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Analysis of computational aeroelastic simulations by fitting time signals

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ABSTRACT
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ANALYSIS OF COMPUTATIONAL AEROELASTIC SIMULATIONS BY FITTING TIME SIGNALS

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Abstract.
The procedures to assess the critical aeroelastic state of an aircraft with the AESIM simulation method are described. The main innovation is the identification with MIMO-class methods which opens up possibilities for efficient usage of aeroelastic simulation methods. Experience with recent applications is reported.

Key words: Aeroelasticity, MIMO, Prony, AESIM, DOULAT, NASTRAN, GUL, Structural Dynamics

1. Introduction

The subject is being addressed because of the industrial need for an efficient aeroelastic simulation system able to improve aircraft design with adequate and efficient assessment of aeroelastic behaviour (flutter and/or dynamic responses) for transonic flight or other nonlinear conditions.

Today's industrial aeroelastic studies are performed mainly with a set of classical methods restricted to linear assumptions due to their efficiency in assessing the critical state cases for a large state space.

For transonic flow these results are questionable and the aforementioned methods are often matched with data obtained from experiment and or other CFD methods.

The NLR AESIM method is developed with the objective to assist in the design of future aircraft which are subjected to increases in flexibility, aerodynamic loading and nonlinearity and might be of value in the early design and development phase for assessing flight stability and control, safety and risk valuation and ride qualities. The method focuses primarily on aeroelasticity at transonic and mildy separated flows where aerodynamic nonlinearity is a non-negligible factor which cannot be estimated with extrapolating current methodology which is suited for flight at subsonic and low angle-of-attack supersonic speeds.

Over the past 20 years research centres and universities have put effort in the development and validation of advanced time-accurate aerodynamic CFD methods for the aforementioned purposes, resulting in a variety of methodologies for mostly clean wings and for rigid motions using the modal way of coupling. The recent algorithms are already very efficient and a further significant reduction of turn-around time from algorithm improvements is not expected. Also, the industry seems to be reluctant in taking on these new technologies due to the fact that in many occasions attention was given only to the modelling of the physical unsteady aerodynamic phenonema and much less to the complete aeroelastic problems more relevant to industry. This is supported by the fact that almost no methods have been reported which deal with the interpolation issues at the fluid-structure interface for non-flat plate geometries [1], that the coupling methodology is occasionally investigated [3] and the fact that hardly nothing (methods and strategy) has been reported that deals with the system identification in computational aeroelastic simulation.

One of the fundamental tasks in an aeroelastic analysis is the determination of the frequency and damping of aeroelastic modes (e.g. to detect if one of the generalized displacements becomes unstable and flutter will occur) which is a subset of the afore-mentioned system identification.

In most time domain aeroelastic applications the analysis of the time signal is a closing entry which does not get much attention and is often left out in presentations. For the well-known Isogai case any analysis method is good enough in contrast with more realistic multi-DOF structures. To single out a few modes for analysis from a multi-modes system is not good enough compared to classical p- or pk-methods of flutter analysis that give the user a complete analysis of every mode. As many different time response signals may have to be analyzed, sev-

[1] The volume spline method has been introduced in 1994 [1, 2] for that purpose.

eral methods for curve-fitting should be available. The analysis can be sensitive to light damping systems, the number of analyzed modes, coinciding modes and the signal being non-physical. To overcome these problems a number of solution strategies is needed.
Stability analysis with time-accurate CFD methods is usually performed with one of the following two strategies:

- **P- or pk- method analysis.** The aerodynamic data required for these methods might be supplied by: **i.** *Harmonic excitation* which is inefficient when the state space [2] is large; **ii.** *Impulsresponse* which is prone to noise and is also inefficient when the state space is large; **iii.** *Diverging rate method* [4]. This method is based on the linearized form of the equations and is suitable in a design cycle because the turn-around time can be brought back to the minimum.
- **Fully-coupled simulation**. This method is especially useful in case of strong non-linearities at low frequencies and a large state space. For a single flight condition the turn-around time is always less than the turn-around time when method 1.i or 1.ii are used for the study of a general stability problem. For a restrictive study, methods 1.i and 1.ii might be more efficient than method 2. It should be mentioned that method 1.iii can be embedded in a reasonably easy way in a time-accurate CFD method.

The main innovation in this presentation is the adoption of MIMO-class [5] technology, with the objective to predict the system state at multiple flight conditions from a MIMO identification of a fully-coupled simulation at a single flight condition, by extracting useful data (e.g. Generalized Forces) from the coupled simulation which can be used for other purposes.

By the aforementioned continuation it is expected to increase efficiency, so that industrial aeroelastic studies might be performed with fully-coupled CFD methods in assessing the critical state cases for a large state space.
This presentation describes the experience with the currently available fitting methods and strategies in applications.

[2] The state space here is the union of the geometrical state (Vibration modes etc.), the structural state (Mass, stiffness, eigenfrequencies etc.) and the fluid state(Airspeed, altitude, etc.)

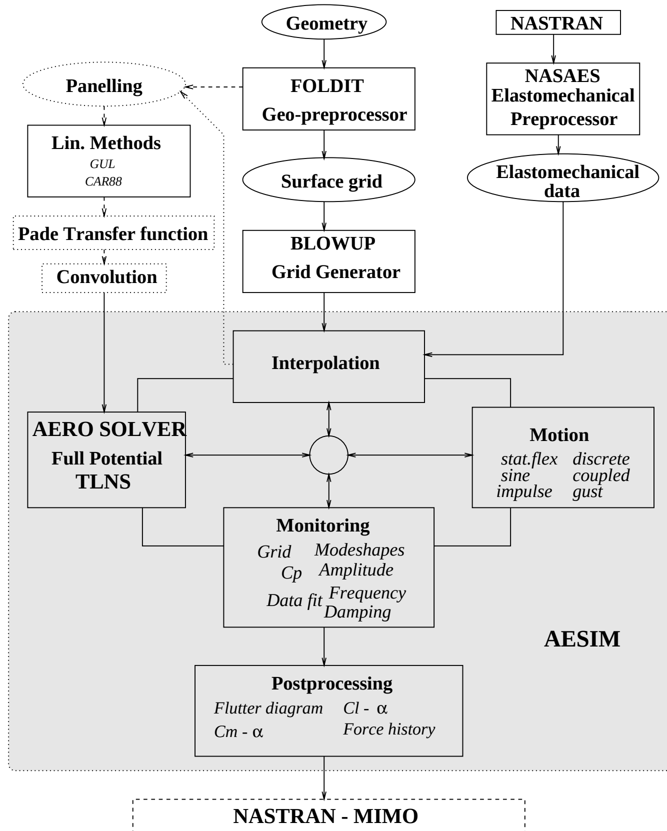

Figure 1. AEroelastic SIMulation system

2. Aeroelastic Simulation System

At NLR much effort has been spent to create a complete AEroelastic SIMulation system, to be used primarily for the flutter certification of transport-type aircraft in the transonic speed regime. Time-accurate simulation of fluid and airframe structure interaction is emphasized. The AEroelastic SIMulation system is referred to as AESIM, after the name of the core program.
The AEroelastic SIMulation system is built around the AESIM core and consists of six independent main program modules, see figure 1:

