DEVELOPMENT OF A METHOD TO ESTIMATE GUST LOADS ON A NON-ROTATING FLEXIBLE BLADE

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Abstract

In the present work ADAMS has been used to define a method for calculating the loads acting on a non-rotating rotor blade in presence of gust on the ground.
The blade has been modelled as a flexible body and its mechanical properties in terms of structural mass, damping and stiffness have been achieved from a finite element beam model built in MSC/NASTRAN.
The aerodynamic forces due to the gust have been introduced by developing user-defined FORTRAN subroutines that describes the behaviour of the air around the rotor using the strip theory. Analogous CAMRAD/JA model has been implemented in order to validate the model.
The flapping movements of the blade are limited by the presence of two flap-stops that have been included as contact-forces.
Since ADAMS does not directly provide the internal section loads, these forces have been computed by developing once again user-defined FORTRAN subroutines.
All this process is performed at the end of the ADAMS dynamic simulation.
During this work importance has been given also to the customisation of the user interface with the development of dboxes and macros.

1 Introduction

The effects of a gust on ground on a non rotating rotor causes one of the critical load condition that are considered in the design of the helicopter rotor system components (blades, hub, control linkage, etc.).
For the tail rotor configuration considered in this work, gust aerodynamic loads may produce large (angular) displacements and violent impacts on the flap stops because of the absence of centrifugal forces that oppose this forces.
The problem is heavily *non linear* due to the geometry of the model and to the forces (aerodynamic, inertial, crashes,…) related.
Furthermore the presence of time-varying entities gives the problem a *non-steady* aspect, which requires a time-marching approach to solve the dynamic equations .

These features make the multi-body time integrating approach quite suitable for this kind of analysis.

2 Description

A typical ADAMS model is mainly composed by a set of parts, joints and external forces. Parts (rigid or flexible) are entities for which six dynamic differential equations can be written; joints describe how these parts can move each other and are often expressed by algebraic equations; external forces make parts to move and generally are imposed by the user.

2.1 Structural model

The *blade* is modelled with MSC/NASTRAN using beam element (CBEAM) and concentrated mass element (CONM2). Then it is imported in ADAMS as a flexible body with the ADAMS Flex Toolkit, choosing an appropriate number of eigenvalues and interface grid point, to better represent the dynamics of the system.
All the other parts of the model are rigid.
The blade is linked

- to the *hub* by:
  - an elastomeric bearing (modelled as a BUSHING), whose mechanical features in terms of stiffness and damping (both translational and rotational) are in general frequency and temperature varying;
  - an elastomeric damper (modelled as a SFORCE), whose mechanical features are frequency and temperature varying too;
- to the *pitch link* by a universal joint.

A spherical joint connects this link to the spider of the control chain, which – in this case. is fixed to the ground.

Finally flap limiters has been implemented so that impact forces arise when the blade hits on them.

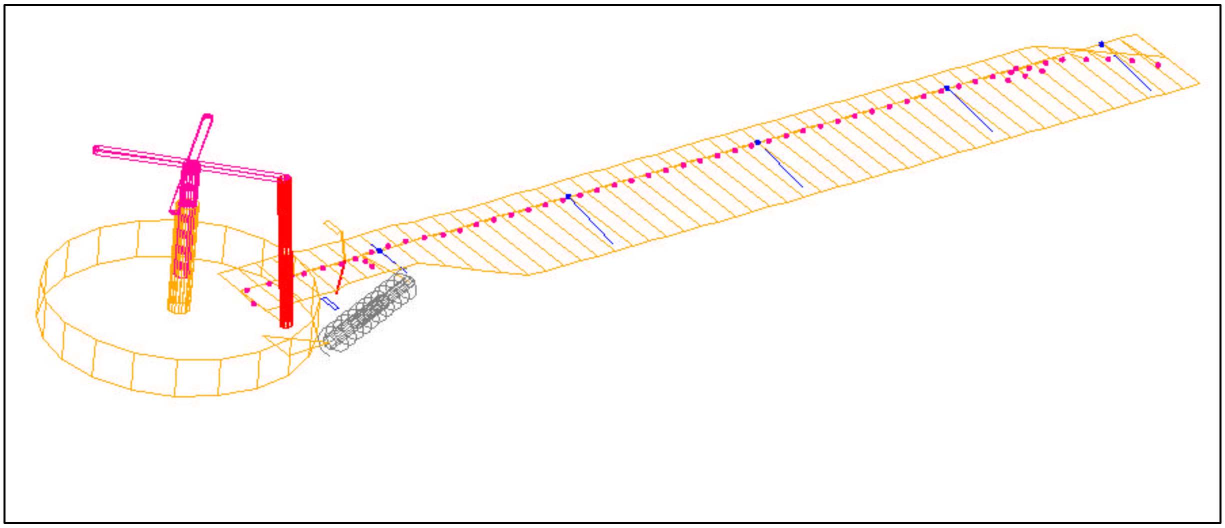

Fig. 1 Model sketch

2.2 Aerodynamic model

Since ADAMS doesn't present in its library an appropriate model for predicting aerodynamic forces, an external subroutine based on the 2D strip theory has been implemented, with viscous and compressibility effects included via table lookup.
The blade has been spanwise divided in a number of panels with:

- aerodynamic characteristics (chord, twist, length of the panel, airfoil section data, etc.)
- an interface node on which resultant aerodynamic forces and momenta are applied.

Steady aerodynamics

For each panel the equations can be expressed in the standard form:

$$L = \frac{1}{2} r v^2 C_L(a, M) c \lambda_{pan}$$

$$D = \frac{1}{2} r v^2 C_D(a, M) c \lambda_{pan}$$

$$M_{AC} = \frac{1}{2} r v^2 C_{M_{AC}}(a, M) c^2 \lambda_{pan}$$

where λ_{pan} and c are respectively the length and the chord related to the panel.
The total wind velocity v acting on a section of a blade consists of two terms :

- the asymptotic wind
- the section velocity due to the motion and the deformation of the blade (that is, *a priori*, unknown), with its time derivatives

and is resolved at each control point, positioned at "1/4 chord".
Then the incidence a and the Mach number M are computed for the table lookup (Fig. 2).

