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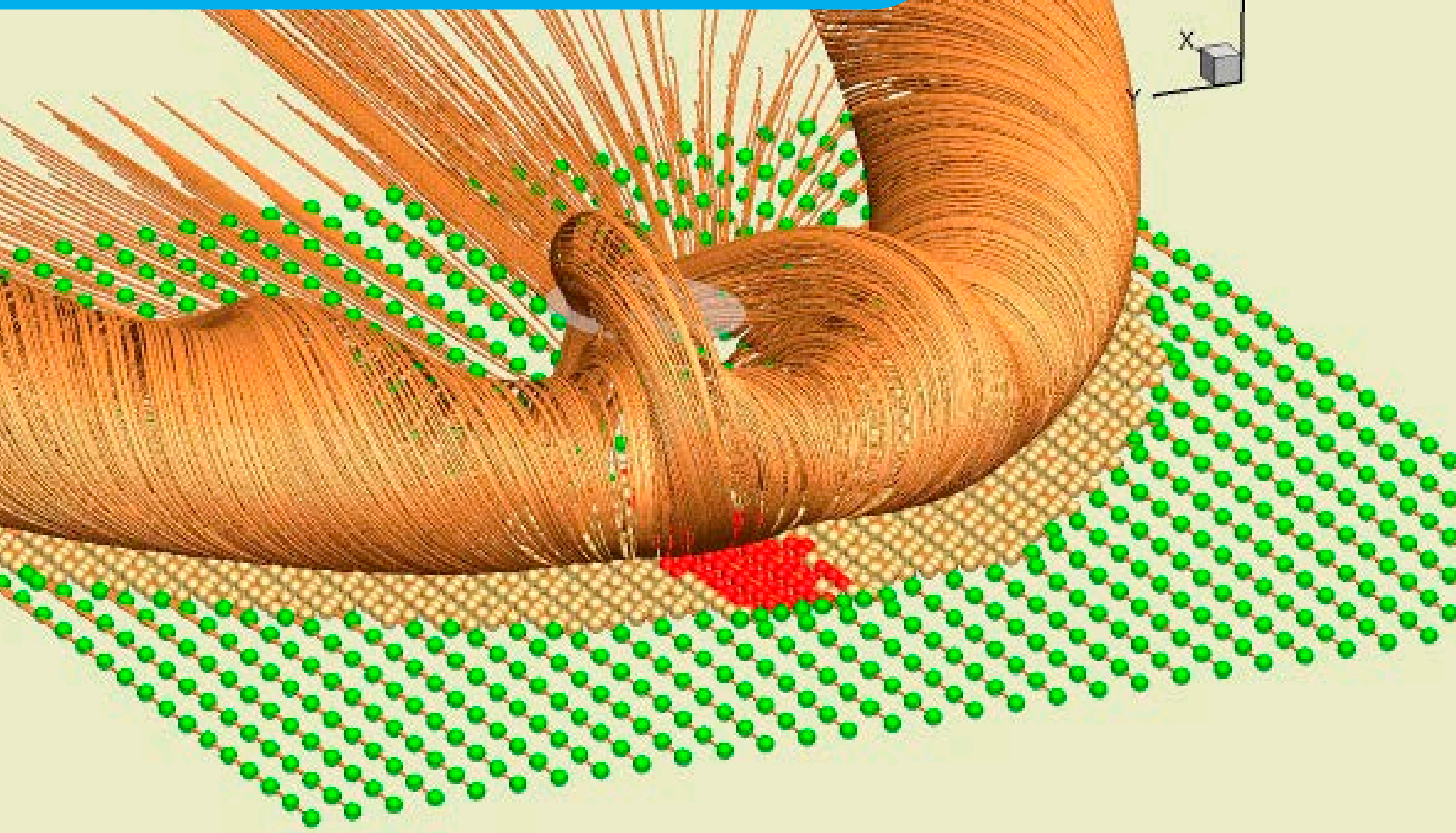
NLR-TP-2016-651 | September 2017

# Modelling and simulation of particle upwash during helicopter landing

CUSTOMER: Netherlands Aerospace Centre

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EXECUTIVE SUMMARY

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# Modelling and simulation of particle upwash during helicopter landing

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## Problem area

Military helicopters operate at landing areas that are often unprepared. In case of a sandy or dusty terrain where the soil is blown up by the rotor wake the helicopter has to operate in a degraded visual environment (DVE). In addition to issues of flight in DVE, the presence of airborne foreign object debris (FOD), in the form of larger sand particles, grit or stones that are blown up from the ground and transported by the airflow, imposes other concerns with respect to flight safety.

## Description of work

A combined aeromechanical and computational fluid dynamics (CFD) simulation is applied to investigate the particle upwash due to rotor down wash and the likelihood of particles hitting the helicopter. The aeromechanical simulations are used to obtain a disk loading from a trimmed helicopter along the descent path. Subsequently a CFD simulation predicts the velocity field around the helicopter and the ground. From this velocity field the stone upwash trajectories are computed an ures.d the likelihood of hitting the helicopter is determined. The methodology is applied with the objective to analyse landing procedures on coarse grained surface terrain; three standard landing procedures and a vertical approach. In addition, three horizontal approaches to hover are addressed, at wheel heights of 30, 40 and 50ft, followed by a vertical descent.

