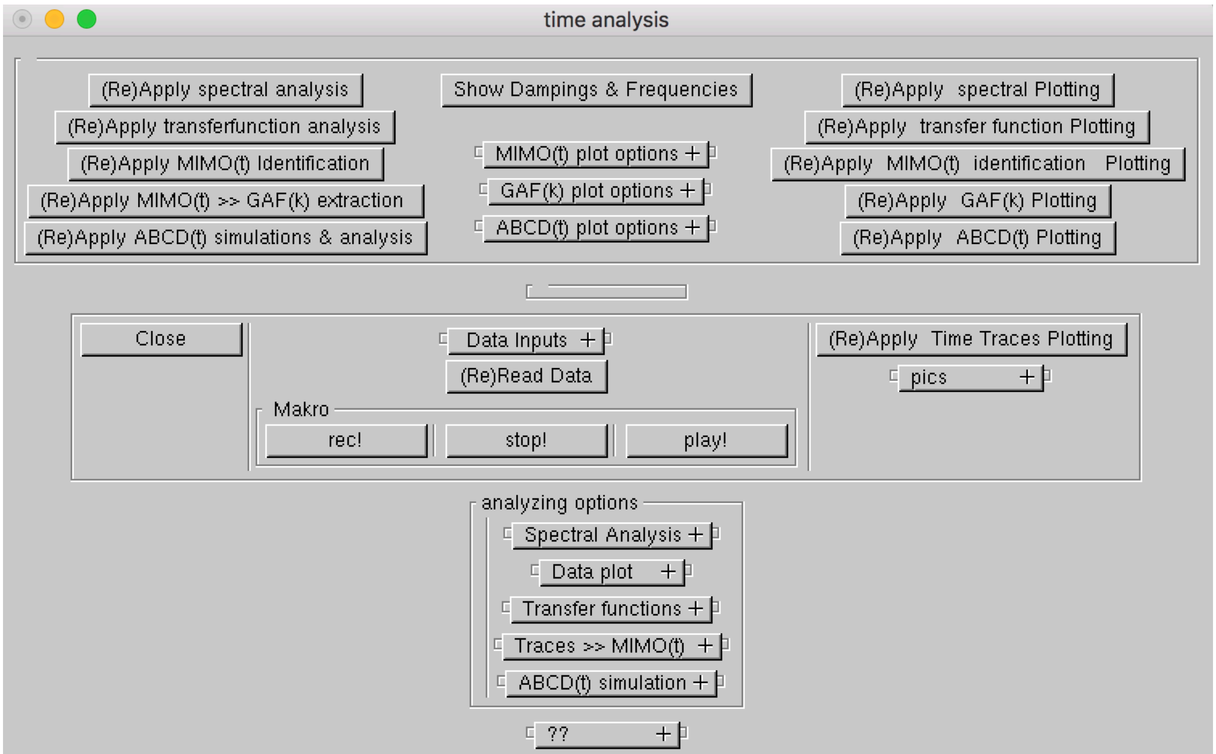


**Figure 21 The time analysis window**

Then you have to press the data inputs button to select the files containing the time traces and/or the ABCD quadruples from the list defined in *aes=v=.cnf*. After the selection by checking the associated boxes the data will be loaded (Figure 22).
The time traces should contain forces and moments, generalized forces, generalized coordinates and generalized velocities. The ABCD's can be time-discrete or time-continuous. The time traces considered here are from a FSI CFD simulation of a wing using 4 modes. The ABCD1 and ABCD2 quadruples which are connected at inputs & outputs model an A/C.

