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Dynamic Measurements on the Nasa CRM Model tested in ETW

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ABSTRACT

The European Transonic Windtunnel (ETW) hosted a test campaign within the framework of the European project ESWIRP (European Strategic Wind tunnels Improved Research Potential). The project was funded by the European Commission "to enhance the complementary research potential and service capabilities of 3 strategic wind tunnels in Europe both in terms of productivity and quality" and to enable a trans-national access to these dedicated facilities for research institutes and universities. ETW as Europe's unique facility for high Reynolds number testing of aerospace applications is one of these strategic wind tunnel facilities in Europe. It enables testing at flight Reynolds and Mach numbers and defined aeroelastic conditions. Within the ESWIRP project proposals for transnational access were called, and a peer review process selected an international consortium for ETW access based on scientific excellence. The consortium performed a test featuring an unsteady wake analysis combined with wall interference investigations by demonstrating the capability to efficiently apply complex techniques under cryogenic conditions. In cooperation with NASA Langley the Common Research Model (CRM) was used as the wind tunnel model, allowing to build up a publicly available database and giving the chance to compare results between wind tunnel facilities around the world. The present paper concentrates on the analysis of dynamic data acquired during the test campaign to assess the eigenmotion modes of the model. It describes the applied instrumentation systems and their usage to identify the eigenmotion modes.

NOMENCLATURE

a_x	acceleration in x-direction (close to model center)	[m/s2]
a_y	acceleration in y-direction (close to model center)	[m/s2]
a_z	acceleration in z-direction (close to model center)	[m/s2]
a_{Nose}	model nose acceleration in z-direction	[m/s2]
a_{Rear}	model rear acceleration in z-direction	[m/s2]
α	model incidence	[rad]
C_L	lift coefficient	[-]
C_{L0}	zero lift coefficient	[-]
C_{Lmax}	maximum lift coefficient	[-]
C_{Lmin}	minimum lift coefficient	[-]

F_x, F_y, F_z	balance forces	[N]
M_x,M_y,M_z	balance moments	[Nm]
P_{dyn}	dynamic pressure	[kPa]
P_{total}	total pressure	[kPa]
Re	Reynolds number	[-]
T_{total}	total temperature	[K]
φ	phase angle	[rad]
f	frequency	[Hz]
ω	angular frequency	[rad/s]
q	pitch rate	[deg/s]
x, y, z	model coordinates	[m]

1 INTRODUCTION

The European Commission funded the ESWIRP (European Strategic Wind Tunnels Improved Research Potential) project to allow research institutions and universities the trans-national access to Europe's strategic wind tunnels and to stimulate joint research and networking activities. In the framework of the project Europe's strategic wind tunnels, the large subsonic DNW-LFF wind tunnel, the transonic ONERA S1MA tunnel and the pressurized cryogenic ETW facility should increase their capabilities for the benefit of the research community by using advanced measurement techniques and new hardware components.

Following a call for proposals, for each tunnel one or two scientific projects were selected by peer reviewers from industry, research and academia. For ETW an international consortium of research institutes and universities was selected to prepare a test on the topic "Time-resolved Wake measurement of Separated Wing Flow & Wall Interference Investigations".[2,6] One goal of this project was to establish an experimental database open to the research community supporting flow physics studies and code validation purposes. Testing a full aircraft configuration model at low and high speed conditions, combined with complex measurement techniques like time resolved particle image velocimetry (TR-PIV), allowed a huge amount of data going into such database. Important to make relevant data available and usable for the public is to have a realistic but also open model geometry, which is quite rare, especially looking at cryo suitable wind tunnel models. The NASA Common Research Model (CRM) combines these requirements. In close cooperation with NASA, this model of a generic, but close-to-application aircraft configuration was provided for the ESWIRP test campaign in ETW. The CRM, already tested in several other wind tunnel facilities around the world, also serves the needs for the second project goal of wall interference investigations. An additional benefit is the possibility to compare experimental measurements and correction methods between facilities around the world.[9]

The present paper focuses on the dynamic data acquired during the ESWIRP campaign in ETW. They are used to identify the different eigenmotion modes of the model. Not being a core subject of the ESWIRP project, the dynamic data analysis allows an additional view on model behavior necessary for a safe performance of wind tunnel tests. Additionally the available dynamic data have the potential to support a better understanding of aerodynamic and aeroelastic phenomena.

2 FACILITY

The European Transonic Windtunnel (ETW) is a pressurized cryogenic high Reynolds number facility located in Cologne, Germany.[3, 4] It is a continuous flow wind tunnel with a test section of 2 m x 2.4 m (Figure 1), a Mach number range from 0.15 to 1.35 at stagnation temperatures between 110 K and 313 K. Using vaporised nitrogen as the test gas to achieve the cryogenic temperatures and the combination with an increased total pressure between 115 kPa and 450 kPa, Reynolds numbers up to 50 million for full-span models and up to 90 million for semi-span models are feasible (Figure 2).