## Results and conclusions

It is shown that the typical flight paths of a helicopter in landing approach always pass a region where it is predicted that the helicopter will be hit by sand particles/stones. The extent of the respective regions for sand particles, medium-sized and big stones depends on typical helicopter characteristics such as main rotor thrust (which mainly depends on the weight), helicopter attitude, etc.

## Applicability

The methodology as developed for certain points in the sky for the landing approaches under scrutiny, can be used to map out the depicted upwash regions. Such a figure can then be used in combination with the runway characteristics (stone sizes, type of stones, etc.) to support the development of safe landing proced

GENERAL NOTE

*This report is based on a presentation held at the RAeS Virtual Engineering Conference, Liverpool, UK, November 8-10, 2016.*

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# Modelling and simulation of particle upwash during helicopter landing

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# Summary

The sand particle and stone upwash caused by the rotor wake of a 10-ton class helicopter was investigated using combined aeromechanical and computational fluid dynamics (CFD) simulations. The aeromechanical simulations are used to obtain a disk loading from a trimmed helicopter along the descent path. Subsequently a CFD simulation predicts the velocity field around the helicopter and the ground. From this velocity field the stone upwash is computed. The final result is the prediction whether stones hit the helicopter, and if so, what size and weight these stones had. The simulations provide information on the likelihood of stones hitting the helicopter.

This paper describes the methodology and its application with the objective to analyse the landing procedures on coarse grained surface terrain. Three standard landing procedures; a steep approach on a glide path of -6 degrees, a normal approach on a glide path of -3 degrees and a vertical approach, are analysed using the methodology. In addition to the approach on a glide path, three horizontal approaches are analysed. For these approaches the helicopter decelerates along a horizontal path at a wheel height of 30, 40 and 50 ft, respectively, to hover. Subsequently, the helicopter performs a vertical approach.

It is shown that the typical flight paths of a helicopter in landing approach always pass a region where it is predicted that the helicopter will be hit by sand particles/stones. The extent of the respective regions for sand particles, medium-sized stones and big stones shown depends on typical helicopter characteristics such as main rotor thrust (which mainly depends on the weight), helicopter attitude, etc. The methodology as developed for certain points in the sky for the landing approaches under scrutiny, can be used to map out the depicted upwash regions. Such a figure can then be used in combination with the runway characteristics (stone sizes, type of stones, etc.) to indicate whether or not a safe landing approach can be performed.

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# Contents

# Abbreviations

| ACRONYM | DESCRIPTION |
|---|---|
| CFD | Computational Fluid Dynamics |
| DVE | Degraded Visual Environment |
| FOD | Foreign Object Debris |
| FD | Flight Path |
| IAS | Indicated Air Speed |
| NLR | Netherlands Aerospace Centre |
| PITS | Point in the Sky |
| ROD | Rate of Descent |

# 1 Introduction

Military helicopters operate at landing areas that are often unprepared. In case of a sandy or dusty terrain where the soil is blown up by the rotor wake the helicopter has to operate in a degraded visual environment (DVE). The associated safety issues of brownout landings have gathered significant attention among helicopter operators and in the helicopter industry. Helicopter brownout is a hazardous and challenging type of DVE since spatial disorientation occurs due to the (sudden) degraded visibility.
In addition to issues of flight in DVE, the presence of airborne foreign object debris (FOD), in the form of larger sand particles, grit or stones that are blown up from the ground and transported by the airflow, imposes another issue with respect to flight safety. The presence of particles in a highly energetic rotor flow has led to dented and cracked wind screens and contributes to the erosion of main and tail rotor blades. Ground particles may be ingested by engine air intakes even in the presence of inlet protective measures and cause wear and even damage to critical engine parts. The deposition of debris may interfere with simple mechanical systems, such as sliding doors, and may impair the effectiveness of crew activities and increase their work load.

The damage by stone upwash also causes economical and financial loss, even while on prepared runways. According to The Boeing Company, FOD on runways have cost the aerospace industry an estimated US$4 billion in aircraft repairs, flight delays and airport maintenance annually (Ref. 1). Repairs to the helicopter components have consequences for the availability of the materiel and in case of the engines, can be very costly.

The project intends to support the development of alternative landing procedures in order to minimise the chance of particles to hit the helicopter both from a safety perspective and also to limit cost of repair, maintenance and to increase the availability of materiel.

The paper addresses the aeromechanical tools and models, the CFD tool and the particle trajectory method used in the simulations, providing references supporting the validity of the models. Simulation results are analysed and presented and conclusions are drawn.

# 2 Modelling

The adopted methodology is the coupling of the aeromechanical tool Flightlab with a computational fluid dynamics code ENSOLV (Ref. 12). A sand particle/stone upwash model is implemented with the trajectories determined by Tecplot post processing. A detailed modelling description is presented.

