DYNAMIC STABILITY ANALYSIS OF A PROPELLER-WING WIND TUNNEL MODEL

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Keywords: Aeroelasticity, Flutter, Whirl Flutter, Multidisciplinary Simulation

Abstract

The research project "Bürgernahes Flugzeug" deals with the configuration of a future airplane with the properties of short take-off and landing and with reduced noise from the acoustic aspect. These properties should permit flight from a smaller airport closer to a city. In this project, under the cooperation of the main research partners: University of Braunschweig, German Aerospace Center (DLR) and University of Hannover, a wind tunnel model for the mainly aerodynamic and acoustic investigations was designed [1],[2],[3]. This Wind tunnel model, as it can be seen in Fig.1, consists of two main subsystems: Wing and Propeller-Nacelle. In 2012, this model will be utilized in low speed German-Dutch wind tunnel (DNW-NWB) in Braunschweig for different research activities and measurements.

Occurrence of any kind of dynamic instability during the wind tunnel test will cause lots of cost and loss of time. Even it is possible to have the situation that the model is stable and no dynamic instability occurs but the oscillation of the model is not desirable. An undesirable oscillation of the model would have cross effects on the aerodynamics and acoustics of the model and therefore would have effect on measurements.

To prevent all the well known dynamic problems during the wind tunnel test, performing dynamic stability analysis in both design stage and after the construction the model is an inevitable task. This paper gives a review of aeroelastic analysis of the designed wind tunnel model under the predefined wind tunnel test conditions.

Wing flutter is one of the dynamic instability phenomena that should be prevented from occurring. In general, movement/oscillation of a wing due to its elasticity induces aerodynamic forces/moments. Depending on the structure of the wing, these originated forces and moments could make the wing to oscillate with increasing amplitude (Flutter). For a propeller-wing system with rotating propeller, gyroscopic effect of the propeller could change the dynamic behavior of the whole system (comparing to a model with non rotating propeller). This effect should be also considered for the flutter analysis.
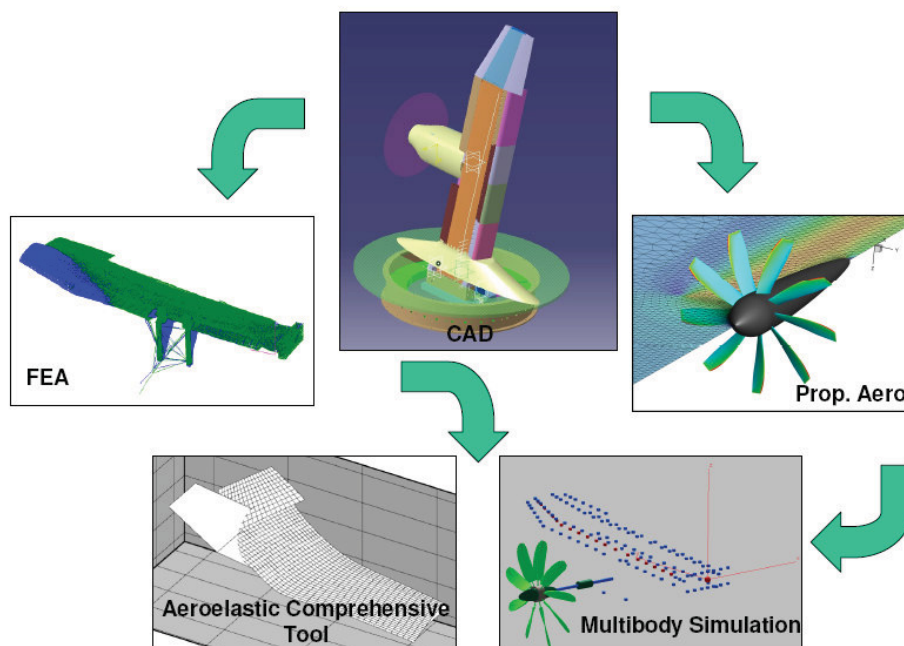
Fig.1 Multidisciplinary simulation to analyze the dynamic instability of the wind tunnel model

Another dynamic instability, which can happen for this model is "whirl flutter". Whirl flutter is a self induced dynamic instability, which originates from the propeller. In general, gyroscopic and aerodynamic coupling effects of the propeller create a so called whirl mode on the propeller. Again, depending on the structure of the model, wind and rotor rotation velocity an unstable whirl movement of the propeller head (hub) can occur. As shown schematically in Fig 1, during this work, the occurrence of two aforementioned dynamic instabilities of the wind tunnel model with the usage of different simulation tools was investigated. Analysis performed includes:

(a) - wing flutter analysis with the consideration of the propeller gyroscopic effect and its motion induced forces/moments

(b) - propeller-nacelle-wing whirl flutter analysis with the consideration of the wing elasticity and aerodynamics.

1. INTRODUCTION

The research project "Bürgernahes Flugzeug" deals with the configuration of a future airplane with the properties of short take-off and landing and with reduced noise. These properties should permit flight from a smaller airport closer to a city. In this project under the cooperation of University of Braunschweig, German Aerospace Center (DLR) and University of Hannover, a wind tunnel model for aerodynamic and acoustic investigations was designed [1],[2],[3]. To prevent any kind of dynamic instabilities during the wind tunnel test, the dynamic behavior of the wind tunnel model under the test condition should be analyzed. Performing of this analysis in design stage allows necessary optimization of the design to prevent the predicted instability.

1.1. Dynamic Stability

An elastic wing under steady aerodynamic loads, depending on the magnitude of the load, obtains an equilibrium position in case of statically stable system or divergent position in case of statically unstable state. Dynamic stability is related to the dynamic behaviour of a system after a small deviation from its equilibrium state. According to the system parameters (structure characteristics) and the external conditions (for example aerodynamic loads/moments), the system after deviation can return back to its equilibrium state (stable system), oscillate with constant amplitude (neutrally stable or indifferent system) or oscillate with increasing amplitude (unstable system). In this paper the results of the analysis of two main dynamic instability phenomena of a propeller-nacelle-wing-system, flutter of the wing and whirl-flutter of the propeller-nacelle-wing, are presented.

