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Automatic tool-based pre-processing of generic structural models for water impact simulations in the aircraft pre-design

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Abstract. The integration of automated tool capabilities for the generation of models for transient dynamic calculations in the scope of the aircraft pre-design is described in this paper. The Python-based DLR framework PANDORA, initially developed for the modelling and the sizing of aircraft structures in multidisciplinary process chains, is considered for this work. The focus lays on the generation of suitable numerical models for the water impact simulation. To enable this, the internal tool database was extended to consider additional features such as contact definitions, mesh-free formulations, enhanced connection models and specific control options. The generation of the CPACS-based FE aircraft model was extended by means of discretisation and additional structural components. The generation of the water domain was also included according to user defined inputs like pool dimensions, initial conditions and the selection of an appropriate fluid modelling approach. In addition, a feature to launch a simulation directly within the framework was included. Finally, options to retrieve and visualize results from finished water impact simulations were also integrated, allowing to display contour and time history plots.

1. Introduction

In early development stages of a novel aircraft type multiple disciplines contribute to find one or more configurations capable to fulfil the certification requirements and the so-called top-level aircraft requirements including capacity, flight range, performance, and fuel consumption. The aircraft specific disciplines in the design process include aerodynamics, structural design, engine design, cabin concept, flight mechanics, costs, and others. This complex multidisciplinary design process requires efficient and accurate iterative virtual process chain solutions to avoid time and cost intensive modifications in the later detailed design stage. Early applications of computer-aided methods for the structural aircraft design include approaches like PrADO (Preliminary Aircraft Design and Optimization), developed at the TU Braunschweig [1], and higher fidelity tools like MIDAS (Multidisciplinary Interactive Design and Analysis System) including developments by NASA [2]. Industrial applications especially for the structural optimization include LAGRANGE by Cassidian (Airbus Defence & Space since 2014) [3] and FAME-W (Fast and Advanced Mass Estimation-Wing) by Airbus [4]. An overview of multidisciplinary design developments is provided in more detail e.g. in [5].

At DLR (German Aerospace Center) a software framework, a data exchange format, and several specific disciplinary tools to contribute to the objective of comprehensive virtual pre-design optimizations have been established. A design framework dedicated to the parametric modelling, sizing and high-fidelity static structural analysis of the airframe is PANDORA (Parametric Numerical Design



and Optimization Routines for Aircraft). This Python-based tool is developed at the Institute of Structures and Design of DLR since 2016 and incorporates functionalities from individual predecessor tools. Also, the modular architecture of the framework allows to extend capabilities and to integrate new features [6]. Motivated by this possibility to integrate new processes and the vast expertise at the Institute in the field of transient dynamic aircraft analyses under crash or water impact conditions (e.g. in [7] and [8]), the extension of PANDORA for the generation of suitable models for FE (Finite Element) analyses with explicit time integration is presented in this work with special focus on the integration of processes and features of a former DLR-tool for ditching simulations. Thus, the range of analyses in aircraft pre-design is enhanced by including crashworthiness aspects in the multidisciplinary process chain.

In the first part of the paper the approach for the structural analysis in the scope of a multidisciplinary process chain using a standardized aircraft model description schema is explained, followed by the implementation of tool capabilities for nonlinear explicit calculations. Then, the application of the new processes and features are presented with an exemplary full-aircraft ditching simulation. Finally, conclusions and an outlook of this work are given in the last section.

2. Structural analysis in a multidisciplinary aircraft design process chain

For the design of new aircraft configurations in the pre-design phase, a multidisciplinary process chain is considered at DLR. The disciplines participating to the process contribute to the generation of specific aircraft parameters with their individual tools and inputs. The iterative design process is accomplished by using a framework with arbitrary tool interfaces to establish a connection to the respective tool. The data exchange between tools is handled using an XML-based data format called CPACS (Common Parametric Aircraft Configuration Schema) that was initiated by DLR [9]. Disciplinary design tools can directly exchange data using the CPACS file format. For the structural analysis of the aircraft fuselage primary structure the tool PANDORA generates structural FE models which are used for numerical calculations according to critical load cases and for subsequent structural sizing of the primary structure.

