PREDICTIVE SIMULATION OF IMPACT PHENOMENA FOR INNOVATIONS IN AIRCRAFT COMPONENT DESIGN

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Abstract

Currently aircraft designers are facing a big change in structural design: the change from metallic components to composite parts. There is a growing demand to accurately predict the behaviour of the innovative materials under various real-world circumstances, e.g. impact encounter. This paper focuses on the mathematical challenges that arise here. Two case studies are presented. First, modelling of landing gear is presented, with focus on real-time simulation. Second, bird collisions on the wing leading edges are modelled, where strength and damage resistance of the structure are of prime importance. It is shown that these seemingly different studies benefit from a common mathematical starting point.

Key words
Landing gear, bird impact, aircraft components, simulation, Lagrange multipliers.

1 Introduction

During the last decades simulation has been playing an increasing role throughout the lifecycle of aircraft components. Especially some critical aircraft components that will lose their functionality after an impact encounter, e.g. a collision, require extensive simulation. Aircraft accidents have occurred many times because of problems with the landing gear, or collisions with wing leading edges, i.e. during impact situations. New and detailed mathematical models are essential to predict the behaviour and the consequences of impact phenomena on aircraft components.

Nowadays, the aircraft designers are facing a big change in structural design: the change from metallic components to composite and fibre metal laminate parts. Recent aircraft developments like the A380 already involve the new material Glare (GLass REinforced laminate) in their structural design. More and more new aircraft are being designed, manufactured and operated that contain an increasing amount of composite or fibre metal laminates in primary aircraft components. There is a growing demand to accurately predict the behaviour of the innovative materials under various real-world circumstances as they have very different properties than metals. Composite materials typically are sensitive to impact damage. Their structural design requires extensive analysis. To achieve this, innovative simulation models must be developed.

This paper focuses on the mathematical challenges that arise from real-world examples in the area of impact, i.e. sudden changes in the system’s behaviour caused by external sources. Two case studies are presented. First, a multi-body type modelling of landing gear is described, with focus on real-time simulation. Second, the modelling of bird collisions on the wing leading edges is described. In this case the strength and damage resistance of the structural design are of prime importance. It is shown that these seemingly different studies benefit from a common mathematical starting point: the simulation of constrained mechanical systems with Lagrange multipliers.

The remainder of this paper is structured as follows. In section 2 mathematical formulations of the impact effects are given. Section 3 presents simulation results of multi-body type landing gear simulation. Section 4 presents recent results of impact on wing leading edges, using computational mechanics. In section 5 conclusions are drawn.

2 Applied impact models

In impact simulation the continuous time dynamics are combined with discrete event simulation that represents the collision/impact effects. In this sense, the nature of impact models is that of hybrid systems, as described in [Ten Dam, 1997]. Mathematical modelling of impact at NLR – especially in relation to real-time simulation [Ten Dam, 1997; Ten Dam, Dwarshuis and Willems, 1997] – has been greatly stimulated by the design and control issues of the European Robotic Arm (ERA). Space-borne manipulators like ERA are typically used for moving payloads. Whenever a space-borne manipulator comes in contact with its environment, e.g. the international space station, it may not damage itself, the space station, or the payload. This makes the design of the control system for the robotic manipulator critical. Therefore the simulations during both the design/test phase and the operations/training phase require effective impact models.

Lagrange multiplier formulations of constrained mechanical systems have proven useful for impact modelling. An advantage of the use of a Lagrange multiplier is that during simulation studies, an expression of a Lagrange multiplier can be used as a model for a force sensor or simply as a nonlinear expression for the contact force. Specific Lagrange formulations for mechanical systems have been derived [Ten Dam, Lammen, and Rozema, 2005] that are particularly useful for real-time simulation.

