FLIGHT MECHANICAL SIMULATION OF THE HELICOPTER-BORNE TURBULENCE PROBE HELIPOD

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Abstract

This paper presents the description of the movement of the turbulence probe Helipod under a helicopter of arbitrary type arbitrary type in non-linear equations and their realisation in a simulation program in Matlab/Simulink. The compiled program provides the basis for broad analyses of the usual behaviour of the probe during a mission. Moreover, the simulation is utilised for a comparison to recorded position data. In a verification of the simulation program the aerodynamics, the rope characteristics and the impact of both the trajectory of the helicopter and wind show a great influence on the accuracy of the simulation. By means of the developed program the eigenfrequencies of the Helipod were detected. One major oscillation with a periodic time of about 8 s was found to match the period of a pendulum with a pendular length same as the rope extensions. Secondly two tilt oscillations about the longitudinal and lateral axis were identified with a periodic time of $T_{K\Phi} = 0.48$ s and $T_{K\Theta} = 3.18$ s, respectively. The first is of greater amplitude due to the geometrical construction of the Helipod. The periods can be analytically confirmed. Measured data analyses reveal the same pendulum periodic time, but the tilt oscillations differ due to changed moments of inertia. Furthermore, the flight path of the Helipod displays an elliptical trajectory when observed from above. In the analysed missions the probe reaches a maximum position relative to the helicopter's position of 0.5 m vertically, 4 m laterally and 0.45 m horizontally.

Symbols

b	span width, damping constant
c	mean chord
C_A	derivative coefficient of lift
C_L	derivative coefficient of rolling
C_M	derivative coefficient of pitching
C_N	derivative coefficient of yawing
C_Q	derivative coefficient of lateral force
C_S	spring constant
C_W	derivative coefficient of drag
D_S	diameter of the rope
F	force
G	force of gravity
g	Earth's acceleration
I	moment of inertia
$\underline{\underline{J}}$	matrix of moments of inertia
l	pendulum length
M	torque
$\underline{\underline{M}}$	matrix
m	mass
Q_L	aerodynamic torque
Q_S	torque produced by the rope
S	area of span, force of the rope
T	periodic time
t	time
$\underline{V}$	vector of translatory velocities
$\underline{V}_A$	vector of inflow velocities
$\underline{V}_W$	vector of wind velocities
$\underline{x}$	vector of position
$\underline{x}_C$	moment arm
ΔL	extension of the rope
Δv_{rope}	change of velocity (rope model)
Φ	roll angle
Θ	pitch angle
$\underline{\Omega}$	vector of rotatory velocities
Ψ	yaw angle

Introduction

Fig 1: Helicopter-borne probe Helipod

Helipod The metrological helicopter-borne probe Helipod (Fig 1) is used for highly dissolved measurements of atmospheric turbulence. 250 kg heavy and of about 5 m length the Helipod operates 15 m below a helicopter towed by a rope at a flight velocity of 40 m s^{-1}. This configuration enables a measurement not influenced by the downwash of the main rotor of the helicopter.

The Helipod can be easily attached to the hook of any conventional helicopter. Having additionally the advantage of a vertical start and landing of the helicopter the probe can be operated even in difficult terrain.

The Helipod was developed by the Aerodata Company in Braunschweig in cooperation with the Technical University of Hannover and the Technical University of Braunschweig in Germany. In 2001 the Helipod was transferred to the Institute of Aerospace Systems of the Technical University of Braunschweig, where it has already been participating in numerous meteorological measurement campaigns all over the world (Ref 1, 5). Its first mission took place in the Arctic 1994.

Fig 2: Helipod towed by a helicopter

Problem By analysing the recorded data of the measurement flights a major problem became obvious: The wind data contained the natural oscillation of the Helipod.

During the flight the measuring instrument performs oscillations caused by the container's aerodynamical and flight dynamical characteristics. These movements have an effect on the meteorological measurements. Especially after take-off or a turn the amplitude of the motion of the container is increased and sometimes even forces the pilot to calm down the oscillation.

In order to gain more insight into this problem the issue of a numerical simulation arose.

The developed simulation and its results are presented more detailed in the following sections.

Simulation

The simulation was demanded to operate as close to reality as possible and to enable both broad analyses about the natural oscillations of the probe and comparisons of simulated to the real-measured data. To gain a general conspectus the simulation's output should afford a display describing the motion of the Helipod container during flight operation in various points-of-view.

Based on these demands a simulation program was developed in Matlab/Simulink consisting of the following subsystems:

1. Flight Dynamics
2. Aerodynamics
3. Rope model
4. Wind Simulation
5. Helicopter Simulation

They are specified in the following.

