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# ONLINE MONITORING OF FLUTTER STABILITY DURING WIND TUNNEL TESTING OF AN ELASTIC WING WITH PYLON AND ENGINE NACELLE WITHIN THE HMAE1 PROJECT

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**Abstract:** Flutter testing in high speed wind tunnels is very challenging and costly. In order to enhance safety levels and to increase the amount of scientific output, real time identification methods are indispensable. This paper addresses a technique for fast and reliable identification of eigenfrequencies and damping ratios using operational modal analysis methods. The procedure has been developed by the Institute of Aeroelasticity of the German Aerospace Center (DLR) in Goettingen, Germany. It uses acceleration signals from turbulence excitation during wind tunnel testing for output-only modal identification. The evolution of eigenfrequencies and damping ratios in the range of interest is tracked over time and wind tunnel parameters.

In more detail, the paper focuses on a wind tunnel test campaign conducted by the aircraft manufacturer Embraer, the German Aerospace Center, the Netherlands Aerospace Centre (NLR) and German–Dutch Wind Tunnels (DNW) on a highly elastic fiberglass wing body pylon nacelle configuration.

## 1 INTRODUCTION

Accurate prediction of flutter stability in the transonic domain is a challenging task. Extensive knowledge of aerodynamic modelling and employment of validated numerical tools is critical to the success. As a prerequisite, accurate experiments must be conducted to validate the numerical tools involved in high-fidelity coupled analysis of computational structural mechanics (CSM) and computational fluid dynamics (CFD). Wind tunnel testing is the major source of validation data for such a coupled analysis approach. However, the accurate determination of aeroelastic stability limits when testing elastic wind tunnel models in the transonic domain is a demanding task of its own.

Flutter testing in high speed wind tunnels is challenging and costly. This applies to operating cost of high speed wind tunnels but also to the design and manufacturing of wind tunnel models. On the one hand, application of efficient tools for the determination of aeroelastic stability will lead to less operating time of the wind tunnel and cost reduction for wind tunnel testing. On the other hand, risk of failure of the wind tunnel model can be mitigated by application of efficient tools for monitoring aeroelastic stability. At the same time, the amount of scientific output can be enhanced if real-time modal identification methods are applied for continuous monitoring of aeroelastic stability, because eigenfrequencies and damping ratios are available more or less continuously in the tested Mach number domain.

This paper addresses a technique for fast and reliable identification of eigenfrequencies and damping ratios using continuous operational modal analysis. Originally, the procedure has been developed by the Institute of Aeroelasticity of the German Aerospace Center (DLR) in Göttingen, Germany, for continuous monitoring of the aeroelastic stability margin in flight vibration testing of aircraft, see[1], [2]. The core of the method is continuous application of output-only modal analysis applied to acceleration responses of the test object subjected to steady broadband excitation as provided e.g. by natural turbulence in flight testing or residual turbulence of the incoming flow during wind tunnel testing. An application in wind tunnel testing will be presented in this paper, where the aeroelastic stability margin of a flexible wind tunnel model has been monitored during wind tunnel testing in the transonic domain. The evolution of eigenfrequencies and damping ratios in the frequency range relevant for flutter are tracked over time or respectively tracked with the evolution of wind tunnel operating parameters. Application of this monitoring technology enabled to test up to the stability limit, so that the transonic dip can be determined with high accuracy. This is a prerequisite for validation of motion induced unsteady aerodynamic pressure distributions in the transonic domain as provided by CFD solvers.

The paper will report on tool framework applied in a wind tunnel test campaign on a highly elastic fiberglass wing body pylon nacelle configuration. The HMAE1 (Half Model AeroElastics) project was initiated by the aircraft manufacturer Embraer and has been conducted in a collaborative project by the German Aerospace Center (DLR), the Netherlands Aerospace Centre (NLR) and German–Dutch Wind Tunnels (DNW). The wing model was designed to deform considerably under aerodynamic load. It was tested at DNW's High-Speed Tunnel (HST) in Amsterdam in the transonic domain from Mach 0.4 to Mach 0.9 for different angles of attack with different stagnation points of pressure.

Figure 1: HMAE1 a model installed in the DNW-HST wind tunnel

## 2 FRAMEWORK FOR CONTINUOUS MONITORING OF THE AEROELASTIC STABILITY MARGIN

In this chapter, the framework of the DLR tool for continuous monitoring of the aeroelastic stability is described. In general, the tool utilizes output-only modal analysis procedures from measured acceleration responses. Additional artificial excitation is not required. In general, additional broad band random excitation can support the analysis but artificial harmonic excitation should be avoided, because it violates the assumptions of output-only modal analysis. With strong random like excitation – regardless if artificial excitation or natural excitation from strong turbulence – short measurement times for output-only modal analysis can be realized. If natural excitation comes from weak turbulence, the method still works but requires longer measurement times for the output-only modal analysis.

In the application presented in the following, the response of the model from pure turbulence excitation of the incoming flow of the wind tunnel is utilized. The enablers for determination of aeroelastic stability margin and even forecast of the aeroelastic stability limit are:

- Efficient online access to the response data via an open interface to the data acquisition system
- Fast, reliable and autonomous modal parameter identification
- Tracking of modal parameters over time and over environmental and operating parameters (angle of attack, Mach number, dynamic pressure, etc.) to identify trends in the evolution of frequency and damping with these parameters
- Extrapolation of changes to predict the aeroelastic stability limit

These aspects will be discussed in the coming subchapters.

### 2.1 Online data access

The selected approach for the assessment of the aeroelastic stability margin is based on output-only modal analysis of acceleration response signals of sensors integrated inside the model. In principle, it is also possible to utilize velocity- or displacement responses. Since data acquisition has to be performed anyway during wind tunnel testing, it is reasonable and efficient to perform the data analysis on a stream of sampled data provided by the wind tunnel data acquisition system. Following this concept, the tasks of data acquisition and data analysis are performed on distributed personal computers (PCs) operating in a common local area network (LAN).