Lagrange multiplier formulations can be obtained as follows. Let x denote the generalized co-ordinates used to describe the 'state' of the system under consideration. For simplicity assume that the mechanical systems can be represented by

$$M(x)\ddot{x} + N(x,\dot{x}) = u. \qquad (1)$$

Here *M(.)* denotes the generalized mass matrix, *N(.,.)* is a vector function that characterizes the Coriolis, centrifugal and gravitational load, and u denotes generalized inputs. Furthermore, for ease of notation, assume that there is a single constraint manifold, modelled by

$$h(x) = 0. \qquad (2)$$

Usually, equation (2) is obtained by modelling the environment in the area of interest. The region in which the system's movements take place can now be given as

$$h(x) \geq 0. \qquad (3)$$

Using equation (1) and (2), a constrained motion model can be given as

$$M(x)\ddot{x} + N(x,\dot{x}) = u + G^T(x)\lambda, \qquad (4)$$

where λ is the Lagrange multiplier, and *G(.)* represents the contact force matrix. Contact is detected when the inequality constraint (3) is not satisfied. The introduction of the Lagrange multiplier makes detection of contact and release during simulation studies nontrivial [Brogliato et al, 2002]. The following rules apply in case contact has already been established.

$$\text{contact when} \quad \left.\begin{array}{l} h(x) = 0 \wedge \\ \dfrac{\partial h}{\partial x}(x)\dfrac{dx}{dt} = 0 \end{array}\right\} \qquad (5)$$

$$\text{release when} \quad \lambda < 0. \qquad (6)$$

The Lagrange multiplier method can be extended to multiple point contact, e.g. for use with finite element modelling (FEM). Specific algorithms should be applied, e.g. modelling surface-to-surface or node-to-surface contact using master/slave formulations. In computational mechanics, contact events are modelled by first performing a contact search to detect possible contacting surfaces. Then the contact normal and tangential forces are calculated for elements that have physical contact. In each time step the nodes or surface segments that are in contact with each other can change, leading to highly non-linear contact behaviour.

In computational mechanics, contact-impact problems are among the most difficult nonlinear problems to solve because the response is non-smooth due to discontinuous velocity fields [Wriggers, 2001]. This introduces significant difficulties in the time integration of the discrete equations. The appropriate choice of methodologies and algorithms is crucial to the success of the robust solution of the contact-impact phenomenon.

The continuous multiple contact problem is now solved by dividing the structure in smaller parts, solving the contact-impact problem for each part and summing up the results for the whole structure. The global contact interface matrix G then becomes

$$G = \sum_e (L_e^\lambda)^T G_e L_e, \qquad (7)$$

in which G_e is the element force matrix and L_e is the connectivity matrix.

In today's commercial finite element codes this process is highly automated but still an area of extensive research as it requires costly numerical operations. The biggest problem in computational contact mechanics is the search for contact between impacting bodies. This is usually done in two steps: a search for elements that might possibly come into contact, and determination of the finite elements which actually intersect. Contact search has to be performed in every time step of the numerical simulation. When fractured materials are considered, many new contact surfaces are generated due to splitting of elements.

With the advantage of computational mechanics methods, and the availability of some of the methods in commercial finite element codes, predicting the effects of an impact on a structure has made great advances in recent years.

3 Landing gear simulation

Landing gear components have been analysed extensively throughout the last decades. Various simulation models of landing gear have been developed at NLR. The applications vary from efficient real-time simulation models for pilot-in-the-loop simulation to detailed models for structural analysis (e.g. damage, fatigue loads). Each application requires a well-considered choice of dedicated mathematical algorithms.

Based on previous experience with generic vehicle models [Ten Dam, Lammen, and Rozema, 2005; Klaasse, 2005] for real-time simulation, a multi-body method has been applied to the simulation of aircraft landing gear, e.g. of an F-16 aircraft [Oskam, 2007-1]. The advantage of the multi-body approach is that one can first decompose the system under consideration in several independent parts, referred to as vehicle parts. Each of the vehicle parts can than be modelled with its own level of detail. Subsequently the parts are combined again via constraint equations to derive a multi-body model of the complete system. Vehicle parts have been modelled that represent the main landing gear and nose landing gear. The approach is to derive a dynamics model for each part based on spring-damper dynamics with point masses, together with discrete event modelling of the impact in the wheel-contact point. The landing gears are connected to each other by means of algebraic constraints that represent a fixed aircraft body (i.e. the aircraft, without the wheels and lower part of the gear struts), see figure 1.