## 2.1 Aeromechanical helicopter model

The helicopter flight mechanics tool Flightlab is used to provide the trim conditions during the landing phase to be used for the CFD calculations. Flightlab is based on the multi-body dynamics formulation. Flightlab contains components to model the physics of helicopter aerodynamics, flight mechanics, loads and control systems. Different components assembled together form a detailed helicopter dynamics model. For the current analyses an existing Flightlab model of a 10-ton class helicopter is used. Primary aim of the use of Flightlab is to acquire accurate predictions of the helicopter trim parameters, the attitude of the main rotor disc and fuselage for the selected Points in the Sky (PITS) under predetermined flight conditions. In addition, due to the availability of an analytical ground vortex prediction algorithm in Flightlab insight is gained into the significance of this phenomenon for the particle upwash.

The main features of the rotor downwash are sufficiently represented by considering a detailed blade element main rotor model, a simplified Bailey tail rotor model and fuselage. The main rotor blades are considered rigid with a fully articulated connection at the rotor hub. The use of more realistic flexible blades would result in a more accurate prediction of the blade motion, but as the rotor is trimmed to a steady state, blade flexibility will not change the downwash significantly. Each blade is divided into ten structural and twelve aerodynamic segments in radial direction. For each segment the aerodynamic lift, drag and pitching moment are calculated as function of the local motion of the blade section and the local aerodynamic inflow conditions. The quasi-unsteady airload model utilizes combined linear unsteady airload with nonlinear table look-up. The contributions of all sections are summed up to obtain the total main rotor aerodynamic forces and moments. The rotor induced velocity distribution is calculated by an aerodynamic inflow model based on a free vortex wake model (Ref. 8).

The tail rotor is modelled as a Bailey disk rotor. There is only collective pitch and no cyclic pitch input. The induced velocity is computed from a uniform inflow model and included in the model. Aerodynamic interference models take care of the interactional aerodynamic effects between the two rotors and between main rotor and fuselage. These effects can be included by summing the airload contributions of model components or to use empirically determined lookup tables. For the current analyses the interference velocities are calculated by the free vortex wake model of the main rotor. The induced velocities are then added to the local velocities to determine the local dynamic pressure, angle of attack and total aerodynamic load of the tail rotor and fuselage.

The fuselage aerodynamic force and moment coefficients as function of angle of attack and angle of side slip are available via table lookup and cover the full range. The coefficients are determined by the formulas from Ref. 5. The aerodynamic model is sufficiently accurate for the trim calculations.

The simulations interfacing with the CFD computations (for the points in the sky) are generated using 72 simulation steps per rotor revolution with the aim to have a more detailed aerodynamic force distribution on the actuator disk.

## 2.2 CFD model

The CFD helicopter model consists of the fuselage geometry and the main rotor disk. The main rotor is modelled as an actuator disk, that is, the aerodynamic behaviour of the main rotor is averaged over a rotor revolution, and the averaged momentum the rotor blades exert on the flow is added to the flow. The parameters for the definition of the actuator disk are obtained from the aerodynamic forces of the Flightlab simulations. The attitude of the main rotor and the fuselage is also obtained from the trimmed Flightlab simulations. This CFD helicopter model is deemed sufficient for the simulation of the stone upwash because of the following reasons:

- the driving force for the stone upwash is the helicopter downwash,
- the helicopter downwash is caused mainly by the main rotor downwash, the tail rotor plays a secondary role,
- variations in the rotor downwash due to individual blade passages are considered to be of secondary importance,
- the blockage of the downwash by the fuselage is primarily determined by the size and rough shape of the fuselage, geometrical details are not important.
- the CFD model does not contain the tail rotor and an actuator disk is an adequate model for the force executed by the main rotor on the flow.

The ground plane is modelled as a smooth surface with viscous friction. When wind is present, this allows a turbulent boundary layer to build up over the ground plane. The boundary layer profile will not necessarily be the same as the boundary layer on the airfield (which is unknown anyway) but capture the first order effects of decreasing wind speeds near the ground. The same reasoning is valid for the assumption of the smoothness of the surface: in reality the surface is rough, effectively changing the boundary layer profile. Since the boundary layer is turbulent in the simulations, the first order effects are captured. The CFD algorithm has been validated for a wide range of aerospace applications (Ref. 3, 4, 9, 11). Helicopter simulations with an actuator disk have been validated in EU projects.

An important aspect in CFD simulations is the grid resolution. A standard technique is to use a series of successively finer grids and to compare the results for a relevant metric. For the current simulations, the first metric is the shape of the trajectories of the stones. When the results do not change significantly when going from one grid to the next, the former grid is considered to have sufficient resolution. It was found that a grid resolution of 8.4 million cells is sufficient for the correct capturing of the sand/stone trajectories, and the prediction of the number of sand particles/stones hitting the rotor disk does not change when the grid is refined.

## 2.3 Sand particle/stone upwash model

The physics of the sand particle/stone upwash is described by the following phenomena:

- sand particles and stones are lifted from the ground when the local wind forces are sufficient to overcome the gravitational forces and the friction forces with the ground; this process is called entrainment,
- once the stones are in the air, their motion is determined by the balance between gravitational and aerodynamic forces.