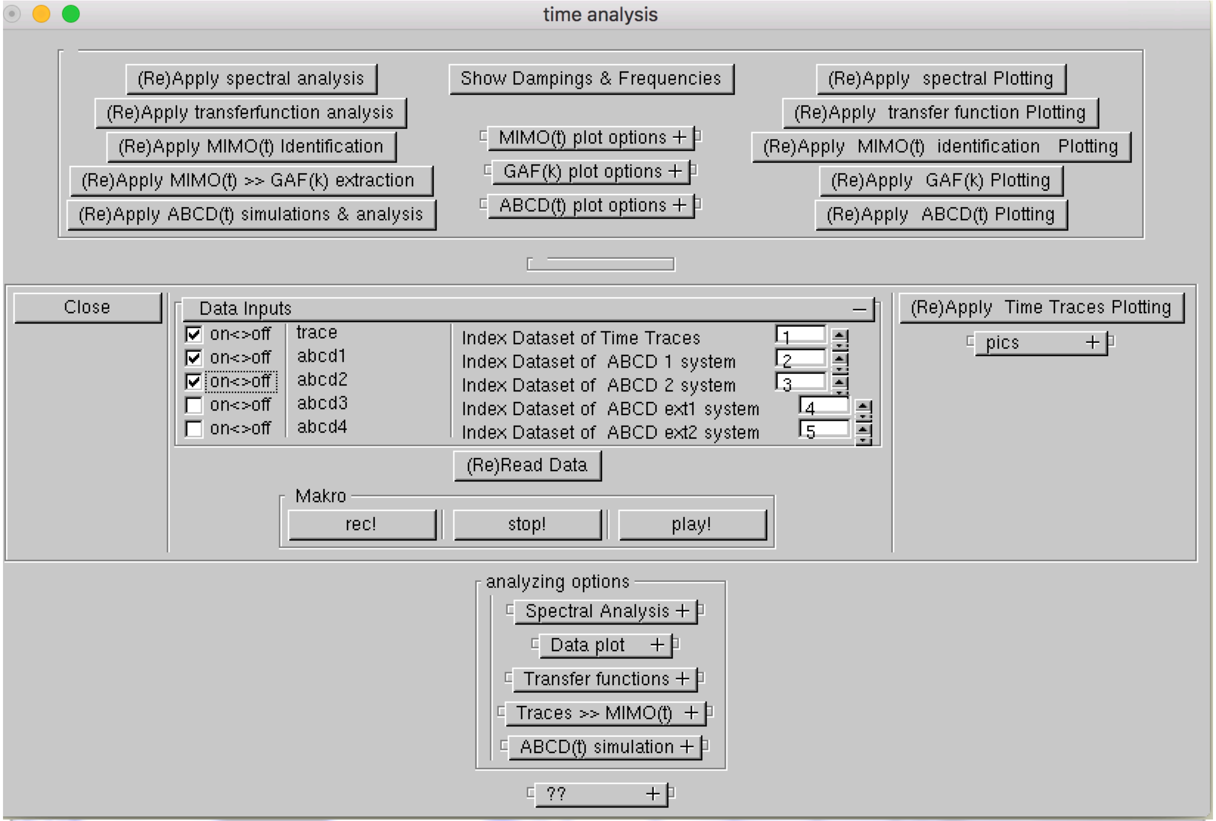


Figure 22 Selection of time traces and ABCD quadruples

## Spectral analysis

The dampings and frequencies of the time traces can be obtained by pressing the (re)apply spectral analysis button.

It is advised to enter the spectral analysis options menu to set/select:

- The One-Shot method (non-iterative) and/or the Exponential Sine method (iterative).
- Select the data (GAF's, GAC's or GAD's) of the time traces to be fit.
- Numeric, fit window et cetera.

Figure 23 shows a comparison of generalized aerodynamic force time trace data (GAF(t)) and the data fitted with the damping and frequencies obtained with the One-Shot method using the parameters as can be seem in the spectral analysis rollout depicted in the time analysis window. The dampings and frequencies are also depicted in a separate window.

