AERIAL STABILITY OF AN IN-FLIGHT WATER SCOOPING SYSTEM

Mario Verhagen¹, Huub Timmermans¹ and Wouter van den Brink²

¹Flight Physics and Loads department, Royal Netherlands Aerospace Centre, Anthony Fokkerweg 2, 1059CM Amsterdam, the Netherlands
²Collaborative Engineering department, Royal Netherlands Aerospace Centre, Voorsterweg 31, 8316PR Marknesse, the Netherlands

Abstract. Given operational restrictions of current firefighting aircraft, a novel concept is proposed within SCODEV. Launched within the Horizon 2020 Fast Track to Innovation framework, SCODEV considers a novel system that refills an aircraft’s water tanks during low altitude flight. The novel scooping system consists of a hose and a scoop that penetrate the water surface during low altitude flight. Though promising major benefits with respect to current firefighting aircraft, the design of such a novel scooping system poses significant and unique challenges. For safe and successful water scooping, it is paramount that the scooping system, consisting of the hose and scoop, maintains a stable shape when being lowered and at any extended position, that the hose maintains a desired shape with a sufficiently vertical attitude, and that the scoop maintains a desired attitude with respect to the airflow, before entering the water. Focusing on system prerequisites that allow for initiation of water ingestion, this paper does not consider system response during water ingestion, reel-in or fly-out. The hose and scoop are designed and assessed through simulations, taking into account the three aforementioned criteria. The scoop and hose are designed and assessed separately in the simulation environment. For the hose, quasi-dynamic aeroelastic analyses are performed by coupling the structural Abaqus solver with an external aerodynamic code and iterating for a hose shape in space. It is assessed whether the hose can maintain a stable shape while being lowered, and at full length. Secondly, it is assessed whether the hose can maintain a desired shape at full length, maintaining a sufficiently vertical attitude. For the scoop, aerial stability analyses have been performed using MSC Nastran. The scoop is designed to maintain a stable and desired orientation with respect to the oncoming airflow. Helicopter flight tests are performed to substantiate analytical results on hose and scoop stability, hose shape and scoop orientation. When the scoop and hose are tested separately, observed behaviour is in good agreement with simulation predictions; the hose remains stable and has a desired shape with sufficiently vertical attitude. The scoop similarly remains stable and maintains a desired orientation with respect to the incoming airflow. For the coupled system, system behaviour differs from analytical predictions. This highlights the need to consider the coupled system in the simulations instead of analysing both components separately.

1. Introduction

A novel aerial firefighting system is proposed within SCODEV, allowing for rapid refilling of the water tanks during low altitude flight. This novel scooping system consists of a hose and scooping
device, where the hose is extended from the empennage of the aircraft. Figure 1 depicts the envisioned system, attached to a Lockheed C-130 transport aircraft. In this paper, the scooping system refers to the entire system of scoop device and hose, while the scooping device solely refers to the water inlet, located at the end of the hose. This system is modular and allows a standard cargo aircraft to be converted for firefighting purposes. Current firefighting aircraft can be categorized into two groups, consisting either of converted cargo aircraft or dedicated amphibious aircraft. A converted cargo aircraft can be utilized for multi-purpose applications, being converted for firefighting missions when required. Such aircraft however require a lengthy layover at an airstrip to refill their water tanks. Conversely, amphibious aircraft allow for rapid refilling by skimming a water surface, yet such aircraft cannot be utilized for other purposes, having been designed for dedicated firefighting purposes. This system allows for standard cargo aircraft to be converted for firefighting purposes where rapid refilling occurs during low altitude flight. Though posing major benefits as compared to current firefighting aircraft, the design of such a novel scooping system poses significant challenges.

One such challenge is that the system must be able to be reeled out in-flight where the system extends in stable fashion. The system must maintain a stable position with respect to the aircraft. While maintaining a stable shape below the aircraft, the shape of the system must have a major vertical component to allow for water scooping during low-altitude flight. If the hose were to have a significant horizontal attitude, the hose would have to be of considerable length to allow for scooping, maintaining the same minimum altitude during scooping flight.

It is furthermore essential that the system contains sufficient dynamic stability relating to gusts, the onset of wave motion or vibrational effects. This is necessary to allow for predictable and safe operation of the system. Under no circumstances should the system show undesired swinging, inflicting peak loads into the attachment point or the risk of the system impacting the aircraft structure and causing damage.

