THE DEVELOPMENT AND VALIDATION OF A NUMERICAL MODELLING APPROACH FOR ROTORCRAFT DITCHING

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In light of a number of instances of helicopters ditching, the safety and survivability of helicopters during and after ditching is undergoing increasing scrutiny by manufacturers, operators and regulators. This paper presents a summary of the numerical simulation approach that Frazer-Nash Consultancy Ltd has been working on to model both the initial ditching transient and the post-ditching stability of helicopters. The time domain simulation tool, HydroDyna, uses a combination of explicit calculations, empirical data and high fidelity Computational Fluid Dynamics simulation data to calculate the fluid loading on the fuselage and the resulting dynamics. Extensive validation has been successfully completed, culminating in the presentation of two case studies based on AgustaWestland's Lynx Wildcat and AW101. These case studies explored the ditching envelope of the Lynx Wildcat and the performance of flotation bags on the AW101. The case studies demonstrate the suitability of HydroDyna to model both the initial ditching transient and the post-ditching stability of helicopters as a flexible, repeatable and economic alternative to scale model tests.

1. INTRODUCTION

A number of instances of helicopters ditching have been reported in national media, putting a spotlight on the safety of offshore helicopter operations, particularly in regions prone to poor weather and sea conditions such as the North Sea (Figure 1). Therefore, the safety and survivability of helicopters during ditching is undergoing increasing scrutiny by manufacturers, operators and regulators [1].

Figure 1 – Helicopter ditching in the North Sea

This paper presents a summary of the numerical modelling approach that Frazer-Nash Consultancy Ltd (Frazer-Nash) has been working on to calculate both the initial ditching transient and the post-ditching stability, as a flexible, repeatable and economic alternative to scale model tests. This approach can be use to support assessment of structural integrity and occupant survivability, advise on the impact of design choices or modifications, or to provide evidence for certification.

This work builds upon a methodology based on Frazer-Nash's HydroDyna software, which has been extensively used and validated in the aerospace and marine industries. This paper in particular focuses on the continued development and validation of the HydroDyna technique for ditching assessment following the initial demonstration of its feasibility [2].

Following an appraisal of the various methods available to assess ditching and a description of the HydroDyna methodology and its validation, this paper presents two case studies of helicopter ditching and post-ditching stability assessed in conjunction with AgustaWestland, including comparison to scale model ditching tests.

2. KEY FACTORS THAT INFLUENCE DITCHING

Manufacturers often have estimates of the ideal speeds and descent rates that pilots will be able to achieve prior to impact. However, as evidenced by recent ditching events, weather and the state of the helicopter may cause the actual ditching conditions to be different. Therefore, it is desirable to be able to assess a wide range of sensitivities to provide comfort that loads on the airframe, dynamic behaviour, and acceleration of occupants remain acceptable across the range of potential impact conditions.

These factors typically include:

- Forward speed
- Descent rate
- Sea state
- Heading
- Attitude

It may also be of interest to understand the effect of airframe features on ditching, such as design modifications, fairings, undercarriage or stores. These features may remain intact during ditching or in some instances may fail or flood.

Furthermore, the influence of rotor lift is uncertain as it depends on the degree of autorotation achieved and the rate at which rotor energy is lost during the flare.

Whichever approach is used to assess ditching, it should be capable of assessing the effect of the factors of interest.

3. APPROACHES TO ASSESS DITCHING

Various ways have been used across industry to assess the ditching performance of fixed and rotary wing aircraft. This section discusses them and some of their advantages and limitations.

3.1. Examination of real ditching events

A great deal can be learnt from the forensic examination of full scale ditching events. Fortunately for crew and passengers, there are only a limited number of actual ditching events and only a few of these are at known conditions that can provide any sort of data against which to assess a design. The US Airways Hudson River ditching (Figure 2) is one useful example where initial conditions and the resulting levels of damage are known.

Figure 2 – US Airways Hudson River ditching

3.2. Scale model tests

Traditionally, ditching tests have been conducted using scale models in tanks, with the performance of the model reported via instrumentation typically in the form of accelerometers and discrete pressure transducers (Figure 3).