In this case, the data acquisition system is a DEWETRON measurement system recording the signals of all sensors in the different physical units such as static and dynamic pressures, wind speed, angle of attack, acceleration responses, constraint forces from a piezo wind tunnel balance, etc. A dedicated PC is controlling the data acquisition using the corresponding DEWESOFT acquisition software. The acquisition software allows for direct remote access to the measured data from client applications of the acquisition software running on other PCs in the same LAN. The other PCs (can be more than one) are performing the data analysis tasks and are referred to as analysis PCs in the following. With the DEWESOFT client application, the sampled data is streamed onto the analysis PCs. On each analysis PC, MATLAB is used as the primary tool for data analysis. The sampled data is provided from the DEWESOFT client application to the MATLAB data analysis software using the component object model (COM) interface. The network and software architecture is illustrated in Figure 2. It shall be mentioned that this architecture is not limited to DEWETRON hardware and software. It has also been realized for National Instruments CompactDAQ hardware with the LabVIEW software and with other flight test specific acquisition hardware operated within DLR. The multiple analysis PCs enable to run continuous modal analysis with different modal parameter estimators or with different analysis parameter settings simultaneously.

The hard- and software architecture provides a continuous stream of sampled data available in the MATLAB workspace for subsequent data analysis. The data stream is typically performed in blocks of data having a pre-defined block length (typically less than three seconds). When the time of one block is elapsed, a new block of data from selected acquisition channels is available. The new block can be appended to previous blocks to form a continuous stream of data whose total length is suitable for output only modal analysis. Within the time interval of one block, new response data is appended and the oldest response data is deleted in the sense of a first-in-first-out (FIFO) buffer.

Essentially, a long block of time data (e.g. one minute of recent response data) is available, which is updated in a time interval of about three seconds. In order to make the data transfer efficient – i.e. to realize short block lengths and frequent response data updates – the signals to be streamed from the acquisition PC to the analysis PCs can be a subset of the total number of signals. For example, only the acceleration signals are streamed in the LAN but not the pressure signals or the constraint force signals.

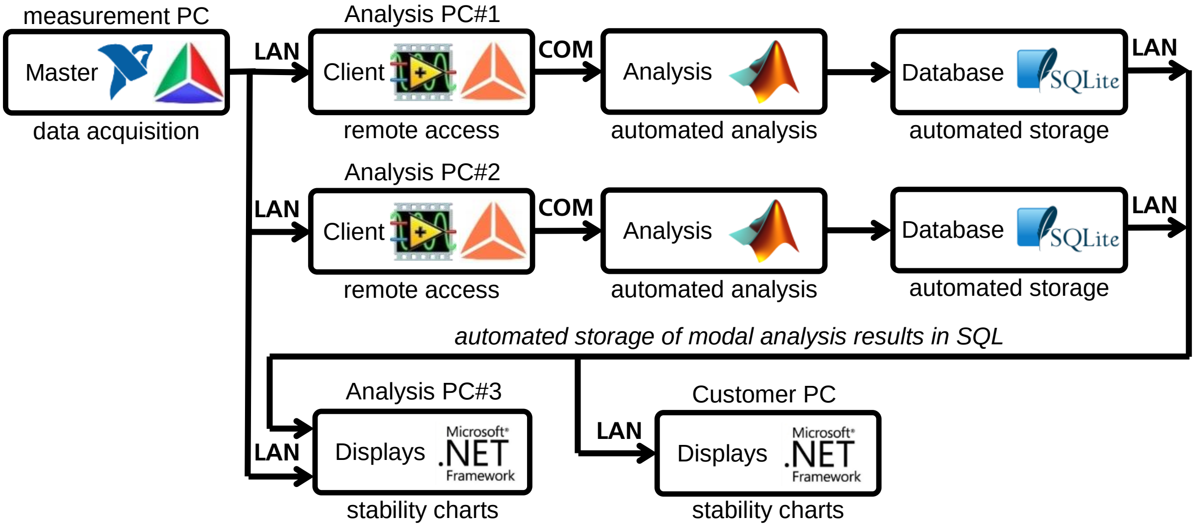

Figure 2: Architecture of acquisition PC and multiple analysis PCs in a Local Area Network

## 2.2 Modal parameter identification

Now that a long FIFO block of response data is available in MATLAB, the respective data analysis procedure shall be explained next. In general, time histories of the acceleration response signals are available at a sample rate suitable for modal analysis in the frequency range relevant for flutter. In addition, a number of slowly changing wind tunnel operating parameters such as Mach number, stagnation pressure, temperature, angle of attack, absolute time etc. are available at low sampling frequency. An ASCII file with the actual values of these parameters is updated every second and is available within the MATLAB workspace for post processing of modal analysis results.

Different modal parameter estimators have been developed and described in literature. Since flutter involves the interaction of multiple modes, it is required to apply multi-degree-of-freedom modal parameter estimators for the determination of flutter stability margin. The toolset of DLR comprises different modal parameter estimators operating in time- and in frequency-domain. The Stochastic-Subspace-Identification (SSI), originally presented in [3], [4], has been used for this application because of its robust and accurate estimates for the damping ratios. The theoretical background is briefly discussed.