With its unique capability to test aircrafts at cruise-flight as well as high-lift conditions at flight-relevant Reynolds numbers it is widely used by the aircraft community in terms of research and development. Especially the possibility to clearly separate between Mach number, Reynolds number and aeroelastic effects has a huge benefit for the clients and their analysis.

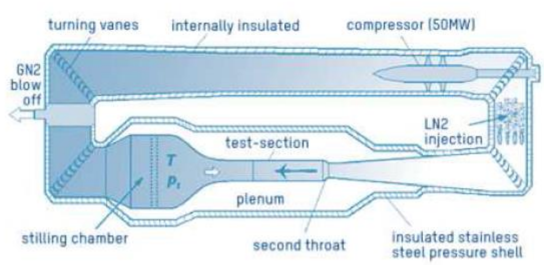


Figure 1: Full-span model in the ETW test section

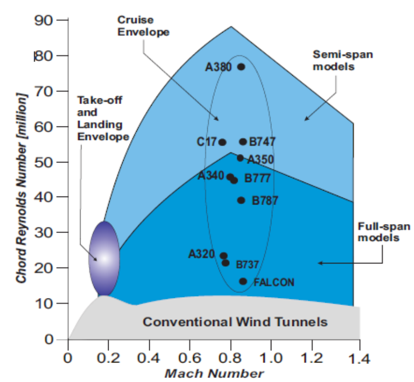


Figure 2: ETW test envelope

3 MODEL

The NASA Common Research Model (CRM)[1] is a generic open geometry model, which was designed and build to develop a contemporary experimental databases allowing the validation of CFD codes for various applications.[10] The NASA Common Research Model was originally designed to be tested in the NASA AMES 11-foot transonic wind tunnel and the NASA National Transonic Facility (NTF) at Langley to provide the experimental data base for the fourth AIAA drag prediction workshop. The CRM consists of a supercritical transonic wing and a fuselage that is representative of a wide-body commercial transport aircraft.

The design Mach number is Ma=0.85 with a corresponding design lift coefficient of $C_L = 0.5$. The aspect ratio is 9.0, the leading edge sweep angle is 35 deg, the wing reference area S is 3.01 ft^2 (0.280 m^2), the wing span is 62.46 inches (1.586 m), and the mean aerodynamic chord is 7.45 inches (0.189 m). The model moment reference center is located 35.8 inches (0.909 m) behind the fuselage nose and 2.04 inches (0.0518 m) below the fuselage centerline. Although the CRM was designed for the NASA wind tunnels the overall geometry is also compatible with ETW's sizing criteria.

In ETW the model was mounted using a comparable blade sting arrangement as it was used in NTF.[9] The model was mounted on ETW's balance B004. Figure 3 shows the model in the ETW test section.

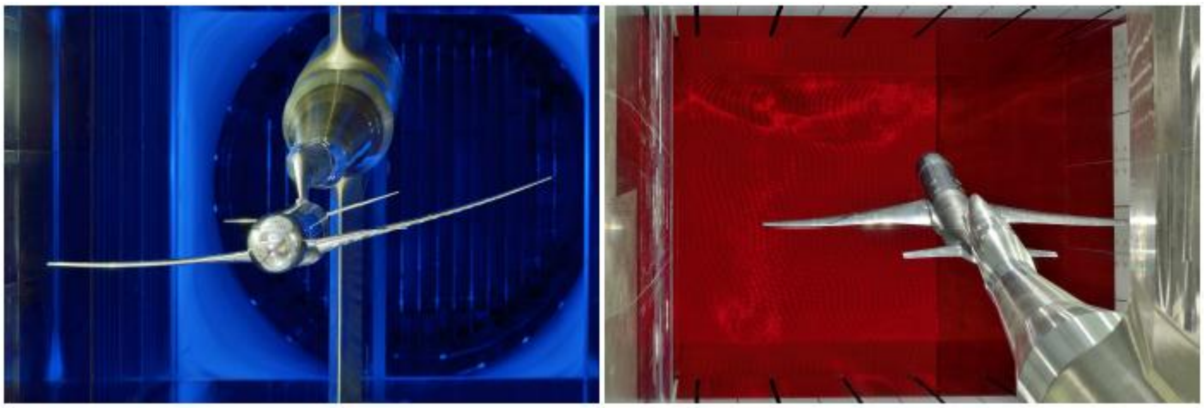


Figure 3: NASA Common Research Model in ETW test section

4 INSTRUMENTATION AND DATA ACQUISITION

4.1 Instrumentation

The test setup of the ETW-ESWIRP entry contained a lot a specialized instrumentation equipment and measurement systems, for example the installed time resolved particle image velocimetry (TR-PIV) system and the high speed stereo pattern tracking (HS-SPT) system. The following section concentrates on instrumentation components particularly useful for dynamic data evaluation. Some of them are part of the fundamental model instrumentation, while others have been developed and integrated especially for this kind of data analysis and became now part of the standard instrumentation.