Flight Dynamics This module contains the differential equations of the translatory and rotatory motion described in the geodetic and the body-fixed axes, respectively.

The translatory equations are derived by the principle of linear momentum (Ref 3)

(1) $$m_P \cdot \left[\frac{d\underline{V}_P}{dt}\right]_g^g = \sum \underline{F}_g = \underline{\underline{M}}_{gf}\,\underline{L}_f + \underline{S}_g + \underline{G}_g$$

implying the mass of the Helipod m_P, the term $[...]^g_g$ describing the in geodetic coordinates differentiated and described velocity vector $\underline{V}_P$ of the Helipod. Moreover, $\underline{F}$ represents a vector of forces, $\underline{\underline{M}}_{gf}$ the matrix transforming body-fixed into geodetic coordinates, $\underline{L}$ aerodynamic forces, $\underline{S}$ the forces of the rope and $\underline{G}$ the force of gravity. The indices g and f indicate, in which coordinate system the variables are described, where g means geodetic and f body-fixed coordinates.

The rotatory equations are obtained by applying the principle of angular momentum.

(2) $$\underline{\underline{J}}\left[\frac{d\underline{\Omega}^{gf}}{dt}\right]_f^g = \sum \underline{\underline{M}}_f = \underline{Q}_{Lf} + \underline{Q}_{Sf}$$

Where $\underline{\underline{J}}$ represents a matrix containing the moments of inertia of the Helipod, $\underline{\Omega}^{gf}$ the rotatory speed of the body-fixed relative to the geodetic coordinates, $\underline{M}$ torques, $\underline{Q}_L$ the aerodynamic torques and $\underline{Q}_S$ the torques produced by the forces of the rope not acting in the centre of gravity.

The mentioned forces and torques are calculated in the different modules of the simulation.

The two equations (1) and (2) provide the background to determine the position and attitude of the Helipod ($\underline{x}_P$ and $\underline{\Phi}$). The position $\underline{x}_P$ is obtained by two integrations of the vector of the acceleration of the Helipod $d\underline{V}_P/dt$ over time.

(3) $$\underline{x}_P = \int\int \frac{d\underline{V}_P}{dt}\,dt\,dt$$

To derive the attitude angles (Φ, Θ, Ψ) it is firstly necessary to integrate the rotatory velocities $\underline{\Omega}_P$ over time

(4) $$\underline{\Omega}_P = \int\left[\frac{d\underline{\Omega}_P}{dt}\right]dt$$