Starting point of the SSI algorithm is the representation of a dynamic multi-degree of freedom system in terms of a discrete-time state space model, where the index $i$ or respectively $i+1$ indicate quantities at discrete time instances $t_i=i\Delta t$: sampled with a sampling frequency $f_s=1/\Delta t$:

$$\begin{aligned}\{x_{i+1}\} &= [A_d]\{x_i\}+[B_d]\{u_i\} \\ \{y_i\} &= [C]\{x_i\}+[D]\{u_i\}\end{aligned} \tag{1}$$

The excitation $[B_d]\{u_i\}$ and its feedthrough $[D]\{u_i\}$ to the measured output $\{y_i\}$ is typically not available in output-only applications. Their effect is taken into account by the vector of input disturbances $\{v_i\}$ and output disturbances $\{w_i\}$. Equation (1) therefore becomes:

$$\begin{aligned}\{x_{i+1}\} &= [A_d]\{x_i\}+\{v_i\} \\ \{y_i\} &= [C]\{x_i\}+\{w_i\}\end{aligned} \tag{2}$$

The desired modal parameters of the system can be obtained from eigenvalue analysis of the state transition matrix $[A_d]$:

$$\left(-\bar{\lambda}[I]+[A_d]\right)\{\bar{\psi}_r\}=0 \quad \rightarrow \quad \lambda_r=\frac{\ln\bar{\lambda}}{\Delta t}, \quad \{\psi_r\}=[C]\{\bar{\psi}_r\}, \quad r=1,2,\ldots,2n \tag{3}$$

As can be seen from equation (3), the state transition matrix $[A_d]$ must be identified to obtain the complex eigenvalues $\lambda$ and the observation matrix $[C]$ is required to obtain the mode shape vectors $\{\psi\}$. Available is the measured output vector $\{y_i\}$. Observing this output vector for a number of time points and taking into account equation (2), the following relation can be derived:

$$\begin{aligned}
\{y_0\}&=[C]\{x_0\}+\{w_0\}\\
\{y_1\}&=[C][A_d]\{x_0\}+[C]\{v_0\}+\{w_1\}\\
\{y_2\}&=[C][A_d]^2\{x_0\}+[C][A_d]\{v_0\}+[C]\{v_1\}+\{w_2\}\\
\{y_3\}&=[C][A_d]^3\{x_0\}+[C][A_d]^2\{v_0\}+[C][A_d]\{v_1\}+[C]\{v_2\}+\{w_k\}
\end{aligned} \tag{4}$$

This expansion can be continued for further time instances $t_i=i\Delta t$ with $i>3$. Now the responses contained in $\{y_i\}$ are consistent responses of a dynamic system to unknown stochastic excitation $\{v_i\}$ and contaminated stochastic measurement errors $\{w_i\}$. When the response of a large number of time points is considered, it is assumed that the influence of these stochastic vectors is negligible, i.e. the average approaches zero. Furthermore, it can be seen that the response depends on the so called observability matrix $[O]$ which can be constructed from the observation matrix $[C]$ and the state transition matrix $[A_d]$:

$$\{y_{i+k}\}=[C][A_d]^k\{x_i\} \quad \rightarrow \quad \begin{Bmatrix}\{y_0\}\\ \{y_1\}\\ \vdots\\ \{y_k\}\end{Bmatrix}=\begin{bmatrix}[C]\\ [C][A_d]\\ \\ [C][A_d]^k\end{bmatrix}\{x_0\}=[O]\{x_0\} \tag{5}$$

The idea of SSI now is to identify these matrices from responses $\{y_i\}$ measured at a large number of time instances $t_i$. To do this, the response data $\{y_i\}$ arranged in two block Hankel matrices comprising time-shifted response data. The integer factors $\alpha$ and $\beta$ can be used to adjust the shape of the rectangular block Hankel matrices. With increasing $\beta$, the model order can be increased, i.e. the number of eigenvalues to be identified. With an increase of factor $\alpha$ poor signal to noise ratios can be tackled.

$$[H_0]=\begin{bmatrix}\{y_0\} & \{y_1\} & \cdots & \{y_\alpha\}\\ \{y_1\} & \{y_2\} & \cdots & \{y_{\alpha+1}\}\\ \vdots & \vdots & \ddots & \vdots\\ \{y_\beta\} & \{y_{\beta+1}\} & \cdots & \{y_{\alpha+\beta}\}\end{bmatrix} \quad , \quad [H_k]=\begin{bmatrix}\{y_k\} & \{y_{k+1}\} & \cdots & \{y_{k+\alpha}\}\\ \{y_{k+1}\} & \{y_{k+2}\} & \cdots & \{y_{k+\alpha+1}\}\\ \vdots & \vdots & \ddots & \vdots\\ \{y_{k+\beta}\} & \{y_{k+\beta+1}\} & \cdots & \{y_{k+\alpha+\beta}\}\end{bmatrix}, \tag{6}$$

Singular value decomposition of the first block Hankel matrix yields an equivalent model composed of singular values and singular vectors. Upon the magnitude of the singular values a truncation to *n* effective degrees of freedom can be performed.

$$[H_0]=[U][\Sigma][V]^T \approx \sum_{r=1}^{n}\sigma_i\{U_i\}\{V_i\}^T=[U_n][\Sigma_n][V_n]^T \quad , \quad n\le\alpha,\beta \tag{7}$$

The desired state transition matrix $[A_d]$ is now obtained from a projection of the truncated model of singular values and singular vectors on the second time-shifted block Hankel matrix, see e.g. [5]:

$$[A_d]^k=[\Sigma_n]^{-1/2}[U_n]^T[H_k][V_n][\Sigma_n]^{-1/2} \tag{8}$$

From equation (8), it can be seen that it is reasonable to choose a time shift between the block Hankel matrices of $k=1$ or respectively one sampling interval $\Delta t$. Furthermore, the observation matrix is obtained from:

$$[C] = [E_o][U_n][\Sigma_n]^{1/2} \tag{9}$$

The matrix $[E_o]$ is a Boolean block matrix which enables to extract the observation matrix $[C]$ from the first block partition of $[U_n][\Sigma_n]^{1/2}$.