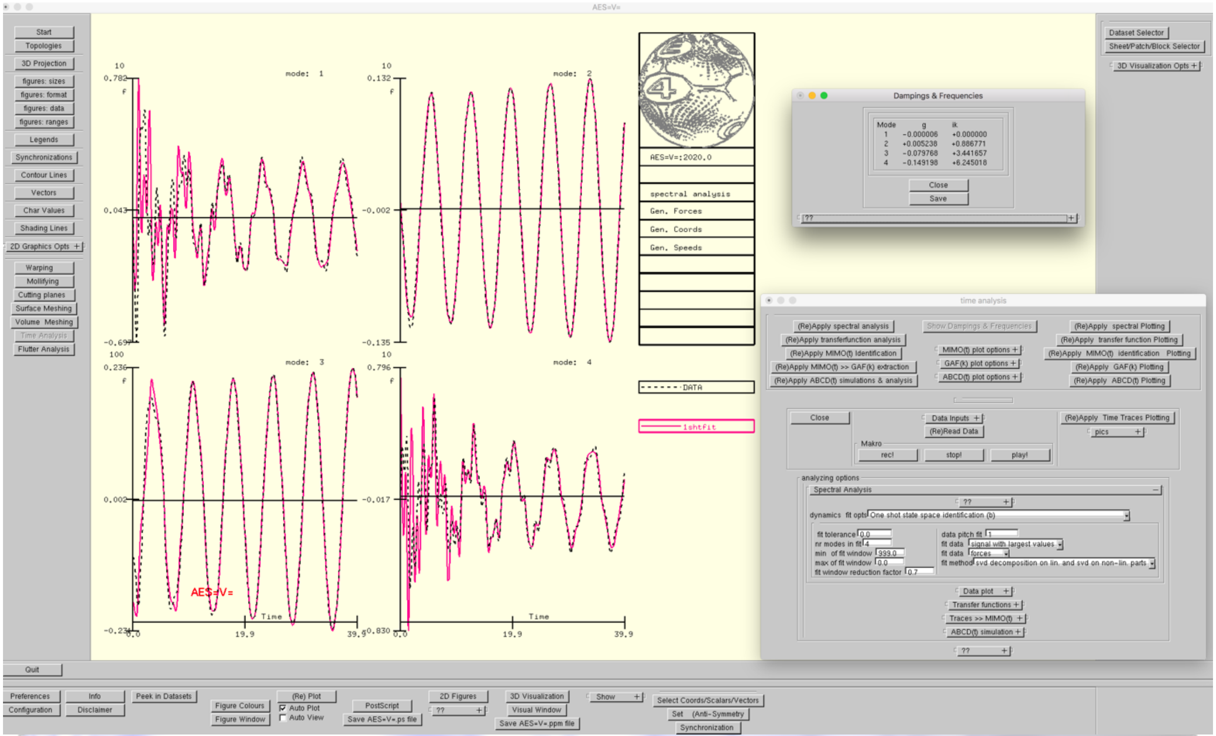

Figure 23 Spectral analysis of  time traces of generalized forces

## Time trace inspection & analysis

You can inspect/select the time traces (see Figure 24) by pressing the (Re)Apply time traces plotting button. Open the data plot options rollout to change plots and to select various options:

- The data to plot versus time and/or frequency.
- Select/restrict the modes to plot.
- Create Transferfunctions restricted to GAF and GAC.
- Padé fit of Transferfunctions restricted to GAF and GAC.