- **FOLDIT**: surface grid generation.
- **BLOWUP**: grid generation.
- **NASAES**: elastomechanical data manipulation.
- **AESIM** core.
- Output interfacing e.g. to NASTRAN or MIMO.
- Linear methods library.

The AESIM core program is divided into 5 individual modules and contains those subroutines which are CPU intensive and make it possible to run the core in stand alone mode:

- **Interpolation:** Interpolation of elastomechanical and aerodynamic data (Volume Spline Method [1, 2]).

- **Aero solver:** Time-accurate solving of aerodynamic equations (Full Potential and TLNS[3]).
- **Motion:** Either description of motions, seeded flows, or solving of elastomechanical equations with or without external loadings.
- **Monitoring:** Visualization of simulated data.
- **Postprocessing:** Recollection and assimilation of facts and figures of past simulation(s).

Recently activities have been started to extend the AESIM method in the direction of flows and geometries which are encountered in military aircraft. Then the code will be ready to prove its value in applications with mild flow separation which is primarely responsible for inducing strong limit cycle oscillation structural responses, which might restrict the flight envelope of the aircraft.
In this paper we give attention to the time-analysis and strategies to use the method efficiently. The other parts have been presented in [8].

3. Time signal analysis

The fundamental task in an aeroelastic analysis is the determination of the frequency and damping of aeroelastic modes (e.g. to detect if one of the generalized displacements becomes unstable and flutter will occur). As many different time response signals may have to be analyzed a comprehensive set of methods for curve-fitting should be available. In general each time response signal exists of contributions of various modal modes, of which the frequency and damping of each one have to be determined.
Therefore, during an unsteady simulation the data must be analyzed on-line in the time domain in order to determine the behavior of a coupled system. The main purpose of this analysis is to determine the frequency and damping characteristics of the discrete time signal. To fulfil that task the following methods have been embedded (see section 3.2):

- The exponential sine fit,[9]
- Prony's method,
- Fast Fourier Transform analysis,
- Curve-fitting of transfer functions.

Very recently, in a cooperation with TUDelft a feasibility study has been started to apply the promising MIMO-class techniques [5] for that purpose too. They will enhance the analysis capability as depicted in figure 2.

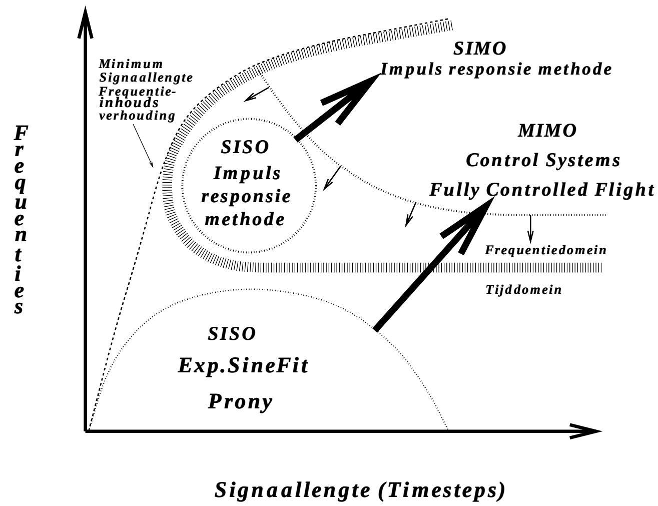

Figure 2. Deployment time-analysis methods with respect to aeroelastic sytems

Since a wide array of time response signals is available several ways exist to make use of the aforementioned time-fitting tools. The most common time response signals which can be used to determine the frequency and damping characteristics of the discrete time signal consist of:

- • For every modal mode separately:
  - the generalized coordinate,
  - the velocity of the generalized coordinate,
  - the generalized force.
- • Also a combination of modal modes and/or the pressure or deformation data at selected points can be analyzed.

Experience has learned that for a fail safe analysis of an elastomechanical system the above mentioned fitting routines are applied first to the non-aerodynamically loaded system and next to the system loaded using linear aerodynamics, [10], through convolution of transfer functions, [4]. The data from these analyses might act as a guideline for the analysis of the non-linear time signal, originating from the coupled non-linear fluid structure simulation. The analysis process has been fully automated through use of scripts. This facility allows the analysis process to be repeatible and to be documented.
It should be noted that also the analysis might provide a prognostic way to speed up the simulation by allowing for larger time steps [3].

3.1. MIMO-class system identification

The main innovation in this presentation is the adoption of MIMO [5] technology. This permits a

[3] Recently the TLNS methodology as reported in [6, 7] has been embedded as there is enough evidence that with the Thin-Layer Navier-Stokes equations complemented by a simple turbulence modelling the needs of the industry can be met for many configurations.

black box [4] evaluation of the aeroelastic system in such a way that after a single fully-coupled simulation for one flight condition the system state for other flight conditions (e.g. q_{dyn}) might be predicted and to extract useful data (e.g. Generalized Forces) from the coupled simulation which can be used for other purposes.
The main purpose is to extend the single point application of coupled simulation methods to multiple points and wayhead is given to perform postprocessing activities, pk-, k-method etc, with extracted data from an application of a fully-coupled simulation.