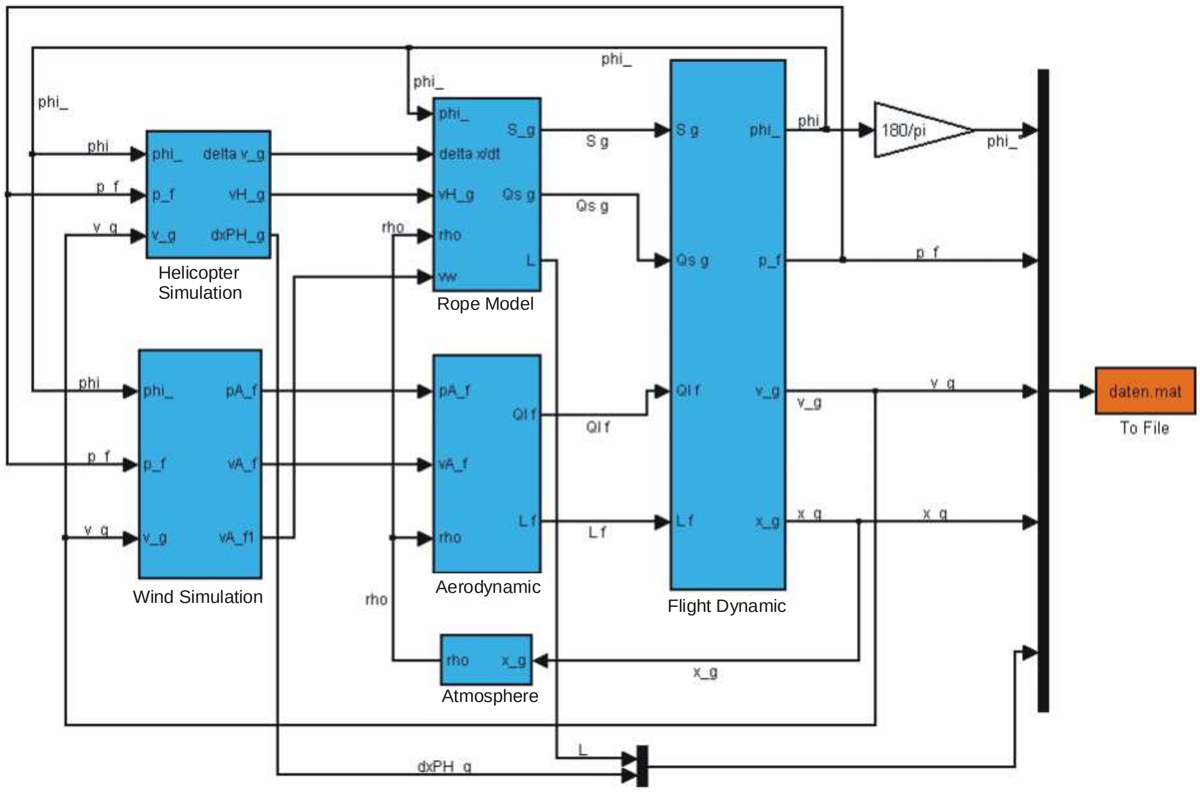

Fig. 3: Main simulation program

A vector equation using the matrix $\underline{\underline{M}}_{\Phi f}$ yields to the time differentiations of the attitude angles

(5) $$\frac{d\underline{\Phi}}{dt} = \underline{\underline{M}}_{\Phi f}\,\underline{\Omega}_P$$

A integration over time results in the attitude angles $\underline{\Phi}$.

Aerodynamics This module contains the determination of the aerodynamic forces $\underline{L}$ and torques $\underline{Q}_L$ by availing the aerodynamic derivatives of the Helipod as shown below (Ref 3).

(6) $$\underline{L}_e = \frac{\rho}{2} V_A^2 S \begin{bmatrix} -C_W \\ C_Q \\ -C_A \end{bmatrix}$$

(7) $$\underline{M}_e = \frac{\rho}{2} V_A^2 S \begin{bmatrix} \frac{b}{2} C_L \\ \bar{c}\, C_M \\ \frac{b}{2} C_N \end{bmatrix}$$

The aerodynamic forces $\underline{L}$ are calculated with the air density ρ, the velocity of inflow V_A, the wing area S, the derivative coefficients of drag C_W, of transverse force C_Q and of lift C_A.
To acquire the aerodynamic torques the span width b, the mean chord c and the derivative coefficient of rolling, pitching and yawing C_L, C_M, C_N, are additionally needed.
Both the aerodynamic forces and the torques are described in the experimental coordinate system (shown by the index e). They can be transformed into the body-fixed and geodetic systems by the matrices $\underline{\underline{M}}_{fe}$ and $\underline{\underline{M}}_{gf}$

Rope Model The towrope consists of a 10 m long, elastic rope ending in two about 5 long steel ropes that are attached to the container of the Helipod. The elastic part of the rope was built of special polyester

by the company Seilflechter in Braunschweig, Germany. The diameter constitutes 16 mm. The diameter of the steel part is 5 mm.
In experiments the rope showed especially an extending behaviour. For including this characteristic into the simulation a rope model basing on a spring/damper performance was chosen. The steel part of the towrope is assumed to be inductile and therefore is not considered in the model described in the following.
The force acting on the Helipod by the rope contains a spring force, a damping force and an air drag force.
The spring force can be calculated with the 1st Hook's law involving the spring force S_{spring}, the extension of the rope ΔL_S and the spring constant C_S (Ref 4).

(6) $$S_{spring} = \Delta L_S \cdot C_S$$

The damping force S_D is determined by the change of velocity in the direction of the rope Δv_{rope}, the damping constant b, the diameter of the rope D_S, the spring constant C_S and the mass of the Helipod m_P.

(7) $$S_D = b \cdot \Delta v_{rope} = 2 \cdot D_S \cdot \sqrt{C_S \cdot m_P} \cdot \Delta v_{rope}$$

The sum of the two mentioned forces and the air drag force produced by the rope results in the total force of the rope.
In a verification of the whole program an insignificant influence of the air drag force on the accuracy of the program was revealed. Hence the air drag force description is skipped in this paper.
The torques of the rope are derived via cross product of the moment arm $\underline{x}_C$ and the total force of the rope $\underline{S}$.

(8) $$\underline{Q}_s = \underline{x}_C \times \underline{S}$$

The force and the torques are described in a special coordinate system (index *s*) and therefore need to be transformed into the geodetic and the body-fixed coordinates by the matrices $\underline{\underline{M}}_{gs}$ and $\underline{\underline{M}}_{fg}$.

Wind Simulation Enabling an input of wind values in the module "Wind Simulation" the compiled program can imitate environmental conditions. For example the wind can be preset to be a constant value. Moreover, as the meteorological probe Helipod is able to record the actual wind data during its flight a simulation of a real flown mission can be emulated by a timed input of the measured wind data.
Wind influences the velocity of inflow $\underline{V}_A$ (Ref 3) by

(9) $$\underline{V}_A = \underline{V}_P - \underline{V}_W .$$

$\underline{V}_P$ represents the velocity of the Helipod and $\underline{V}_W$ the wind vector.