Scale model testing brings several benefits over numerical modelling. Being a real model there are no assumptions or approximations of the physics. Furthermore, as a mature form of assessment the results from testing are generally the most trusted of any dataset. The limitations of the testing configurations and measurements are well understood and accepted.

However, there are a number of significant disadvantages associated with testing. Physical tests are rarely at full size, introducing scale effects that need to be accounted for in both the test design and subsequent data analysis. For example, in aircraft ditching, the aerodynamic effects (e.g. capturing the stalling characteristics of a wing) has been shown to be as important a factor as hydrodynamic effects at and beyond impact. These effects can be challenging to capture exactly within a single scale model and, therefore, some compromise is generally required to achieve an acceptable representation of both.

In order to capture ditching dynamics at scale it is necessary to represent both the geometry and inertial characteristics. In order to achieve the correct scaled mass and mass distribution, this can lead to the use of model materials that are susceptible to breakage or degradation through repeated impact with water.

Finally, another limitation of physical testing is that of repeatability. The ability to compare the performance of several designs under identical conditions is of clear importance. However, as the complexity of tests increases, controlling all the variables becomes more difficult; for example, reproducing an identical irregular wave train, or achieving impact on a certain part of the wave. Confidence can be obtained through repeated measurement of specific configurations, although this can have a significant impact on the time to complete a test programme. Once the tests are finished there is seldom opportunity to revisit specific configurations to further understand interesting trends emerging from the measured data.

In summary, using scale models for ditching assessments is a well understood and accepted approach and can provide valuable data for use in design or for the validation of numerical models. However, there are several limitations associated with scale effects and repeatability that can be alleviated through numerical modelling.

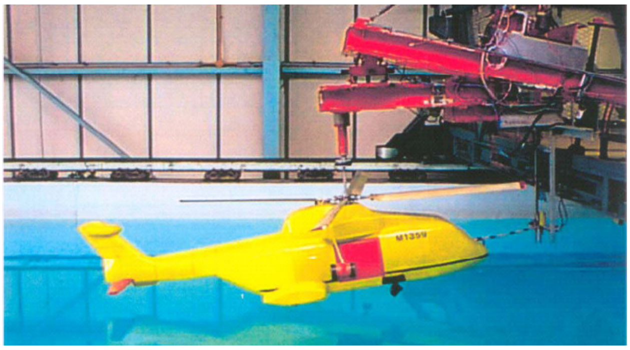

Figure 3 – Scale model of AW101

3.3. Numerical analyses

Numerical simulation provides a means to efficiently model different designs at full scale. The timescales and costs associated with constructing multiple CAD models are generally lower than for building physical scale models, particularly when an iterative or parametric study is being undertaken. Results gained from modelling are more extensive and readily available than from physical testing and can include:

- Translational and rotational accelerations, velocities and displacements
- Fuselage surface pressure transients
- Slamming pressures upon impact
- Degree of submergence

The constraints, such as tow tank size, present with physical testing can be removed in virtual space, increasing the range and duration of tests that may be run in a controlled environment (e.g. post-ditching stability). This provides the opportunity to gather statistical data and relate it to, for example, the performance of a floatation system in irregular seas.

When the detail of a single event (e.g. the initial ditching transient) is of interest, the ability of numerical modelling to repeat a combination of test variables exactly makes the comparison of designs significantly easier. Once complete the results of numerical assessments can be easily accessed to further interrogate the data.

The major limitation of numerical modelling is that in order for the benefits to be realised, the user must have confidence in the outputs. In practice, this requires some formal validation against experimental data or cross-verification of the model against another trusted assessment approach.

In summary, numerical models can be extremely powerful as they often enable experimental constraints to be relaxed and permit the rapid assessment of a range of configurations. However, in order for them to be used within the design and certification processes with confidence they need to be thoroughly validated.

3.3.1. High fidelity methods

Much work has been undertaken by various companies and researchers into the use of high fidelity numerical methods for ditching assessment. These include Finite Volume Computational Fluid Dynamics methods (commonly referred to as CFD), Smoothed Particle Hydrodynamics (SPH) and Arbitrary Lagrangian-Eulerian (ALE) methods.