1.2. Flutter

Flutter is a self-excited dynamic instability. For a wing in vacuum, any disturbance from its equilibrium position causes a vibration of the structure in its normal modes, which is damped due to the existence of the structural damping. For a moving wing in air (in free flight or wind tunnel), any disturbance from equilibrium state induces aerodynamic loads, which can reduce the damping of the system to zero (structural damping + aerodynamic damping = 0) or to a negative value. Flutter happens, when the whole damping of the system becomes negative. Flutter analysis considers the interaction of inertial and elastic forces, which are related to the structure, and aerodynamic forces induced by the elastic deformation and oscillation of the structure. In general the equation of the motion of a system can be written in form of equation 1.

$$(1) \quad [M] \cdot [\ddot{X}(t)] + [C] \cdot [\dot{X}(t)] + [K] \cdot [X(t)] = [F(t)]$$

Hier M,C and K are mass, damping and stiffness of the system and F is the aerodynamic load. This load can be decomposed to a time dependent element, which is also called external load, and a deformation dependent part:

$$(2) \quad [F(t)] = [F_a(X)] + [F_{external}(t)]$$

As Flutter is related to the dynamic behaviour of a system after a small deviation from its equilibrium state, one can solve for the flutter analysis the equation 3 instead of solving the equation 1.

$$(3) \quad [M] \cdot [\ddot{X}(t)] + [C] \cdot [\dot{X}(t)] + [K] \cdot [X(t)] - [F_a(X)] = [0]$$

The solution of this equation shows then the displacement from the equilibrium state. All the existing methods of the flutter analysis deal with the methods of the solution of this equation and calculation of the unsteady aerodynamic forces and explain different ways to solve it in time or frequency domains.

It should be mentioned that, there are different type of flutter instability caused by different physical effects like flow separation or strong shock waves. In this work, the classical flutter phenomenon is analyzed. This classical flutter analysis considers just the motion induced aerodynamic forces and moments.

1.3. Whirl Flutter

Whirl flutter is an aeromechanical instability occurring in a flexibly mounted propeller-nacelle. Considering a rotating propeller with an axial air stream, when the axis of the propeller is pitched or yawed, induced aerodynamic moments and forces are generated. These forces and moment can cause instability, depending on the properties of the structure (stiffness and structural damping) [4],[5],[6].

Figure 2 shows a simplified whirl flutter model, which considers just the propeller-nacelle system. In this model rotor is supported horizontally by a rigid shaft that is pivoted at one end to a point of the rigid wing. This shaft models the mass property of the nacelle and motor. The whole system can pitch or yaw at the pivot point. Two rotational springs at the pivot point model the stiffness at the propeller to wing mounting point.
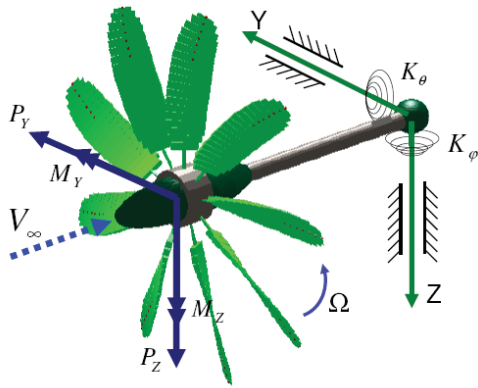
FIG. 2   Simplified whirl flutter model

The differential equations of the motion of this system can be given by equations 4 and 5. In these equations on the left side, the first element is a moment due to the inertia, the second term introduces the structural damping, the third term is a moment due to the elastic property of the system and finally the last element shows the gyroscopic effect, which in fact couples the two degrees of freedom of the system. It can be seen from these equations that this coupling happens when the propeller rotational velocity is non-zero.

$$(4) \quad I_X \ddot{\varphi} + C_\varphi \dot{\varphi} + K_\varphi \varphi + I_X \Omega \dot{\theta} = \sum M_\varphi = M_Z + h \cdot P_Y$$

$$(5) \quad I_X \ddot{\theta} + C_\theta \dot{\theta} + K_\theta \theta - I_X \Omega \dot{\varphi} = \sum M_\theta = M_Y - h \cdot P_Z$$

On the right side of the equations the motion induced aerodynamic moments and forces are considered. Solving these two coupled differential equations in time domain would result in the dynamic behaviour of the system shown in Fig.2.
Figure 3 shows another modelling approach of whirl flutter effect. In this model the elasticity of the wing is also considered.
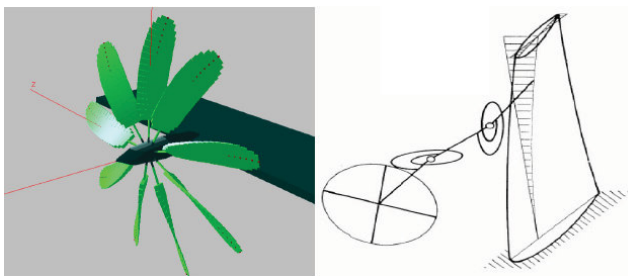

FIG. 3   Whirl flutter model with elastic wing

Considering the elasticity of the wing will not necessarily lead to a better result. Selection of a modelling method depends on the dynamic characteristic of the whole system. If the whirl modal frequencies are far from the wing main eigenfrequencies (lower frequencies), then the model showed in Fig. 2 should be good enough for the analysis of the whirl flutter.

1.4.   Simulation Tools

In this work different simulation tools were used to analyze the dynamic behaviour of the wind tunnel model.

Some of these tools are used directly and some others created just the data needed by the other tools. In the following part, there is a brief description of the applied simulation tools and their usage for the stability analysis

1.4.1.   Multi-body Simulation Tool: SIMPACK

SIMPACK (**SI**mulation of **M**ultibody systems **PACK**age) software package is used to simulate, analyse and design all types of mechanical systems. It can analyse the vibrational behaviour of multi-body systems and allows predicting and describing the motion of a complex machine or mechanisms. The software was developed at the German Aerospace Centre (DLR) and now is further developed and commercially distributed by SIMPACK AG [7].The software has a comprehensive range of modelling and calculation features. Therefore it is applied within industry, university and research institutions. This tool was selected for the whirl flutter analysis of the wind tunnel model. One of the main reasons of this selection is the existence of experience with this tool inside DLR Institute of Aeroelasticity [8], [9], [10].

1.4.2.   ZAERO

ZAERO is a software system that integrates the essential disciplines required for aeroelastic design and analysis. Modules of ZAERO allows modelling a full aircraft with stores and nacelles, importing the modal data from FEM codes, accurate FEM/Aero displacements and forces transfer and nonlinear flutter analysis. One of the major strength of the ZAERO software is its ability to generate unified aerodynamic influence coefficient matrices for a complete aircraft configuration at any Mach number. ZAERO has several flutter methods [11]:
   - the K-method
   - the P-K-method
   - the g-method

1.4.3.   PROPPY

PROPPY is a propeller design and analysis program developed by M. Hepperle based on Larrabee [12], [13]. This program applies both blade element and momentum theory for an optimized propeller design. All the aerodynamic data of the propeller, which were needed to model the propeller aerodynamics inside SIMPACK, were produced with this tool.