1. *Model*

The main six component internal balance is commonly at the core of each wind tunnel test and fundamental for measuring dynamic and steady model loads. The balance provides the analog signals of the attached strain gauges and, sampling it at high frequency, allows the assessment of dynamic model loads combined with inertial forces. This information provides valuable input to clients' understanding of the model's aerodynamic performance and its dynamic aeroelastic behavior. For the ESWIRP test campaign the cryogenically compatible balance B004 was installed, providing six strain gauge bridges for measuring forces and moments in all directions.
Beside the balance, by default, the model was equipped with a triaxial accelerometer (a_x, a_y, a_z), used to assess acceleration and frequency spectra for all three model axes. It was installed in a heated package together with the model inclinometer close to the model balance flange. Due to this location near the balance and model center some movements, especially oscillations around the balance center, are hardly visible on the sensor output. To acquire the missing information additional small and cryogenic compatible single axis accelerometer packages were developed allowing their installation also in small model parts. For the ESWIRP test, one of them was installed in the model nose (a_{Nose}) and one in the model rear section (a_{Rear}). Both are measuring accelerations in z-direction and allow a detailed analysis of the fuselage movement in the vertical plane. A gyroscopic sensor measuring the pitch rate of the model completed the specific model instrumentation.

2. Sting

The sting housed ETW's Anti Vibration System (AVS).[8] This system is based on the principle of counteracting the model vibrations at the eigenfrequencies of the aeroelastic system. Actually, the AVS is composed of two independent hardware systems, controlled by one integrated control software. The first system is located between sting and balance using twelve piezoceramic elements as actuators. The setup of the piezos allows counteracting model motions in five degrees of freedom, but mainly acting against model axial, pitch and yaw vibrations. To overcome limitations of the piezo interface in counteracting the pitch and especially the heave mode, a second system was implemented. It is located inside the stub-sting close to the sting boss. Using powerful electric linear motors enables the system to efficiently damp the model's pitch and heave modes. Due to the fin sting assembly of the ESWIRP entry an installation of the piezo interface was not possible, so the AVS performance in the vertical plane was ensured by the stub-sting mounted motor interface. The AVS system was activated for all relevant test conditions, thus also for the polars discussed in the next section

3. Tunnel

Two Stereo Pattern Tracking (SPT)[7] systems were installed in the tunnel top wall to assess the wing and the HTP deformation. While the basic deformation data are acquired synchronized to the high level acquisition in pitch-pause mode at a frequency of 5 Hz, the SPT systems themselves are running at higher sampling rates, acquiring data also during continuous pitch polars. The system used to assess the wing deformation system was a standard SPT system sampling at 58 Hz, while the system aligned to the HTP was ETW's high speed SPT (HS-SPT) system. The later has been designed especially for aeroelastic investigation and has the capability to sample at 386 Hz at full image resolution or at higher rates with reduced resolution. Thus, to a different extent according to their sampling frequency both systems are usable for a dynamic data analysis. The purpose of the high speed system during the ESWIRP test campaign was to investigate the influence of the separating wing wakes on the HTP.

4.2 Data Acquisition

All of the model internal sensor signals were continuously recorded by ETW's high level acquisition system[8] at varying sampling rates, by default at 5 Hz for productive polars and 1 Hz in survey mode. In addition the data are acquired by ETW's high speed data acquisition system (HSDAS). This system provides 128 analog input channels with 24bit resolution and a fully programmable signal conditioning front end with a full range of signal input options including direct voltage or strain gauges support with AC or DC coupling. The system is capable of measuring at a sampling rate of up to 50 kHz, irrespective of the number of channels recorded or even higher by reducing the number of channels. It can also be connected to the amplified signals of the high level conditioning units, what was done for the ESWIRP test. To limit the amount of data the sampling frequency was set to 2 kHz, allowing a good resolution in the frequency range of interest.

5 RESULTS

To present sample results of the dynamic data analysis four different test conditions have been selected to illustrate the basic influences of the different test conditions on model dynamics and to point out the general relations between the different measurement signals. Table 1 shows the different test conditions under consideration, all performed at same Mach number, but at different Reynolds numbers and dynamic pressures, two conditions at low and two at high dynamic pressure:

Polar Nr	131	213	226	233
Mach number	0.85	0.85	0.85	0.85
Reynolds number	5 Mio.	19.8 Mio.	19.8 Mio.	30 Mio.
T_{total}	302.4 K	153.8 K	116.8 K	116.6 K
P_{total}	192.4 kPa	300.2 kPa	200.0 kPa	302.6 kPa
P_{dyn}	60.6 kPa	94.6 kPa	63.1 kPa	95.4 kPa