CFD could be used for ditching applications when combined with moving mesh physics to capture the full six degree-of-freedom behaviour. However, the capture of free surface behaviour in a purely Eulerian solver is challenging and can result in either a highly diffuse (foam-like) air-water interface for reasonable model time-steps. Sharply captured air-water interfaces can be obtained at significant additional computational cost. The use of CFD for the assessment of wedge drop tests and free-fall lifeboats has been well document. However, in these cases the lack of forward speed aids the calculation by significantly reducing the size (hence cost) of the computational domain.

SPH methods were also assessed for their ability to model helicopter ditching. Unlike CFD, SPH is a Lagrangian method which represents the fluid continuum as discrete particles. For free-surface applications it is generally not necessary to model the air phase, with the air-water interface being defined by the extent of the water-phase particles. The computational cost of the SPH method is broadly comparable to that of CFD.

Whilst the ditching animations that were returned were visually plausible, it was found that the results, in terms of the calculated body dynamics and surface pressures, were very sensitive to the selection of geometry scale and particle properties (e.g. smoothing length). These parameters had to be tuned to each specific application to match the test data. This significantly reduces confidence in the ability of SPH to support the design and assessment of new platforms where such data for model tuning is not readily available. Although this could change in future.

ALE methods could be a more suitable approach combining the best aspects of Lagrangian and Eulerian techniques within a single tool. However, there appears to be little available in the literature detailing the application of ALE methods to aircraft ditching. Initial tests with ALE methods for ditching have returned similar results to SPH, in that whilst credible dynamics and free-surface deformations can be produced, it is significantly more difficult to obtain surface pressure distributions and time histories which appear physical.

With any of these methods, high forward speeds and the need to represent both hydrodynamics and aerodynamics means that long simulation times are required. While computational capability is rapidly growing, these methods are not yet capable of simulating ditching or post-ditching performance in many instances.

3.3.2. HydroDyna

HydroDyna is a fluid-structure interaction (FSI) code, developed by Frazer-Nash, which is used for a wide range of studies including the assessment of aircraft ditching and high speed planing craft. HydroDyna is based on the LLNL-DYNA3D dynamic finite element package and has been developed over approximately fifteen years. The code has being used extensively for ditching assessments for Bombardier Aerospace and AgustaWestland.

The HydroDyna work programme for Bombardier Aerospace commenced with successful validation of the code against test data and has been followed by its use to support the certification of the CSeries 100 aircraft and variants.

The following section describes the code and its philosophy and functionality in more detail.

4. HYDRODYNA

4.1. Philosophy

The most common approach to model aircraft ditching within HydroDyna is to represent the fuselage as a rigid body; although, the deformation of the structure under the imparted loads can also be modelled. This technique discretizes the airframe surface into small elements and at each instant in time calculates the forces acting on each one. The total force acting on each element is the sum of hydrostatic, hydrodynamic, added mass and slamming components.

These forces are integrated over the airframe and used to predict its motion over a small time step. This process is iterated over the length of the simulation, which normally varies from ten seconds for an initial ditching transient to over an hour for post-ditching stability in an irregular sea.

One of the key features of HydroDyna is the ability to run these simulations very quickly (approaching real time), which allows a wide range of conditions, environments or designs to be economically assessed. To achieve this, the fluid and body behaviour are one-way coupled such that the fluid forces can influence the body motion but the perturbation of the water surface by the body is not modelled. However, the implementation of the fluid loading components (see Section 4.3) accounts for this. Water surface perturbations such as waves can be prescribed *a priori*.

For fixed and rotary wing aircraft ditching it is also possible to represent the salient aerodynamic effects and include frangible components with prescribed failure criteria

4.2. Inputs

The main input to a HydroDyna model is the surface mesh used to define the airframe. This is constructed from a 3D CAD model whose geometry can be imported directly from commonly used CAD packages. The model is built and run at full scale avoiding any potential scaling problems. Figure 4 shows a typical surface mesh, applied in this case to Lynx Wildcat.