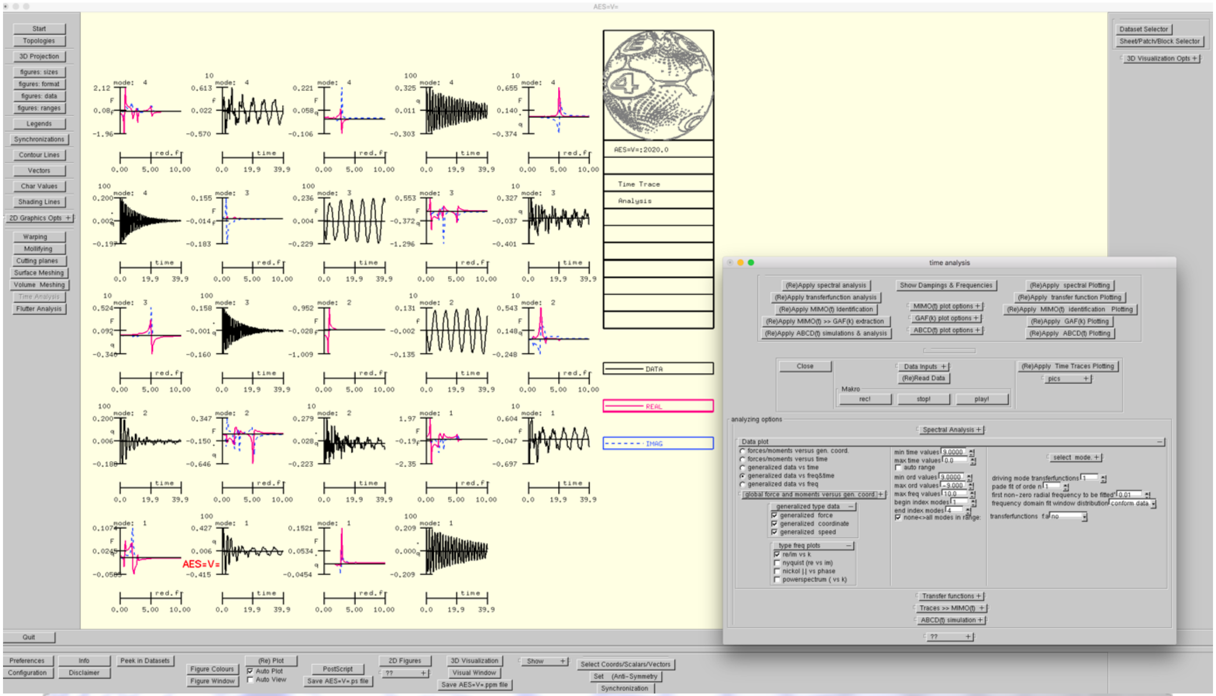

Figure 24 Fourier analysis of time traces

## Transfer functions

You can inspect/select all kind of transfer function derived from FFT analysis applied to the time traces (see Figure 25) by pressing the (Re)Apply transfer function button. Open the transfer function options rollout to change plots and to select various options:

- Select the modes to analyze.
- Transfer functions (GAF(f), GAC(f), GAD(f)) : (GAF(f), GAC(f), GAD(f)).
- Plot types (Real, Imaginary, Bode, Nickols, Nyquist).
- Padé fits of Transfer functions.
- Et cetera.