2.1. Multidisciplinary data exchange

The exchange of data in the multidisciplinary aircraft design environment is achieved using CPACS. This data set format describes the aircraft system as a whole in a standardized hierarchical manner. Aircraft data are gathered in branches for specific disciplines and all individual parameters are stored in nodes in an XML-file [9]. Each individual tool uses the CPACS file to read the parameters needed for a certain operation. New or modified data are stored in the same file and handed over within the process chain. The application of this open source data exchange schema has already been demonstrated in several aircraft design projects. Figure 1 shows a representative part of the CPACS data schema.

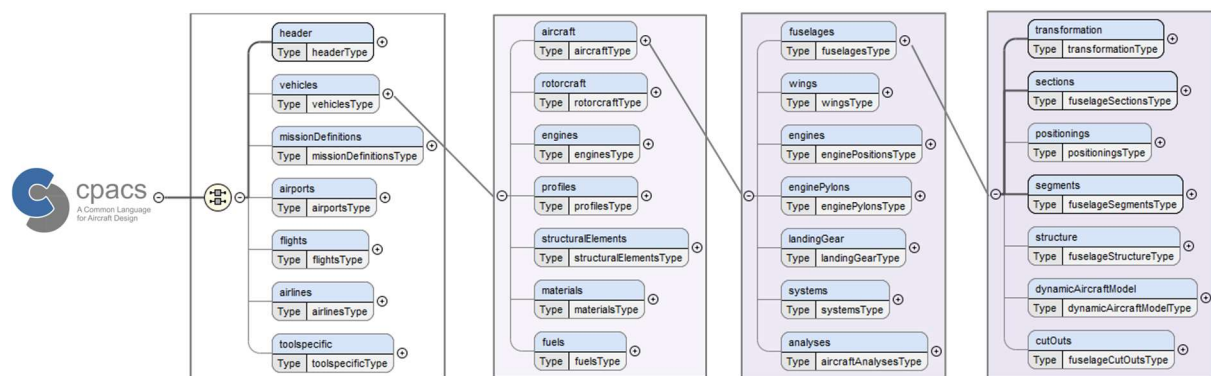


Figure 1. CPACS data schema. Aircraft fuselage nodes containing parameters displayed on the right.

The topmost CPACS branches describe the air transport system. The vehicle type is located in the next level, e.g. 'aircraft' in Figure 1. This branch includes the description of the fuselage, wings, engines, and systems with a detailed data input below each node. The fuselage, for example, includes selected nodes for geometrical description using sections, positionings and segments, structure, and others.

2.2. Framework for the virtual structural analysis of aircraft structures

An important objective of the iterative multidisciplinary process is to design a lightweight aircraft structure capable to withstand all expected critical loading conditions according to certification requirements. Considering different structural concepts able to fulfill these requirements, the assessment of the most favorable concept can be determined by its weight. For the estimation of the structural mass of the fuselage the PANDORA framework is used. In general, PANDORA retrieves the data stored in a CPACS file related to the geometry, structural description, profiles, loads, and materials (see Figure 1) to generate a FE model. The description of this FE model includes nodes, elements, properties, and other data that are stored in the internal data format. By using additional tool functionalities these generally tool independent data can be converted to a specific format of an external solver in order to launch linear static analyses which are used in a structural sizing loop. For this sizing an arbitrary number of load cases and different sizing criteria in an iterative process are considered, resulting in the estimation of the primary mass. A detailed description of PANDORA can be found in [6].

PANDORA is written using the Python programming language and structured in a modular fashion with independent packages dedicated for specific functions. These packages can be classified in three main classes: CPACS-based, FE-data based and packages for additional utilities. CPACS-based packages are used to access the XML-file, to handle the CPACS data and to generate a surface geometry or a FE model based on these data. Further, the functionalities of the FE-data based packages are used to define the internal FE data format (FE_PYPREP), to provide interfaces to specific solver formats (FE_CONVERTER) and to process the sizing of the model (FE_SIZER). In addition, utility packages provide auxiliary functions such as for mathematical transformations, to support geometrical activities or for the visualization of data. A GUI (graphical user interface) is integrated in the framework to handle models and results outside the Python environment. Figure 2 gives an overview of PANDORA.