1.4.4.   ANSYS

FEM code ANSYS was used to simulate the structure of the wind tunnel model and to perform modal analysis. ANSYS was used first to create the modal and structural data needed by ZAERO and second to create a dynamic reduced model and finally based on this reduced model the structural and modal data needed by SIMPACK.

2.   WIND TUNNEL MODEL AND AEROELASTIC MODELLING APPROACH

With the aim of different research activities like aerodynamics, acoustics and so on, a wind tunnel model was designed within the project "Buergernahes Flugzeug". Dynamic stability analysis of this model in design stage

was performed by the author. In this part a brief description of the wind tunnel model and its aeroelastic modelling approaches are given.

2.1. Wind Tunnel Model

Figure 4 shows schematically the designed wind tunnel model.
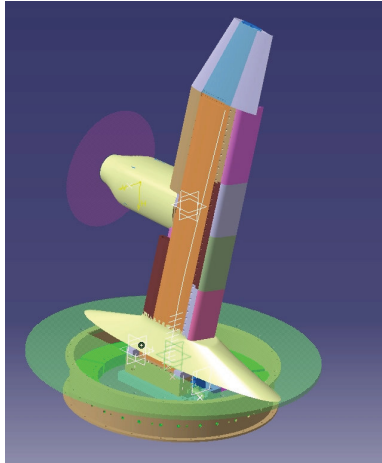

FIG. 4   CAD model of the wing-nacelle-propeller

This model will be utilized in 2012 in low speed German-Dutch wind tunnel (DNW-NWB) in Braunschweig. This model consists of five main parts: wing root, main wing, outboard wing, coanda flap and propeller-engine-nacelle. The main wing has a layout of a parallelogram and the outboard wing is a trapezoid. The whole length of the wind tunnel model is 2.1m. Propeller is powered by a 120 KW electric engine and has a diameter of 0.6 m. Sweep angle of the main wing is 10 deg. The center of gravity of the propeller-nacelle system is located in front of the elastic axis of the wing and below the wing lower surface. The main wing weighs nearly 56 Kg, the outboard wing 11.6 Kg and the whole motor-propeller nearly 130 Kg. This leads to a whole mass of 197.6 Kg. Relative to the wing, the massive propeller-nacelle shows its effect at the first stage on the mode shapes of the whole system.

2.2. Modelling of the Wing, FEM

FEM simulation of the wind tunnel model was created with ANSYS. For the modelling of the structure, different element types were used. Main wing and outboard wing were modelled using solid elements. Motor shaft and flange were modelled using beam elements. Propeller and nacelle were modelled as concentrated mass with the consideration of their mass moments of inertia. Because the mass distribution has a main effect on the mode shapes, all masses were considered inside the FEM model. Parts of motor and propeller were divided in two main groups: rotating parts and non-rotating parts. For the rotating parts, the polar mass moments of inertia were defined inside SIMPACK and not inside the FEM model. In general, for all concentrated masses inside the FEM model, the mass moments of inertia were considered too. Figure 5 shows schematically both CAD and FEM models.
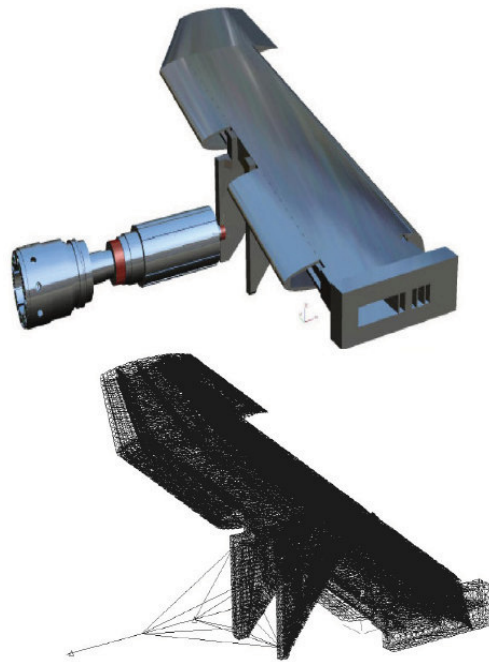

FIG. 5   From CAD model to FEM model

This FEM model was used to perform the normal modal analysis inside ANSYS. Because the modal output produced in this stage will be directly used for the whirl flutter analysis, the eignefrequencies and mode shapes of this FEM model should correspond well with the wind tunnel model. In 2012, after the performance of the ground vibration test, a new dynamic analysis based on the experimental results will be performed.

For an aeroelastic comparison analysis, two cases regarding the material were defined. For the first case, aluminium was selected as the material of the wing box of the main wing and for the second case steel was selected as the material.

2.2.1. Wing Structure, Modal Data

The first part of the dynamic investigation of the wind tunnel model starts with the analysis of the modal data: eigenfrequencies and mode shapes. Figure 6 shows as an example, the third mode shape of the model with wing box made of aluminium.
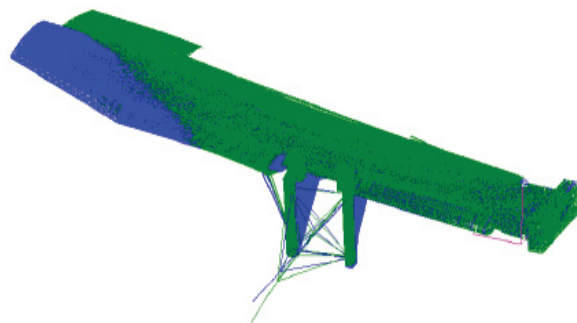

FIG. 6   ANSYS model, third mode shape

Here none of the model frequencies coincided with the

rotor frequency. The Following table shows the first 20 rounded frequencies of the model with the wing box made of aluminium and steel.

Mode	Aluminium Frequency [Hz]	Steel Frequency [Hz]
1	10	14
2	19	30
3	35	49
4	57	80
5	87	116
6	145	171
7	147	200
8	192	227
9	198	246
10	296	320
11	317	352
12	351	387
13	376	418
14	414	465
15	439	486
16	464	498
17	480	515
18	491	548
19	518	570
20	556	578

As it can be seen on this table, as it was expected, an increasing of the eigenfrequencies of the modes with material change from aluminium to steel is evident.

2.3. Multibody Simulation of the Wind Tunnel Model

To perform the whirl flutter analysis of the wind tunnel model, the whole system was modelled inside multibody simulation tool SIMPACK. In general the SIMPACK model consists of two main parts:
- Elastic wing and elastic nacelle
- Propeller

Each of these parts has two modelling steps:
- Modelling the structure
- Modelling the aerodynamics

In the next part, there is a brief description of the simulation procedures.