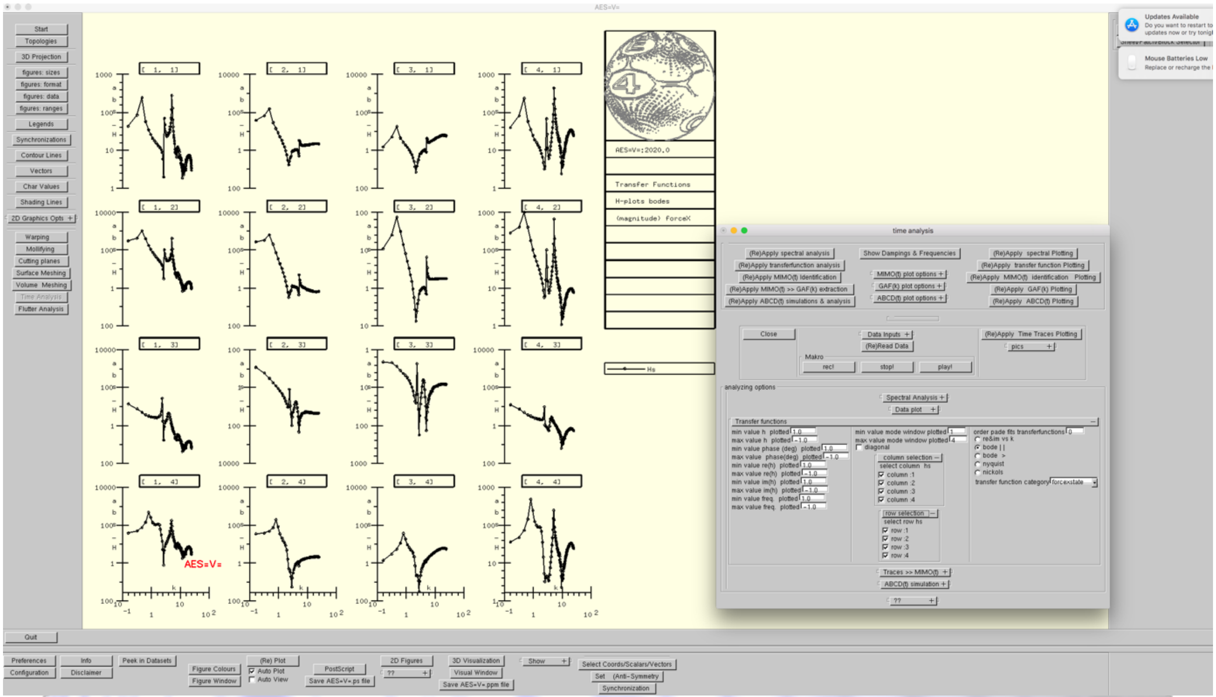

Figure 25 Bode plot (magnitude) of transfer functions GAF:GAC

## MIMO models

You can generate a MIMO model of the GAF time traces by pressing the (Re)Apply MIMO identification button (see Figure 26). Open the traces>>MIMO options rollout to select various options:

- A minimum and a maximum of the degree of freedom associated with the inputs (GAC and/or GAD).
- A minimum and a maximum of the degree of freedom associated with  the outputs (GAF).
- Pitch order used in the optimization procedure.
- A diagonal or full model of the output GAF matrice.
- Tolerances.

Open the MIMO plot options rollout to adapt the figure.

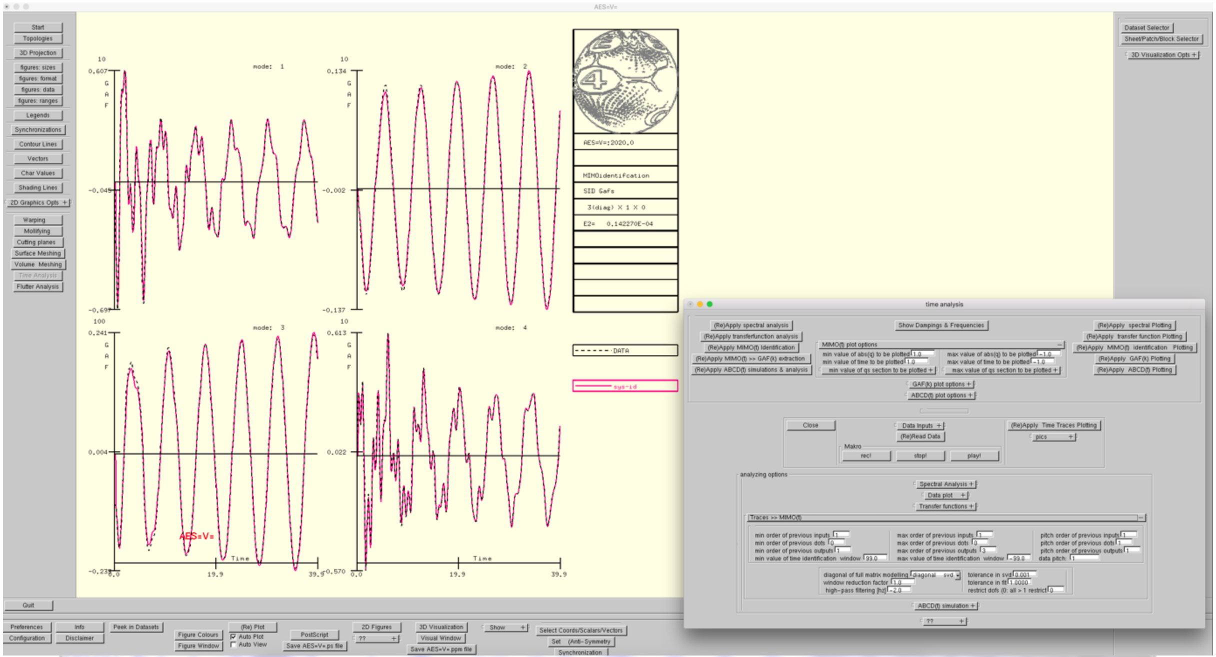


Figure 26 Comparison of MIMO(t) model and original GAF(t) data

## GAF frequency table generation

You can generate a frequency table from the generated MIMO(t) model by pressing the (Re)Apply MIMO >> GAF extraction button (see Figure 27). Open the GAF plot options rollout to adapt the figure and/or to perform Padé fitting.