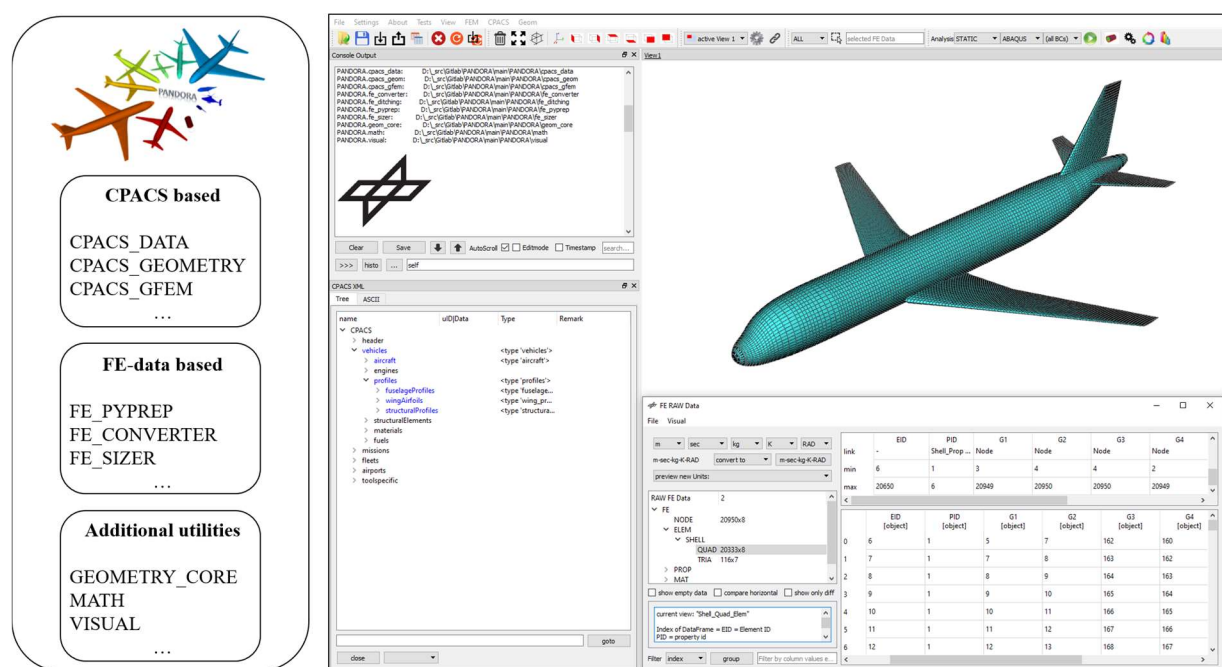


Figure 2. PANDORA framework. Left: main packages and classes. Right: GUI including a CPACS-based aircraft model, some FE data in the internal data format, and the CPACS hierarchical tree.

Conversion algorithms to read and write specific solver formats are included for different proprietary and open-source FE codes. Also, an interface for HDF5 (Hierarchical Data Format) is available. After numerical computations for the static sizing are completed, the updated structural description (e.g. sheet thickness) and the estimated fuselage structural mass are stored in the corresponding nodes in the CPACS data, e.g. in the aircraft mass breakdown (lower level of the analyses node in Figure 1). To close the loop, an XML-file with the modified CPACS data can be exported for further utilization in the multidisciplinary aircraft process chain. The functionalities of the tool PANDORA were demonstrated in the project VICTORIA with the modelling and sizing of the fuselage structure of a long-range twin-aisle aircraft design [10].

3. Tool capabilities for the structural analysis in water impact scenarios

PANDORA functionalities were extended for transient dynamic numerical computations in the scope of a DLR project on innovative commercial aircraft cabin design concepts. The assessment of the structural integrity of fuselage designs integrating these new cabin concepts is extended in this project by the analysis under ditching conditions. Ditching, the planned emergency landing on water, is considered in the crashworthiness requirements for the certification process of new aircraft (e.g. CS 25.801) and its investigation including the structural response during impact, in the subsequent landing phase and during evacuation is demonstrated by the aircraft manufacturer in order to increase the survivability of the occupants [11]. At DLR, ditching is investigated with numerical computational methods which are favorable in terms of kinematic and structural analysis. In the past, the tool AC-Ditch was developed for the automated pre-processing of FSI (Fluid-Structure Interaction) models for ditching computations with a coupled SPH-FE (Smoothed Particle Hydrodynamics - Finite Element) approach using a proprietary explicit FE code [12]. The integration of functionalities from this tool into the PANDORA environment and required extensions for the automatic generation of generic code-independent ditching models for calculations with diverse FSI numerical approaches are presented in this section.