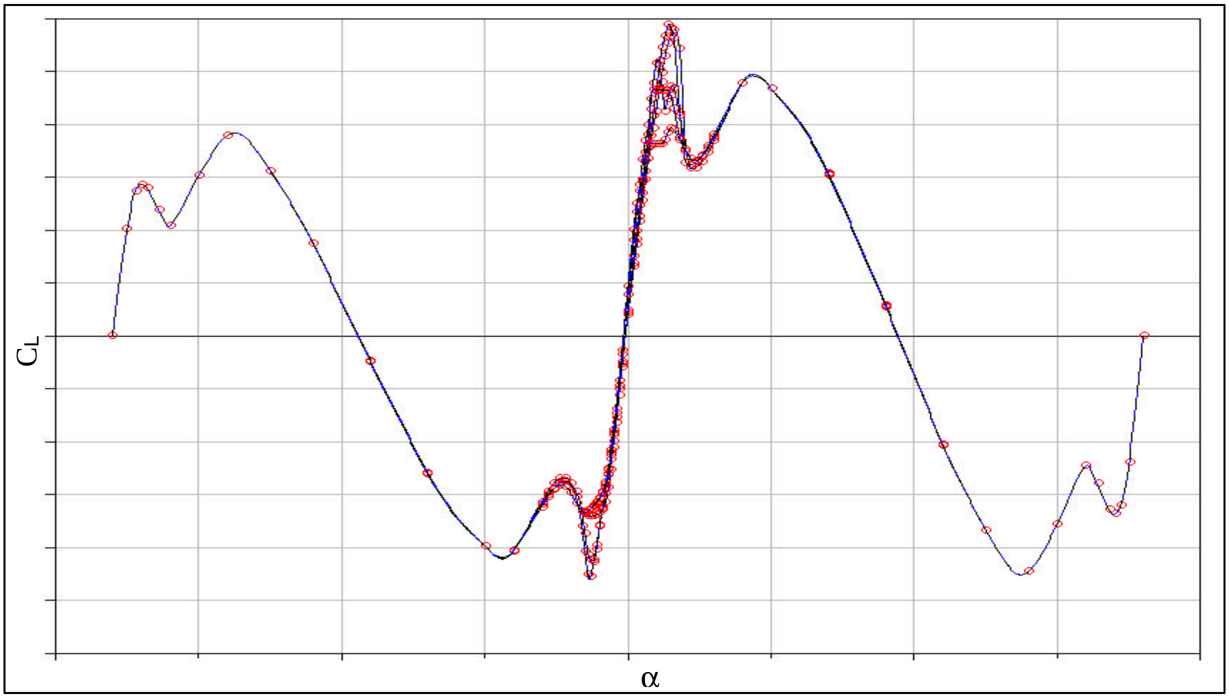

Fig. 2 $C_L - a$ curve for different Mach numbers.

In order to have an "aerodynamic tool" ready to be used also for rotating case of rigid blade, further improvements have been introduced for taking account of other aerodynamic effects.

Quasi –steady aerodynamics

A second approach, called *quasi-steady*, has been implemented; it is more complex and splits aerodynamics into a circulatory and non circulatory portion (Ref. 1). Velocity, incidence and Mach number are evaluated at “3/4 chord” (Ref. 2) and aerodynamic loads are applied at “1/4 chord”. In this formulation also the second time derivatives of degrees of freedom have a role in the computation of the loads.

Inflow

When a rotating rotor is examined, induced inflow can’t be neglected.
The uniform inflow approach (momentum theory) implemented computes the total thrust at the current time step by summing the net forces along the shaft axis, uses it to evaluate the mean inflow to be used in the successive time step.
This velocity term has to be added to the two ones previously defined.

Transversal flow

When a marked transversal component of the flow is present on the blade, additional radial drag and increased max lift coefficient arise.
These effects can be taken into account, when the transversal flow option is selected (Ref. 3).

2.3 Internal Section Loads

In order to evaluate internal loads in the blade, in terms of axial, shear and momenta loads, it has also been necessary to implement an “ad hoc” procedure.
This is possible by writing for each time step equilibrium equations for a piece of blade on which external (aerodynamic, inertial, reaction and discrete loads) and internal forces act.

Once an analysis has been run, time histories of all external loads are included in ADAMS standard output, but the inertial ones must be evaluated.
This can be made possible by combining the accelerations of all points endowed by mass, which are usually known at the end of the run, and inertial properties of these points, which can be found in the FEM model.

3 RESULTS

Before analysing the condition of gust acting on a tail blade, three “validation” problems are presented.
The first and the second one are typical didactical test cases (Ref. 4) and have been implemented principally in order to validate the aerodynamic subroutines and the influence of this on the dynamic behaviour of the system; in the third one the rotation of the rotor has been included and results have been compared with CAMRAD/JA solution.

3.1 Non rotating rigid flapping blade

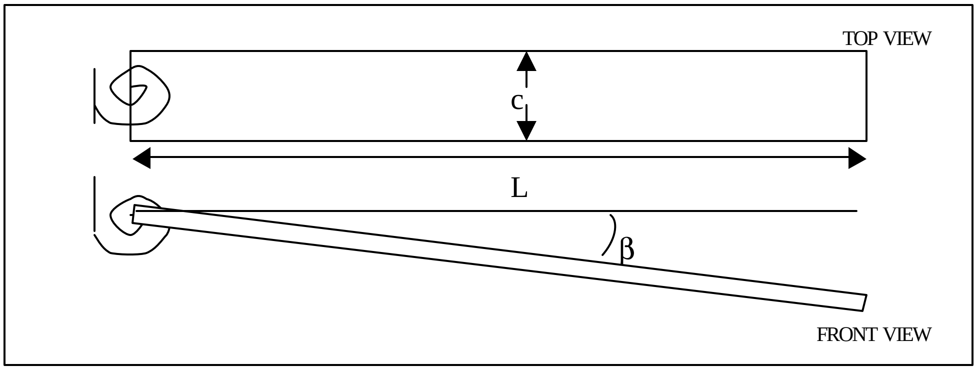

Fig. 3

In this case the only degree of freedom is represented by the flap angle (Fig. 3)
The equations of motion with or without aerodynamics are:

$$I_b \ddot{b} + K_b b = 0 \qquad \text{(no aerodynamics)}$$

$$I_b \ddot{b} + K_b b = -\frac{1}{2} r V^2 S L \frac{c_{La}}{3}\left(\frac{\dot{b}L}{V}\right) \qquad \text{(with aerodynamics)}$$

where:
I_b is the blade flapping moment at the hinge;
K_b is the angular stiffness of the spring
r is the air density
V is the wind velocity
S is the area of the blade

The aerodynamics introduces only a *damping* contribution, but it doesn’t affect the inertial and stiffness terms, which are responsible of the modal frequency of the system.
Fig. 4 confirm this.