It is desirable to have a fine mesh on the airframe, especially in areas of high curvature or where there may be high pressure gradients to allow the forces to be more finely resolved. A coarser mesh is used on areas which are not expected to have loads on them, such as the upper fuselage. As with the water surface, it is not strictly necessary to include these 'dry' regions in the mesh; however, the visual appearance can be greatly increased with their inclusion.

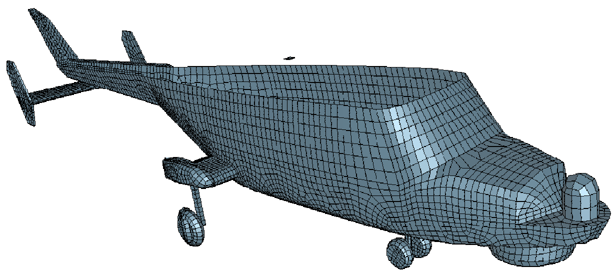

Figure 4 – Surface mesh of Lynx Wildcat model

The mass, centre of gravity and inertia are defined for each rigid body, along with the type and strength of any frangible joints connecting them (for example, an engine nacelle to a wing).

Having defined the aircraft, the environment and initial conditions are set up, including attitude, forward speed, descent rate, rotor lift and its decay or wing lift and stalling characteristics. The sea state can either be flat water, regular waves or a time-domain synthesis of an irregular wave spectrum, with the helicopter moved such that the precise point of impact on a wave can be set.

We have found that the ditching dynamics can be significantly changed by impacting the nose on to the crest of a wave instead of the mid fuselage. This level of precision and repeatability was not evident in comparisons to tank trials where the helicopter model is manually released as it approaches the wave of interest.

4.3. Fluid loading

Fluid loading is calculated on an element-by-element basis for each submerged element at each time-step.

4.3.1. Hydrostatic forces

Hydrostatic forces are explicitly calculated for each element throughout the transient based on depth of each element centroid below the local water surface.

4.3.2. Hydrodynamic forces

The motion of high speed ditching events is dominated by the hydrodynamic loading on the airframe. The hydrodynamic pressure acting on an element is defined by:

(1) $$P = \frac{1}{2}\rho V^2 C$$

The pressure coefficient *C* is a function of the orientation of the element surface to the angle of incident flow. This variation of *C* with incident flow angle is, by default, based on our work on high speed craft. HydroDyna does not explicitly calculate the flow of water around the hull, permitting a very quick solution time. Therefore, to account for the effect of upstream surfaces on the local incident flow direction, it is necessary to determine the variation of *C* across the fuselage through a calibration process.

This calibration process involves running both a CFD and HydroDyna simulation of the helicopter at a common fixed attitude and sinkage in flat water. The CFD runs are static snapshots of the motion (see Figure 5) and are quick to run relative to a full ditching simulation within CFD (See section 3.3.1). The fuselage in HydroDyna is split into smaller regions over which the local flow direction is expected to be reasonably constant. Comparing the hydrodynamic pressure contours from both simulations for each region allows the *C* coefficient to be calibrated, building up a hydrodynamic pressure map in HydroDyna to reflect that derived from CFD.

Figure 5 – CFD simulation of AW101 for calibration of hydrodynamic pressures

4.3.3. Added mass forces

The added mass force is determined from the body acceleration and the entrained mass of fluid adjacent the body. The entrained mass of fluid may be calculated using either a proportion of the displaced mass of water or as a film thickness adjacent each wetted surface element.

The added mass force is applied by the definition of elemental surface pressures which are calculated on a pro-rata basis depending on the projected area of each element.

4.3.4. Slamming forces

Slamming forces are associated with the high magnitude, short duration pressures experienced as a body enters the water. These are based on empirical wedge drop tests and can generate very high loads when structures are nearly parallel to the water surface on impact. These pressures can be attenuated by local panel flexibility, although the extent of this is very dependent on the local structure.