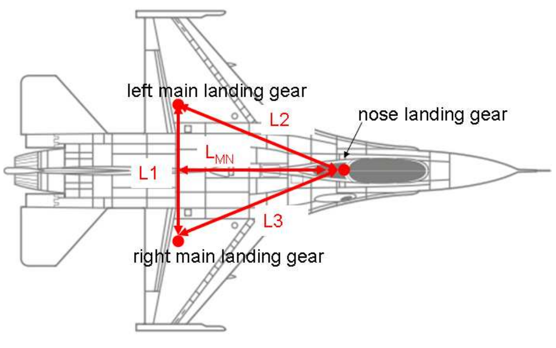

Figure 1. Visualization of the connection of the landing gear by means of constraint modelling that represents a fixed aircraft body.

With the real-time simulation requirements in mind, computational efficiency has been an important driver in the design of the mathematical algorithms. For this reason a simplified model with linear spring damper characteristics has been used for the equations of motion of each landing gear. For each main landing gear the combination of two spring dampers on top of each other, representing the shock absorber and the tyre, were used, see figure 2. The upper point mass represents the part of the aircraft body mass that is carried by the particular main landing gear. The middle point mass represents the wheel mass and the lower point mass represents a small piece of tyre that contacts the ground.

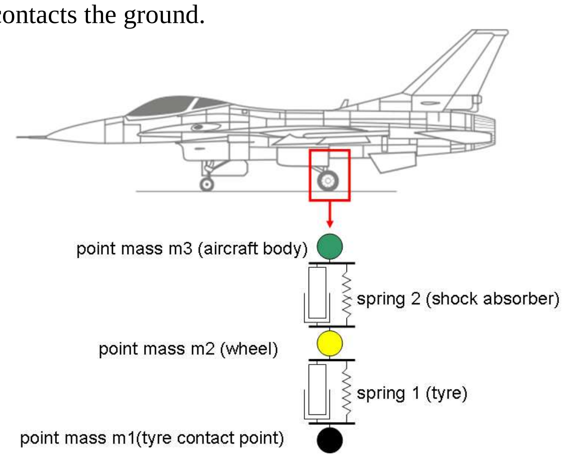

Figure 2. Spring damper model of one main landing gear.

The equations of the unconstrained motion are as follows. Denote $d_{ij}:=d(m_i,m_j)$, the absolute distance between point mass i and j in meters of the same landing gear. The upper index l=1,2 indicates the (left or right) main landing gear. All equation parameters (except g) depend on this index. For notational convenience the index l is only shown with the point mass m.

$$\left.\begin{aligned} m_1^l\ddot{x}_1 &= k_1(d_{12}-z_{rel1})\underline{s}_1 + c_1\frac{\partial}{\partial t}d_{12}\underline{s}_1 + \underline{F}_{ex_1} + m_1^l g \\ m_2^l\ddot{x}_2 &= -k_1(d_{12}-z_{rel1})\underline{s}_1 - c_1\frac{\partial}{\partial t}d_{12}\underline{s}_1 + \underline{F}_{ex_2} + m_2^l g \\ &\quad + c_2\frac{\partial}{\partial t}d_{23}\underline{s}_2 + k_2(d_{23}-z_{rel2})\underline{s}_2 \\ m_3^l\ddot{x}_3 &= -k_2(d_{23}-z_{rel2})\underline{s}_2 - c_2\frac{\partial}{\partial t}d_{23}\underline{s}_2 + \underline{F}_{ex_3} + m_3^l g \end{aligned}\right\} \quad (8)$$

With:

g : gravitational constant [m/s^2],
k_j : spring constant of spring $j=1,2$ [N/m],
c_j : damping constant of spring $j=1,2$ [kg/s],
z_{rel_j} : relaxed spring length of spring $j=1,2$ [m],
m_i^l : the mass of point mass $i=1,2,3$ [kg],
$\underline{x}_i = (x_i, y_i, z_i)^T$: position of mass $i=1,2,3$ [m],
$\underline{F}_{ex_i}$: external force on mass $i=1,2,3$ [N].