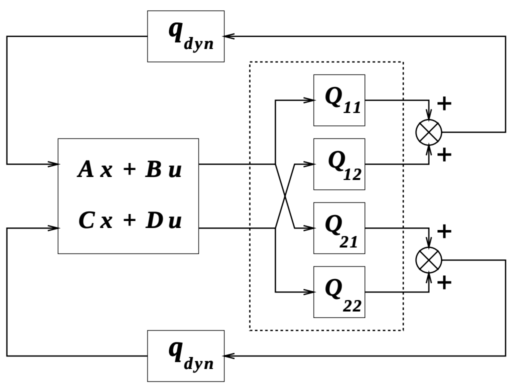

Figure 3. Generic 2 mode aeroelastic system

A 2-DOF example is presented in figure 3 where we want to assess the transfer functions (generalized forces) from the coupled simulation. From the coupled responses x, u at a fixed q_{dyn} the MIMO analyses will deduct the $A, B, C, D, Q_{11}, Q_{12}, Q_{21}$ and Q_{22}. The condition of the system is equivalent to the amount of proportional feedback. The symbols used in the figure are explained in the appendix.
In order to obtain an estimate for the flutter condition from a single time simulation, the aerodynamics that relate the generalized aerodynamic forces to the generalized displacements are to be modelled and identified. Since the system operates in a closed loop with the elastomechanical system, multivariable algorithms for closed-loop identification are required. The data that is to be used is obtained by simulation, so the signals are not contaminated by measurement noise. However, a small amount of process noise is present, since round-off errors are introduced on the propagation of the signals through the two systems.
The complicated dynamics that govern the system for a large number of modes, suggest the use of frequency-domain methods. This class of algorithms is well applicable to systems where several closely located poles have to be distinguished. However, the closed-loop character of the identification problem poses a major problem. Since there is no external input or reference signal, the aerodynamical model that is identified will converge to the inverse of the mechanical model. This effect is due to the absence of an external signal that drives the systems. In addition, the aerodynamic model is insufficiently excited to use stochastic theories on which frequency-domain identifiers are based. In fact, the input signal is completely deterministic and contains only the system dynamics.
Finally, frequency-domain analysis is mainly useful for signals that are distorted by large amounts of noise and where specific frequency ranges are of interest. Both are not the case for the problem at hand.
Therefore time-domain analysis has been selected. The use of time-domain methods to estimate the aerodynamic model, allows for the isolation of causal and non-causal relations between the inputs and the outputs. Non-causal effects are not to be modeled, since these are caused by the elastomechanical system in the closed loop. Because the structure of the mechanical system is known to be strictly non-causal, i.e. there is no direct feedthrough from the forces to the displacements, both a filter model and a prediction model can be used for the aerodynamic system.
For identification, a multivariable regression model is chosen for the more general filter case. Details of the aforementioned procedure will be published in a forthcoming publication.

3.2. Data analysis methods embedded in AESIM

The methods described in this section obtain the frequencies and dampings of a dataset with constant time step:

$$x_l = x(l\Delta t) \mid l = L_b \dots L_e, \tag{1}$$

where L_b denotes the beginning and L_e denotes the end of the data set. Furthermore the time is defined as:

$$t_l = t = l\Delta t \mid l = L_b \dots L_e. \tag{2}$$

3.2.1. *Exponential sine fitting and determination of dampings and frequencies*

The data set is approximated in time in a least squares sense by the real valued function $X_f(t)$

[4] No knowledge is assumed of coefficients of the structural and aerodynamic system

defined by [9]:

$$X_f(t) \ = \ \sum_{k=1}^{N^f} a_k e^{\lambda_k t}. \qquad (3)$$

N^f is the order of the fit which is less or equal to twice the number of modal modes N^h. The coefficient a_k is complex. For every such term there is a companion term which is the complex conjugate, so that the components of the sum are real. Such a sum arises as the homogeneous solution of a linear system of ordinary differential equations with constant coefficients. In particular dynamical systems with symmetric mass, stiffness and damping matrices.
The complex λ_k is defined as follows:

$$\lambda_k \ = \ \alpha_k + \jmath\beta_k, \qquad (4)$$

from which the frequencies and dampings of $X_f(t)$ are defined:

$$\text{Damped natural frequency} \ = \ \beta_k, \quad (5)$$

$$\text{Characteristic damping coefficient} \ = \ \alpha_k. \quad (6)$$

In the least squares fit the squared error difference between the output fit $X_f(t)$ and the input time-history x_i given by:

$$E \ = \ \sum_{l=L_b}^{L_e} (X_f(t_l) - x_l))^2, \qquad (7)$$

is minimized.
The dampings and frequencies are obtained with the following methods:
A. Prony :
The Prony formulation derived by Prony in 1790 [11] to analyze elastic properties of gasses is described below.
The λ_k are obtained with the following procedure:
Determination of λ_k :

A.1: Introduce the parameter:

$$\eta_k \ = \ e^{\lambda_k \Delta t}. \qquad (8)$$

Which can be written as:

$$\eta_k \ = \ r_k e^{\jmath(\theta_k + 2\pi l)}. \qquad (9)$$

From which the characteristic damping coefficient and the damped natural frequencies can be obtained as:

$$\alpha_k \ = \ \frac{1}{\Delta t} log(\mid r_k \mid),$$
$$\beta_k \ = \ \frac{\theta_k + 2\pi l}{\Delta t} \mid l = 0.$$

θ is defined by:

$$\theta_k = \arctan\left[-\jmath\frac{\eta_k - \bar{\eta}_k}{\eta_k + \bar{\eta}_k}\right], \qquad (10)$$

where $\bar{\#}$ denotes the conjugate part.
From the definition of β_k it is clear that λ_k is not uniquely defined. Here $l = 0$ is taken.
A.2: η_k are the roots of the polynomial equation:

$$\eta^{N^f} + p_{N^f}\eta^{N^f-1} + \ldots + p_1 \ = \ 0. \qquad (11)$$

The zeros of the polynomial equation 11 which occur in complex conjugate pairs are determined using a general root finding routine, see [12]. **A.3:** The coefficients $p_k \mid k = 1 \ldots N^f$ are defined by the matrix equation, see [13]:

$$\begin{pmatrix} c_1 & \ldots & c_{N^f} \\ c_2 & \ldots & c_{N^f+1} \\ \vdots & \ddots & \vdots \\ c_{N^f} & \ldots & c_{2N^f-1} \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_{N^f} \end{pmatrix} = \begin{pmatrix} -c_{N^f+1} \\ -c_{N^f+2} \\ \vdots \\ -c_{2N^f} \end{pmatrix} (12)$$