HydroDyna determines the slamming forces based on the impact velocity and angle of each element as it enters the water using the empirical methods described in Stavovy and Chuang [3].

4.4. Outputs

Being a numerical simulation there is a wealth of data that can be output from the simulation. This can include:

- Time histories of attitudes and speeds;
- Time histories of accelerations at any location (e.g. Centre of Gravity, crew seats, equipment locations);
- Transient maps of surface pressures across the fuselage which can be used to calculate local panel failure, fuselage shear and bending or can be mapped on to Finite Element structural models for further detailed assessment;
- Loads on specific joints or components to identify

potential failures (e.g. undercarriage, stores, control surfaces or flotation equipment);
- Visualisations, which are an effective way to communicate the likely behaviour to a wider audience.

As well as providing a wealth of numerical data, the results can be and have been used to advise pilots on the ditching envelope and preferential impact conditions.

4.5. Validation

As with any numerical model, validation is a vital aspect of building confidence in the results that are produced. An ongoing process of validation has been undertaken with HydroDyna throughout its development and use, giving confidence in its outputs.

The validation has included a range of activities, from benchmarking HydroDyna against fundamental FSI test cases (e.g. bobbing cubes and wedge drops), to extensive comparisons against scale model test data for high speed marine craft, aircraft and rotorcraft. HydroDyna has been used extensively to assess the sea-keeping performance a number of offshore and inshore boats for the RNLI. Extensive validation of the code against tank test data has been conducted for the Shannon-class lifeboat [4].

More recently, HydroDyna was subjected to two formal validation tests to provide Bombardier Aerospace with the necessary confidence in its ability to model ditching. These tests comprised simulating scale model tests and comparing the dynamics and fuselage pressures to the test measurements. One test was of a fuselage with a predefined path on to and through the water, while the other was of a free flying model.

This data is proprietary to Bombardier Aerospace so cannot be published here; however, good agreement was shown between HydroDyna's results and the measurements. Hence, Bombardier Aerospace had confidence to proceed with HydroDyna to provide evidence in support of their ditching certification for the CSeries 100 and related variants.

During the validation of the free flying model, HydroDyna demonstrated that the aerodynamics and stalling characteristics of an aircraft are as important to the ditching behaviour as the hydrodynamic forces following impact. As a result, increased scrutiny was placed on the aerodynamic load definitions within HydroDyna with actual flight test data being used to characterise the HydroDyna models for the CSeries 100.

5. CASE STUDY 1 – INITIAL IMPACT

This case study outlines the work programme completed with AgustaWestland to assess the behaviour of the Lynx Wildcat helicopter during various initial ditching transients.

The objective of this work was twofold: firstly to validate several updates to HydroDyna since the original feasibility study [2] and secondly to explore the trends in ditching behaviour across a range of initial conditions.

Figure 6 illustrates the work flow. Both a HydroDyna model (Figure 6A) and a CFD model were constructed from the CAD model and solved at a fixed speed, attitude and sinkage. Figure 6B shows the CFD solution which provided high resolution details of the local flow structures and surface pressures around the fuselage.

These pressures were used to calibrate the hydrodynamic loading coefficients over a number of regions around the fuselage. This resulted in the patchwork of pressures seen in Figure 6C, which accounts for the local recirculation around the aft of the radome, and for the suction pressures generated by the change in angle of the aft fuselage. The CFD confirmed that this region of the fuselage does not ventilate or cavitate at the speeds considered.

It should be noted that the objective of the calibration process was to achieve a representative average pressure over each region of the fuselage that will give the correct dynamics, rather than perfectly match each detail identified by the CFD model.

Having calibrated the HydroDyna model, simulations were run at different combinations of initial speed, roll angle and yaw angle in both flat water and regular waves. These conditions included several that were consistent with tank tests AgustaWestland had previously run (Figure 6E) to allow comparison. Simulations were run for 10s which was sufficient for the helicopter to complete the initial ditching transient.