Once the state transition matrix $[A_d]$ and the observation matrix $[C]$ have been identified from singular value decomposition of the first block Hankel matrix $[H_0]$ and projection of the truncated model on the time-shifted block Hankel matrix $[H_k]$, the eigenvalues and eigenvectors can be obtained from eigenvalue analysis and transformation into continuous-time domain according to equation (3). Finally, eigenfrequencies and damping ratios of the modes shape vectors $\{\psi\}$ are obtained from the complex eigenvalues:

$$\omega_r = |\lambda_r| \quad , \quad D_r = -\frac{\Re(\lambda_r)}{|\lambda_r|} \quad , \quad r = 1, 2, \ldots, n \tag{10}$$

The steps necessary to identify the eigenfrequencies, damping ratios and mode shape vectors have been presented here. The essential steps are:

1. Arrange measured outputs in two time shifted block Hankel matrices
2. Perform singular value decomposition of first block Hankel matrix and truncate to effective degrees of freedom
3. Identify state transition matrix and observation matrix from projection of truncated model to second block Hankel matrix
4. Perform eigenvalue analysis on state transition matrix and transform eigenvalues and eigenvectors into continuous-time domain
5. Extract eigenfrequencies and damping ratios from complex eigenvalues in continuous-time domain

### 2.3 Mode tracking

The modal parameters of time-invariant structural dynamic systems result from the interaction of elastic restoring forces and inertia forces. In case of aeroelastic systems, motion induced unsteady aerodynamic forces will enter into the system and will affect the modal parameters of the underlying structural dynamic system. For example, eigenfrequencies and damping ratios will change due to the influence of the unsteady aerodynamics. Furthermore, the unsteady aerodynamics will lead to coupling of the modes of the underlying structural dynamics systems so that also the mode shapes will change as a function of the unsteady aerodynamics.

In monitoring of modal parameters, these changes must be taken into account. When assuming that the essential fluid dynamic parameters for scaling the aerodynamic forces (i.e. velocity and density of the incoming flow, or respectively Mach number and stagnation pressure) are changing slowly with time, the aeroelastic system can be considered as a linear parameter-varying system. This is in contrast to parameter excited systems, where the system is excited by fast changes in some governing parameters.

It shall be noted that a measurement period of a certain length is required to collect enough response data for output-only modal analysis. If the changes in fluid dynamic parameters within one measurement period are small, the system can be considered as time-invariant within the measurement period. However, if the system is monitored over a number of successive measurement periods, changes in the system characteristics can be identified from modal analysis of the system response.

When considering aeroelastic systems, the sequence of modes can change with variation of the fluid dynamic parameters, or respectively wind tunnel operating parameters. It is important to follow the evolution of eigenfrequencies and damping ratios especially when crossings of the eigenfrequencies take place. The modal assurance criterion (MAC) is the standard tool for vector correlation. Different variants of this criterion have been proposed, among others, a variant to cope with complex modes, see [6]. The MAC value for two complex modes $\{\psi_k\}$ and $\{\psi_l\}$ is defined as:

$$MAC_{k,l} = \frac{\left| \{\psi_k\}^H \{\psi_l\} \right|^2}{\{\psi_k\}^H \{\psi_k\} \{\psi_l\}^H \{\psi_l\}} \tag{11}$$

It can be used to track the evolution of eigenfrequency $\omega_r$ and the damping ratio $D_r$ of the mode shape vector $\{\psi_r\}$ based on the MAC correlation of the mode shape vector $\{\psi_r\}$ taken from the last modal analysis with all mode shapes from the current modal analysis. The maximum MAC value will indicate at which sequence number the mode shape vector $\{\psi_r\}$ to be tracked can be found in the current set of modes. Consequently, its current eigenfrequency and damping ratio can be obtained, which correspond to the current setting of environmental or operating parameters. When these environmental or operating parameters, such as total time, wind speed, stagnation pressure, angle of attack, etc. are stored with the mode shapes, it is possible to track the changes of the eigenfrequencies and damping ratios of the modes as a function of these parameters.

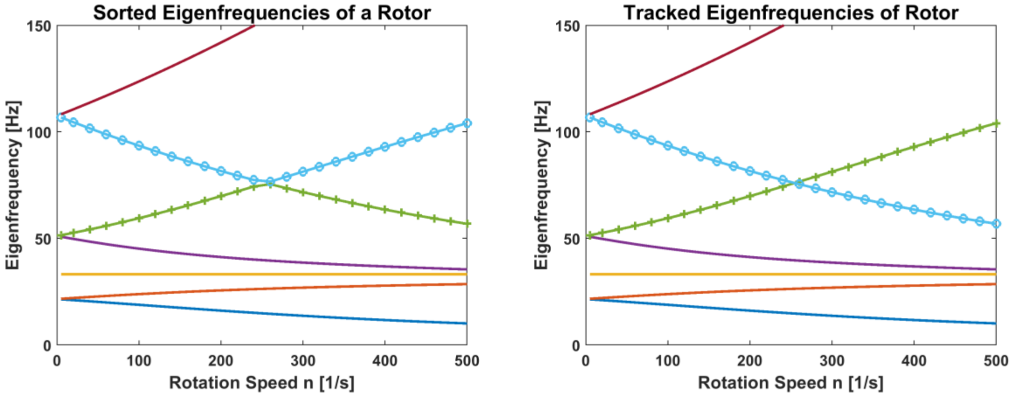

Figure 3: Example for mode sorting by sequence (left) and mode tracking (right) of a rotor with eigenfrequencies varying with increasing rotation speed

The difference of sorting modes by sequence (i.e. sorting in ascending order of eigenfrequency) and tracking of modes is exemplified in Figure 3. An elastic rotor with a rigid disk has been used as an example for the tracking of modes of a parameter varying system. The eigenfrequencies of the rotor change with increasing rotation speed. In the left diagram, the eigenfrequencies are plotted as lines corresponding to the sorting in ascending eigenfrequency. It can be seen for the indicated eigenfrequencies 5 and 6 that the switch of the corresponding modes is not detected in the left diagram. Instead of a mode crossing, it appears rather as a mode reflection. When tracking the mode shapes, the solution branches of the different eigensolutions can be traced individually even after the modes 5 and 6 change their sequence order.