The coefficients in the matrix of equation 12 are defined as follows:

$$c_l = \qquad (13)$$

$$= \begin{cases} x_l & \mid (l = L_e - 2N^f + 1 \ldots L_e \\ & \wedge L_e - 2N^f + 1 = L_b), \\ \frac{1}{r}\sum_{i=1}^{r} x_{l-i+1} & \mid (l = L_e - 2N^f + 1 \ldots L_e \\ & \wedge L_e - 2N^f + 1 > L_b), \\ & r = 2 \vee \ldots \vee L_e - L_b - 2N^f + 1 \end{cases},$$

where I_e denotes the end of the selected time interval.
In principle a set of $2N^f$ equally spaced values of the function $x(t)$ is sufficient to determine the function $X_f(t)$.
However, a more robust procedure is obtained according to [13] when the set of data points contain more than $2N^f$ points and the coefficients are obtained by averaging the evenly spaced values of $x(t)$.
The a_k's parameters are obtained as explained below.
B. Levenberg-Marquardt Method :
Previous obtained λ_k's can be improved by the Levenberg-Marquardt Method, see [14]. This iterative non-linear fit procedure is applied here using frozen a_k parameters.
A reasonable guess to the aforementioned λ_k and a_k parameters is necessary for reliable results. The initial guesses for λ_k are provided by:

1. the aforementioned Prony method.

2. the natural harmonic frequencies (eigenfrequencies) of the structure.

3. obtained by the curve fitting method explained later on.

The a_k's parameters are obtained as explained below.

C. Complex curve fit :

When the assumption can be made that after $l = L_b$ no external forces are applied (the input-signal to the system is zero). The $\lambda_k' s$ can also be derived by the procedure below.

After applying the discrete Fourier transform to the data:

$$x_f = \mathcal{F}x, \tag{14}$$

the data is approximated by a complex curve fit[15] and the coefficients of the rational polynomials are obtained:

$$x_f(\jmath\omega) \simeq \frac{\sum_{i=0}^{N^a} A_i (\jmath\omega)^i}{\sum_{i=0}^{N^b} B_i (\jmath\omega)^i}, \tag{15}$$

where:

$$B_0 \equiv 1. \tag{16}$$

N^a, N^b are the order of the polynomials. N^b is equal to twice the number of modal modes $N^b = 2N^h$ and in general $N^a \leq N^b$.

The $\lambda_k' s$ are the roots of the denominator polynomial which again are obtained by a general root finding method.

With the λ_k's determined as indicated above, it only remains to determine the a_k's. The following system of equations remains to be solved for determining the a_k's:

$$\begin{bmatrix} 1 & 1 & \dots & 1 \\ \eta_1 & \cdots & \eta_{N^f} & \\ \vdots & \ddots & \vdots & \\ \eta_1^{L_e - L_b} & \dots & \eta_{N^f}^{L_e - L_b} & \end{bmatrix} \begin{pmatrix} a_1 e^{\lambda_1 t} \\ a_2 e^{\lambda_2 t} \\ \vdots \\ a_{N^f} e^{\lambda_{N^f} t} \end{pmatrix} = \begin{pmatrix} x_{L_b} \\ x_2 \\ \vdots \\ x_{L_e} \end{pmatrix}. \tag{17}$$

Equation 17 is solved by a General Linear Least Squares method in which the design matrix is inverted by one of the following procedures:

- Gauss elimination, [16]
- LU Decomposition, [17]
- SVD, singular value decomposition [17]. If the system of equations is numerically very close to singular, Gaussian elimination and LU decomposition may fail to give satisfactory results. In that case SVD is a more powerfull tool.

It can be concluded from the aforementioned procedure that a strategy has to be developed to obtain the best fit. The strategy developed sofar consist of:

- User-supplied specification of the selected interval (subset) $t_b = L_b \Delta t, t_e = L_e \Delta t$.
- When Prony's method is applied evaluation of the $\lambda' s$ and the $a_k' s$ is performed for a range of averages with $r = 1, 2, 4, 8 \dots$ and selection of the coefficients which result in the smallest error.
- Evaluation of the $\lambda' s$ and the $a_k' s$ is performed by using a sequence of modes $(1, 2, 4 \cdots N^f)$.

4. Applications

The examples here focus on current ongoing activities with respect to the time-analysis and demonstrate the status of the aeroelastic environment.

4.1. T-tail

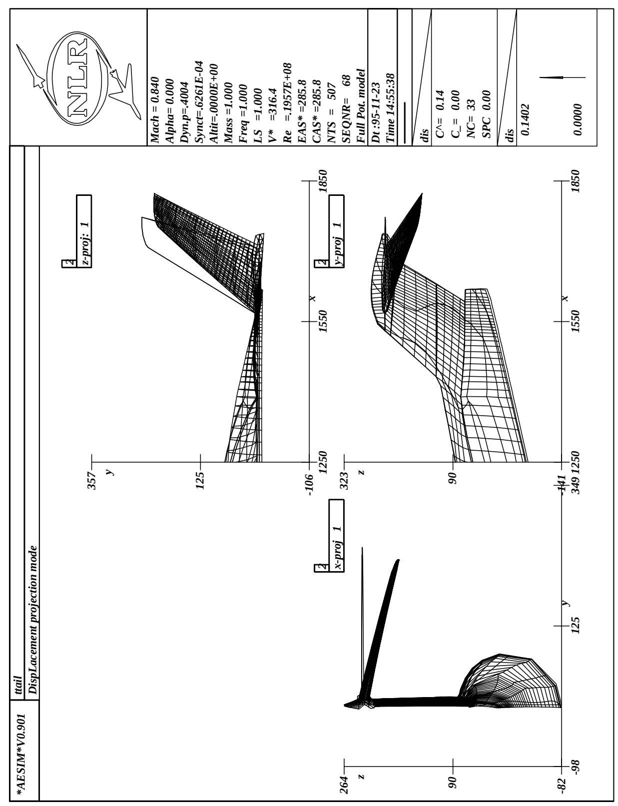

Figure 4. Second mode shape of T-tail

In order to demonstrate the ability of the system to deal with existing aircraft structures a transport-type T-tail fuselage configuration was considered. The elastomechanical model consisted of ten modes. The geometry and the second mode are depicted in figure 4.