2.3.1. Wing Structure inside SIMPACK

For modelling the wing structure inside SIMPACK, the interface of this tool with finite element code ANSYS is used. This interface, FEMBS, generates data needed inside SIMPACK for modelling a flexible body. In finite element, the motion of an elastic body is described by a large number of nodal coordinates but in SIMPACK this motion and elastic body deformation is described by modal representation (Ritz approach). In this modal approach, the displacement of an elastic body is computed as a linear combination of modes and time dependent modal coordinates. One of the conditions to work with FEMBS is to have a reduced model. Normally, FE model has a large number of degrees of freedom. This has to be reduced using a model condensation method.

After reduction of the ANSYS model, using the component mode synthesis method, a super-element matrix was created (*.sub file). Later, a modal analysis was performed to create a result file (*.rst file). With these two files as input for FEMBS, SIMPACK creates first a SID file (Standard Input Data). This file can be read later by a body to be defined as an elastic body.

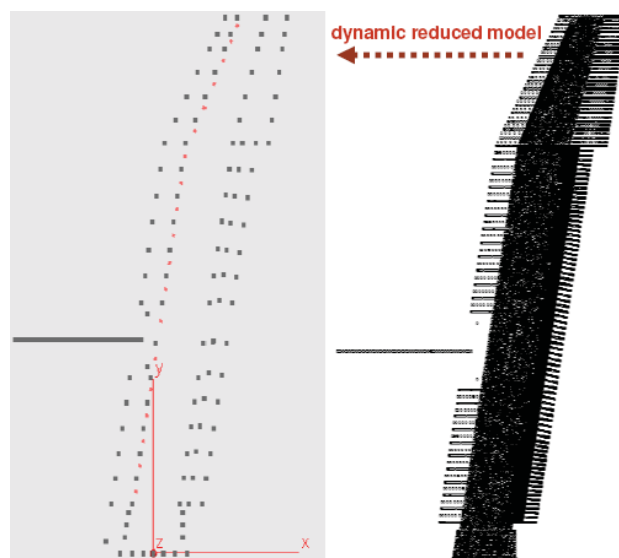Figure 7 shows the nodes of the original FEM model and the dynamic reduced model.

FIG. 7   Nodes of the left: Dynamic reduced model, right: original FEM model

Improper dynamic reduction of a model will change the structural dynamic properties of the model and leads to wrong eigenfrequencies. Therefore, this reduction should be done in a way that the changes in the structural dynamic properties are minimum or acceptable. A way to control the quality of the reduced model is to compare the eigenfrequencies and their related mode shapes after and before reduction.

Figure 8 shows schematically the second mode of the ANSYS model (before reduction) and the second mode of the SIMPACK model (created with the reduced ANSYS model). A comparison shows that their mode shapes are similar and their frequency difference is negligible. Here as an example the frequencies of the first and second modes before and after reduction are compared:
- first mode, original model: 9.6 Hz
- first mode, reduced model: 9.1 Hz
- second mode, original model: 18.9 Hz
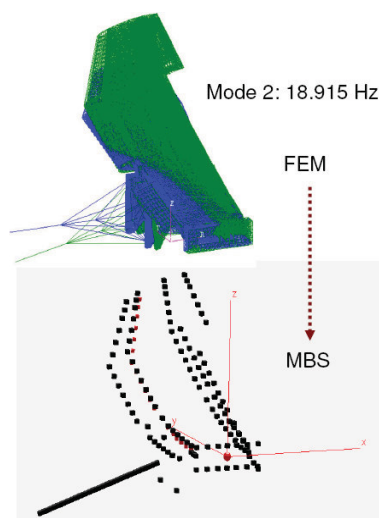- second mode, reduced model: 18.6 Hz

FIG. 8   Dynamic equivalency of the FEM model and MBS model

2.3.2. Wing Aerodynamics, SIMPACK Model

To consider the effect of the wing aerodynamics on the dynamic behaviour of the whole system, this was modelled inside SIMPACK. As shown in Fig. 9, the wing was divided into 19 sections along the span and at the middle of each section an aerodynamic point to apply the forces was created. These points are located at the 25% chord length (aerodynamic centre).
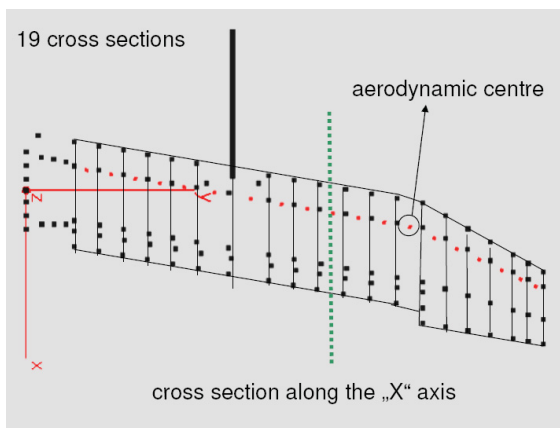

FIG. 9   Wing aerodynamic sections

As shown in Fig. 10, at each aerodynamic point, one local coordinate system was defined.
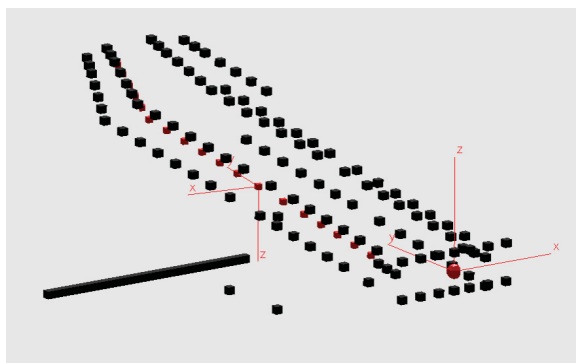
FIG. 10   Aerodynamic marker for calculation of air loads

At each local coordinate system, a sensor measures the wind velocities at the aerodynamic point. These velocities have also the unsteady velocity components, induced due to the elastic motion of the wing relative to the air stream. For the calculation of the lift, two different methods were used. The first method is based on the quasi steady aerodynamics and strip theory and second method considers the unsteady aerodynamics based on the Wagner approximation [14]. For both methods, the lift coefficient used in calculation was 2π.
To compare both methods and their effects on the kinematics of the system, the damping of the eignemodes of the wing using both aerodynamic models were compared together. These results can be seen in Fig. 11. Analysis of this result shows that, the aerodynamic modal damping based on the quasi steady aerodynamic model is lower than the other model. Applying of the quasi steady aerodynamic model due to the lower damping would lead to a conservative flutter result. Therefore, for the whirl flutter analysis this model was used.
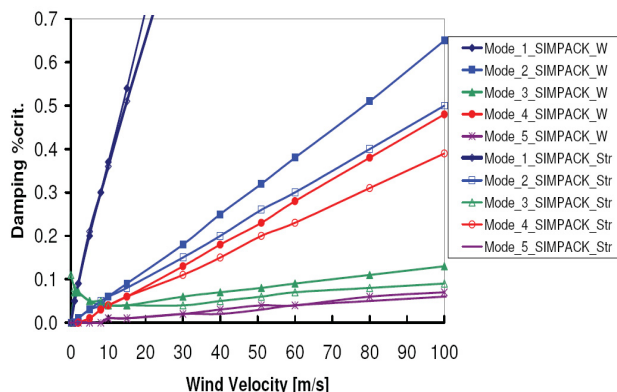

FIG. 11   Comparison of the modal damping with both aerodynamic models (W: Wagner approx.)