When the identified modes are sufficiently linearly independent, the mode tracking based on MAC is applicable even when the modes change their sequence. It is known, however, that the linear independence of mode shapes depends on the number and location of observation points. If just a few sensors are available and their positions are not optimal for observing the modes, mode tracking using the MAC might fail. The MACXP has been proposed in [7] as an improvement to the MAC for better discrimination of complex mode shapes. It uses in addition to the mode shape vectors $\{\psi\}$ also the complex eigenvalues $\lambda$ to discriminate between individual mode shapes:

$$MACXP_{k,l} = \frac{\left( \dfrac{\left| \{\psi_k\}^H \{\psi_l\} \right|}{\left| \lambda_k^* + \lambda_l \right|} + \dfrac{\left| \{\psi_k\}^T \{\psi_l\} \right|}{\left| \lambda_k + \lambda_l \right|} \right)^2}{\left( \dfrac{\{\psi_k\}^H \{\psi_k\}}{2\left| \Re(\lambda_k) \right|} + \dfrac{\left| \{\psi_k\}^T \{\psi_k\} \right|}{2\left| \lambda_k \right|} \right) \left( \dfrac{\{\psi_l\}^H \{\psi_l\}}{2\left| \Re(\lambda_l) \right|} + \dfrac{\left| \{\psi_l\}^T \{\psi_l\} \right|}{2\left| \lambda_l \right|} \right)} \tag{12}$$

## 2.4 Database storage and stability assessment by extrapolation

In subchapter 2.2 the modal analysis task was described. The results obtained from output-only modal analysis comprise a set of modes. Each mode in the dataset is characterized by a mode shape vector and the complex eigenvalue, or respectively by the eigenfrequency and the damping ratio.

In subchapter 2.1, the online data access has been described. The online data access basically generates MATLAB workspace variables comprising response data. These MATLAB workspace variables are being updated within time intervals of about three seconds. Every time the workspace variables are being updated, the output-only modal analysis is repeated. It is crucial for the success of the stability monitoring procedure, that the data analysis, refresh of displays and storing to the database is performed faster than the update rate of the response data.

When taking into account that wind tunnel testing can have duration of multiple hours, the amount of analysis data generated is immense. It is obvious that these huge amounts of data must be stored in a database, such as SQL (structured query language), for example, as used in the DLR framework for continuous monitoring. When storing mode shape datasets in a database, additional information can be stored together with the essential modal parameters, for example:

- ID number of the mode set and sequence numbers of the modes in the set
- analysis time parameters (e.g. min/max/mean of the total time in the time block used for modal analysis)
- min/max/mean values of environmental and operating parameters (Mach number, stagnation pressure, temperature, density, angle of attack, etc.)
- the modal analysis method (like LSCF [8] in the frequency-domain or SSI in the time domain)
- parameter settings for digital signal processing (block length, window functions, filter frequencies)
- parameter settings of the modal parameter estimator (size of Hankel matrix in case of SSI, polynomial model order in case of LSCF)
- min/max/mean of the absolute time and date of the data points included in the FIFO buffer for modal analysis, e.g. to be used as the corresponding analysis time

With these additional meta-parameters stored in the database, structured access to the modal analysis results is granted. Data filters can be established to retrieve specific subsets of analysis data from the database in order to plot them in a suitable format. DLR has developed a graphical user interface using the .net framework (see architecture in Figure 2) for retrieving data from the database and for plotting the data in user defined diagrams. The software is configured in a way to continuously (i.e. in time intervals of three seconds) request data from the SQL database corresponding to the current set of data filters. If new analysis results are available, the results display is refreshed and new data points appear. Proceeding this way, real-time stability charts can be displayed while a test is running. They show e.g. all eigenfrequencies and damping ratios (or just a selected subset of eigenfrequencies and damping ratios) identified at a certain day, within a certain time period of the day, as a function of an operating parameter of the wind tunnel like e.g. the Mach number. Figure 4 shows an example of such a real-time diagram with eigenfrequency vs. Mach number on the left and damping ratio vs. Mach number on the right. At the beginning, e.g. low Mach numbers, just a few points appear in the real-time diagrams. With additional testing time, the Mach number will be increased and additional points will appear in the diagrams. At first, the diagrams just look as point clouds. But after a reasonable increase of the Mach number, a steady trend of these point clouds will be observed.

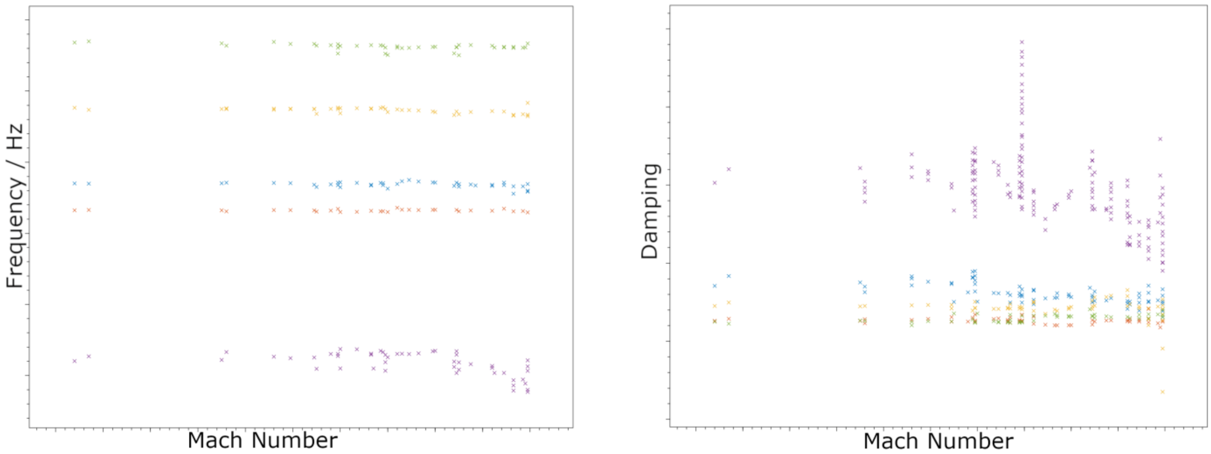

Figure 4: Example of a real-time diagram – Evolution of eigenfrequencies vs. Mach number (left) and evolution of damping ratios vs. Mach number (right)