The generalized coordinates of each individual mode were calculated in time as a result of a nonzero initial value for the acceleration of the generalized coordinate. In figure 5 the time response information is evaluated through exp. sine fit signal pro-

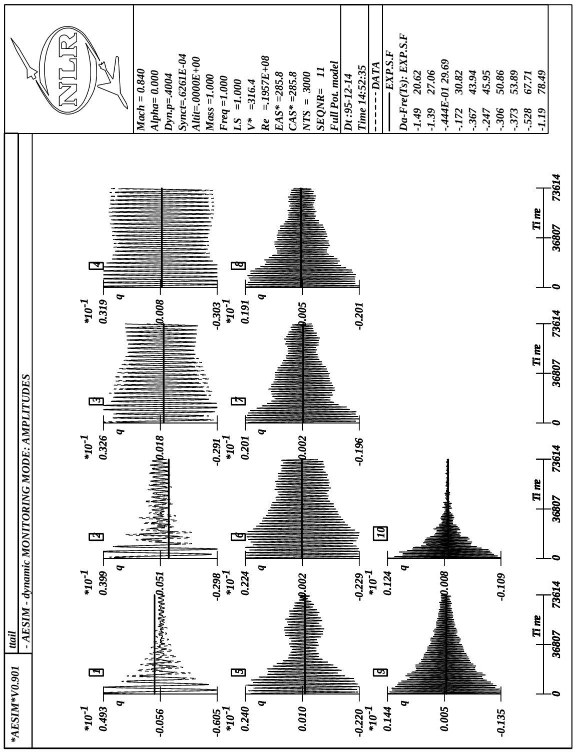

Figure 5. Result after exp. sine fit signal processing of dynamic response of generalized coordinates at Mach=0.84 and zero altitude in Standard Atmosphere

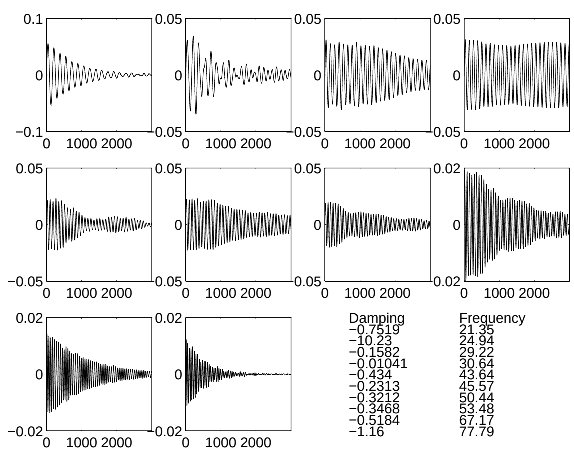

Figure 6. Result after MIMO signal processing of dynamic response of generalized coordinates at Mach=0.84 and zero altitude in Standard Atmosphere

cessing to get damping and frequency information. Results of the MIMO-class procedure are depicted in figure 6. The exp. sine fit results compare reasonably well with the simulated data. However, the MIMO-class fit results are astonishingly good. Both methods revealed about the same damping and frequencies. The results of these simulations show that the T-tail has a stable dynamic behavior for the flight condition under consideration.

4.2. Embedding of lineair aerodynamics

To ease applications and to build confidence a coupled simulation should also be run based on linear aerodynamics. This requires the generalized forces (transfer functions) which are in general available in the frequency domain to be fitted [4, 18] and transformed to the time-domain [19]. A feasibility study with 2-D airloads and 3-D airloads has been performed to investigate the most efficient way to embed linear aerodynamics in the AESIM method. The assumption is made that the behavior of any unsteady parameter of interest such as an aerodynamic load or a pressure coefficient can be described by a appropriate form for the transfer function which is a ratio of two s dependent polynomials which is known as the Padé approximation:

$$G(s) = \frac{A_0 + A_1 s + A_2 s^2 + A_3 s^3 + \cdots}{1 + B_1 s + B_2 s^2 + B_3 s^3 + \cdots} \tag{18}$$

The complex curve fitting procedure is used also here to obtain the approximation.
The rational polynomial is transformed to state space form:[5]

$$\begin{pmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{1}{B_3} & -\frac{B_1}{B_3} & -\frac{B_2}{B_3} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} u$$

$$y = \begin{pmatrix} \frac{A_0}{B_3} - \frac{A_3}{B_3}\frac{1}{B_3} & \frac{A_1}{B_3} - \frac{A_3}{B_3}\frac{B_1}{B_3} & \frac{A_2}{B_3} - \frac{A_3}{B_3}\frac{B_2}{B_3} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \frac{A_3}{B_3} u \tag{19}$$

This system is solved using the Newmark scheme embedded in AESIM, [1].

4.2.1. *Two-dimensional application*

Calculations of unsteady airloads have been performed with DOULAT for a flat plate pitching about an axis $0.5c$ in front of the leading edge (mode 2) and heaving (mode 1) at $M_\infty = 0.5$ and a reduced frequency range up to $\mid s \mid = 1.0$. [6] The generalized forces data generated by DOULAT were fitted with the aforementioned procedure. Thereafter the Newmark scheme was applied to oscillatory motions in the same frequency range and the time traces were transformed to the frequency domain.

[5] Equation 19 is given here for a third order system.
[6] The reduced frequency is defined here as $k = Im(s) = \frac{\omega c}{2U}$ where c denotes the chord.

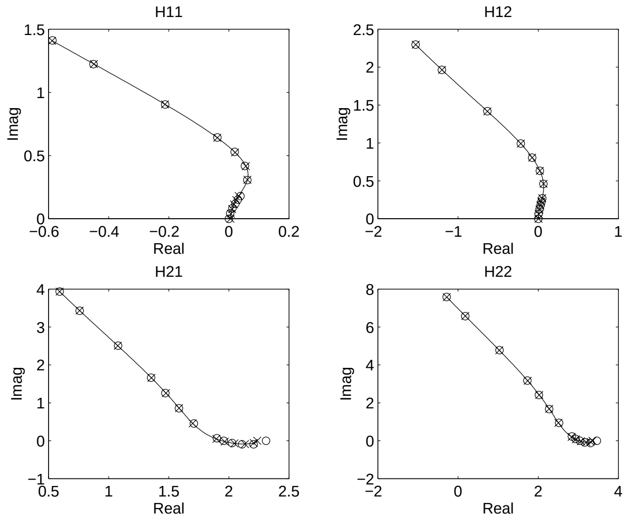

Figure 7. Comparison of directly calculated and fitted unsteady coefficients of a harmonically heaving and pitching flat plate at M_∞=0.5.

Figure 7 shows a comparison in the frequency domain between the original data (circle) and the fitted data (line-cross) which show a good agreement.