The vectors $\underline{s1}$ and $\underline{s2}$ represent the (upward) directions of the lower and the upper spring.

The runway is modelled by the simple unilateral constraint:

$$z_1 > 0\,. \quad (9)$$

The handling of this constraint is based on formulations (5) and (6) with the exception that elastic collisions may occur, i.e. numerical velocity values can be non-zero. In this case the system is transferred within one time step from one unconstrained state to a new unconstrained state following the approach as described in [Brogliato et al, 2002].

For the nose landing gear an additional linear spring has been used to model the stiffness of the drag strut, which affects the simulation of 'spring-back' during landing impact, see figure 3.

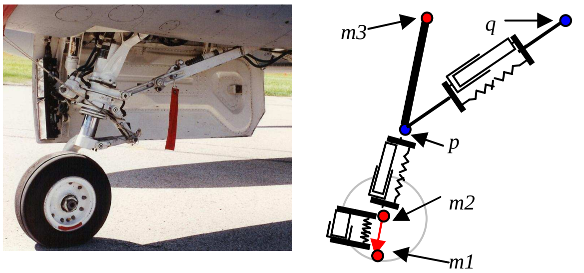

Figure 3. Spring damper model of the nose landing gear (source: www.f-16.net). The effect of the drag strut spring on the existing point masses (marked red) is modelled by means of two extra points *p* and *q* without mass (marked blue).

The equations of motion for the nose landing gear are analogous to formulations (8) and (9). Extra terms that represent the spring damper force F_{ds} of the drag strut are added to both the equations of the main landing gear and nose landing gear:

$$F_2^3 = \frac{d_{p3}}{d_{23}} F_{ds}, \qquad F_3^3 = \left(\frac{d_{23} - d_{p3}}{d_{23}} - \frac{L_{MN} - d_{q3}}{L_{MN}} \right) F_{ds},$$

$$F_3^1 = -\frac{1}{2}\frac{d_{q3}}{L_{MN}} F_{ds}, \; F_3^2 = -\frac{1}{2}\frac{d_{q3}}{L_{MN}} F_{ds}, \qquad (10)$$

$$\text{in which} \quad F_{ds} = k_{ds}\left(d_{pq} - z_{rel_{ds}}\right)\underline{s}_{ds} + c_{ds}\frac{\partial}{\partial t} d_{pq}\underline{s}_{ds},$$

with

F_i^l the extra force on point mass m_i^l, *i=1,2,3* the mass index, *l=1,2,3* the landing gear index,

d_{pi} the absolute distance [m] between point *p* and point mass *i* of the nose landing gear,

d_{ij} the absolute distance [m] between point mass *i* and *j* of the nose landing gear,

L_{MN} the absolute distance [m] between the main landing gear and nose landing gear.

The spring parameters in the formulation of F_{ds} are analogous to equation (8).

The landing gear models have been connected to each other by means of algebraic equations that maintain the fixed distances between the components within the aircraft body, see also figure 1.

$$\begin{aligned} d(m_3^1, m_3^2) - L_1 &= 0 \\ d(m_3^2, m_3^3) - L_2 &= 0 \qquad (11) \\ d(m_3^3, m_3^1) - L_3 &= 0 \end{aligned}$$

Additional equality constraints (e.g. to maintain fixed angles) are described in [Oskam, 2007-1]. The DAE system described above has been implemented in MATLAB, using a fixed-step RK-4 solver, together with a discrete Lagrange multiplier [Ten Dam, Lammen, and Rozema, 2005] that handles the constraints. This implementation is suitable for transfer to real-time simulation environments. An illustration of the model behaviour with respect to the constraint formulations (5), (6) and (9) is shown in figure 4 below.