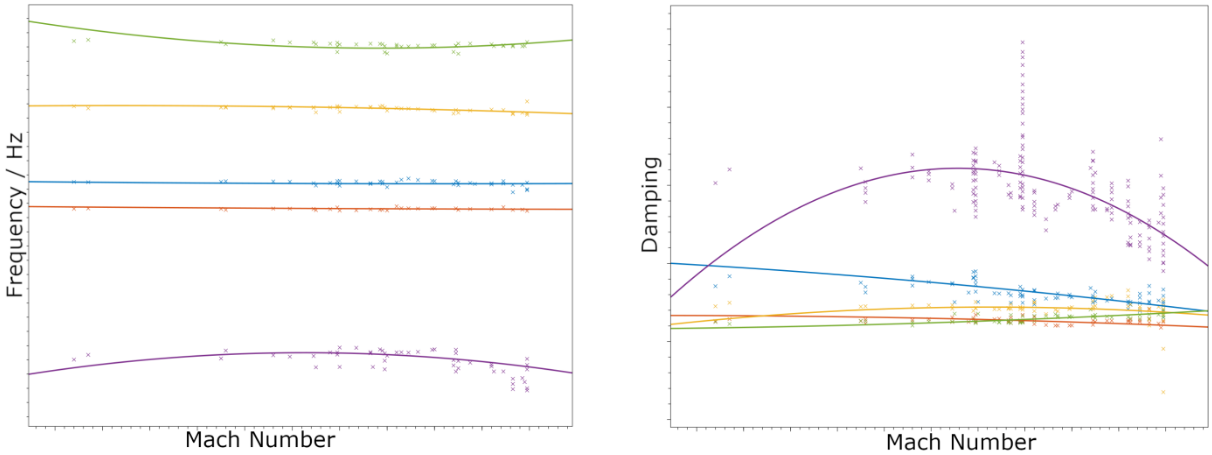

Figure 5: Example of a real-time stability diagram – Evolution of eigenfrequencies vs. Mach number for tracked modes (left) and evolution of damping ratios vs. Mach number for tracked modes (right)

With regard to mode tracking subchapter 2.3, the tracking ID number of a mode can also be stored in the database as an additional feature of a mode. This requires, however, that the mode tracking is performed in parallel to the modal analysis. Having this tracking parameter available in the database, a structured access to display the evolution of properties of selected modes in the database can be realized. This enables the real-time display of stability diagrams, where the evolution of eigenfrequencies and damping ratios of a selected subset of modes are shown as a function of selected environmental and operating parameters. Figure 5 shows an example of such a real-time stability diagram with eigenfrequency vs. Mach number for some tracked modes is shown on the left and damping ratio vs. Mach number for some tracked modes is shown on the right. The effect of mode tracking can clearly be observed by the interpolation/extrapolation curves fitted through the data points of the different modes. From Figure 5 it can be seen, that the curves extrapolate towards coming values of the operating parameters.

In fact, at the beginning of testing, these interpolation/extrapolation curves change considerably with increasing points in the database. However, after some minimum parameter range is tested, the extrapolation is rather stable and reliable. In particular, the extrapolation of the damping ratios has been adopted as a criterion to determine the aeroelastic stability limit. This means, the zero-crossing of the first modal damping ratio is considered as the stability limit. Consequently, the actual stability margin can be expressed either in terms of residual damping or in terms of distance to the stability limit. In more detail, the stability margin can be expressed as the current damping ratio of the mode that is going to become unstable, or respectively, it can be expressed as the distance in the current operating parameter towards the stability limit.

With regard to the architecture in Figure 2, it should be mentioned that output-only modal analysis is performed in parallel on two different analysis PCs, e.g. using different modal parameter estimators or even the same modal parameter estimator with different analysis parameter settings. Each analysis PC feeds the modal analysis results into its own SQL database. All databases are accessible from the third analysis PC, where the generation of real-time stability charts as shown in Figure 5 is performed. The interpretation of these diagrams is the essential information about the distance to the stability limit and is used for the decision making process whether to continue a test or to abort. On the optional fourth analysis PCs, the customer can generate stability charts on his own, e.g. to take part in the decision making process or to verify the findings from the third analysis PC.

In general, the quality of the results from a specific modal parameter estimator depends on the fulfillment of the assumptions made in its mathematical formulation. Violation of these assumptions will lead to poor and non-reliable modal parameters. In order to cope with this limitation, it is best practice to run different modal parameter estimators on different analysis PCs in parallel. The second estimator will provide different results of modal analysis from the same data, and consequently, the stability limit indicated will also be different. When the name of the parameter estimator is also stored as a feature of a mode set in the database, different real-time stability diagrams can be generated in parallel obtained from the results of different modal parameter estimators. A conservative approach to flutter testing would be to consider the nearest stability limit.

## 3 ONLINE IDENTIFICATION DURING WIND TUNNEL TESTING

During the start of the HMAE1 wind tunnel test campaign, two estimators namely LSCF in the frequency-domain [8] and SSI in the time-domain [3], [4] have been used in parallel. SSI turned out to provide more reliable and stable damping estimates over time. For this reason SSI was chosen for all further analyses.