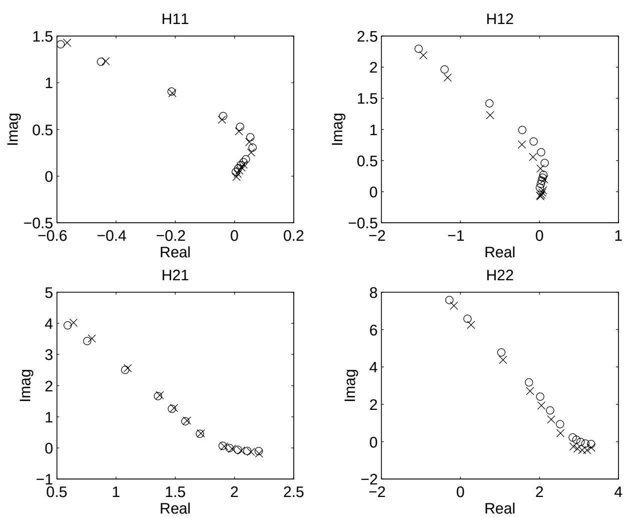

Figure 8. Comparison in the frequency domain of directly calculated and to and fro transformed unsteady coefficients of a harmonically heaving and pitching flat plate at M_∞=0.5.

Figure 8 shows a comparison in the frequency domain between the original data (circle) and the data (cross) obtained by analysing the time traces which again show a good agreement. From this the conclusion might be drawn that the aforementioned procedure is applicable in 2D.

4.2.2. *Three-dimensional application*

Calculations have also been performed with GUL for the 3-D AGARD standard aeroelastic wing at Mach=0.901. This configuration is described in [20]. Again two modes have been selected.
A similar procedure as outlined above was applied.

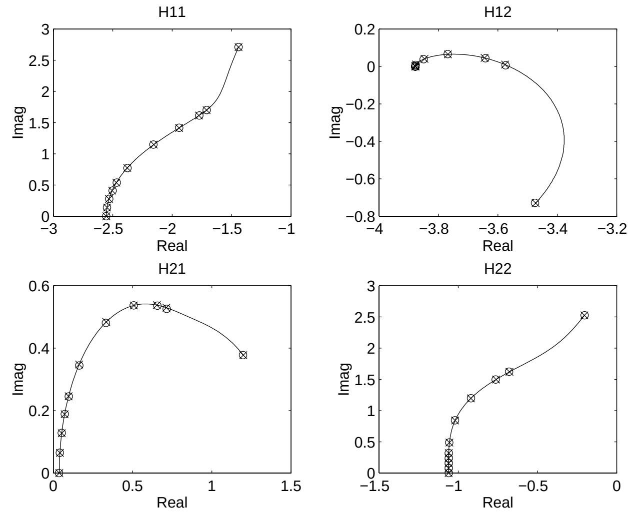

Figure 9. Comparison of directly calculated and fitted unsteady coefficients of the harmonically oscillating wing 445.6 at M_∞=0.901.

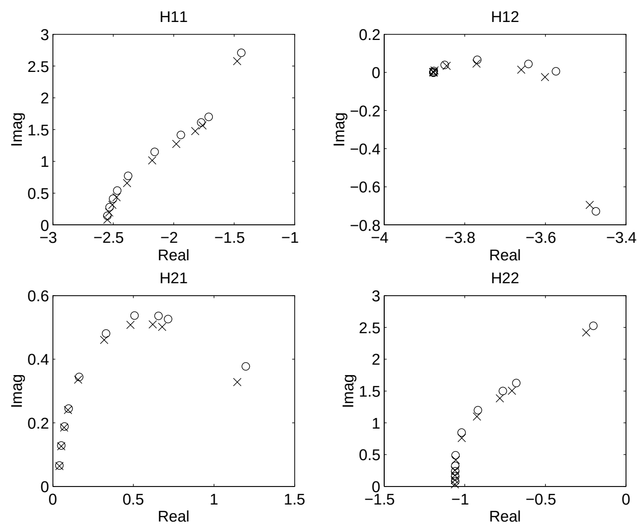

Figure 10. Comparison in the frequency domain of directly calculated and to and fro transformed unsteady coefficients of the harmonically oscillating wing 445.6 at M_∞=0.901.

Figure 9 shows a comparison in the frequency domain between the original data (circle) and the fitted data (line-cross) which show a good agreement.
Figure 10 shows a comparison in the frequency domain between the original data (circle) and the data (cross) obtained by analysing the time traces which again show a good agreement. From this the conclusion might be drawn that the aforementioned procedure shows good promise for embedding in the AESIM system.

4.3. MIMO-class application

The applicability of the MIMO method [5] in flutter analysis is presented for an aeroelastic investigation which was conducted for one of the 3-D AGARD standard aeroelastic configurations in subsonic, transonic and supersonic flow. This configuration is described in [20]. The configuration for dynamic response I wing 445.6 model "weakened no. 3" was selected at Mach=0.901. The data were obtained from [3].

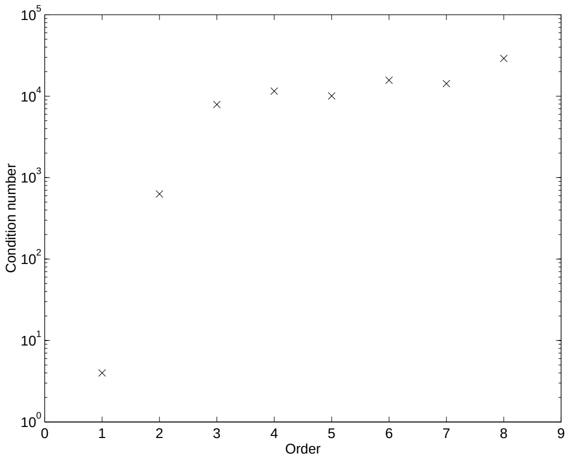

Figure 11. Order of excitation versus condition number for AGARD aeroelastic system at subcritical flight condition

Persistency of excitation for the four-mode system is illustrated in figure 11, where the order of excitation is shown along the horizontal axis and the condition number for the correlation-function Toeplitz matrix is printed along the vertical axis. From these condition numbers, the input is found to be persistently exciting of order two at most.

The model order is determined by separating the data in three subsets. The first subset contains the first half of the available time series and is used for identification. The second set contains only 12% of the data points and is used to track the state vector of the new model without using the subset that was used in the identification step. Finally, the last 38% of the original time series is used to validate the new model using the estimated state vector as an initial condition.