The aforementioned aspects are considered in the design and evaluation of the scooping system, where helicopter trials are performed as an initial means of validation to determine the system’s dynamic behaviour and stability. Due to the many facets that are assessed, this paper solely focusses on the stability analyses with corresponding hose shape. This is assessed for discrete hose lengths. Assessment is done by means of an Abaqus finite element model that has been expanded to include aerodynamic forces that are exerted on the scooping system. Results presented here do not consider the effects of sideslip.

Chapter 2 discusses the hose analysis while chapter 3 delves into the evolution of the scoop design. Substantiation of simulation results is done by means of helicopter flight tests, briefly discussed in chapter 3.

---

**Figure 1.** SCODEV system fitted to the Lockheed C-130 aircraft
2. Hose analysis
Aerial stability of the hose and scooping device are modelled by means of an Abaqus Finite Element Method (FEM) model, which has been expanded to include aerodynamic forces on the hose and scoop. The origin is located at connection with the aircraft. Fixed at the origin, the hose is placed at an initial angle in space. The hose position is iterated till convergence is reached, where equilibrium is found between inertial and aerodynamic forces.

2.1. Structural constituents of hose and scoop
The hose’s structural model consists of 100 consecutively linked elastic finite beam B31 elements using a dynamic implicit solver. At intermediate nodes, these elements are connected with 6 degrees of freedom (DOF). The physical hose has been tested to determine bending stiffness. Values have subsequently been translated to the B31 beam element stiffness parameters using an intermediate hose model, in the process shown in figure 2.

![Image of hose and intermediate model](image)

**Figure 2.** Physical hose material tested (left) and intermediate model (right) used to define material stiffness properties for the simulation model.

The scoop is structurally modelled as a point mass. The hose is able to rotate freely at the underbelly of the aircraft (the origin). Similarly, the scoop is rigidly fixed to the end of the hose. The aerodynamic loads are applied based on the orientation of the local hose element with respect to the surrounding airflow. A script is used to iterate between shape and aerodynamic loading of each hose element.

2.2. Aerodynamic constituents of hose and scoop
The aerodynamics of the hose and scoop system are modelled by means of analytical equations.

2.2.1. Hose elements
The aerodynamic force components of the hose are modelled as dynamic constituents containing aerodynamic drag and inertial forces of the air surrounding the hose. This is done in the local normal and tangential axes of a hose element, as provided in equations (1) and (2) [1]. These functions have been developed to represent the dynamic behaviour of aerially towed cables and have been found to represent an aerial refuelling hose-drogue combination to a high degree of accuracy [2].

\[
f_n = f_n(\theta) \frac{\rho_a D}{2} \ddot{u}^2 + C_m \rho_a A \dddot{u}_n\]

\[
f_t = f_t(\theta) \frac{\rho_a D}{2} \ddot{u}^2\]

Here, \( f_n \) and \( f_t \) are the normal and tangential components of the aerodynamic forces. \( f_n(\theta) \) and \( f_t(\theta) \) are the normal and tangential loading functions, \( \theta \) is the angle of attack, \( \ddot{u} \) is the cable velocity, \( \dddot{u}_n \) is the normal component of the cable acceleration, \( \rho_a \) is the air density, \( D \) is the outer diameter of the hose, \( A \) is the cross sectional area of the cable, and \( C_m \) is the added mass coefficient of air. For a circular
hose, $C_m$ is taken as unity. The normal and tangential force loading functions are provided in equations (3) and (4), as derived for cable-towed bodies [3]:

\[
f_n(\theta) = 0.02 \sin(\theta) + 1.18 \sin(4\theta) + 1.18 \sin(2\theta) \cos(2\theta)
\]

\[
f_t(\theta) = 0.02 \cos(\theta) \theta
\]

2.2.2. **Scoop**

The scoop is aerodynamically modelled as a flat plate in the xz-plane, as shown in figure 3. Thickness effects, tip radius effects, stall and compressibility effects and other geometric features such as scoop opening and hydrofoils are not considered. The flat plat assumption is deemed acceptable given the geometry and operating regime of this system in the air. Scoop dimensions are shown in figure 3.

![Scoop geometry (left) and aerodynamic representation in the simulation (right)](image)

**Figure 3.** Scoop geometry (left) and aerodynamic representation in the simulation (right)

2.2.3. **Flow field**

Due to the representation of aerodynamic forces on an element-based level, flow complexity can be chosen as desired. In these analyses, uniform and constant inflow, in space and time, were solely considered. The time-independent flow field allows for the transient of the system to be determined, together with accompanying hose shape. Uniform flow negates the effects of compressibility, viscosity, slipstreams, induced velocities, vorticity and the aircraft boundary layer. These omissions are considered acceptable given the airspeed and altitude in which this system is used. Studies support that neither propulsion-related interference [4] nor aircraft-induced wake effects [4] [5] [6] occur anywhere over the length of the system, when considering similar operating conditions. This has to do with the attachment point of the system and its strong vertical attitude in downward direction, as shown in figure 1.