Table 1: Compared test conditions

A good starting point of the analysis are the raw outputs of the balance strain gauges, giving a first impression of the general differences between the test conditions and the amount of overall dynamics. Looking at the different test conditions (Figure 4) it is clearly visible that the dynamic pressure is the differentiating factor between the polars, causing a large change of aerodynamic loads on the model. The high P_{dyn} polars end around 1 deg earlier than the low P_{dyn} ones, due the well known increase in model dynamics, especially visible in the signals BalM3 and BalM5. The general dynamic level at lower model incidences is similar for the polar 213, 226 and 233, while it is smaller for polar 131. This dynamic level is encouraged by the aerodynamic model loads, acting comparable to a wide band excitation to the model. Reaching a certain excitation level the eigenfrequencies of the model are excited. Because they are considered as model dependent and neither relevant nor comparable to the real flight conditions, the goal for wind tunnel tests is to suppress them as far as possible. Therefore ETW's anti vibration system (AVS) was developed and applied here. When the model reaches e.g. the buffet region at higher incidences the aerodynamic excitation of the model is getting stronger than the AVS damping capabilities, resulting in the observed model dynamics.

Beside the dynamics the signals already show the change of model loads with incidence, as expected, this was mainly visible in the changing absolute value of BalM1, BalM3 and BalM5. The other signals, representing side force, yawing moment and rolling moment, do not change their absolute level, because the symmetric flow conditions are not affected by changes in model incidence. The observed static changes are also acquired by the high level data acquisition system sampling at 5 Hertz and applying a 1 Hertz low pass filter to the signals, and demonstrate ETW's excellent repeatability.

Force or Moment	Raw signal
Axial Force F_x	BalM1
Side Force F_y	BalM2-BalM6
Normal Force F_z	BalM3-BalM5
Rolling Moment M_x	BalM4
Pitching Moment M_y	BalM3+BalM5
Yawing Moment M_z	BalM2+BalM6

Table 2: Main dependencies between balance raw signals and balance loads

Because the final measured forces and moments are characterized by combination of raw signals, Table 2 presents an overview of all main dependencies between raw signals and loads. The final balance forces and moments are calculated using a temperature dependent second order calibration matrix covering all interactions.

5.1 Model Motion Modes

1. Vertical Plane

For the dynamic analysis of the aeroelastic system, the angle of attack range associated to maximum vibrations is considered as the most interesting one. According to Figure 5 this region is around α = 6.4deg for the high P_{dyn} polars and around α = 7.5deg for the low P_{dyn} cases. Looking at polar 213 and 233 with α = 6.4deg, signal BalM3 has a higher amplitude than BalM5 although measuring the same force direction and having nearly same sensitivity. This is due to the fact that the distance between the load application point at the balance flange and the two bridges is different. Considering the balance as a beam, BalM3 is closer to the end of the beam measuring a higher bending than BalM5. Thus, BalM3 has a stronger reaction on the normal force, while BalM5 has a stronger dependency on pitching moment. This difference is the first indication of the dominant motion mode in the vertical plane, the heave mode or the pitch mode. The heave mode is caused by the bending of the complete sting resulting in an up and down movement of the complete front-sting/model assembly. The pitch mode is a rotation around the balance center causing the model nose and rear section moving up and down in opposite directions. Following this argumentation points out that the heave mode should be dominant in this case, because of the stronger reaction of BalM3. The results of a Fast Fourier Transformation (FFT) (Figure 5) at the interesting α regions of the maximum dynamics, confirms the observation that BalM3 has higher dynamics amplitude than BalM5.