The validation step results in three criteria to signal overfitting of the system. The normalized mean square error indicates the best model. However, this may not be the optimal model since this criterion contains no penalty for hugh models. Akaike's information criterion (AIC) and the final prediction error criterion (FPE) both do include the number of model parameters in the resulting cost. However, all three criteria usually indicate the same optimal model order.

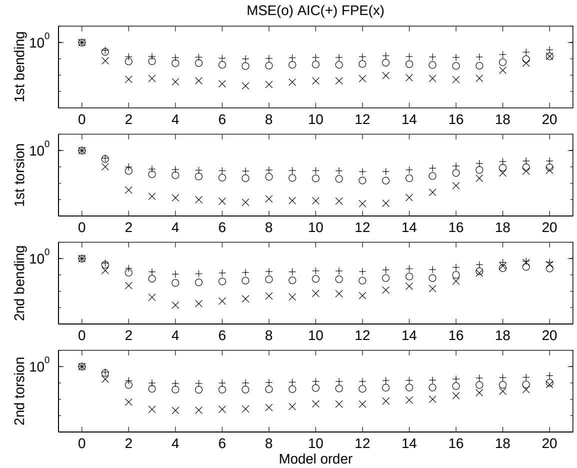

Figure 12. Validation criteria for AGARD aeroelastic system at subcritical flight condition

Figure 12 shows the validation criteria for each of the multiple-input single-output models in the four-mode system that was mentioned before. The order of the multiple-output model is equal to the sum of the orders of the single-output models.

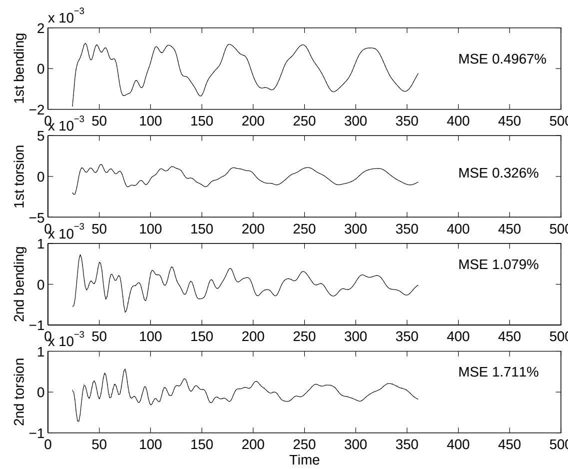

Figure 13. Comparison of MIMO fitted (...) and original (-) generalized forces data for AGARD aeroelastic system at subcritical flight condition

Figure 13 shows the generalized forces as obtained from simulation with the identified model, together with the original data. The data is plotted for time points after the transition has damped out. An excellent agreement is shown between both datasets (they coincide entirely).

A slightly different model structure (MIMO*), including auto regressive terms on the outputs, leads to slightly larger errors for the same simulation, as shown in figure 14.

Finally we come to the main purpose of the excercise. We increase the airspeed to a supercritical value and apply the MIMO results obtained from fitting the subcritical airspeed data and make the

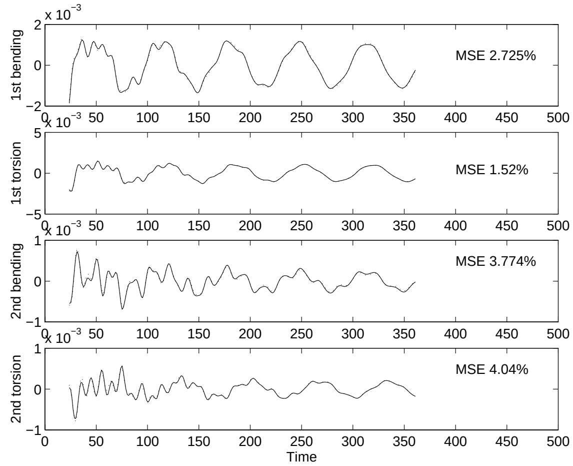

Figure 14. Comparison of MIMO* fitted (...) with auto regressive terms on outputs and original (-) generalized forces data for AGARD aeroelastic system at subcritical flight condition

comparison with results of the aeroelastic simulation at the higher airspeed.

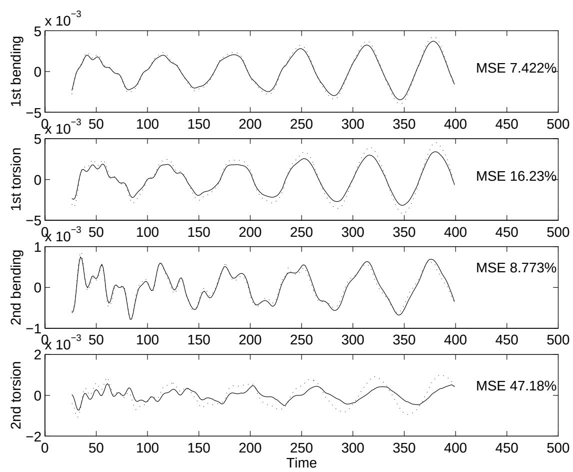

Figure 15. Comparison of MIMO **predicted** (...) and reference (-) generalized forces data for AGARD aeroelastic system at supercritical flight condition

Figure 15 and 16 depict the comparison which shows that the system at the supercritical airspeed is unstable and that the linear MIMO model prediction performs very well for the lower 3 modes. Mode 4 is overpredicted.
The modified model MIMO* results in smaller errors than the model from the original model set. Which model set results in the best estimates for aerodynamic modeling in aeroelastical closed-loop systems is yet to be investigated.

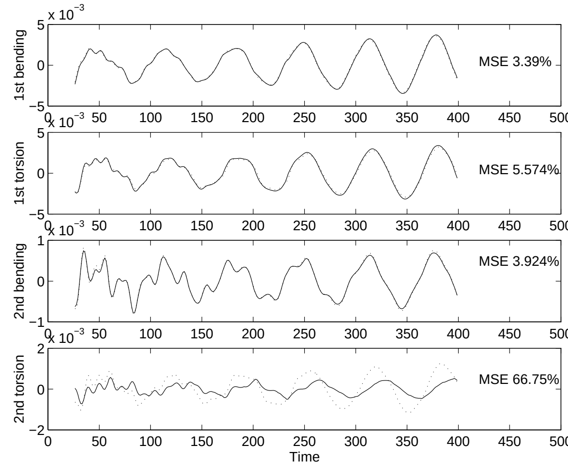

Figure 16. Comparison of MIMO* **predicted** (...) and reference (-) generalized forces data for AGARD aeroelastic system at supercritical flight condition

5. Conclusions

In this paper the status of the NLR system for aeroelastic simulation has been presented and demonstrated with the emphasis on time-analysis. Experience with recent applications and ongoing developments led to the following observations:

- The analysis of time signals can be carried out satisfactorily with the available models.
- The MIMO-class fit procedures are superior to the ones currently embedded in the AESIM method.
- The MIMO-class analysis application has shown good promise for increasing the **efficiency** of coupled simulations by allowing results made for a single flight condition being extented to multiple flight conditions.
- The procedures for utilization of lineair aerodynamics from the frequency domain to the time domain have shown good promise for embedding in the aeroelastic simulation system.