2.3.3. Modelling of the Propeller

Propeller of the designed wind tunnel model hast 9 blades and its diameter is 600 [mm]. The Blade of this propeller was created inside SIMPACK. Due to the higher frequencies of the blade (results from FEM model), the elasticity of the blade for the whirl flutter analysis was neglected. As it can be seen in Fig. 12 the blade was divided into 21 aerodynamic sections. These sections are all mass less, because the mass of the blades was modelled inside FEM-model. The blade model is just for modelling the blade aerodynamics.
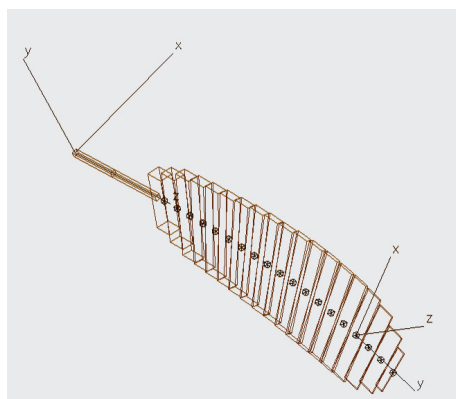

FIG. 12   MBS-model: Propeller blade sections

The profiled part of the blade starts from the third element. (see Fig.12). The aerodynamic points, seen graphically on Fig.12 in the middle of each section, are located in fact on the line defining the 25% chord length of the blade. At each aerodynamic point, one local coordinate system was created. The angles between the local coordinates model the aerodynamic twist of the blade.
A FORTRAN program, implemented inside SIMPACK and used as user defined force element, calculates the local angle of attack and then the aerodynamic forces and moments.
The aerodynamic coefficients related to the airfoil of each section were defined by the propeller design code PROPPY. As shown schematically in Fig. 13, for each aerodynamic section of the propeller blade the aerodynamic coefficients were calculated and entered as input in to the SIMPACK model.
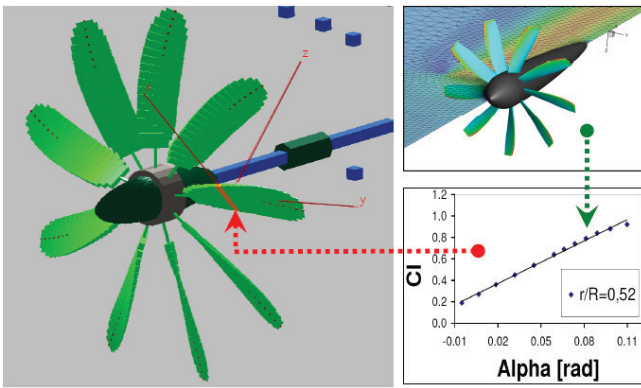
FIG. 13 Modelling of the MBS propeller-aerodynamics using the propeller design code PROPPY

Here, just briefly and as an example, the method of the calculation of the lift coefficients is described. Figure 14 shows the lift coefficient distribution along the blade radius. This lift coefficient distribution was given for different blade pitch angle. As a definition, the pitch angle is the angle between the chord of the airfoil at the location of 75% radius and the propeller plane of rotation.
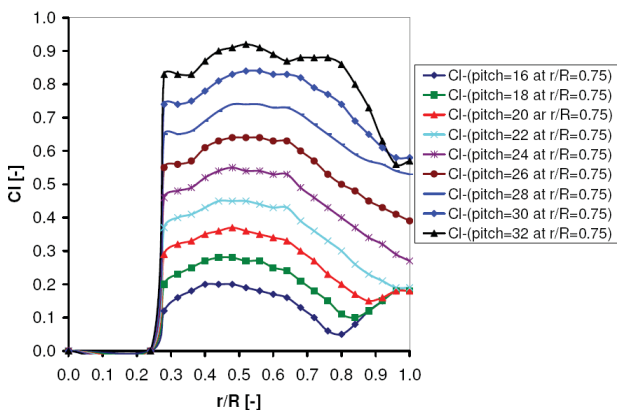

FIG. 14 Radial distribution of the lift coefficient for different pitch angle

With the changes of the pitch angle and calculation of the aerodynamic coefficient distribution for different pitch angle, the result shown in Fig. 14, were produced. Considering the calculated lift coefficients at one fixed radial position and different pitch angles, one can plot diagram like the one shown as an example in Fig.15.
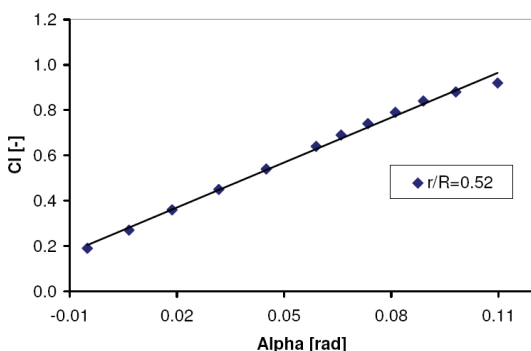
FIG. 15 Lift coefficient versus angle of attack at blade section r/R=0.52

From this plot, the slope of the line can be calculated. This value will be then used inside SIMPACK for calculating the aerodynamic forces with changes in the angle of attack. For calculation of the lift distribution along the blade, along with the knowledge of the airfoil distribution and airfoil aerodynamic coefficients, we need to calculate the angle of attack at each aerodynamic point. As mentioned before, a FORTRAN program implemented for the calculation of the aerodynamic loads and moments calculates the angle of attack based on the motion of the aerodynamic points. This motion includes the air velocity, rotor rotational velocity and motion due to the elastic deformation of the wing and nacelle. The angle of attack calculated with these motions does not consider the induced velocity field on the propeller rotation plane. This induced velocity field could be for example, an effect of the existence of the blade vortices. The idea is to correct the angle of attack calculated with SIMPACK with the values calculated and given by PROPPY. With this correction, in fact the effect of induced velocity filed would be considered inside SIMPACK. Figure 16 shows the distribution of the angle of attack along the radius and for different pitch angles. These results were produced with PROPPY.
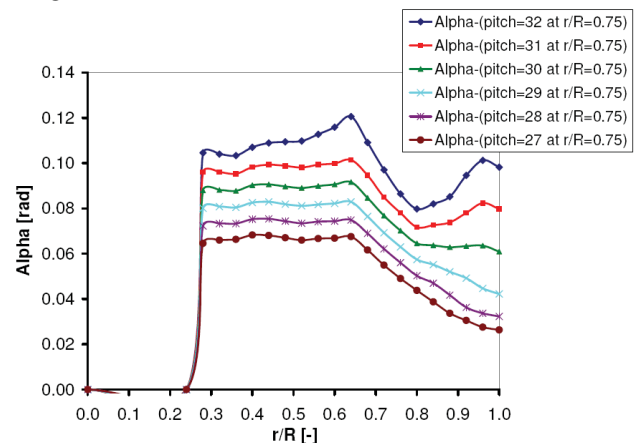