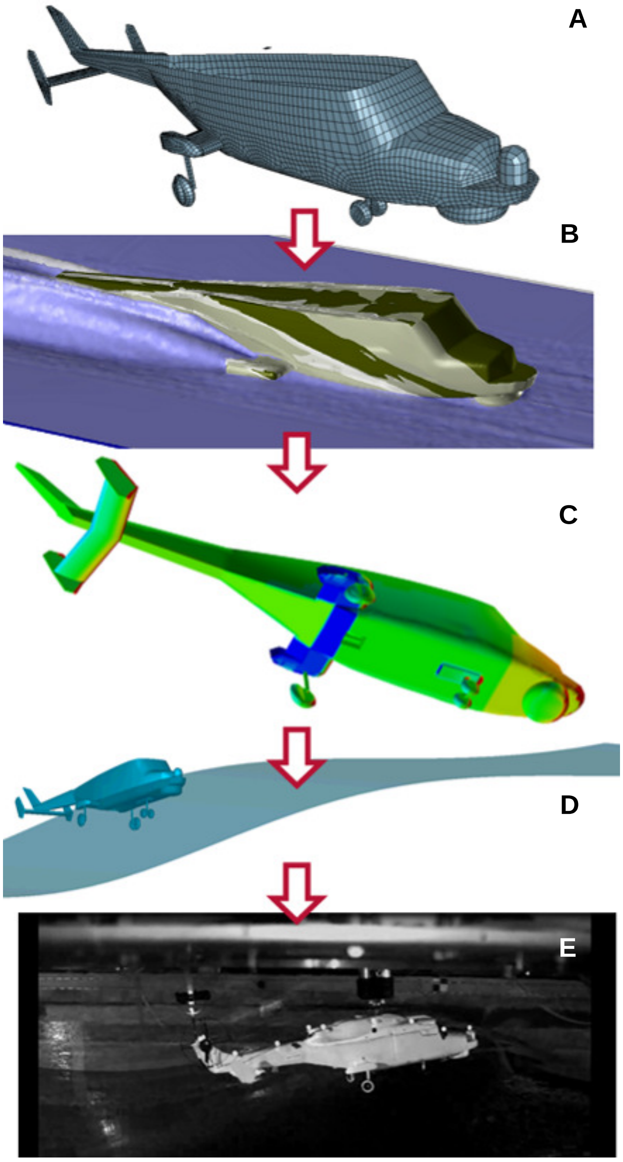

Figure 6 – Work flow of Lynx Wildcat ditching assessment

Some of the key findings from these simulations were:

- The dynamic ditching behaviour (i.e. accelerations, velocities and displacements) predicted by HydroDyna was qualitatively and quantitatively consistent with that observed during the tank tests.
- When ditching into a rough seaway, the behaviour was sensitive to the specific point of impact on the wave crest. If the nose impacted the crest the helicopter would quickly slow and settle in the water, whereas if the flat bottom of the fuselage impacted, the helicopter could skip off the wave into the following trough. This change in impact point to further aft reduced the longitudinal and increased the vertical accelerations.
- The impact of the undercarriage did not cause any notable nose down pitching.
- The behaviour of the helicopter in flat water was found to be sensitive to initial roll and yaw angles, and a two way coupling between roll and yaw was identified. This behaviour was consistent with the behaviour of other helicopters where sponsons and a high Centre of Gravity tend to exacerbate asymmetric dynamics. Furthermore, the asymmetry of the tailplanes generated lateral forces which identified a preference to ditch with roll and yaw to one side rather than the other in flat water.
- AgustaWestland's processing of the measured surface pressure data showed that the distribution and trends in pressures on the fuselage were consistent with the HydroDyna results.

It should be noted that in reality the helicopter's flotation systems would start deploying very quickly. The effect that this would have on the dynamics shortly after impact was not assessed during these simulations, but the sensitivity could be determined by running simulations with a fully deployed system.

In summary, HydroDyna was successfully used to assess the likely behaviour of the Lynx Wildcat across the ditching envelope, and results were validated against scale model tests.