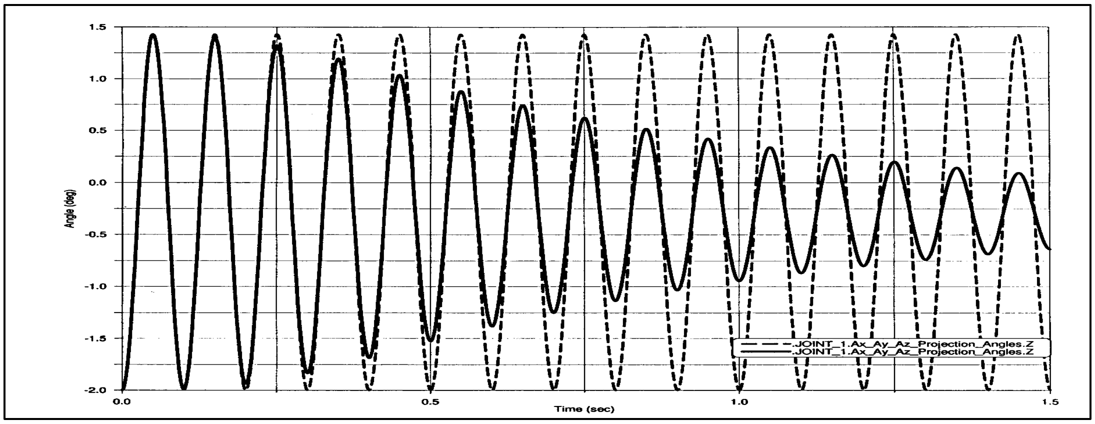

Fig. 4 Flapping dynamics with (line)or without (dashed line) aerodynamics

Analytical damping ratio ζ of the solution with aerodynamics is confirmed by the evaluation of the time half amplitude of the signal.

3.2 Non rotating rigid pitching blade

In this case the only degree of freedom is represented by the pitch angle (Fig. 5)

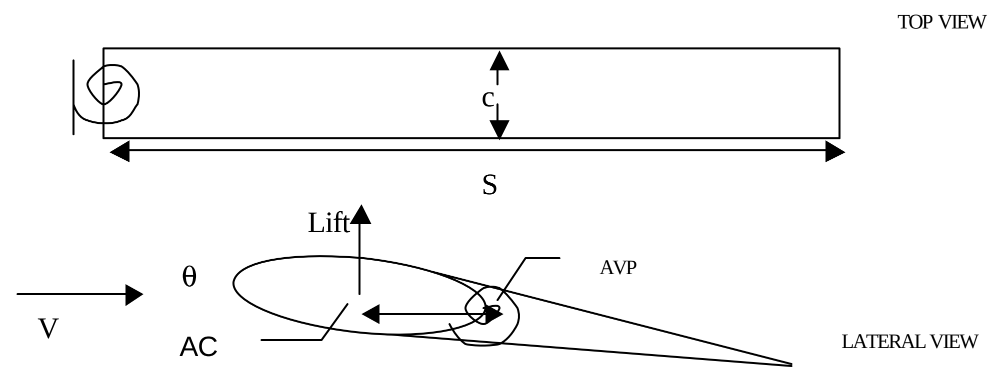

Fig. 5

The equations of motion with or without aerodynamics are:

$$I_\theta \ddot{\theta} + K_\theta \theta = 0 \qquad \text{(no aerodynamics)}$$

$$I_\theta \ddot{\theta} + K_\theta \theta = \frac{1}{2} \rho V^2 S c c_{L\alpha} e \theta \qquad \text{(with aerodynamics)}$$

where:
I_θ is the blade pitching moment at the hinge;
K_θ is the angular stiffness of the spring

The aerodynamic effect is now quite different from the previous examples, because it directly acts on the stiffness of the system, which becomes:

$$K_\theta^A = K_\theta - \frac{1}{2} \rho V^2 S c c_{L\alpha} e$$

In this way the frequency of the system will be modified.
Furthermore this *aeroelastic* stiffness depends on the the wind velocity and can be equal to zero for a specific value V_D of this velocity:

$$V_D = \sqrt{\frac{2K_\theta}{\rho S c c_{L\alpha} e}}$$

Fig. 6 and Fig. 7 show this behaviour, when an initial position different from the equilibrium one and a step wind velocity profile are imposed.