One of the objectives of the HMAE1 wind tunnel test campaign is the determination the aeroelastic stability boundary of the tested configuration in the transonic domain in order to use this information for the validation of an aeroelastic modelling and simulation process. Typically, the aeroelastic stability boundary is determined from the eigenvalues of a coupled analysis model comprised of structural dynamics and motion induced unsteady aerodynamics. An effect called the transonic dip refers to a critical (i.e. non-conservative) deviation of the aeroelastic stability boundary indicated when computational fluid dynamics (CFD) is incorporated to represent the unsteady aerodynamics as compared to the aeroelastic stability boundary indicated when potential flow methods or panel methods like the Doublet-Lattice-Method (DLM) is incorporated for the unsteady aerodynamics.

For accurate determination of the aeroelastic stability boundary, it is desired go as close as possible to the aeroelastic stability limit in the corresponding experiment. The test procedure adopted consists of slowly increasing the dynamic pressure at a given point of constant Mach number, see Figure 6. During the increase of the dynamic pressure, early indication of the critical pressure of the stability limit is needed. Consequently, the dynamic pressure is the monitoring parameter. Evolution of damping ratios (and eigenfrequencies) over dynamic pressure was used to generate real-time stability charts for the determination of the stability limit. While slowly (but continuously) increasing the dynamic pressure the distance to the stability limit is slightly reduced. Once the stability limit is reached, the test at the current Mach number is stopped and the test is started again with the next constant Mach number. It should be mentioned that it is good practice to introduce some rest points in the test sequences, as indicated in the sketch of Figure 6. At a rest point, the dynamic pressure (and the Mach number) are kept constant e.g. for a duration of approximately 2 or 3 times the total block length of the FIFO buffer required for the modal analysis. The results from the rest points can be used after the test for accurate post processing as will be shown in Figure 9.

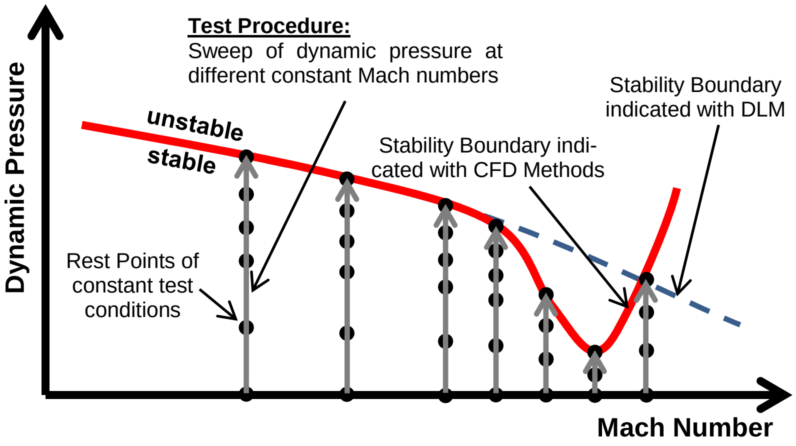

Figure 6: Test procedure to precisely determine aeroelastic stability boundary in the transonic domain

Modal identification results for at least the first five modes have been displayed on screen with an update rate of three seconds while the last 60 seconds of time data was analysed. The modal parameters were not only displayed but also tracked over time to see the evolution of frequency and damping curves which was shown on a monitor in the control room (see Figure 8). It is worthwhile to mention that the modal identification and tracking procedure was extraordinarily stable. Therefore the online monitoring provided a good overview of the current aeroelastic stability of the model and served as a reliable basis for a decision to continue to the next test point or to terminate due to stability problems.

It is mandatory to start the test at safe conditions. It has been mentioned in subchapter 2.4 that after a minimum parameter range has been tested, the extrapolation of the identified damping ratios indicates if a critical damping state will be reached. This can be observed in Figure 7, where the damping extrapolation at the beginning of a test sequence is shown in diagram no. 1. At almost half of the parameter range, a robust indication of the critical stability limit is obtained. The indicated damping trend of the critical mode is shown as the blue curve in diagrams 1 to 6. It can be seen that the critical limit is robustly indicated in the diagram 4, 5 and 6.