Entrainment models which take into account the friction forces are complex and require detailed information on shape and type of the sediment. Assuming that the gravitational forces are dominant in this process and considering the flow field to move parallel to the ground surface at close distance, we may assume that the friction with the ground is zero as the gravity will pull down the stones anyway. Using this assumption the particles are released a short height above the ground: if the particles are too heavy, they will simply drop to the ground. Under this assumption, the final predictions of which stones hit the helicopter will be conservative: in real-life less stones will hit the helicopter since frictional forces inhibit them from leaving the ground in the first place.

As the variety of sand particle/stone sizes and shapes on the runway will be large, a statistical argument can be used to assume that on average the stones are spheres. The aerodynamic force on a sphere is determined by the relative air velocity and the diameter of the sphere. There is a wide body of literature on the aerodynamic behaviour of spheres. This has been collected in engineering formulas for the motion of spheres with given mass and diameter in fluid flow (for instance Ref. 7). These formulas have been implemented in the commercial visualisation package Tecplot (Ref. 10), which is used for the calculation of the sand particle/stone trajectories. The equations describing the motion of the sand particles/stones are discretised in time, so the user has to define a time step for the time integration. Like for the CFD simulations, a time step convergence study has been performed to determine an adequate time step. It has been found that using a time step of 0.000625 seconds, for the given CFD grid, is adequate: decreasing the time step further did not result in significantly different stone trajectories. Once the sand particle/stone trajectories have been computed, it is determined whether they hit the helicopter or not. A hit is defined by the sand particle/stone either passing the rotor disk, or hitting the airframe at the location of the windscreens and doors.

# 3 Simulations

## 3.1 Aeromechanical simulation of landing

The standard landing procedures are taken as starting point for the analysis. Figure 3 shows the landing procedures in a height–airspeed diagram, Table 1 present an overview of the approach parameters. The landing procedures are (PITS = Point in the sky):

- a steep approach on a glide path of -6$^o$ (the red line through PITS 1.1 - 1.4),
- a normal approach on a glide path of -3$^o$ (PITS 2.1 - 2.3),
- a vertical approach (PITS 3.1 and 4.1).

Based on the experiences during the project the analysis has been restricted to the final part of the approach. Hence, the conditions at wheel height $h_{wheel}$ of 50ft and an indicated air speed (IAS) of 30 knots have not been analysed.
In addition three horizontal approaches have been analysed. For these approaches the helicopter first decelerates at a constant height to an indicated air speed of zero knots and then performs a vertical landing. The simulated horizontal landing procedures are:

- a horizontal approach at $h_{wheel}$=30ft (PITS 2.1, 1.1, 4.2, 4.3 and 3.1),
- a horizontal approach at $h_{wheel}$=40ft (PITS 5.1 and 5.2),
- a horizontal approach at $h_{wheel}$=50ft (PITS 6.1).

*Table 1: Simulation conditions, Point in the Sky identification number, airspeed, wheel height, rate of descent*

| PITS | IAS | hwheel | ROD | FP angle |
|---|---|---|---|---|
| [-] | [knots] | [ft] | [fpm] | [deg] |
| 1.1 | 15 | 30 | 200 | -7.6 |
| 1.2 | 11 | 25 | 116.4 | -6 |
| 1.3 | 8 | 21 | 84.7 | -6 |
| 1.4 | 0 | 10 | 150 | -90 |
| 2.1 | 20 | 30 | 150 | -4.3 |
| 2.2 | 13 | 23 | 69 | -3 |
| 2.3 | 9 | 19 | 47.7 | -3 |
| 3.1 | 0 | 30 | 200 | -90 |
| 4.1 | 11 | 30 | 0 | 0 |
| 4.2 | 7 | 30 | 0 | 0 |
| 4.3 | 4 | 30 | 0 | 0 |
| 5.1 | 7 | 40 | 0 | 0 |
| 5.2 | 4 | 40 | 0 | 0 |
| 6.1 | 4 | 50 | 0 | 0 |

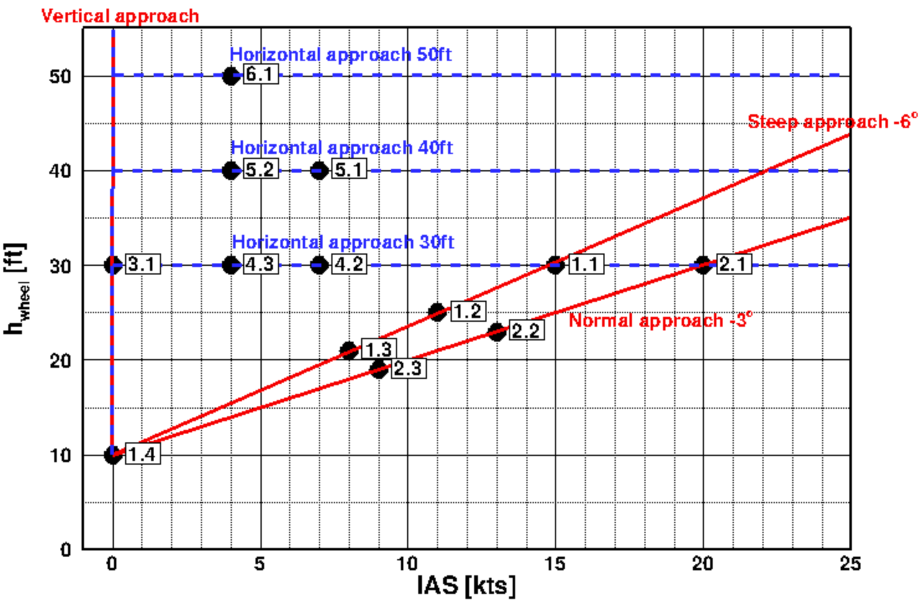


*Figure 1: Points in the sky (PITS) used for the CFD simulations. Different approach options, i.e. steep approach -6°, normal approach -3°, vertical approach and horizontal approach are indicated*