FIG. 16 Radial distribution of the effective angle of attack for different pitch angle

Using these data, the distribution of the angles of attack calculated with SIMPACK was corrected. This correction allows a better modelling of the lift and drag distribution. A better modelling of the lift and drag distributions leads to a better estimation of the static equilibrium state. But for the dynamic analysis of the system the dynamic behaviour of the system after disturbance from the calculated equilibrium state is studied. This means that, for dynamic analysis of the model an exact modelling of the distribution of the derivatives of the aerodynamic coefficients (slope of the line in Fig. 16) is necessary.

2.4. ZAERO-Model for Flutter Analysis

For the Flutter analysis of the wing the aeroelastic analysis code "ZAERO" was used. In general the modelling procedure with ZAERO for the flutter analysis has the following main steps:
- Creating the structural modal data using directly an FEM code compatible with ZAERO or preparing the structural modal data with help of the results of the modal analysis in a free format defined and could be read by ZAERO
- Creating the aerodynamic panel surfaces

- Connection of the aerodynamic model to the structure model using a SPLINE method of ZAERO
- Selection of an appropriate method of flutter analysis ,performing the analysis and post processing the results

As mentioned before, an ANSYS model of the wind tunnel model was created at the first step of the simulation. With the results of the ANSYS modal analysis a new file with the format (free format structural data), which can be read by ZAERO was created. Aerodynamic surfaces of the wing were modelled with three panel surfaces for the main wing, flap and outboard wing. Aerodynamic surface of the nacelle was neglected. Nodes of the structure for the connection to the panel surfaces were defined. Fig. 17 shows schematically the FEM model, aerodynamic panel surface of the wing and the connection points on the FEM model.
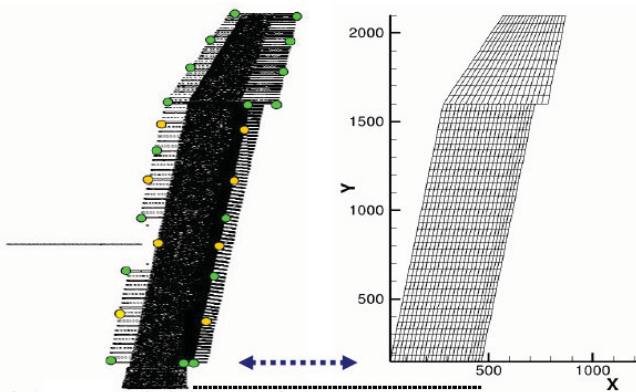
FIG. 17   Connection of the aerodynamic surface to the structure nodes using SPLINE

Increasing the number of connection points will lead to local deformation of the aerodynamic surface after interpolation of the mode shapes of the structure on the aerodynamic surface and reduction of the connection points will lead to an inaccurate/wrong mode shapes of the aerodynamic surfaces. For this model, the number of connection points, defined in SPLINE option of ZAERO, was changed until the interpolated mode shapes on the aerodynamic surfaces were acceptable. Figures 18, 19 and 20 show the first three modes of the structure and their interpolation on the aerodynamic surfaces. For a better comparison, each mode shape was plotted with the non deformed wing.

Modelling the rotating propeller inside ZAERO is not possible but one can model the propeller effects using the direct matrix input of the ZAERO. This option allows defining additional damping and stiffness terms at the structural finite element grid points. This option was used to model the gyroscopic effect of the rotating propeller and also the effect of the propeller trust and aerodynamics in the form of a local stiffness and damping on the wing structure. To calculate the local stiffness effect of the propeller aerodynamics on the wing, the data related to the changes of the loads and moments at the propeller hub with the changes of the angle between the direction of the air stream and the propeller rotation axis was considered. Gyroscopic effect of the propeller on the wing depends to the propeller rotational velocity and the polar mass moment of inertia of the rotating part of the propeller.
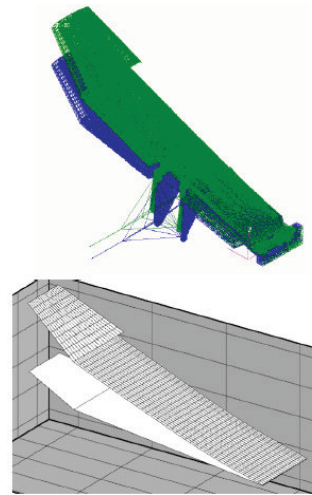

FIG. 18   Interpolation of the first structure bending mode on the aerodynamic surface
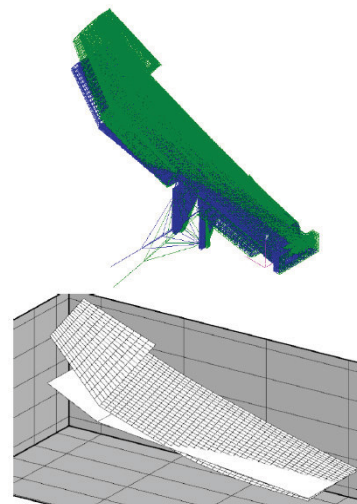

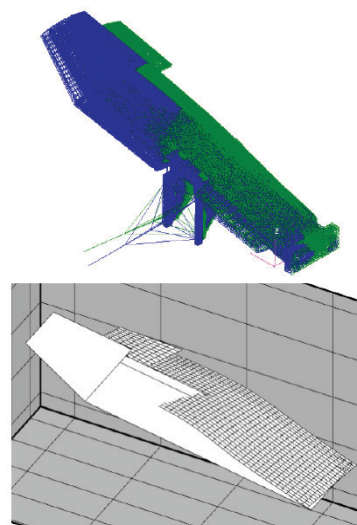FIG. 19   Interpolation of the second structure mode on the aerodynamic   surface