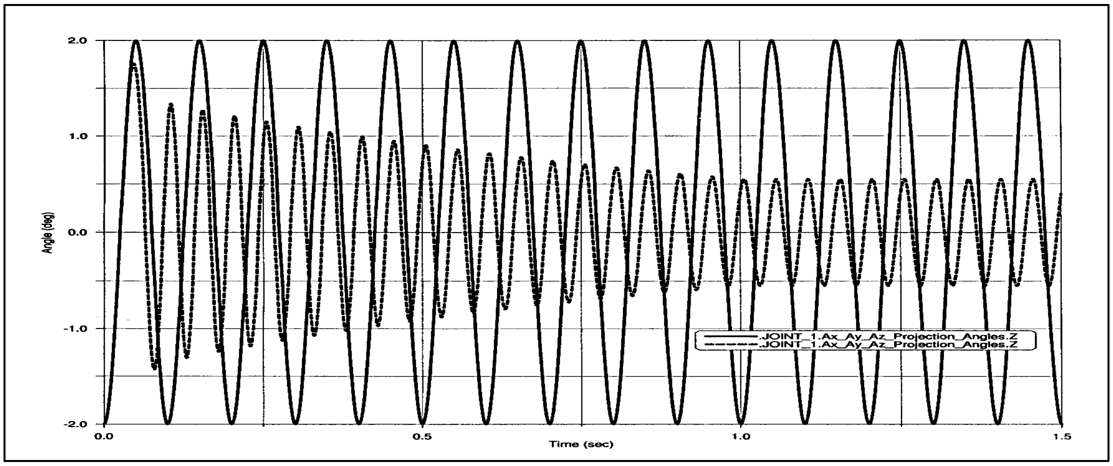

Fig. 6 Pitching dynamics with (solid) or without (dashed) aerodynamics ($V<V_D$)

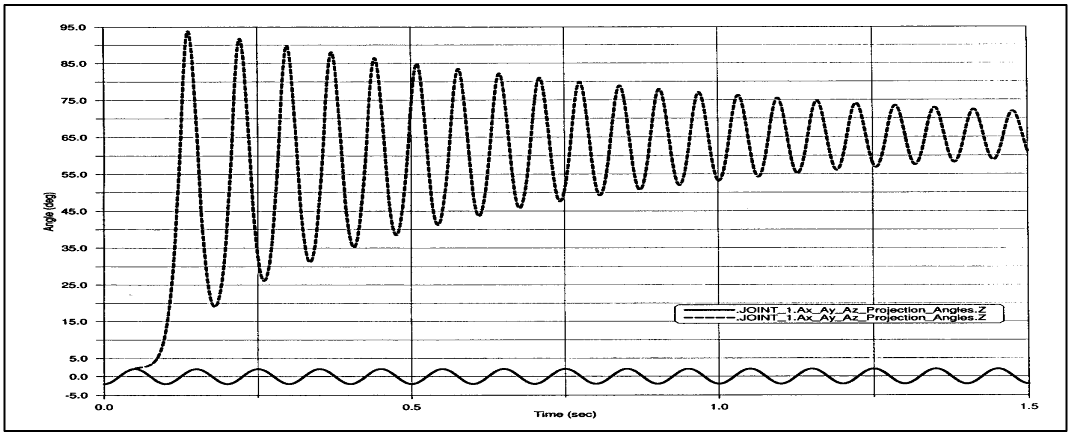

Fig. 7 Pitching dynamics with (solid) or without (dashed) aerodynamics ($V>V_D$)

3.3 Rotating rigid blade

The objective of this example is to introduce the blade rotation and to validate all the aerodynamic modelling implemented included.
This test case was also dealt with CAMRAD/JA, although it was not possible to reproduce the same identical ADAMS problem, due to differences in modelling between the codes.
These differences, however, don't affect heavily the possibility to compare the results.
The model is the same shown in Fig. 1

A steady aerodynamic model has been introduced, with a uniform inflow for the induced wind velocity.
Aerodynamic forces act on five panels endowed with:

- chord
- length
- thickness
- geometrical twist
- 2D airfoil characteristics (as $C_L(\alpha,M)$,$C_D(\alpha,M)$,$C_M(\alpha,M)$)

Finally the imposed motion of the blade is a step motion from zero to 100% NR in 0.5 seconds.
The pitch applied is about 50% of total operating range.

The thrust of the blade is the sum of the aerodynamic forces projections on the mast axis.

Its trend is shown in Fig. 8.

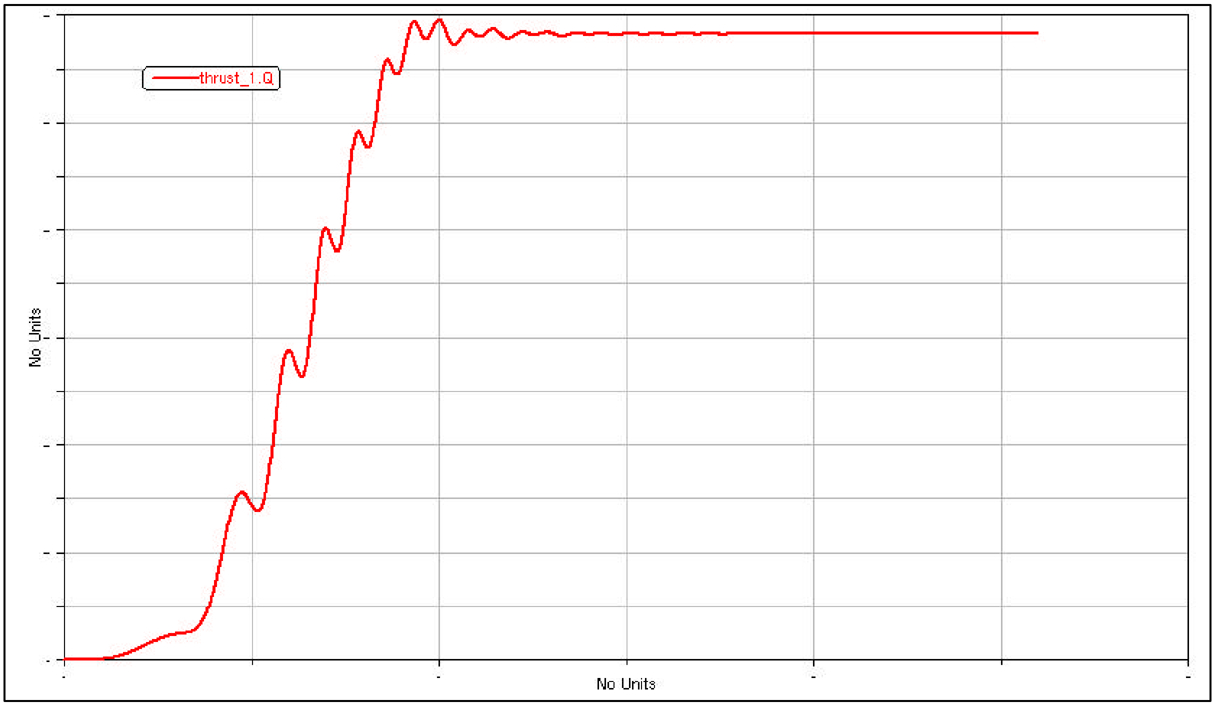

Fig. 8 Thrust with uniform inflow model for wind induced velocity

The equivalent model in CAMRAD/JA gives a steady thrust value that is in good agreement with ADAMS one.