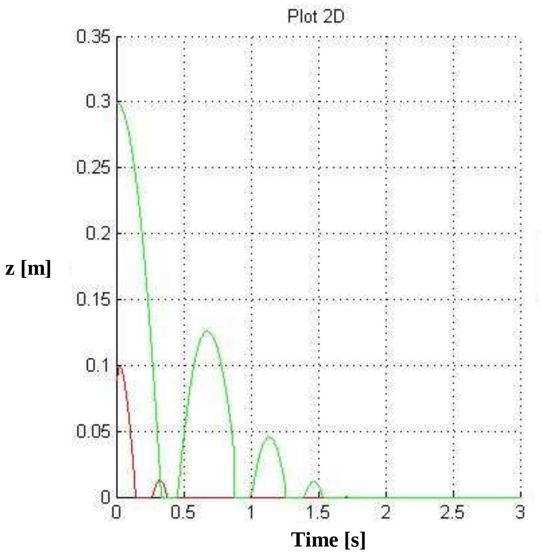

Figure 4. Impact simulation in MATLAB. Plot of vertical position of wheel contact points of main landing gear (red curve) and nose landing gear (green curve). The intervals during which *z=0* represent the contact. Release is caused by an upward motion due to the spring dynamics, resulting in $\lambda < 0$.

An important part of the landing gear system, which concerns the landing impact is the shock absorber. Aircraft landing gear typically contain oleo-pneumatic shock absorbers, with the interaction of oil and nitrogen gas (see figure 5). To take the modelling one step further, the linear springs that represent the shock struts of the landing gear have been replaced by the non-linear gas springs, with the behaviour according to the formula

$$p = p_0 / (1 - A\Delta l / V_0)^{\kappa}, \qquad (12)$$

with:

P : pressure of the nitrogen gas,

p_0 : pressure of the gas in fully extended condition,

A : area of the pressure surface,

Δl : compression of the shock strut,

V_0 : volume of the gas in fully extended condition,

K : gas law power coefficient.

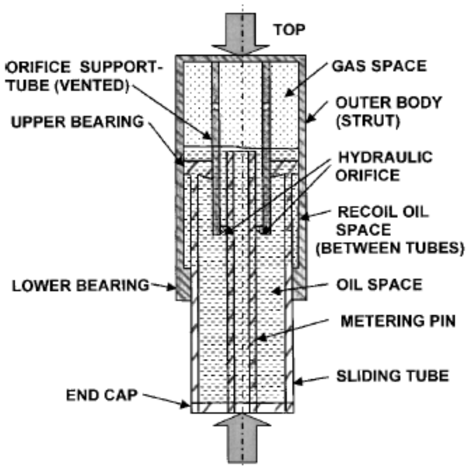

Figure 5. Two-dimensional view of a typical shock absorber [Chester, 2002].

Besides the application of real-time simulation the landing gear simulation model has been adapted for structural analysis. To fit in with the application of structural analysis of landing gear, models have been derived also to be applied in combined FEM/ multi-body simulations (e.g. with the ADAMS and Abaqus simulation software), see figure 6 below and [Oskam, 2007-2].

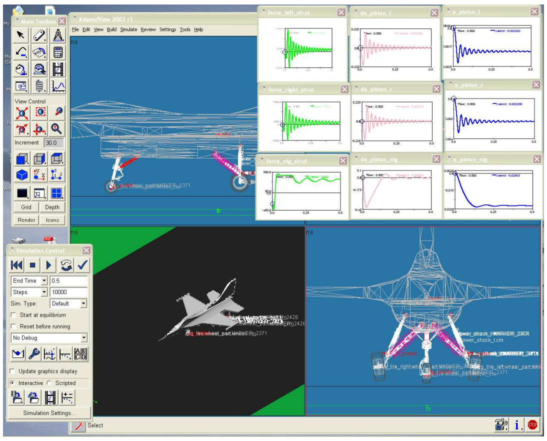

Figure 6. Example of F-16 simulation in ADAMS.