FIG. 20   Interpolation of the third structure mode on the aerodynamic surface

3. DYNAMIC STABILITY ANALYSIS

As mentioned before, two types of flutter analysis were performed to analyse the stability of the wind tunnel model under the test condition:
- Wing flutter analysis with the consideration of the propeller gyroscopic effect
- Propeller-nacelle-wing whirl flutter analysis

The main wind tunnel test conditions, considered for the flutter and the whirl flutter analysis are:
- Air velocity = 51 [m/s]
- Rotor rotational velocity = 748.07 [rad/s]

3.1. Wing Flutter Analysis, ZAERO: results

Fig. 21 and 22 show one of the main results (modal damping) of the flutter analysis performed with ZAERO.
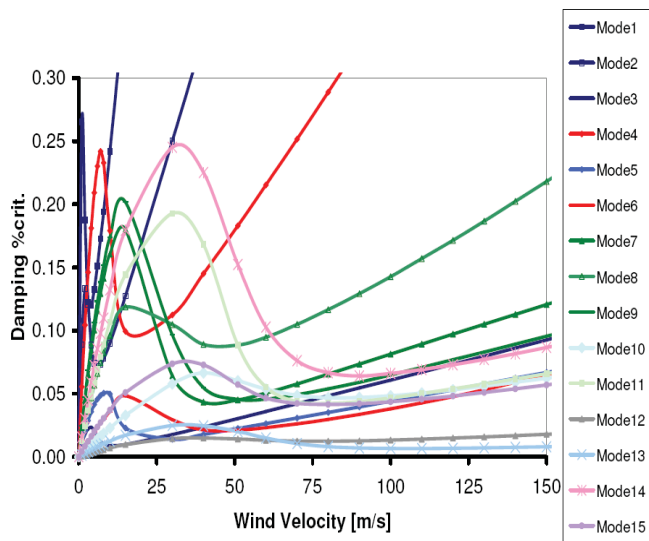
FIG. 21   Modal damping of the first 15 modes
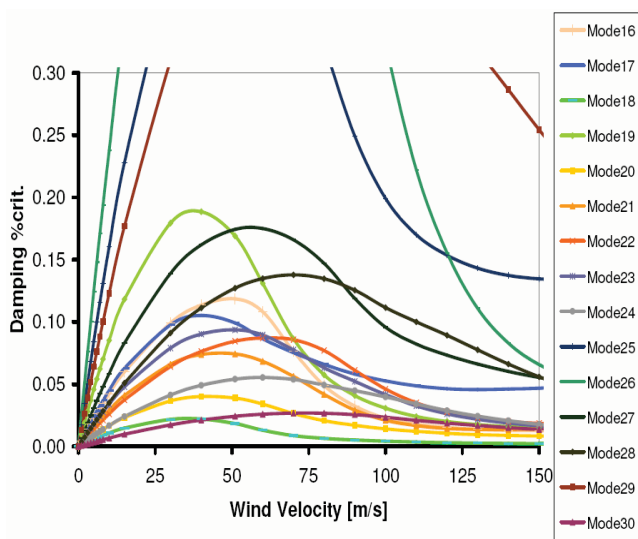
FIG. 22   Modal damping of the modes 16 to 30

It can be seen that the damping of all modes are positive, which shows that the model is stable. For the performed

flutter analysis, the structural damping was considered zero. This means that adding the structural damping to the system makes the model even more stable. For a wind velocity 4 times higher than our test condition no flutter was established. The results shown in Fig. 21 and Fig. 22 belong to the model made of aluminium. A second flutter analysis was performed with model made of steel (material changes was performed just for the wing box of the main wing). The results of this analysis can be seen in Fig. 23 and Fig. 24. These results show that the model made of Steel is stable too. Figure 23 and 24 also compare the modal damping of both models. It can be seen that the aerodynamic damping reduces, when the main wing becomes heavier, which is plausible.
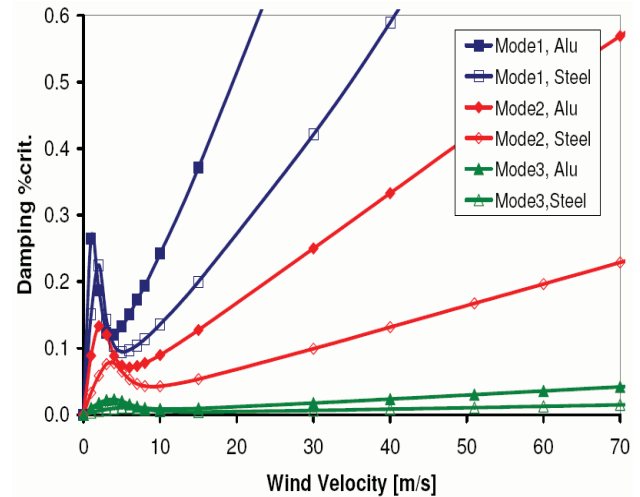

FIG. 23   Comparison of the modal damping of the models made of aluminium and steel
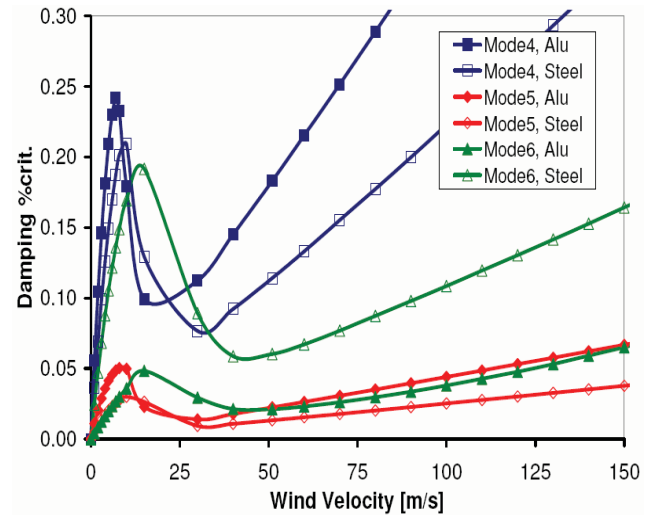

FIG. 24   Comparison of the modal damping of the models made of aluminium and steel

But as it can be seen in Fig. 24, this is not the case for the mode 6 (model from steel has higher aerodynamic damping). This could be explained after comparing the mode shapes of both models. Mode shape of the mode 6 has a local deformation of the nacelle relative to the wing. This could increase the gyroscopic effect of the propeller on the wing. For the model made of Aluminium (lower

stiffness) the gyroscopic effect of the propeller on the wing is higher. It should be mentioned that the idea of changing the wing material from Aluminium to Steel was to see the effect of this change on the frequencies and the mode shapes of the model and their effects on the stability of the model.