The contributions of single panels are shown in Fig. 9.

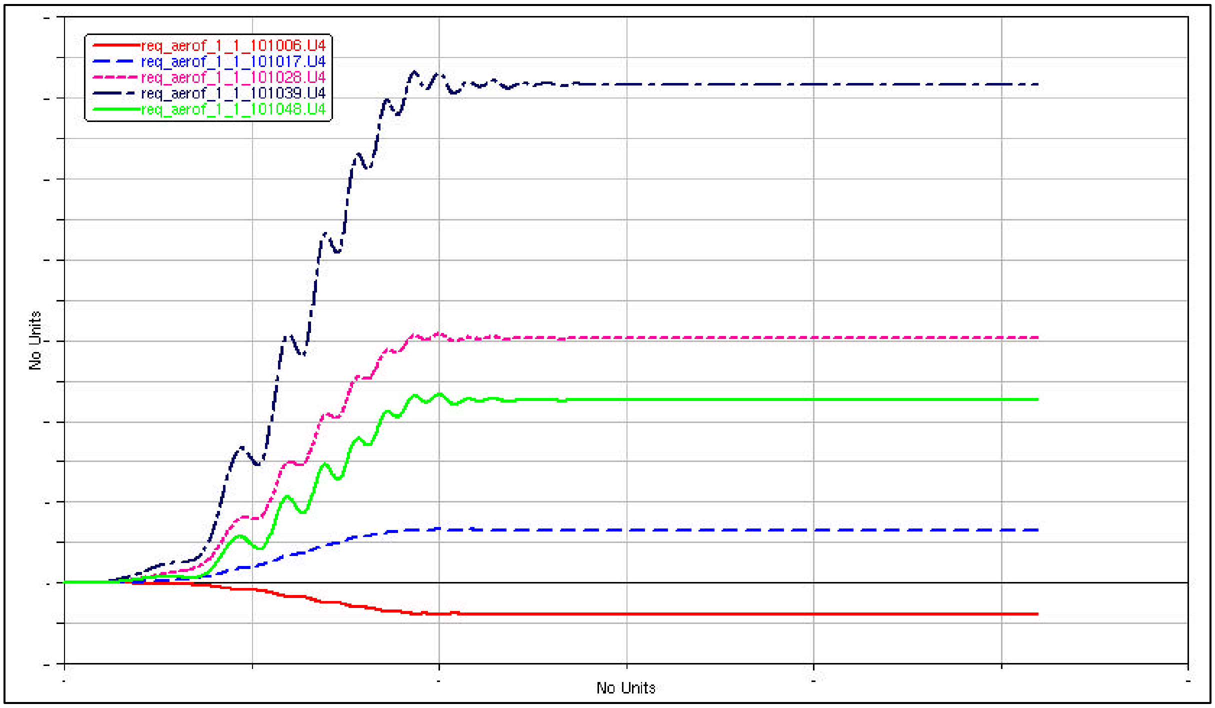

Fig. 9 Contribution to the thrust of single panels

3.4 Non rotating flexible blade with gust

This case is the core of this work. The following items are now introduced:

- the flexibility of the blade
- the presence of a gust
- the impact of the blade on flap limiter
- the recovering of the internal loads

in order to determine critical conditions, in terms of stress for the blade

The blade has been modelled in MSC/NASTRAN with CBEAM (for stiffness properties) and CONM2 (for inertial properties) and has been imported in ADAMS with the Component Mode Synthesis technique, choosing a suitable number of modes and master nodes.The remaining parts are rigid.
Elastomeric damper and bearing are introduced respectively as single and bushing force, with their stiffness and damping properties evaluated at 15°C and at the frequency of interest.
The model is sketched in Fig. 1

Aerodynamic gust loads are evaluated as seen in 3.3.
Induced flow velocity, yawed flow effects are not considered here.
For the impact forces on the flap limiters the built-in IMPACT ADAMS subroutine has been used with parameters typical for steel to steel contact.

Once fixed the gust magnitude, it has been possible to run a parametric study in order to determine the direction of the wind and the external temperature (which affects elastomeric properties) so that the impact force reaches the highest value.
This condition has been analysed and the results are shown below[1], in terms of:

- upper flap stop load (Fig. 10)
- blade section momenta (M_x beamwise, M_y chordwise, M_z torsion) (Fig. 11 ÷ Fig. 13)
- elastomeric bearing forces and momenta (Fig. 14 ÷ Fig. 15)
- damper load (Fig. 16)
- axial pitch link load (Fig. 17)