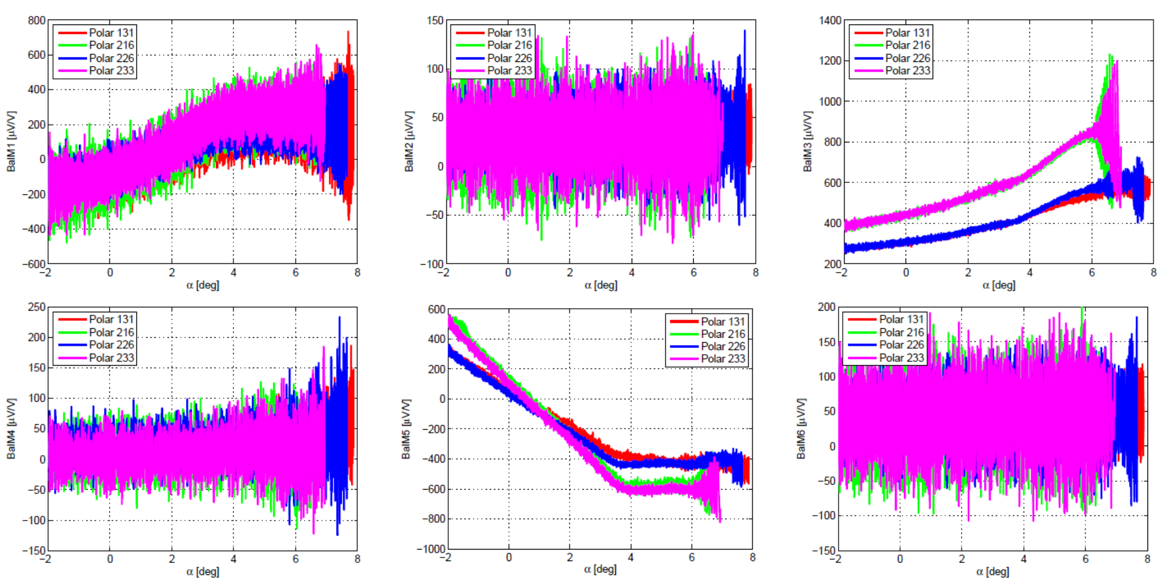


Figure 4: Raw balance signals versus model alpha

The dominant frequency is visible around 9-10 Hz. The amplitude at this frequency is highest for the high P_{dyn} polars 213 and 233, a little bit less but still quite high for polar 226, while polar 131 only shows a small amplitude at this frequency. Although the frequency resolution of the FFT analysis is only around 1 Hz (2048 samples at 2 kHz sampling rate) the results denote a slight shift in frequency between the low P_{dyn} and the high P_{dyn} polars, which is not explainable so far. Further analyses have to be made on this subject.

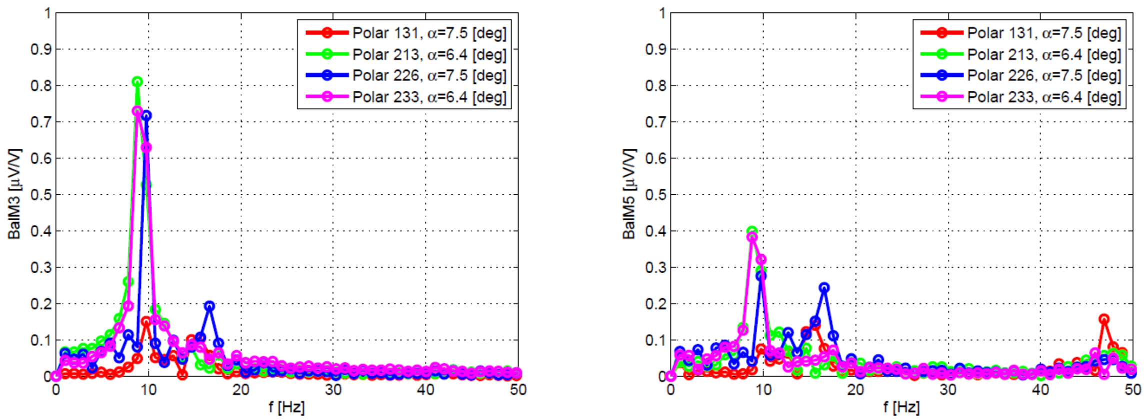


Figure 5: FFT results of raw balance signals BalM3 and BalM5 at the α regions of high dynamics

To finally confirm the heave to be the dominant motion mode, it is helpful to use the available accelerometer data in z-direction. Figure 6 and Figure 7 display the FFT results for the three z-accelerometers of the polars 233 and 226. According to the "sting bending" heave motion and confirming it, the nose accelerometer has the highest amplitude decreasing over the main accelerometer down to a small amplitude of the rear accelerometer. Looking at the phase angles of the three accelerometers of polar 233 (Figure 8), they should be all in phase, but this is not the case. While a_{Nose} and a_z are nearly in phase, a_{Rear} has a significant phase shift.

The same behavior is visible for the low P_{dyn} polar 226 (Figure 9), but here the two forward accelerometers are even more in phase. One aspect is that the rear accelerometer is close to a nodal point of the heave motion. Therefore the acceleration is very low, resulting in an inaccurate phase angle determination. Another possible explanation is that the phase shift is caused by a counteracting aerodynamic force from the HTP. The heave motion leads to a changing α at the HTP, which reacts as a damping force against the motion. The same force would also counteract the pitch motion, the higher the P_{dyn} the higher would be the damping force of the HTP. Therefore for polar 233 the pitch motion is only rudimentary characterizable in the rear accelerometer by a small peak around 17 Hz. The phase angles at 17 Hz (Figure 10) don't allow a conclusion on the motion mode because the other two accelerometers are not affected at this frequency. This differs for the low P_{dyn} polar 226, there also a_{Nose} has an significant amplitude at this frequency. Looking at the phase angles of polar 226 (Figure 11) confirms the assumption that the 17 Hz represent the pitch motion. The two accelerometers have a phase shift close to 180 deg, representing a model movement around a point close to the balance center and the main accelerometer, which doesn't experience any acceleration.