3.1. Extension of features and conversion capabilities for transient dynamic calculations

In this work, the FE-based packages of the tool were extended to include the description of the water impact model in the internal PANDORA data format and to include new interfaces to convert these data to different codes for transient dynamic numerical calculations with an explicit time integration schema. First, a new fluid material input was implemented in the data format to consider the EOS (Equation of State) via a polynomial or an exponential definition. In addition, element, properties and control data required for the fluid description were implemented for the SPH approach. To couple the fluid particles to the FE representations (e.g. the fuselage or fluid volumes) the format was extended for a node-to-surface penalty contact model. Moreover, initial and time dependent conditions for the fluid and the structure (displacement, velocity and acceleration) were included in the data base. Additional data tables for features like tied interfaces, joint elements, lumped masses, slide contacts, and functions (e.g. stress-strain curves) were also implemented to cover advanced detail levels of structural models. Finally, new schemes for control parameters such as time step inputs, simulation end time, output settings and solver-specific entries were also integrated.

Secondly, new conversion algorithms were implemented for the data conversion to explicit solvers. Two proprietary codes suitable for water impact computations were initially considered. In this process, the new conversion algorithms were also extended to retrieve result data in addition to the parser and writer functions. Since in transient dynamic calculations models can be defined using different unit system declarations, the handling of data was enhanced by the development of a function to set or convert a user-defined unit system to the model, which automatically modifies length, time, mass, temperature and rotational displacement units according to the selection.

The verification and validation of the described extensions, especially of the conversion capabilities, were conducted using a benchmark study with the coupled SPH-FE approach with models of different complexities, from drop-test models with a purely vertical impact velocity over water impact models with combined vertical and horizontal impact velocities in a guided motion to simple ditching tests with vertical and horizontal impact velocities in a free motion. Simulation results are exemplary presented for the guided ditching test (Figure 3, left). The benchmark study showed a very good agreement between calculations with both codes after model conversion with PANDORA, as presented in the example with the comparison of the response of a flexible reinforced panel to the hydrodynamic loads in the guided ditching condition (Figure 3, center and right).

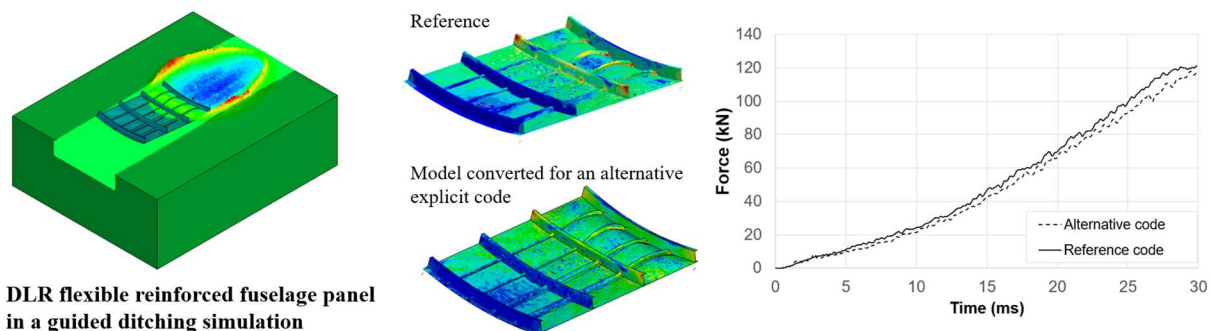


Figure 3. Exemplary benchmark to assess new features and conversion capabilities. Left: contour plot of the vertical displacement of the fluid at 30 ms. Center and right: comparison of the structural behavior between the reference (top) and the model converted for an alternative solver using PANDORA.