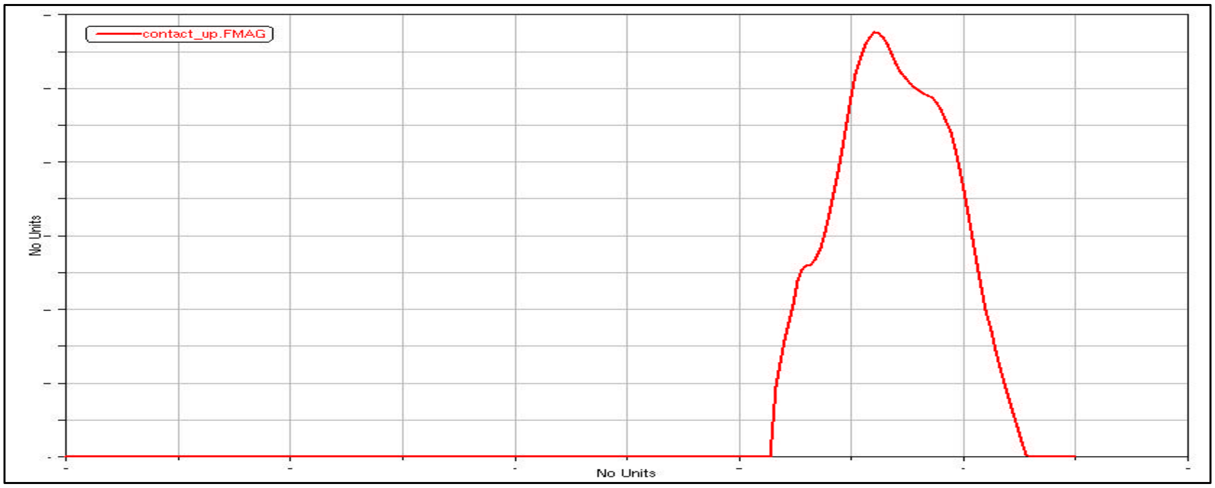

Fig. 10 Impact forces on flap limiters

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[1] Plots have been scaled with an appropriate factor.