2.3. **Results for hose stability and hose shape**

Results, in terms of hose stability and hose shape, are provided in the dedicated subsections below. These results have been attained with the model detailed above.

2.3.1. **Analysis 1: stability for fixed lengths**

The hose and scoop are assessed for 130kts and 150kts true airspeed (TAS) with constant and uniform horizontal inflow. For this analysis, the hose is assessed at lengths of 1m till full length of 21m, with discrete intervals of 1m. As an indication of hose stability for each discrete length, it is seen whether the hose can take on an equilibrium steady-state position in time. Various initial angles, aside from the 30 degrees angle shown here, were tested and showed no influence on converged shape. Since results for each initial angle converge, it can be concluded that the system is stable. Figure 4 shows results for the two extreme positions; 1m and 21m hose lengths. Figures show the hose shape in time/iteration,
starting from the initial 30 degrees with the horizontal (shown in blue) to its final shape (shown in red). Intermediate locations are shown in green. As is evident from these intermediate lines, the hose shape converges and stabilizes. This is true for all hose lengths and all initial release angles.

2.3.2. Analysis 2: hose shape during unreeling

The hose assumes a stable position for each discrete hose length. Additionally, for each given hose length, the hose converges to the same shape from any initial release angles. From this, it is assumed that the hose will be stable when being lowered in quasi-dynamic conditions, and that the hose shape will follow one specific path when being lowered. The shape of the hose will correspond with the converged shape of each discrete length. Based on this reasoning, figure 5 displays the scoop location as the hose is quasi-statically reeled out from the belly of the aircraft. Results are shown for 130kts and 150kts TAS, demonstrating the influence of airspeed on the steady hose shape. Nonetheless, for both airspeeds, the hose maintains a sufficiently vertical attitude, allowing for scooping at minimum flight altitude.

![Hose shape for 1 m and 21 m hose; 130 kts forward flight. Initial shape (blue), intermediate shapes (green) and converged shape (red)](image)

**Figure 4.** Hose shape for 1 m and 21 m hose; 130 kts forward flight. Initial shape (blue), intermediate shapes (green) and converged shape (red)

![Scoop location for each meter extension, as seen from the (left wing) side](image)

**Figure 5.** Scoop position as the hose is lowered during 130 kts and 150 kts TAS flight; 1 m intervals from 1 m till 21.
3. Scoop design

A separate simulation effort is undertaken within SCODEV to design the scoop. The scoop is designed to maintain a statically and dynamically stable position, and to maintain the desired attitude before entering the water. Maintaining the desired attitude before entering the water is paramount. Firstly, this guarantees that the scoop is able to enter the water at high speed. Secondly, this allows for the scoop to maintain a desired attitude with respect to the incoming water flow, allowing for efficient water ingestion. The water inlet is located at the bottom of the scoop. In order to penetrate the water, a downward force is required to pull the scoop into the water. For the final design, shown furthest right in figure 6, a hydrofoil is installed at the bottom of the scoop. Being mounted with a negative incidence angle, the hydrofoil aims to establish this downward force, allowing the scoop to penetrate the water surface at high speed.

![Figure 6. Evolution of the SCODEV scoop design, from left to right](image)

The initial scoop design, shown furthest left in figure 6, has proven to be highly unstable during initial flight tests. Based on this outcome, it has been decided to enhance the scoop design by performing aerodynamic, stability and FEM analyses. On the basis of these analyses, the initial scoop design has evolved via the second design into the third design, as shown in figure 6.

3.1. Scoop analysis models

The scoop’s stability derivatives are determined with an aerodynamic model. This model is based on the Vortex Lattice Method (VLM) and has been created in MSC Nastran. A delta wing is chosen and features positive dihedral to increase the lateral stability of the scoop. This intermediate scoop design is shown as the middle concept in figure 6. A first iteration of the VLM aerodynamic model is visualized in the left image of figure 7. The middle image of figure 7 displays the pressure distribution for this second scoop design. Due to the increase in the scoop’s weight, the size of the wing atop the scoop is increased. This allows for the scoop to maintain the envisioned attitude before penetrating the water. The final scoop design, shown as the third concept in figure 6, features a delta wing for favourable behaviour at large angles of attack. Steady Computational Fluid Dynamic (CFD) analyses are performed for this third design. For this third and final scoop design, the third image of figure 7 depicts the resultant lift as a function of angle of attack. Included in this figure is the lift distribution of a comparable delta wing [7].