3.2. Extension of additional aircraft structures

For structural analysis with transient dynamic computations models discretized with a high level of detail and finer mesh sizes compared to classical stress models reproduce large deformations and structural failure more precisely. Using the CPACS-based packages in PANDORA an aircraft GFEM (Global FE Model) can be generated. In [6] the generation of the center wing box and the keel beam in the center fuselage section, the cabin and cargo floor, the pressure bulkheads, and the reinforcements in the tail section was under development using shell elements. The use of an aircraft model with the mentioned structures is intended for water impact simulations. However, purely extruded representations with restrictions in element size and aspect ratio lead to a high computational effort. The package for the generation of the model was therefore extended to consider an alternative approach with the discretization of the floor structures and the tail reinforcements using beam elements. Further, for the generation of a DFEM (detailed FE model) a new algorithm was created for the refinement of the flexible FE model with a finer mesh discretization in selected sections. This new feature is under development. Figure 4 presents an example of a refined aircraft fuselage section including the cabin and cargo floor structure. The fuselage design corresponds to a short to mid-range aircraft model.

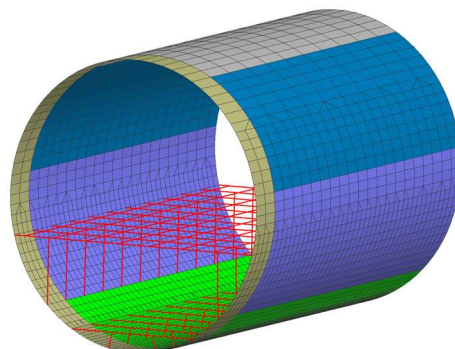


Figure 4. Refined aircraft fuselage section model. The finest mesh (in green) is located in the bottom, as this is the most relevant area for structural analysis under water impact conditions. Cabin and cargo floor structures are depicted in red.

3.3. Extension of ditching capabilities

A new package based on the functionalities of the former DLR-ditching tool AC-Ditch was integrated into the FE-based packages in PANDORA to generate the fluid model and include FSI features. The set-up of the package is modular and parametrical, allowing to incorporate separate algorithms for different numerical fluid modelling approaches with specific definitions. The fluid domain is a water basin with a calm and flat top surface definition. Geometrical parameters are introduced to define the dimensions of the domain for each individual application case. The main approach using Python routines is hybrid. The interior of the fluid domain (used for the impact of the structure) consists of SPH particles that represent a specific water volume. This method is required due to the expected high fluid deformations in this zone during impact. Continuum elements to represent water volumes are then automatically generated surrounding the SPH core on the sides and the bottom to reduce computational effort and to avoid numerical boundary effects. The outer surface nodes of these elements are used to fix the pool in space using boundary conditions. The algorithm generates also global properties for the particles and the FE volumes. The Murnaghan EOS (type exponential) is introduced in the material definition for both representations. Further, the SPH core and the surrounding FEs are coupled via a node-to-surface penalty contact model. The new package called FE_DITCHING is completed by a new widget in the GUI to handle pool generation and ditching features outside the Python environment. Figure 5 shows the new integrated capabilities for water impact computations.