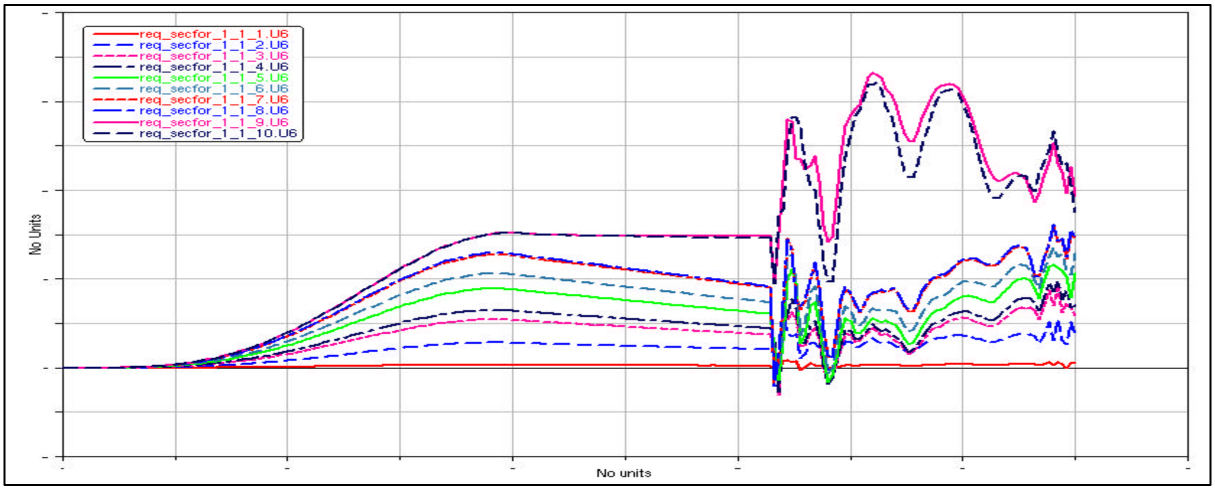

Fig. 11 M_x in 10 spanwise stations

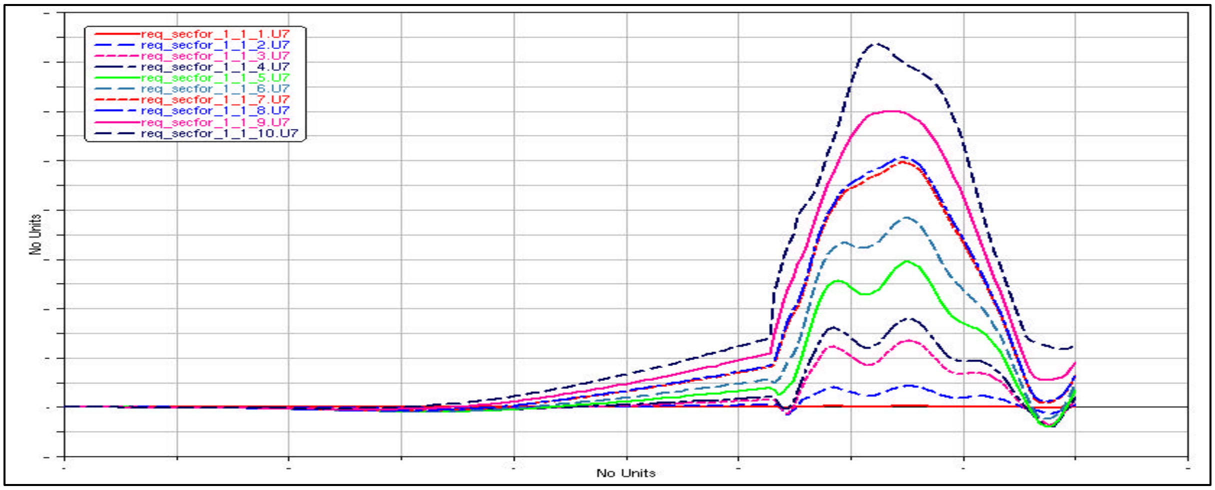

Fig. 12 M_y in 10 spanwise stations

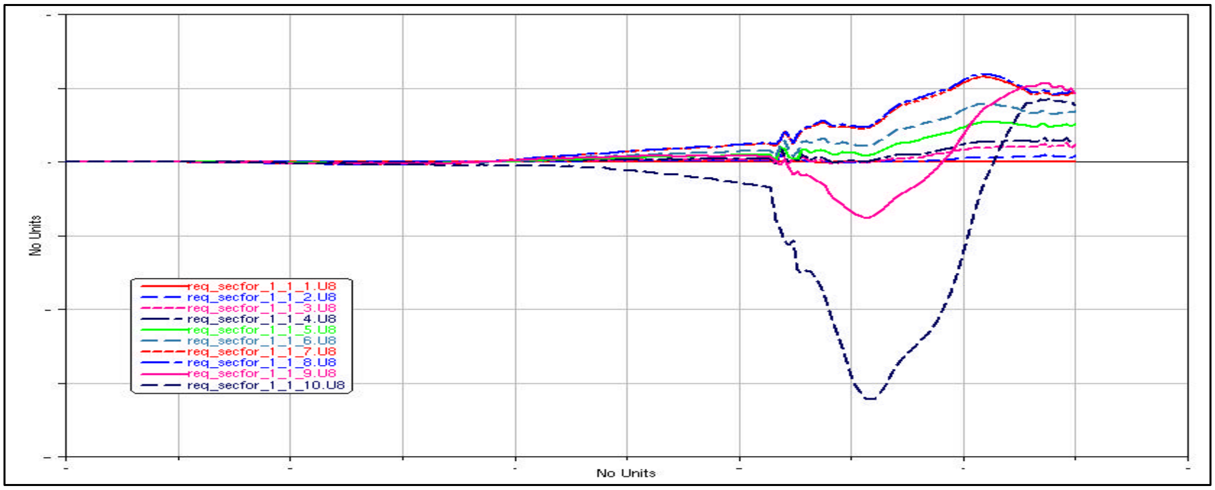

Fig. 13 M_z in 10 spanwise stations

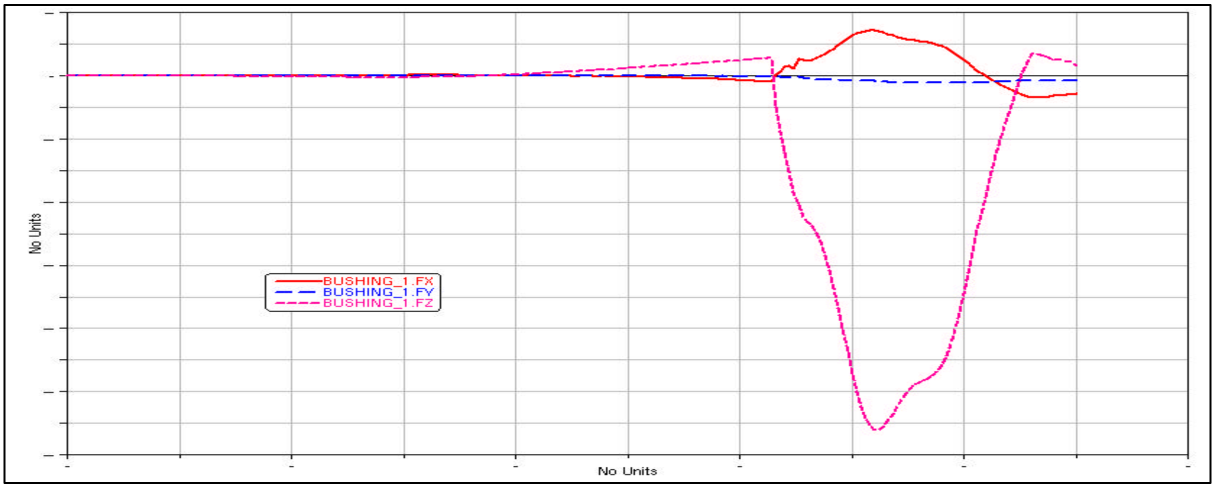

Fig. 14 Elastomeric bearing internal loads (forces)

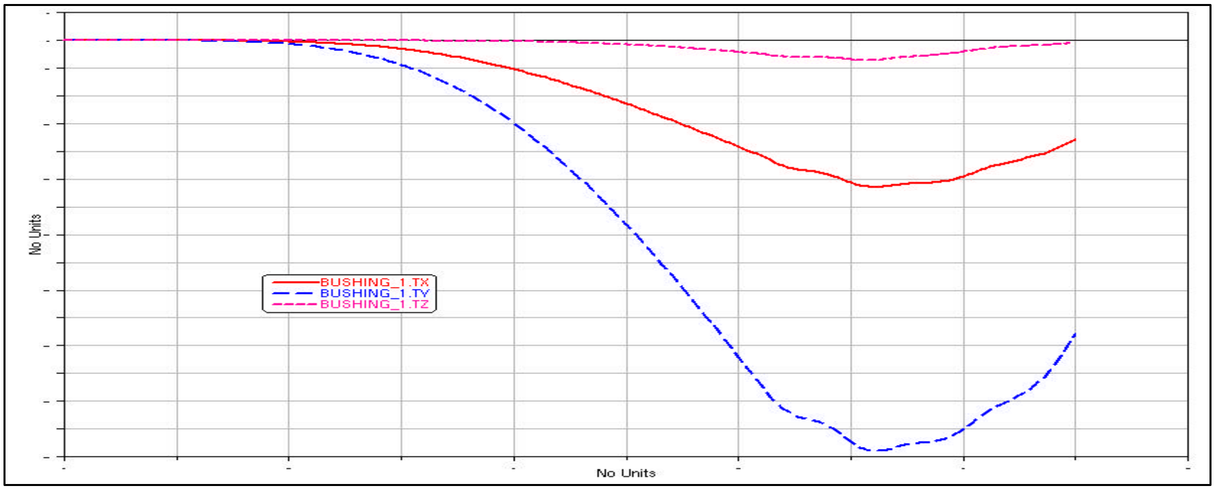

Fig. 15 Elastomeric bearing internal loads (momenta)