6. CASE STUDY 2 – POST-DITCHING STABILITY

Following the initial ditching impact, helicopters are required to stay afloat to provide a stable platform for egress for the crew and passengers. The main focus is, therefore, on ways to reduce the risk of capsize. This case study was undertaken to assess whether or not HydroDyna is a suitable tool for assessing post-ditching stability and, hence, is a credible and economic alternative to scale model tank testing.

An AW101 model was modified to include deployed flotation bags and HydroDyna simulations were run in a variety of regular and irregular waves. For the purposes of this feasibility study, the flotation bags were rigidly connected to the fuselage. However, the functionality exists within HydroDyna to allow them to pivot or to be tethered with lines if required.

HydroDyna was originally developed to assess the sea keeping performance of high speed boats, so significant effort has already been invested to ensure that the wave environment is accurately represented. Irregular waves can be generated based on wave spectra, or specifically defined to allow direct comparison with a wave train from a tow tank.

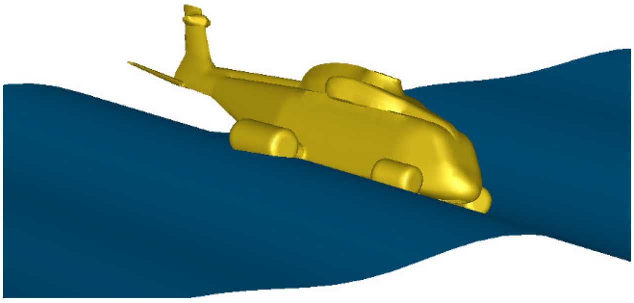

Figure 7 – Un-tethered HydroDyna model

Figure 8 – Tethered scale model in wave tank [1]

The models were run unconstrained (see Figure 7), which highlighted the tendency of the helicopter to yaw as it dropped down the back of a wave, mitigating some of the tendency to roll. It is noteworthy that scale models are tethered in wave tanks (see Figure 8) to keep them from washing down the tank and to keep them side on to the waves, creating the highest risk of capsize. If required, the models in HydroDyna could also be constrained in this way.

The simulations were run in sea states 4 and 5 using a JONSWAP irregular wave spectrum. During the half hour of simulated time per run (sufficient for several hundred wave passings) the helicopter did not capsize.

It is recognised that breaking waves are most likely to cause capsize; however, these are very difficult to create in a wave tank or to model numerically. Therefore, post-ditching stability assessments do not typically consider breaking waves. One benefit of numerical modelling with HydroDyna is that wave profiles can be forced beyond the breaking limit, which is typically defined as a 1/7 wave steepness. It was found that if this was done it was possible to generate wave sequences that would cause the helicopter to capsize.

The notable observation here is that it is more typically a sequence of waves that causes capsize rather than any single wave. This is because preceding waves can orient the helicopter in such a way that it is more susceptible to the following wave. For example, if the helicopter rolls off the top of one wave into the trough, as it rights itself the rolling momentum is amplified by the passing of the next wave sufficient to cause capsize.

7. SUMMARY

This paper has reviewed the key factors that influence rotorcraft ditching and appraised the various methods available for ditching assessment.

From the appraisal it is clear that a number of candidate numerical methods exist that will, with future advances in computational power, play an increasing role in supporting design and complementing tank testing. However, these methods are at present too computationally demanding to support wide ranging parametric and sensitivity studies.

The HydroDyna method has been discussed as an alternative approach, which uses some select assumptions to significantly reduce the computational effort whilst maintaining a faithful representation of the fuselage and key physical phenomena which influence ditching. Hence, the tool can be deployed to assess a wide parameter space with relative ease.

A key aspect of any numerical modelling tool is its validity, and this paper has discussed the range of activities that have been undertaken to demonstrate the robustness of HydroDyna. This has included a suite of formal validation exercises undertaken for Bombardier Aerospace in advance of its use to support certification.

Two rotorcraft-specific case studies have been presented based on work completed in conjunction with AgustaWestland. These case studies have considered the application and validation of HydroDyna for the assessment of the ditching and post-ditching stability of helicopters.

As a result, HydroDyna has been shown to be a flexible, repeatable and economic tool as an alternative to scale model tests or to complement a wider test programme.

8. REFERENCES

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