Table 1 shows that for PITS 1.1 and 2.1, the actual flight path angle as derived from the rate of descent (RoD) and the indicated air speed (IAS) have been used. For all other points in the sky the theoretical flight path angle, i.e. -6° (PITS 1.2 and 1.3), -3° (PITS 2.2 and 2.3), 0° (PITS 4.1, 4.2, 4.3, 5.1 and 5.2) or -90° (PITS 1.4 and 3.1), and corresponding rate of descent has been used.
On the basis of two reported incidents with stone particle/stone damage, the weight of the helicopters was taken as 9000 kg. The trim and CFD simulations are performed for the above set of flight conditions.

## 3.2 Simulation of the sand particle/stone upwash

Given the flow fields from the CFD simulations, the sand particle/stone upwash has been simulated for stones of varying diameter and density. The sand/stone parameters are given in Table 2. The density range is representative for a broad range of both sand and stone types, see Table 3.

*Table 2: Stone mass m in metric units [$10^{-3}$ kg]*

| m | | d [m] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| [10-3 kg] | | 0.0021 | 0.0031 | 0.0045 | 0.0067 | 0.0098 | 0.0144 | 0.0211 |
| ρ | 1392 | 0.00681 | 0.0216 | 0.0681 | 0.216 | 0.681 | 2.16 | 6.81 |
| [kg/m3] | 2044 | 0.01 | 0.0317 | 0.1 | 0.317 | 1 | 3.17 | 10 |
| | 3000 | 0.0147 | 0.0465 | 0.147 | 0.465 | 1.47 | 4.65 | 14.7 |

The sand particle/stone diameters have been chosen such that the weights of the particles released to the flow fields follow a linear distribution on a logarithmic scale. This results in sand particle/stone diameters ranging from 0.083”

(2.1 mm) to 0.829" (2.1 cm). The minimum and maximum sand particle/stone mass are 1.50 $10^{-5}$ lb (6.81 mg) and 3.24 $10^{-2}$ lb (14.7 g), respectively. If for a specific Point in the Sky a sand particle/stone of a certain weight (i.e. combination of diameter and density) is elevated this means that all sand particles/stones with a smaller weight also are elevated. Thus, if a sand particle/stone with a sand-like density (see Table 3) is airborne, also sand particles/stones with smaller diameters but a stone-like density will be airborne.

*Table 3: Characteristic sand and stone density. Data taken from: 1) http://www.simetric.co.uk/si–materials.htm, 2) http://www.engineeringtoolbox.com/density-solids-d–1265.html*

| Type | Density [kg/m3] | Density [lb/ft3] | Source (see caption) |
|---|---|---|---|
| Gravel, loose, dry | 1522 | 95 | 1 |
| Gravel, with sand, natural | 1922 | 120 | 1 |
| Gravel, dry 0.25 to 2" | 1682 | 105 | 1 |
| Gravel, wet 0.25 to 2" | 2002 | 125 | 1 |
| Sand, dry | 1602 | 100 | 1 |
| Sand, dry | 1400-1600 | 87.4-99.9 | 2 |
| Sand, wet | 1922 | 120 | 1 |
| Sandstone, solid | 2323 | 145 | 1 |
| Sandstone, broken | 1370-1450 | 85.5-90.5 | 1 |
| Sandstone | 2100-2400 | 131.1-149.8 | 2 |
| Stone, crushed | 1602 | 100 | 1 |
| Stone (common, generic) | 2515 | 157 | 1 |
| Stone | 2300-2800 | 143.6-174.8 | 2 |

For the upwash analyses the particles have been released at a specified height of 0.5" (1.27 cm) above the ground plane. As an example the results of the sand particle/stone upwash analyses for PITS 4.3 are presented in figures 2 to 4. Figure 2 depicts the particles hitting the helicopter (red dots) or lifted but not hitting (green dots), for conditions pertaining to the PITS and for specified particle characteristics