![Figure 7. VLM model (left) and VLM results (middle) of second scoop design. CFD results of third scoop design (right)](image)
Additionally, a detailed FEM model has been created in Abaqus to assess the structural behaviour of the scoop, shown in figure 9.

3.2. Scoop design results
A multi-body dynamic simulation has been developed within Matlab/Simulink, using the data from the aerodynamic and structural models as input. This model determines the dynamic stability and orientation of the scoop following subjection to a perturbation. This Matlab/Simulink model is shown in figure 8. From this, a centre of gravity location and wing design are derived that allow for the scoop to maintain the desired orientation. When designing the wing atop the scoop, the following parameters have been chosen as variables: surface area, incidence angle, dihedral angle and location of the wing’s aerodynamic centre with respect to the scoop’s centre of gravity. This latter variable allows for longitudinal stability to be obtained.

![Figure 8. Matlab/Simulink flight dynamics model used to determine dynamic stability of the scoop](image)

As can be seen from the left image of figure 9, the final scoop design includes a large delta wing. This delta wing has been incorporated to offset the considerable and unfavourable effect of the centre of gravity on the orientation of the scoop. Additionally, a mechanism has been included to vary the incidence angle of the wing. This mechanism is solely included for flight test purposes.

![Figure 9. Final design of the scoop (left). Helicopter flight test with the hose and scoop (right).](image)

The final scoop design has been evaluated by means of helicopter flight tests. Tests have been performed in twofold: firstly only considering the scoop as an isolated system, and secondly considering the combined system consisting of the hose and scoop. The flight test involving the latter is shown in the right image of figure 9. When tested as an isolated system, the scoop is mounted at the end of a chain, thus avoiding aerodynamic effects imposed by the hose. As an isolated system, the scoop is shown to be stable for all flight speeds considered herein, and that the scoop maintains the correct orientation. However, when considering the combined system, neither a desired scoop attitude nor stable system shape could be maintained at high speed flight.
4. Conclusions
This paper presents an approach used to develop and assess a system consisting of a hose and scoop, before entering the water during low speed flight. Design and assessment is done based on unique criteria that have been devised for this particular application of in-flight, low-altitude, water scooping.

Results demonstrate that when the hose is exposed to a uniform and constant inflow, the hose takes on a stable shape. This happens for various hose lengths and for inflow velocities shown herein, and is irrespective of initial release angle. For considered horizontal inflow conditions, the system demonstrates operational shapes with sufficient vertical attitude to initiate scooping at low-altitude flight. These findings have been substantiated by means of an isolated flight test of the hose.

The scoop is designed with the aim to maintain a stable position and to maintain a desired orientation before entering the water. The final scoop design is substantiated through flight tests, where the scoop is shown to remain stable while maintaining a desired orientation.

No analyses have been performed where both system constituents have been combined. Results from tests have shown that the combined system becomes highly unstable at certain speeds.

References
[1] Zhu Z H and Meguid S A 2006 Elastodynamic Analysis of Aerial Refueling Hose Using Curved Beam Element AIAA J. 44 1317-24
[2] Zhu Z H and Meguid S A 2007 Modeling and simulation of aerial refueling by finite element method Int. J. Solid Stuctures 44 8057-73
[3] Etkin B 1998 Stability of a towed body J. Aircraft 197-205
[4] Ghoreyshi M, Jirasek A and Lofthouse A 2017 Simulation of C-130 H/J Troop Doors and Cargo Ramp Flow Fields AIAA SciTech Forum (Grapevine)
[5] Bergeron K, Ghoreyshi M and Jirasek A 2018 6-DOF Exit Simulations for C-130 H/J Airdrop Configurations AIAA Aviation Forum (Atlanta)
[6] Schmidt S 2010 Detached-Eddy Simulation of the Dynamic Loads of C-130H with Open Cargo Bay 17th Australasian Fluid Mechanics Conf. (Auckland)
[7] Wentz W H and Kohlman D L 1971 Vortex Breakdown on Slender Sharp-Edged Wings J. Aircraft 8 156-161

Acknowledgements
Research and development of the novel scooping system presented in this paper has been performed in the framework of SCODEV. This project has received funding through the European Union Horizon 2020 scheme.