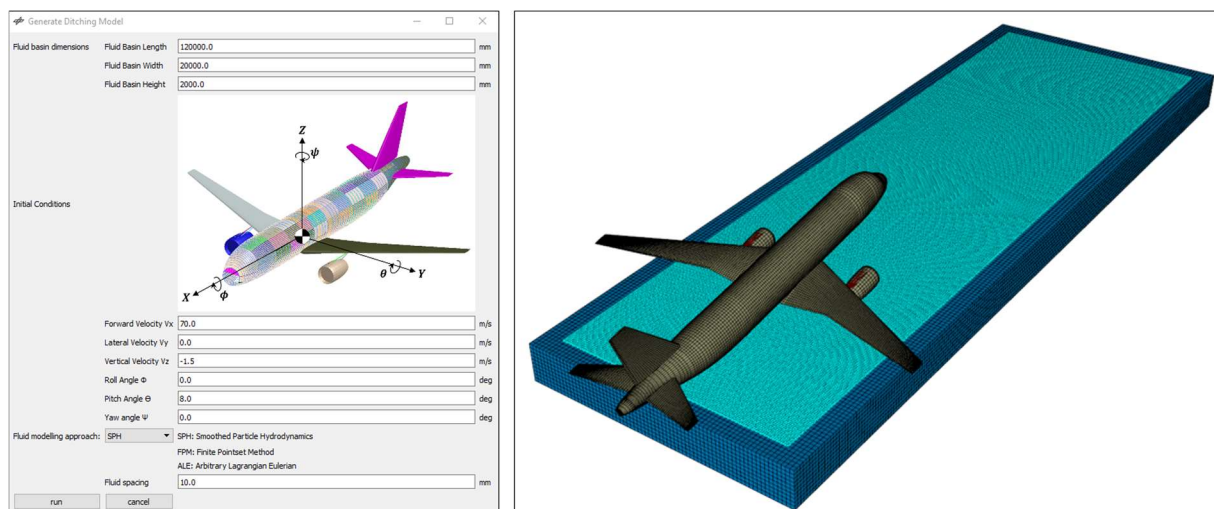


Figure 5. Novel tool capabilities for water impact simulations. Left: New widget for the user-defined pool generation and ditching model description. Right: pool generated using the hybrid SPH-FE approach. Generic aircraft model included in the model set-up.

In addition to the SPH method the integration of alternative fluid modelling approaches is under development, such as of the FPM (Finite Pointset Method) and the ALE (Arbitrary Lagrangian Eulerian) methods, which can be used with at least one of the considered explicit solvers. The generation of the water domain is integrated within the internal PANDORA data format. The aircraft model is generated as a rigid or flexible body using the tool functionalities described above to be then coupled to the global ditching model. Also, the inputs for the initial conditions of a ditching simulation (Figure 5, left) are added. Finally, to limit the computational effort the aircraft model is positioned close to the water surface at the end of the water domain to achieve the water impact within the first iterations of the analysis.

Besides the features described above, further PANDORA functionalities were extended to launch the explicit calculation with a user-selected solver, to retrieve results after the completed simulation, and to plot results directly in the PANDORA GUI. By this, capabilities for structural analysis in transient dynamic ditching simulations can be integrated into the established aircraft design process.

4. Application in a ditching simulation

The implemented PANDORA capabilities for water impact calculations are demonstrated with a ditching simulation using a CPACS-based generic fixed-wing aircraft model. The aircraft configuration is conventional, a commercial single-aisle twin-engine model for short to mid-range applications. The fuselage, empennage and engines are discretized using shell FEs. In the presented case the model is rigid with pre-defined mass properties defined at the center of gravity position of the aircraft. The initial conditions of the aircraft before impact on the fluid surface are sink rate 1.5 m.s^{-1} , forward velocity 70 m.s^{-1} , and pitch angle 8° . The water domain is modelled using the hybrid SPH-FE approach. The total dimensions of the domain are length 84 m, width 28 m and height 4 m. The simulation run time is 250 ms and includes the impact and the initial landing phase. The simulation was launched using PANDORA for the calculation with an explicit solver in a local computer using 4 processors. After the ditching simulation was completed around 3.5 h later, the results were automatically retrieved in the tool. Figure 6 depicts simulation results in PANDORA with the contour plot of the nodal displacement in z-direction.

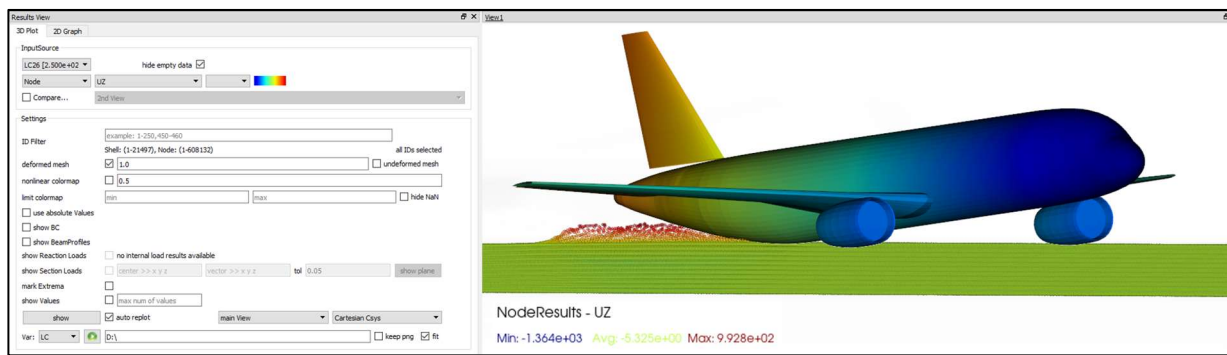


Figure 6. Visualization of results in PANDORA of a ditching simulation with a transport aircraft model at 250 ms. Contour plot of the nodal vertical displacement of the fluid particles and the aircraft (in mm). Outer FE fluid volumes hidden for visualization of the water particles in the interior.