Appendix

A. Aeroelastic MIMO analysis

A very important application of the MIMO analysis is the black box evaluation of the aeroelastic system in a way as to be able to predict the flutter condition after just a single time-simulation.
The system condition is equivalent to the amount of proportional feedback as depicted in figure 3.

To be analyzed, by the MIMO software, in figure 3 are the aerodynamic transfer functions, Q_{11}, Q_{12}, Q_{21} and Q_{22}, in the case of a two mode structural

system.
The definition of the structural system is as follows:

The generalised coordinates q^i for each vibration mode may be different in time and are based on the generalized modal deflection approach.
The dynamic deformations are expressed in generalized coordinates q^i and their associated modal mass M, damping D, stiffness K and vibration modes $\vec{h}^i$ for N^h modes which satisfy the equation:

$$[M]\ddot{q} + [D]\dot{q} + [K]q = F \tag{20}$$

The coupling of the structural model and the aerodynamic model involve the generalised aerodynamic forces acting on the aircraft configuration which are obtained by solution of the aerodynamic equations:

$$F^i = -q_{dyn} \int_s (C_p - C_p^{stc})\vec{h}^i \cdot \vec{N} ds, \tag{21}$$

where C_p^{stc} is obained by a previous static simulation or by application of a low-pass filter.
Equation (20) is transformed to first order:

$$d\dot{Q} + kQ = f, \tag{22}$$

where $Q = \begin{pmatrix} q \\ \dot{q} \end{pmatrix}$, $f = \begin{pmatrix} 0 \\ F \end{pmatrix}$, $d = \begin{bmatrix} 1 & 0 \\ 0 & M \end{bmatrix}$ and

$$k = \begin{bmatrix} 0 & -1 \\ K & D \end{bmatrix}. \tag{23}$$

$$\dot{Q} + d^{-1}kQ = d^{-1}f. \tag{24}$$

Therefore the system in figure 3 can be defined as:

$$A \equiv -d^{-1}k \tag{25}$$
$$B \equiv d^{-1} \tag{26}$$
$$C \equiv 1 \tag{27}$$
$$D \equiv 0 \tag{28}$$

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References

1. M.H.L. Hounjet and B.J.G. Eussen, *Outline and Application of the NLR Aeroelastic Simulation Method*, ICAS-94-5.8.2, September 1994
2. M.H.L. Hounjet and J.J. Meijer ,*Evaluation of Elastomechanical and Aerodynamic Data Transfer Methods for Non-planar Configurations in Computational Aeroelastic Analysis* Contribution to CEAS Symposium: 'International Forum on Aeroelasticity and Structural Dynamics 1995'
3. B.B. Prananta and M.H.L. Hounjet, *Large time step aero-structural coupling procedures for aeroelastic simulation* . In Proceedings CEAS Symposium: International Forum on Aerelasticity and Structural Dynamics, CEAS, Rome, June 17-20 1997
4. M.H.L. Hounjet and B.J.G. Eussen , *Prospects of time-linearized unsteady calculation methods for exponentially diverging motions in aeroelasticity* AIAA paper 92-2122, April 1992
5. M.W. Soijer , *Frequency Domain Identification of Rotorcraft State Space Models and Applications to a BO105 Rigid Body Model* Master's thesis, Delft University of Technology, Faculty of Aerospace Engineering, December 1996
6. B. Prananta, M.H.L. Hounjet and R.J. Zwaan, *A Thin Layer Navier-Stokes Solver and its Application for Aeroelastic Analysis of an Airfoil in Transonic Flow* Proceedings CEAS Symposium: 'International Forum on Aeroelasticity and Structural Dynamics 1995'
7. B.B. Prananta and M.H.L. Hounjet, *Aeroelastic Simulation with Advanced CFD Methods in 2D and 3D Transonic Flow*, In Proceedings Conference on Unsteady Aerodynamics, RAeS, London, July 17-18 1996
8. B.J.G. Eussen, M.H.L. Hounjet and R.J. Zwaan *Experiences in aeroelastic simulation practices* , EUROMECH colloquium 349, Göttingen, Germany, 1996
9. Bennett, Robert M. and Desmarais, Robert N. *Curve Fitting of Aeroelastic Transient Response Data with Exponential Functions*, NASA SP-415
10. M. H. L. Hounjet. *Calculation of unsteady subsonic and supersonic flow about oscillating wings and bodies by new panel methods*, NLR TP89119 U, April 1989.
11. C. Lancosz . *Applied Analysis*, Prentice Hall, 1956.
12. Stoer, J., and Bulirsch, R. *Introduction to Numerical Analysis*, New York, Springer Verlag
13. Charles L. Keller. *Determination of Complex Exponentials, Least Squares and Prediction Methods*, AFWAL-TR-88-3042, Air Force Wright Aeronautical Laboratories
14. Marquardt, D. W. *J. Soc. Ind. Appl. Math.*, Vol. 11, pp. 431-441, 1963
15. E.C. Levy *Complex-Curve Fitting* IRE Transactions on Automatic Control, May 1959
16. Carnahan, Brice, Luther, H.A., and Wilkes, James O. *Applied Numerical Methods*, Wiley, New York 1969
17. Forsythe, George E., Malcolm, Michael A., and Moler, Cleve B. *Computer Methods for Mathematical Computations*, Prentice-Hall, Englewood Cliffs, New York 1977
18. M. H. L. Hounjet and B. J. G. Eussen.*Beyond the frequency limit of time-linearized methods*, NLR TP91216 U, June 1991.
19. Edwards, J.W. *Unsteady aerodynamic modeling and active aeroelastic control* NASA CR-148019
20. Yates, C. *AGARD Standard Aeroelastic Configurations for Dynamic Response I-Wing 445.6*, AGARD Report No. 765, 1988.