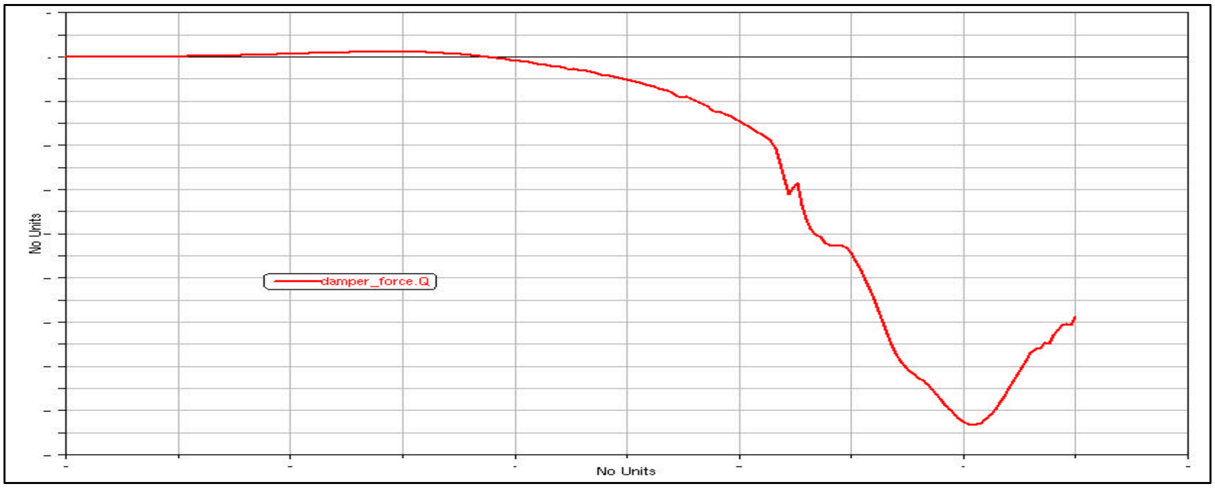

Fig. 16 Damper load

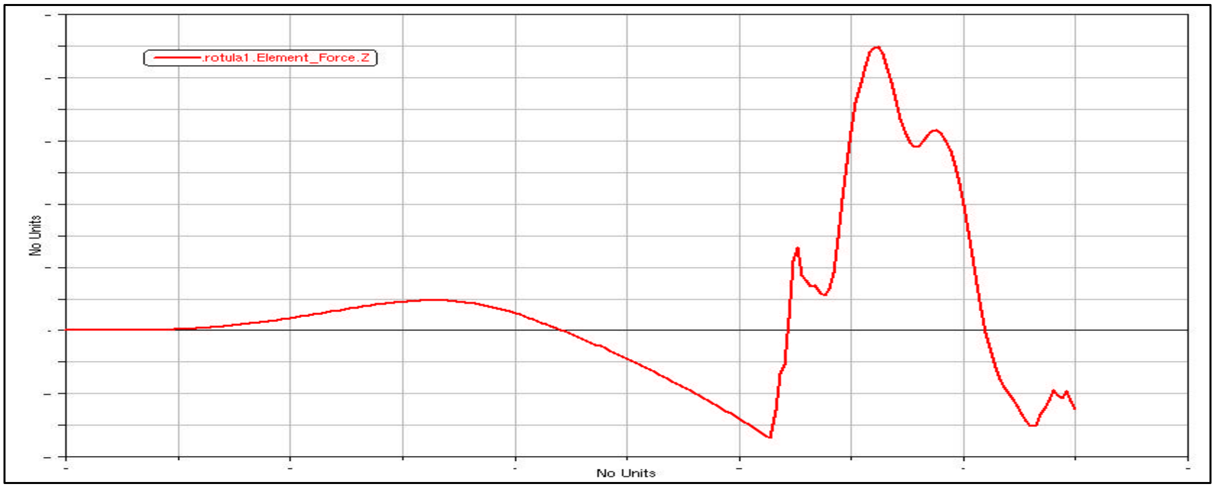

Fig. 17 Axial load on the pitch link

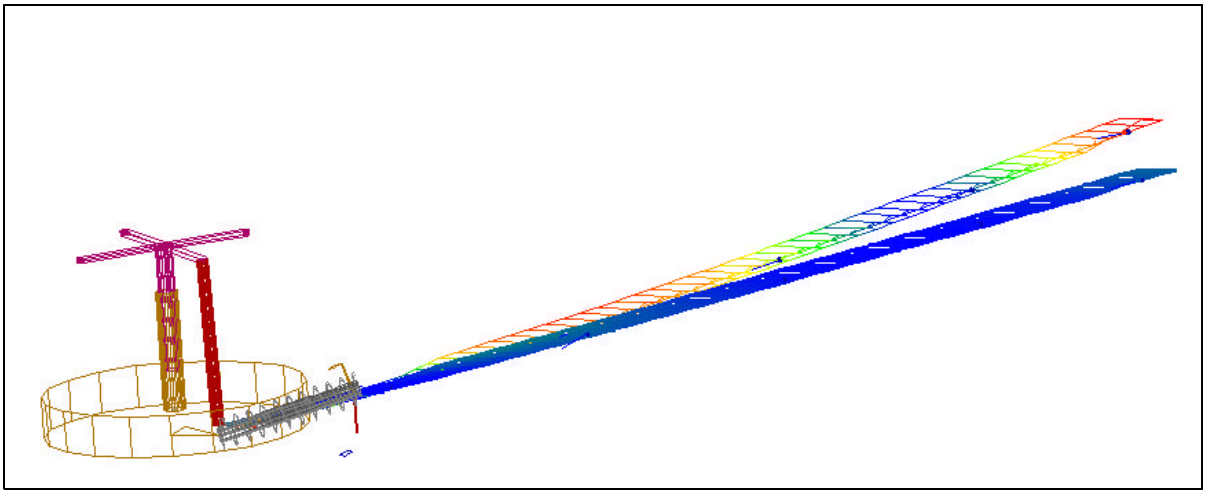

Fig. 18 Blade deformation

4 CONCLUSIONS AND DEVELOPMENTS

A method to estimate gust loads on a non rotating flexible blade has been presented.

The strongly transient behaviour of the phenomenon, with non linear features principally due to kinematics, aerodynamics and impact loads, doesn't recommend a frequency-domain solution and suggests a time-integrating multi-body approach.

The flexibility of the blade has been imported from MSC/NASTRAN *via* the FlexTool kit, that generates a MNF input file for ADAMS.
External subroutine has been implemented to evaluate aerodynamic, inertial and internal section loads.

Test cases has been solved and comparison with CAMRAD/JA results have been made in order to validate the procedure.
After this a case of industrial interest has been studied and solved.

Further improvements on aerodynamics are certainly possible, both refining the subroutine (including 3D effects, different model of wake, …), and evaluating it with external codes which compute loads starting from the current model configuration.

The extension of flexibility to a full rotating rotor may be interesting, but care should be taken in order to use blade modes suitable for representing a rotating regime.

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