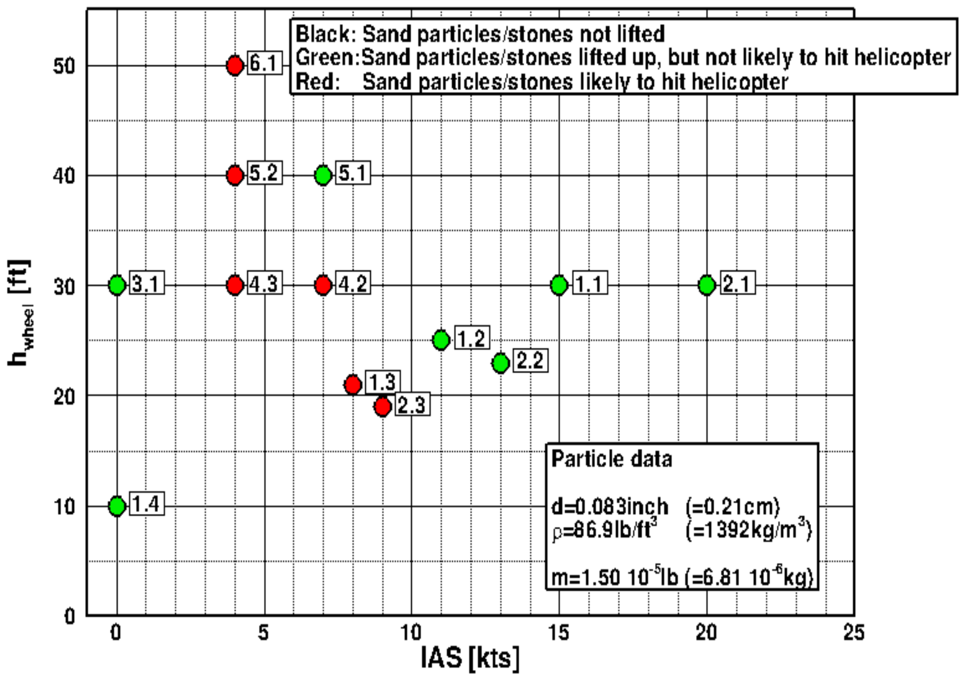


*Figure 2: Summary of stone upwash for density = 86.9 lb/ft$^3$ (1392 kg/m$^3$), diameter d = 0.083" (0.0021 m). Black: stones are not lifted; Green: stones are lifted, but predicted to not hit the helicopter; red: stones are predicted to hit the helicopter*

To obtain spatial information on the upwash, the ground plane is coloured depending on the upwash of the sand particles/stones for each combination of sand particle/stone diameter and density and the specified point in the sky (for example Figure 3 for PITS 4.3 and stones with density 86.9 lb/ft3 and diameter 0.083").

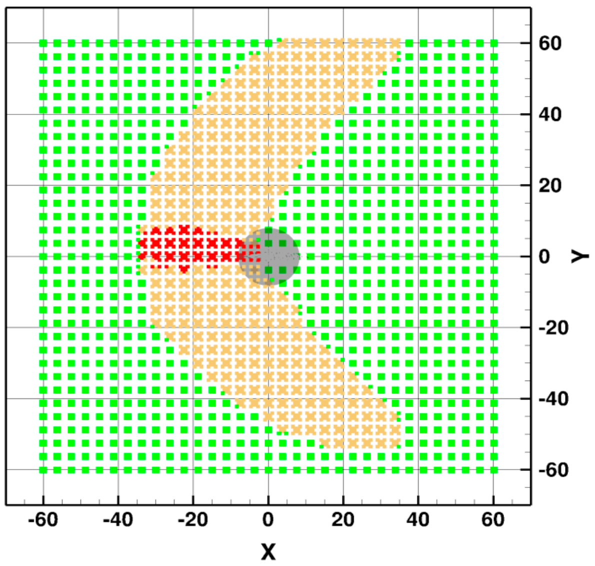


*Figure 3: PITS 4.3, Sand particle/stone upwash for density = 86.9 lb/ft$^3$ (1392 kg/m$^3$), diameter d = 0.083" (0.0021m). Green: stones remain on the ground; peach: stones are lifted, but do not hit helicopter; red: stones hit the helicopter*

In addition for the combination of sand particle/stone diameter and density and point in the sky a perspective view of the sand particle/stone trajectories is generated (Figure 4). The same colouring scheme as for the other sand particle/stone upwash figures is used.