In addition to the generation of 3D plots for nodal displacements, other display options are available such as the visualization of stresses for shell elements, similar to classical linear analyses. Time history data may be displayed either in 2D or 3D graphs. In Figure 7, an exemplary time history graph of the nodal displacement in vertical direction of the center of gravity position of the aircraft is presented. Moreover, displacements and rotations in other directions may be plotted to analyze the kinematics of the model in more detail.

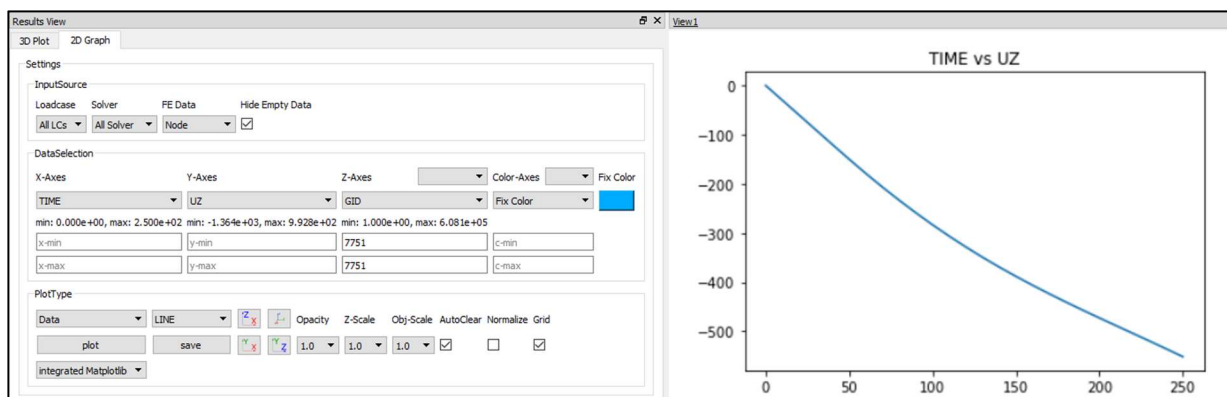


Figure 7. Visualization of ditching simulation results in PANDORA for a generic transport aircraft model. Nodal vertical displacement time history of the center of gravity position of the aircraft (in mm).

5. Conclusions

New functionalities were integrated into the framework PANDORA to include structural analysis under crash or water impact conditions in the aircraft pre-design process chain. The extension of capabilities includes internal data format enhancements, new conversion algorithms for explicit solver formats, and improved discretization options for structural representations. Based on the former DLR ditching tool AC-Ditch, a new package for the automatic generation of models for water impact simulations was integrated. The aircraft FE model is created using model generation packages in PANDORA. For the discretization of the water domain alternative methods can be implemented. The current focus is on a hybrid SPH-FE approach. The ditching simulation can be launched directly within the GUI and results can be automatically retrieved after the calculation is finished. Finally, results can be plotted in the GUI, allowing for the analysis of the structural or kinematic response of the aircraft during ditching.

6. Outlook

With the introduction of the novel tool capabilities further objectives are pursued. The integration of a new interface for data conversion to an additional proprietary explicit code is foreseen for further numerical method comparisons. Also, the automatic generation of refined sections in flexible structural models and new features like the modelling of cutouts are in development to increase the level of detail of models for water impact simulations. In addition, the algorithms to generate the water domain with the alternative fluid modelling methods FPM and ALE will be finished to complement the SPH approach. Finally, larger and more detailed models may be considered with the extension of the framework to launch ditching simulations with a computer cluster. In the end, characteristic ditching parameters can be included in the data exchange format for its consideration in the virtual process chain.

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