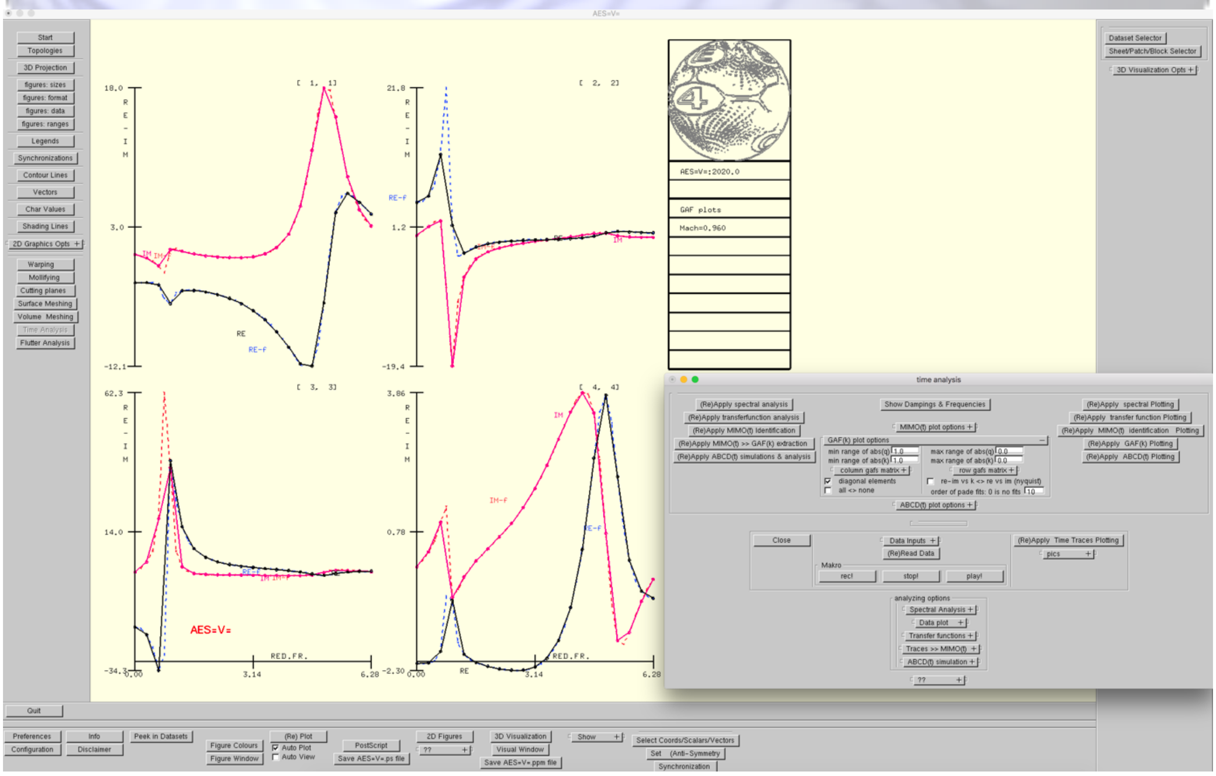


Figure 27 GAF's in frequency domain extracted from the MIMO fitted time trace model and compared to its Padé fitted data

## ABCD quadruple simulations

4 sets of ABCD quadruples can be connected to model an A/C.

You can enter the ABCD simulation options menu (see Figure 28 ) to set:

- time step, observation time & sub iterations
- type of time integration (explicit, Newmark, Exponential Matrix Transition.
- ABCD1 and ABCD2 are explicitly or implicitly coupled.
- Eigenvalue analysis of coupled ABCD1 and ABCD2.
- Tolerances.
- Connections of u1<>y2, u2<>y1, y1e>>u1, y2e >>u1.
- Discrete and simple functions to prescribe u1..u2e behavior.
- Et cetera.

Open the ABCD plot options rollout to adapt the figure (see Figure 28) and to select the inputs and outputs to be shown. The figure shows the y1 and y2 outputs from a connected ABCD1&ABCD2 quadruple simulation with discrete u1(2) and u1(4) inputs and a |sin| u1(6) input.