In the ADAMS environment tyre models have been added to the simulation, based on Pacejka's Magic Formula [Pacejka, 2002]. This will allow for the study of other important non-trivial phenomena like shimmy [Besselink, 2000]. Also in this case the simulation of impact effects will remain an important challenge as it involves the modelling of multiple contact points.

4 Impact on wing leading edges

Among the most challenging impact problems is the prediction of bird strike on aircraft leading edges. Bird impact simulations are of a highly non-linear nature. From computational point of view the contact algorithm has to cope with large deformation and splitting of the bird, sliding of the bird over the flexible structure and the creation of multiple contact interfaces due to fracture and penetration of the leading edge.

Bird strikes are difficult to avoid and therefore it is important to reduce the effects of a strike. Each aircraft must be designed to assure capability of continued safe flight and landing of the aircraft after impact with a bird. As such, certification requires an expensive bird strike test to show compliance with the rules. Aircraft designers therefore are eager to predict the behaviour of the structure first-time-right which reduces greatly the design and development time and costs.

In a preliminary design phase, where the structure to be designed is only roughly known, it is difficult to size the structure against impact. For metallic components, basic design guidelines for bird impact exist. These guidelines consist of empirical formulae derived from experimental results. An often used formula is the Royal Aircraft Establishment (RAE) formula [McNaughtan, 1972]. It was derived in the early seventies based on numerous impact tests with real birds. The formula predicts the penetration velocity (i.e. the critical velocity at which the bird penetrates the wing) of the leading edge as function of the bird and geometrical properties:

$$V_p = 98 t W^{-1/3} \cos^{-2/3} \alpha e^{1234(r^2+30r+1000)^{-1}} \qquad (13)$$

with

V_p : penetration speed (in knots),
t : leading edge thickness (mm),
W : weight of the bird (kg),
α : impact angle (radians),
r : nose radius of the leading edge (mm).

Application of (13) to the design of impact resistant leading edges does however lack the inclusion of material information on composites or fibre metal laminates. Also important structural information about the type of connection between parts (e.g. riveted or bonded) is not included. Impact tests on components built of composites or fibre metal laminates have shown that this formula must be adapted. This observation has been confirmed in actual material tests performed at NLR [Van Houten and Kaplan, 2006]. Direct application of (13) leads to rather conservative lay-out and thickness characteristics of components, and in turn leads to thicker and hence heavier structures than necessary.

Due to innovative leading edge designs with an increased use of composites and fibre metal laminates, there is a strong need in industry for a more accurate methodology which can assist the designer in the pre-design and development phase. At NLR there is a strong research focus [Van Houten, 2006] on improved algorithms that accurately predict impact behaviour such that actual tests are performed on a first-time-right basis.

The bird impact behaviour on the wing leading edges is simulated according to the multiple contact model as explained in section 2, equation (7). The most common way to model the bird is the smoothed particle hydrodynamics (SPH) method. The SPH method is a meshless or grid-less method where the bird is divided into a set of discrete elements, see figure 7.

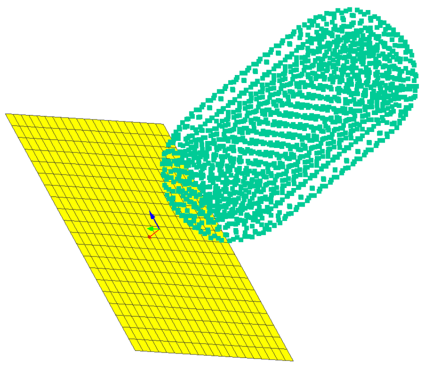

Figure 7. The standardized SPH bird model has a cylindrical shape with hemispherical end caps. On impact, contact between the particles and the surface of the leading edge is established in a node-to-surface contact definition.