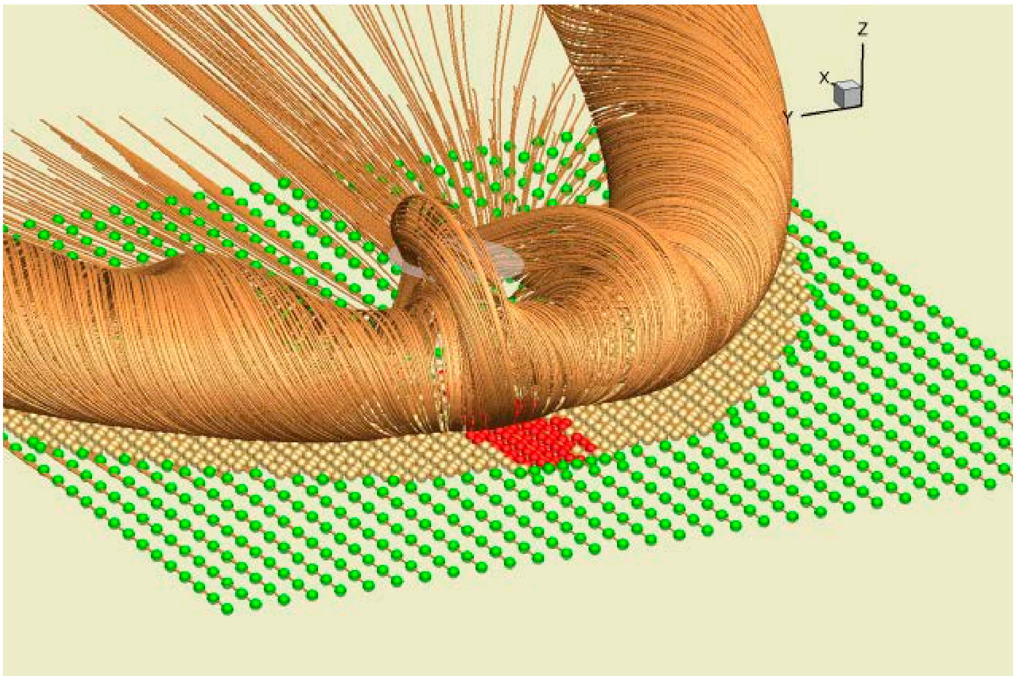


*Figure 4:Perspective view PITS 4.3. Sand particle/stone trajectory for density = 86.9 lb/ft$^3$ (1392 kg/m$^3$), diameter d = 0.083" (0.0021 m). Green: stones remain on the ground; peach: stones are lifted, but do not hit the helicopter; red: stones hit the helicopter*

## 3.3 Analysis of the landing procedures

Three different landing procedures (a steep approach on a glide path of -6°, a normal approach on a glide path of -3° and a vertical approach) have been described. These landing procedures are evaluated against the sand particle/stone upwash

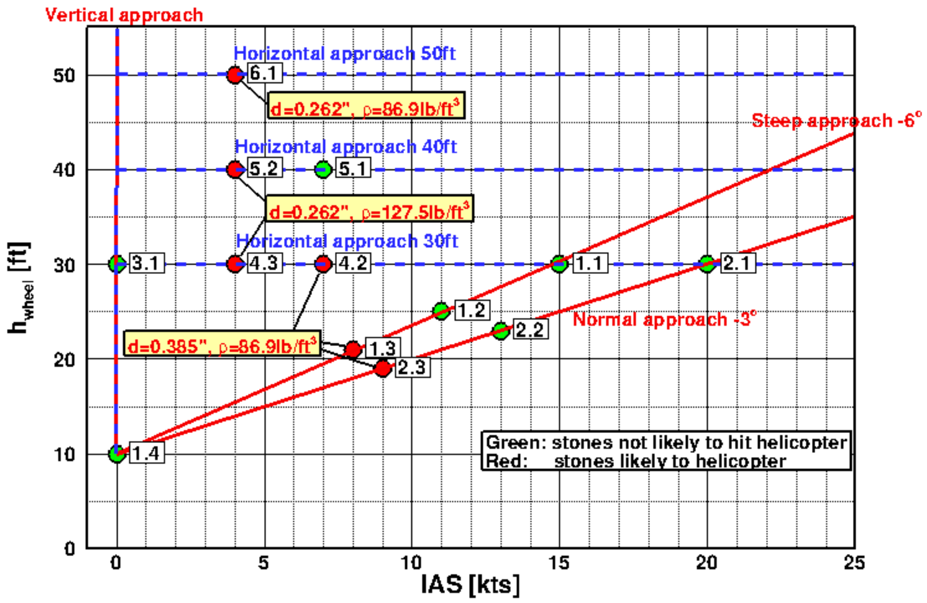


*Figure 5: Likelihood of sand particles and stones to hit the helicopter for the PITS used for the CFD simulations. Also the maximum sand particle/stone diameter and density with a predicted hit of the helicopter are shown*

For both the steep approach on a glide path of -6° and the normal approach on a glide path of -3°, the analysis showed that sand particles/stones are predicted to hit the helicopter. This is also illustrated in Figure 5. The maximum diameter and density of the sand particles/stones predicted to hit the helicopter is for both these approaches 0.385" (0.98 cm) and 86.9 lb/ft³ (1392 kg/m³), respectively, and correspond to sand particles/stones with a mass of 1.50 $10^{-3}$ lb (0.681 g). As stated earlier, this means that all sand particles/stones with a smaller weight are also elevated. Note that these findings correspond to approximately a wheel height of 20 ft and an indicated air speed of 8.5 kts. When going further down along these approach paths the likelihood of encountering heavier stones may increase. The heavier stones that are lifted by the downwash of the main rotor stay closer to the ground due to the larger gravitational force acting on them. The descent of the helicopter may, however, result in the helicopter entering the area where these stones are airborne.

The analysis further shows that for the vertical approach the likelihood of sand particles/ stones hitting the helicopter is small. This is mainly due to the fact that for this kind of approach the downwash of the main rotor does not induce a ground vortex which lifts the sand particles/stones in the air. Instead the downwash just pushes the sand particles/stones sideways along the ground.