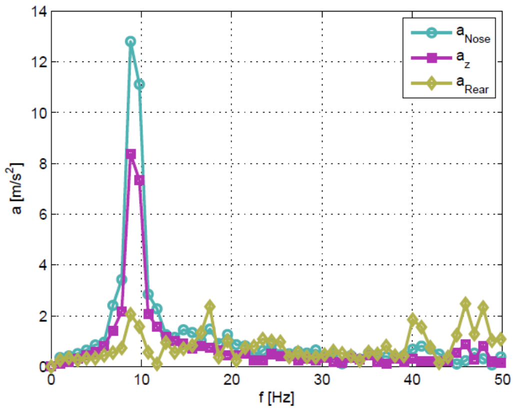


Figure 6: FFT amplitudes of polar 233Fig.

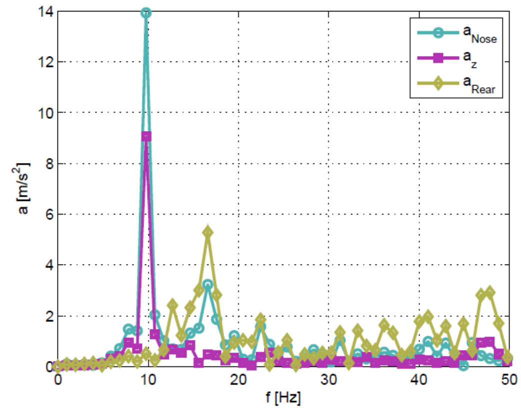


Figure 7: FFT amplitudes of polar 226

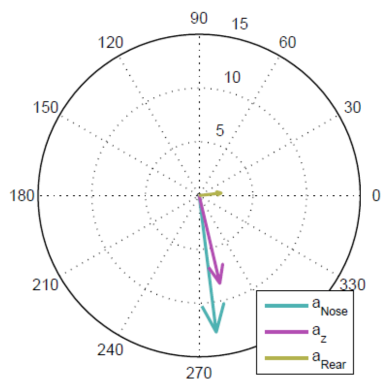


Figure 8: FFT phase angles at the heave frequency of 9.5 Hz of polar 233

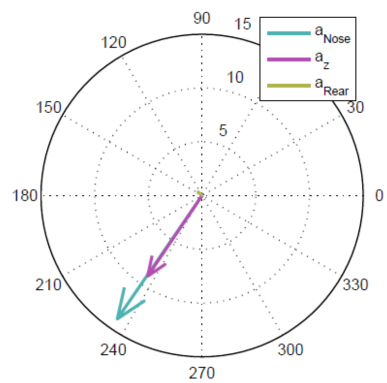


Figure 9: FFT phase angles at the heave frequency of 9.5 Hz of polar 226

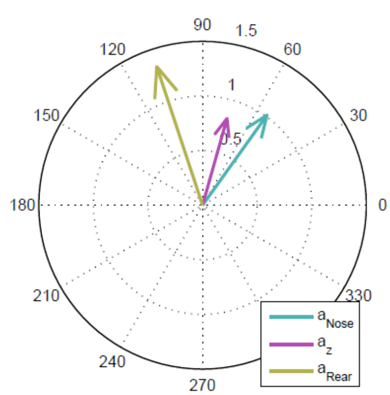


Figure 10: FFT phase angles at the pitch frequency of 17 Hz of polar 233

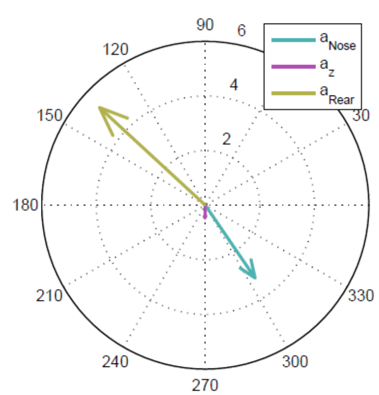


Figure 11: FFT phase angles at the pitch frequency of 17 Hz of polar 226

2. Horizontal Plane

Analogous to the normal force direction, two motion modes are existing in the horizontal plane, one again dominated by the sting bending and one characterizing the yawing motion of the model. Figure 12 displays the FFT results of raw balance signals BalM2 and BalM6, representing side force and yawing moment (Table 2), for the four different test conditions. Several significant peaks are visible; the highest amplitudes are now in low P_{dyn} condition of polar 226, possibly caused by the smaller stabilizing effect of the vertical tail plane.