These particles have a spatial distance known as the smoothing length *h*, over which their properties are smoothed by a kernel function *W*. This means that any physical property of any particle can be obtained by summing the properties of all other particles which lie within two smoothing lengths distance. The value of any scalar quantity φ at any position *r* is given by the equation:

$$\varphi(r_i) = \sum_j m_j \frac{\varphi_j}{\rho_j} W\left(\left|r_i - r_j\right|, h\right) \qquad (14)$$

with

- φ_j : any scalar physical quantity φ per m^3 volume about particle *j*,
- m_j : the mass of particle *j* [kg] ,
- ρ_j : the density of particle *j* [kg/m^3],
- W : kernel function,
- h : smoothing length [m],
- r_i : 3-dimensional position of particle *i* [m].

Instead of performing numerous experimental bird impact tests, bird impact simulations have been performed on leading edges of various size, lay-out and material based on a full factorial design of experiments. A typical leading edge shape is shown in figure 8. At a speed of 160 m/s the leading edge is penetrated.

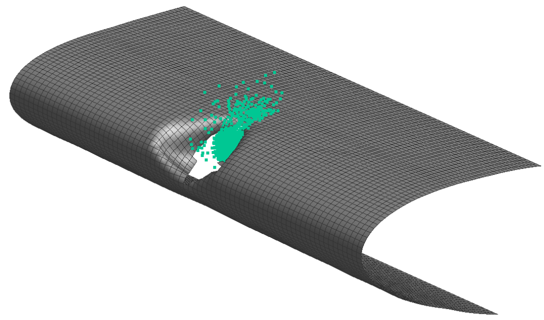

Figure 8. Result of a bird impact simulation with a speed of 160 m/s. Full penetration of the leading edge occurred. Part of the SPH bird is diverted over the outer skin and a part has penetrated the wing.

The contact forces for two impacts at a different speed are shown in figure 9. The non-smooth contact behaviour is clearly visible.

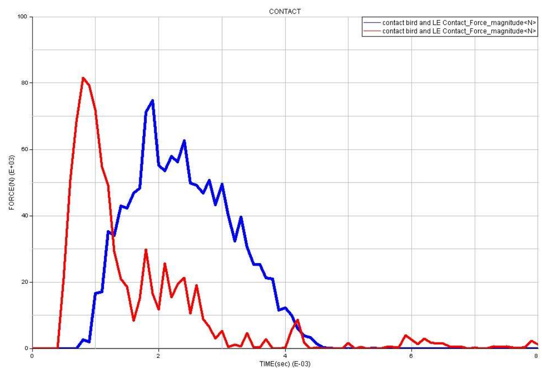

Figure 9. Impact force of the bird on the leading edge (blue line 100 m/s, red line 160 m/s).

The evaluation of the results of the experimental design is part of work in progress. It will lead to improved design methods for impact on leading edges.

5 Conclusions

This paper shows that one common mathematical approach is suitable for different applications of impact simulation in critical aircraft components. Both the multi-body type landing gear models with the emphasis on real-time simulation and the computational mechanics model of bird wing collisions for wing structural analysis originate from the same Lagrangian approach of contact modelling.
The innovations of the mathematical models are essential to fulfil the demand for predictive impact simulation of aircraft components. It is widely acknowledged that predictive simulation models provide a methodology for virtual testing and therefore reduce the time of development and testing of aircraft components. Especially in the current trend of using innovative materials like composites and fibre metal laminates rather than metal, digital impact

studies are a critical factor in the successful design of aircraft components.

At NLR current work is dedicated to the simulation of landing gear dynamics interaction with flexible bodies and to the improved design methods for impact on wing leading edges. Both applications involve innovative design methods.

Acknowledgement

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