In addition to the above three landing approaches, three horizontal approaches have been analysed. For these approaches the helicopter decelerates along a horizontal path at a wheel height of 30, 40 and 50 ft, respectively, to hover. Subsequently, the helicopter performs the vertical approach described above. For these three horizontal approaches, the analysis showed that the helicopter may be hit by sand particles/stones. The maximum diameter and density of the sand particles/stones predicted to hit the helicopter is 0.262" (0.67 cm) and 127.5 lb/ft³ (2044 kg/m³), respectively, for a horizontal approach at 30 or 40 ft wheel height. This corresponds to sand particles/stones with a mass of 0.699 10−3 lb (0.317 g). For a horizontal approach at 50 ft wheel height the mass of the sand particles/stones predicted to hit the helicopter decreases to 0.476 $10^{-3}$ lb (0.216 g) (maximum diameter and density equal 0.262” (0.67 cm) and 86.9 lb/$ft^3$ (1392 kg/$m^3$)). It is expected that with increasing horizontal approach height the diameter and mass of the sand particles/stones predicted to hit the helicopter will further decrease until a certain height above which the helicopter will be able to approach the hover condition without being hit.

# 4 Conclusions

NLR has investigated the upwash of sand particles/stones for a 10-ton class helicopter, using combined aeromechanical and computational fluid dynamics simulations. The outcomes of the investigation, with the objective to analyse the current landing procedures on coarse grained surface terrain, have been described in the present report.

The analysis of the sand particle/stone upwash showed the following for a helicopter weighing 9000 kg:

- For both the steep approach on a glide path of -6$^{o}$ and the normal approach on a glide path of -3$^{o}$, sand particles/stones (up to 0.385”) are likely to hit the helicopter.
- For the vertical approach the likelihood of sand particles/stones hitting the helicopter is small.
- For the three additional horizontal approaches at a wheel height of 30, 40 and 50 ft respectively, sand particles/stones are also predicted to hit the helicopter. The diameter and mass of the sand particles/stones likely to hit the helicopter, however, decreases with increasing wheel height above the ground. It is therefore expected that above a certain wheel height above the ground the helicopter will be able to perform a horizontal approach to hover without being hit.

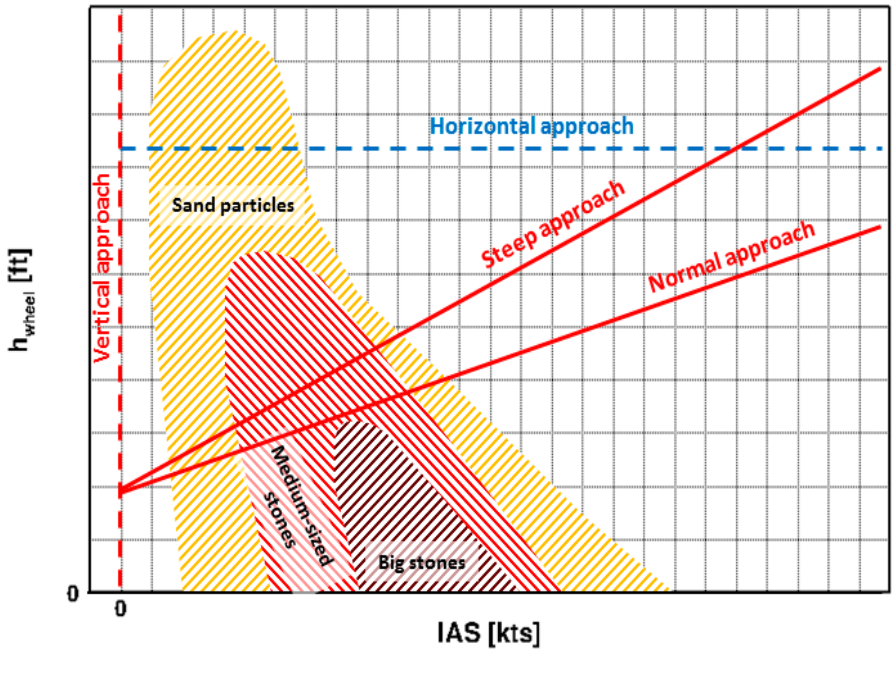


*Figure 6: Schematic representation of sand particle/stone upwash for a helicopter in landing, as function of the Indicated Air Speed and the wheel height above the ground. Typical landing approaches are indicated*

The results are summarized in Figure 6. This figure gives a schematic representation of the sand particle/stone upwash for a helicopter in landing approach as function of the Indicated Air Speed (IAS) and the wheel height above the ground. This schematic representation shows that the typical flight paths of a helicopter in landing approach always pass a region where it is predicted that the helicopter will be hit by sand particles/stones. The extent of the respective regions for sand particles, medium-sized stones and big stones shown depends on typical helicopter characteristics such as main rotor thrust (which mainly depends on the weight), helicopter attitude, etc. The methodology as developed for certain points in the sky for the landing approaches under scrutiny can be used to map out the depicted upwash regions. Such a figure can then be used in combination with the runway characteristics (stone sizes, type of stones, etc.) to indicate whether or not a safe landing approach can be performed.

During the present analysis the main rotor has been modelled by an actuator disk, that is, the aerodynamic behaviour of the main rotor is averaged over a rotor revolution, thus losing the effect of individual blades. In addition, the flow is simulated as time-averaged steady-state. In reality the flow around a helicopter is highly unsteady. This unsteadiness may give rise to locally higher flow velocities, and the associated upwash of larger sand particles/stones. Therefore, it is recommended to use the outcomes of the present investigation only as a guideline. The final clearance of a flight path used for a helicopter landing approach should be based on actual flight tests.

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