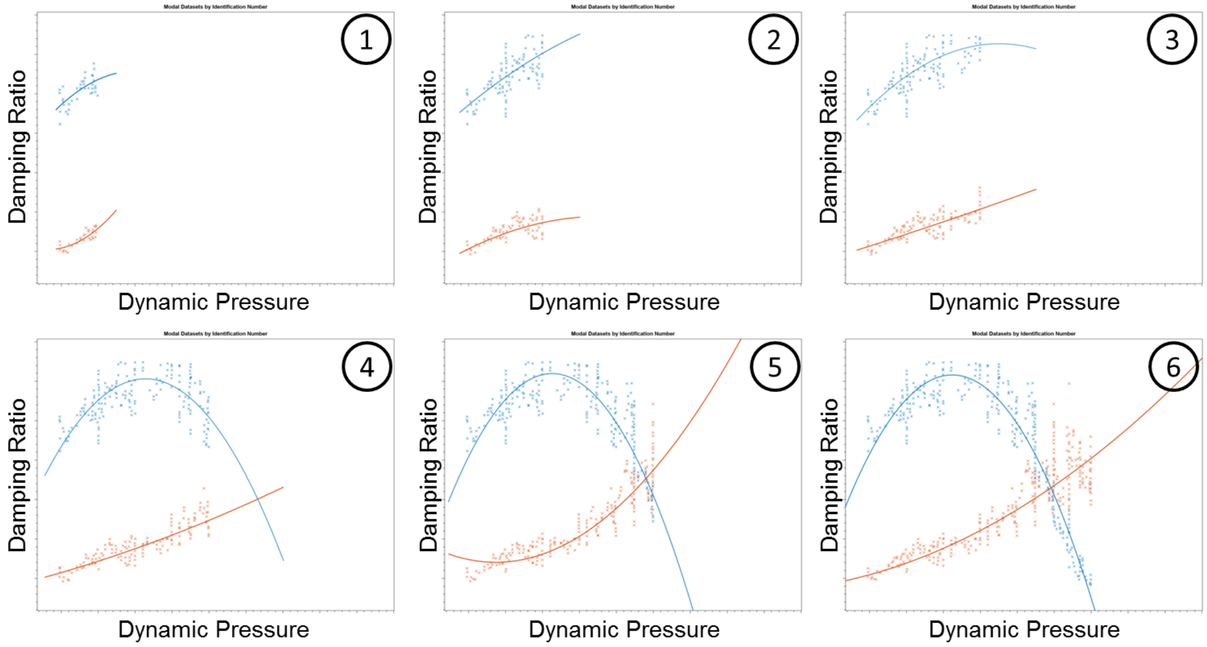

Figure 7: Example of extrapolation of identified damping ratios in early detection of stability limit

The online data was used to feed DLR's online monitoring software suite to directly estimate eigenfrequencies and damping ratios from operational modal analysis shown in Figure 8 on the left hand side. The modal parameter estimates were plotted over time using an efficient mode tracking algorithm.

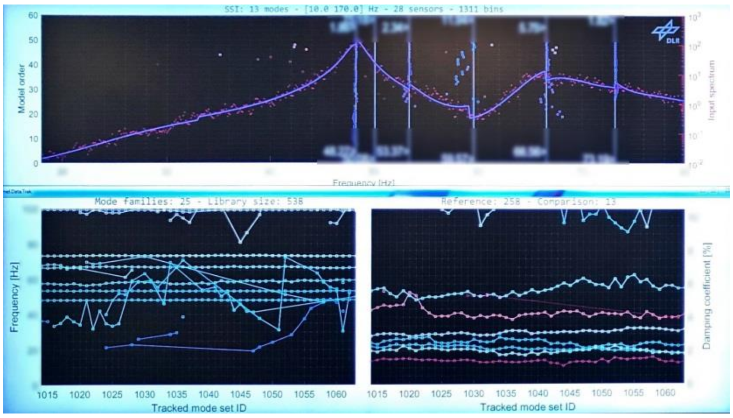

Figure 8: Display in control room showing evolution of modal parameters over time.

After the test points have been acquired completely post processing of the modal analysis results obtained at the rest points yields an even more reliable tracking of the evolution of modal parameters over the monitoring parameter, see Figure 9.

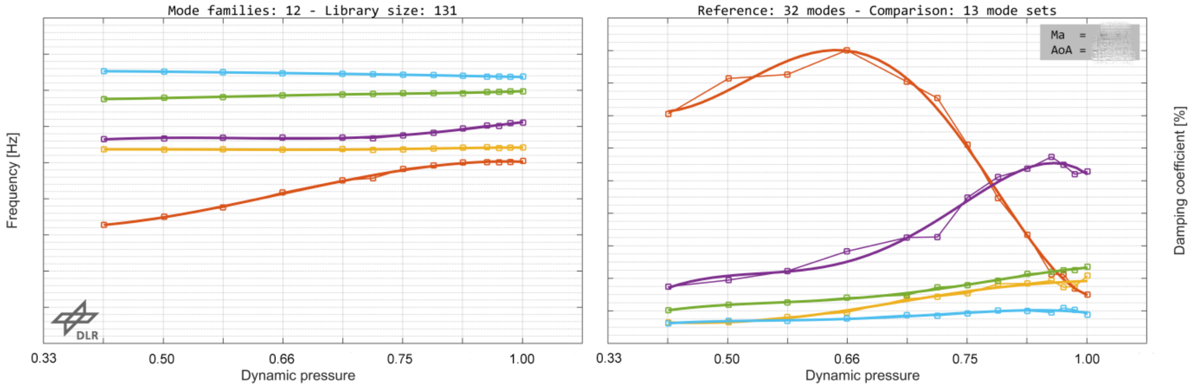

Figure 9: Frequency and damping evolution of first 5 modes obtained from the modal analysis results at the rest points (dynamic pressure normalized)

## 4 CONCLUSIONS

The framework of a tool for continuous monitoring of the aeroelastic stability margin has been presented. It is based on output-only modal analysis of acceleration responses performed repeatedly on a block of response data updated within an interval of roughly one second. The use of distributed architecture of data acquisition and multiple data analysis PCs has been described and the theoretical background of the time-domain multi-degree of freedom output-only modal parameter estimator SSI has briefly been reviewed. Due to the huge amount of data generated during hours of testing, database storage of modal analysis results, together with environmental and operating parameters, is mandatory. Mode tracking is the key enabler for structured access to data in the database. With mode tracking, the eigensolution branches displayed in the so-called real-time stability diagrams can be extrapolated to obtain an early indication of the aeroelastic stability limit and the margin in terms of distance in operating parameters toward this limit can be given. Even though a simple polynomial approach has been adopted here for extrapolation, it turned out in the wind tunnel tests that, after some minimum operating parameter range has been tested, the stability limit has already been indicated in a robust way. Of course, additional indicators can be implemented, such as the Zimmermann-Weissenburger flutter criterion, see [9]. However, this would require confidence in the understanding of the flutter mechanism and the major modes contributing to it. From that point of view, the extrapolation of all identified damping ratios does not require such a mode shape pre-selection and it has been demonstrated to provide reliable and robust indications for the stability limit at an early phase of testing. With the continuous real-time indicator for the aeroelastic stability limit at hand, it was even possible to change the sequence and the number of the discrete wind tunnel test points interactively based on the output of the monitoring tool. This has been pursued by the Embraer-DNW-DLR wind tunnel test team towards the end of the campaign, so that a coarsening of test points has been proposed when the indicated stability margins suggests to do so, while a refinement of the test point has been agreed in close vicinity to the stability boundary.

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