Figure 25 shows one of the results produced after the modelling the propeller gyroscopic effect and propeller aerodynamic within the ZAERO model. This result compares the damping of the modes 4, 5 and 6 in three different cases: 1-wing without propeller aerodynamic and gyroscopic effect, 2-wing with gyroscopic effect but without propeller aerodynamic and 3-wing with gyroscopic and aerodynamic effect of the propeller.
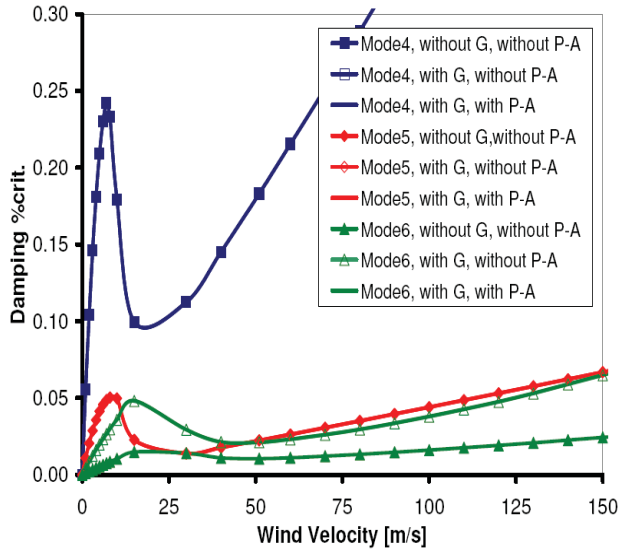
FIG. 25   Effect of the propeller on the modal damping

It can be seen in Fig. 25 that the gyroscopic effect shows itself first on the mode 6.

In general, strong reduction of modal damping is critical. Because even in this area the values of the damping are positive and the system is stable, it is possible due to a small change of one of the model parameter, the system turns to an unstable one. Fig. 26 shows such a strong reduction of damping in the area marked with an ellipse. In such a case, one should perform a sensitivity analysis.
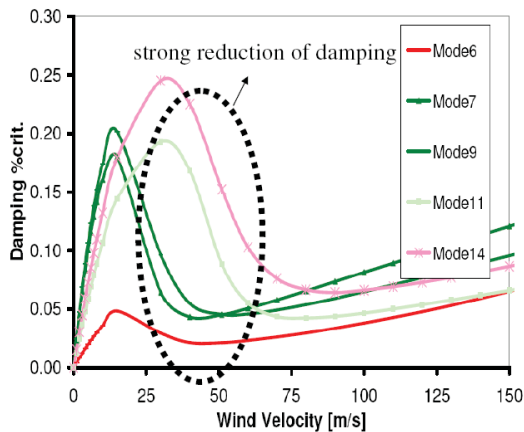
FIG. 26   Rapid changes of the modal damping

For this model at the moment no sensibility analysis was performed.

3.2.   Propeller-Nacelle-Wing Whirl Flutter Analysis, MBS

Figure 27 shows the simulated wind tunnel model inside SIMPACK.
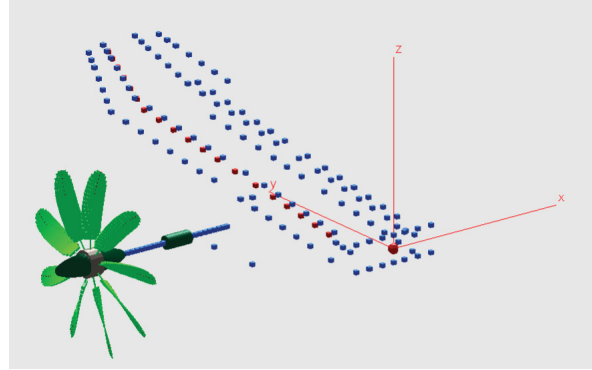
FIG. 27   Multibody simulation of the wind tunnel model

In this model, the propeller gets its rotation from a simulated motor, which rotates with a constant rotating velocity. Wing and nacelle are elastic bodies. Time integration of the system allows analyzing the stability of the wind tunnel model in times domain.

Figures 28 and 29 shows two results produced with the created SIMPACK model and after the time integration of the system.
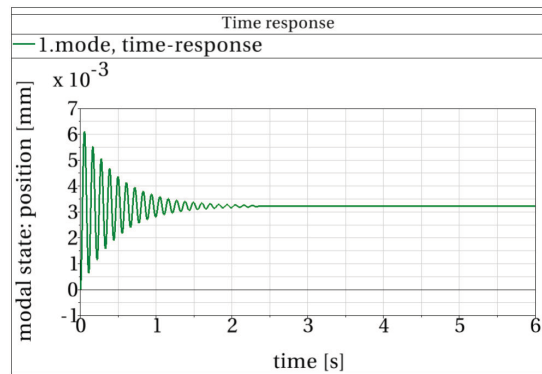
FIG. 28   Time response of the model under wind tunnel condition
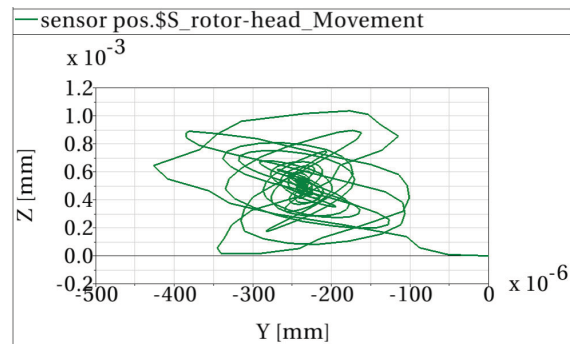
FIG. 29   Spatial movement of the propeller hub

Figure 28 shows the time response of the model (model

made of aluminium) in the first modal coordinate and Fig. 29 shows the movement of the propeller hub relative to the wing after a small deviation from its equilibrium state. Results shown in Fig. 28 and Fig. 29 represent the dynamic behaviour of the wind tunnel model considering the defined wind tunnel conditions. These results show that the model should be stable and no whirl flutter should happen.

4. CONCLUSION

For the wind tunnel model, two dynamic analyses were performed. The first dynamic analysis was the flutter analysis of the wing with aeroelastic analysis tool "ZAERO". The second analysis was the whirl flutter analysis of the whole propeller- nacelle-wing. This was modelled inside the multibody simulation too "SIMPACK".
Based on the results of the simulation, the wind tunnel model was established to be stable under the predefined wind tunnel test condition.
After Analysing the flutter and whirl flutter results, some structural optimization was suggested by the author to the design group, which would increase the safety factor of the model regarding the dynamic instability.
In future, a final dynamic stability analysis of the wind tunnel model would be performed based on the experimentally measurements of the structural modal data (performance of the ground vibration test).

ACKNOWLEDGMENT

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