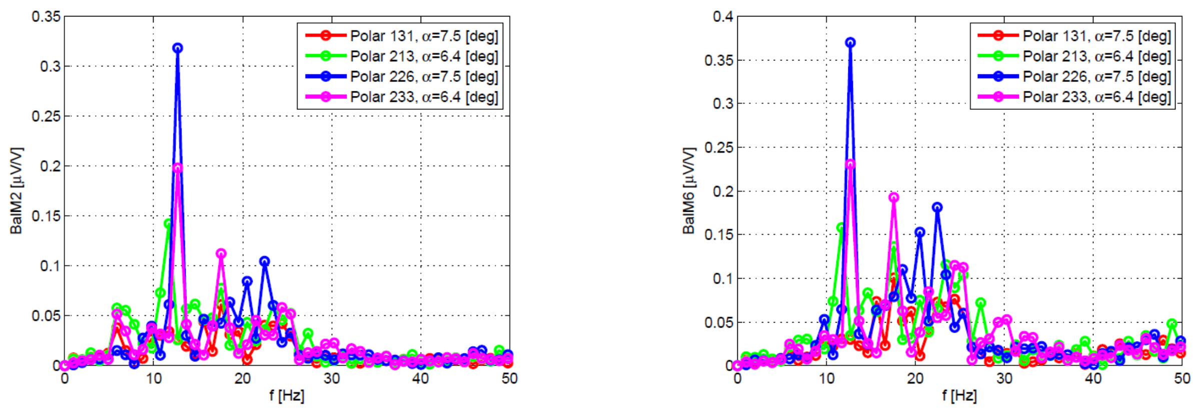


Figure 12: FFT results of raw balance signals BalM2 and BalM6 at the α regions of high dynamics

The FFT results show the dominant peak around 12.5 Hz, a smaller one at 17 Hz and higher amplitudes at various frequencies between 20 Hz and 25 Hz cumulating towards 25 Hz. A smaller peak at 6.5 Hz is visible in the signal BalM2 only. Thus, the analysis of the eigenmotion modes in side force direction seems to be more complex than for the vertical plane. Also analyzing the FFT result of the y-accelerometer a_y does not provide additional clarity. Although the y-acceleration level is quite low the peaks at 6.5 Hz, 9.5-10 Hz, 12.5 Hz and again around 25 Hz are clearly visible. The only missing peak is the one at 17 Hz, leading to the conclusion that the 17 Hz acceleration is close to a nodal point. Remembering that the 17 Hz were identified to be the frequency of the pitch motion, it is likely that BalM2 and BalM6 are measuring this motion due to the mechanical interactions of the balance. Thus, the final separation between the motion modes must be realized based on the SPT results.

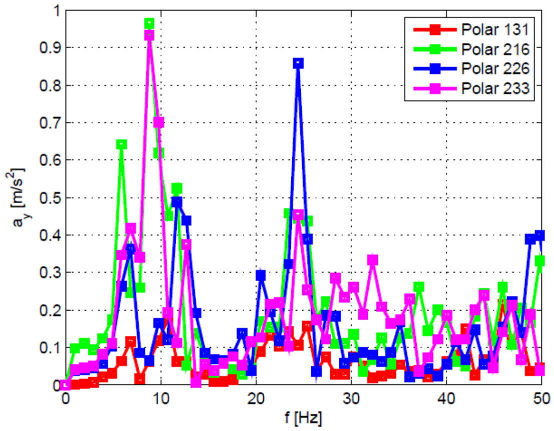
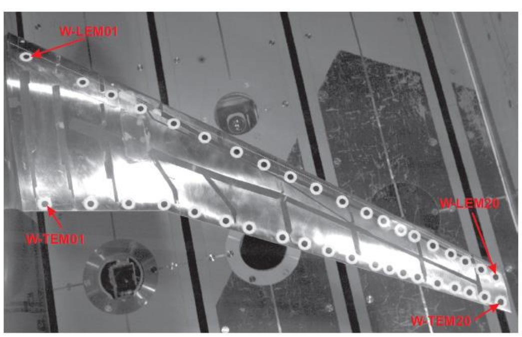


Figure 13: Accelerometer a_y **FFT results**

Each SPT system is measuring the three dimensional coordinates of 40 markers, distributed into 20 leading and 20 trailing edge markers. Thus, the two SPT system together provide 240 (80 markers in three dimensions) measurement signals, which can be used for a FFT analysis to support the dynamics analysis. To investigate the side force motion it is reasonable to select markers located close to the fuselage. Therefore the FFT analysis was done on the y-coordinates of the inner leading and inner trailing edge markers of the main wing (W-LEm01,W-Tem01) and also of the HTP (H-LEm01,H-Tem01) (Figure 14). The results are displayed in Figure 15 for the main wing and in Figure 16 for the HTP, again samples from polars 226 and 233. Due to the smaller sampling rate of the main wing SPT system of 58 Hz, the Nyquist criteria limits the FFT results to a frequency of 29 Hz, but this is still sufficient for the interesting frequencies up to 25 Hz.