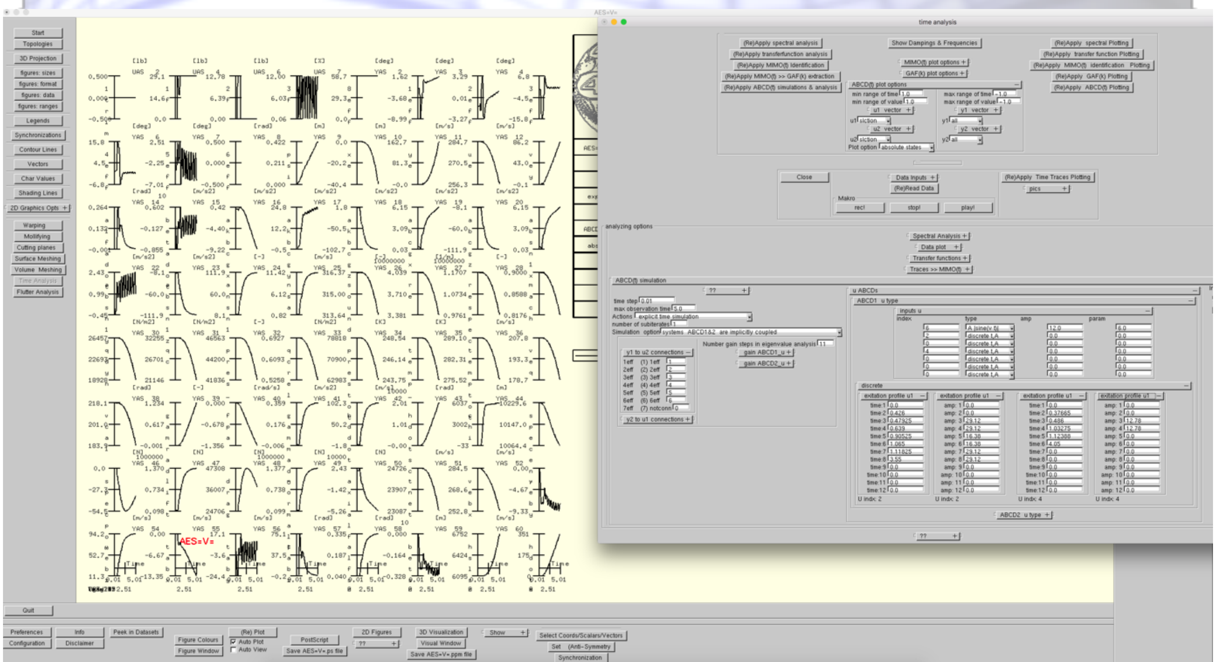

Figure 28 y1 and y2 time traces of ABCD1&ABCD2 simulations

## GAF's generation with AES=3=

For obtaining the generalized forces by means of **AES=3=** three sets of data are needed:

1. The planform.
2. The vibration modes defined on the structural mesh.
3. The structural mesh.

Then:

1. An aerodynamic paneling should be generated with **AES=3=** from the planform data. That's straightforward and easy with **AES=3=** geometric and visualization facilities.
2. The vibration modes should be defined on the aerodynamic paneling with **AES=3=** warping and visualization facilities. Again, this is an easy and straightforward process.

Next a reduced frequency range and Mach number range should be chosen based on the eigenfrequencies and flight envelop. Other options can also be considered: e.g. symmetric, antisymmetric and many more.

Finally execute the calculation and the generalized aerodynamic forces are made available on file within seconds or minutes depending on the number of panels, number of Mach numbers and number of reduced frequencies. The results can be depicted in numerous plots.

More details are presented in (Hounjet, An application of AES=3=, 2017)

## Bibliography

Hounjet, M. H., & Eussen, B. J. (2003). Efficient AeroElastic Analysis. Amsterdam: IFASD-NL-07.

Hounjet, M. H. (2017). *An application of AES=3=.* Berg en Terblijt: AES4AC B.V.

## List of Figures