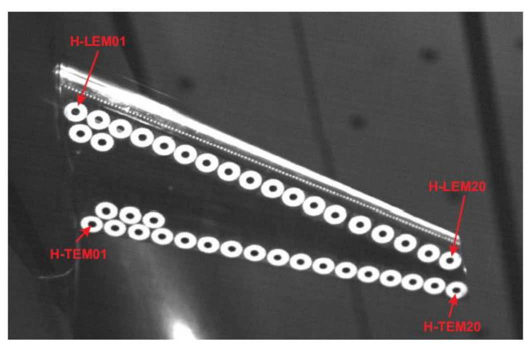


Figure 14: SPT marker distribution on main wing (left) and HTP (right)

The two inboard wing markers show a significant amplitude at 6.5 Hz, with the larger amplitude for the more forward leading edge marker (Figure 15). For the HTP markers (Figure 16) there is no peak noticeable at 6.5 Hz, leading to the conclusion that the frequency represents the lateral sting bending mode with a nodal point close to the HTP position. At 12.5 Hz a peak is visible for the two wing markers as well as for the HTP markers, with a much larger amplitude for the HTP markers. A detailed review indicates the nodal point of this motion mode close to the main wing leading edge marker.

It is nearly unaffected by this motion, while the amplitudes increases with the distance from this marker, resulting in the maximum displacement of the HTP trailing edge marker. In conclusion, this frequency represents the yawing motion mode. Unfortunately the two SPT system are not synchronized in a way which would allow a phase analysis between the markers, which would support the argumentation. The other peaks between 20-25 Hz which are seen in the balance signals cannot be validated by the SPT system and the assumption is that these are caused by the first harmonics of the yawing motion.

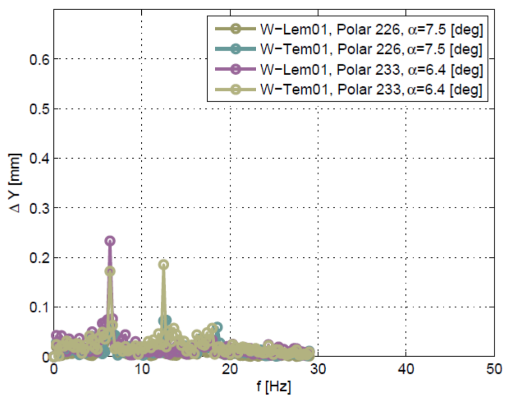


Figure 15: FFT results of selected SPT of the wing system

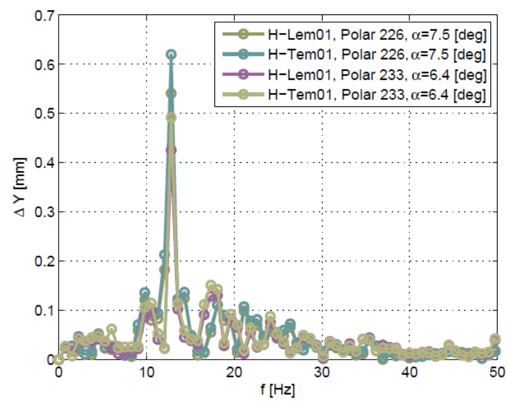


Figure 16: FFT results of selected markers markers of the HTP system

6 SUMMARY

In the framework of the ESWIRP project the European Transonic Windtunnel performed a full-model test campaign with the NASA Common Research Model. Funded by the European Commission the test campaign was prepared by an international consortium of research institutes and universities in order to perform "Time-resolved Wake measurements of Separated Wing Flow & Wall Interference Investigations".[2] Using the NASA Common Research Model opened the opportunity to test a generic but realistic aircraft configuration with an open-access geometry and an already available comprehensive database. With the tests performed in ETW this database has been widely extended in order to provide valuable data to an extended research community for flight physics studies or CFD code development. In addition the fact that the CRM was already tested in other wind tunnel facilities around the world, this extension opens the opportunity for comparison of results and correction methods.

The present paper focuses on the assessment of model eigenfrequencies based on dynamic measurements. Although this was not an explicit objective of the ETW-ESWIRP transnational access project, it provides additional valuable information about the model behavior. The analysis has been based on standard model instrumentation equipment as well as on dedicated equipment especially developed for dynamic investigations. In particular small cryogenically compatible accelerometers, which are applicable also in small model parts, and an additional gyroscopic pitch rate sensor allow a much better understanding of the fuselage motions in the vertical plane. In situations where this equipment was not sufficient for a final assessment of the model eigenfrequencies, the analysis was supported by the data from the two installed Stereo Pattern tracking (SPT) systems, which were installed to measure the model deformation on the wing and the HTP. Using the available data allowed a clear separation between the motion modes in the vertical and horizontal model planes.

The present paper only demonstrates dynamic data analysis opportunities, which are provided by the acquired database. The provided huge amount of data will allow much more comprehensive and detailed investigations. It is recommended to perform further analyses as soon as other investigations using the ETW-ESWIRP data raise questions, which might be linked to dynamic aeroelastic effects.

In future the European Transonic Windtunnel will further develop and enhance its capabilities for dynamic and aeroelastic testing, to provide the best possible data quality to the client also in the dynamic range. One envisaged next step will be the implementation of a central time synchronization system, to enable a timewise synchronization of all involved modular measurement systems. This will ensure that even high speed data can be interpreted in direct comparison to other data.

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