Helicopter Simulation The helicopter provides the driving of the Helipod and forces its flight direction and speed. Furthermore, it balances the gravity force of the probe.
The helicopter is depicted in the simulation as a point of mass acting on the speed of the probe by impulses twice integrated over time.
Both a horizontal flight and a spiraling are simulated.

Implementation

After the compilation of the simulation program in Matlab/Simulink the Helipod was excited in different ways. This procedure was applied in order to

1. analyse the eigenfrequencies of the Helipod,
2. compare the simulated and real measured motion,
3. display the trajectory of the probe from different points-of-view.

For use of the analyses of the first two points the energy spectrum of position and attitude was determined and depicted over frequency.
In the comparison of simulation and experiment adiabatic laminated residual layers of the convective boundary layers of the previous day were chosen. These are characterized by the absence of convection and by little turbulence that enables a especially good identification of the characteristics of the entire system. The data are taken from the meteorological project LITFASS 2003, which was localized in Lindenberg, Germany (Ref 5). The simulation was executed applying three different wind cases.

a) without wind,
b) with constant wind values obtained by a average determination of the measured wind data,
c) with the data input of the recorded wind data during flight.

The trajectory of the Helipod was displayed by picturing the distance of Helipod relative to the helicopter in the three planes of the geodetic coordinate system.
Analyses checking the contribution of various simulation parts to the accuracy of the entire program revealed a minor significance of some calculations like for instance the determination of the air drag of the rope.
The entire simulation program including those parts was used for further analyses.

Results

Simulated dynamics The probe has been excited in different ways like by means of a vertical, lateral or horizontal deflection of the container. In the energy spectrum of the angles of attitude two main types of oscillations were detected (see Fig 4):

1. a pendular oscillation (represented by the first peak)
2. tilt oscillations (second peak)

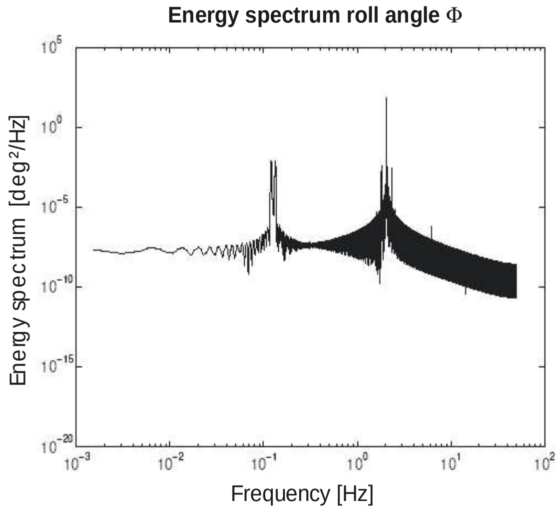

Fig 4: Energy spectrum of the roll angle Φ after a lateral deflection

Pendular oscillation The pendular oscillation represents in general a periodic motion of a mass attached to a rope. The periodic time of the pendular oscillation of the Helipod averages out T_P = 7.99 s as can be seen in Fig 4.This values can be affirmed by a model of a mathematical pendular. The periodic time can be calculated using the pendular length *l* and the acceleration due to gravity *g.*

$$T_P = 2 \cdot \pi \cdot \sqrt{\frac{l}{g}} \tag{10}$$

Tilt oscillations This kind of oscillation describes the motion of the centre of gravity of the probe relative to the point of attachment. There exist theoretically one oscillation about each of the body-fixed axis (rolling, pitching and yawing oscillation). The energy of the three types is descending in the mentioned sequence. In the simulation the tilt oscillation about the yaw axis is not present for the vertical fin of the Helipod exhibit a good yaw damping. The pitching tilt motion of the container can be rarely observed, while the rolling tilt motion is clearly obvious (see Fig 4, second peak). They have a period of $T_{K\Theta}$ = 3.18 s and $T_{K\Phi}$ = 0.48 s, respectively that can be affirmed analytically by the simple model of a physical pendular. The model yields to the following equation involving the mass *m*, the pendular length *l,* the acceleration due to gravity *g* and the moment of inertia about the particular axis *I*.

$$T_K = 2 \cdot \pi \cdot \sqrt{\frac{I}{mgl}} \tag{11}$$

Comparison simulation/measurement The simulations that were used for the comparison to the measured data involved a timed input of the recorded wind data. This assures similar environmental conditions.
Fig 5 shows the energy spectrum of the yaw angle Ψ of both the simulated and the experimental data.

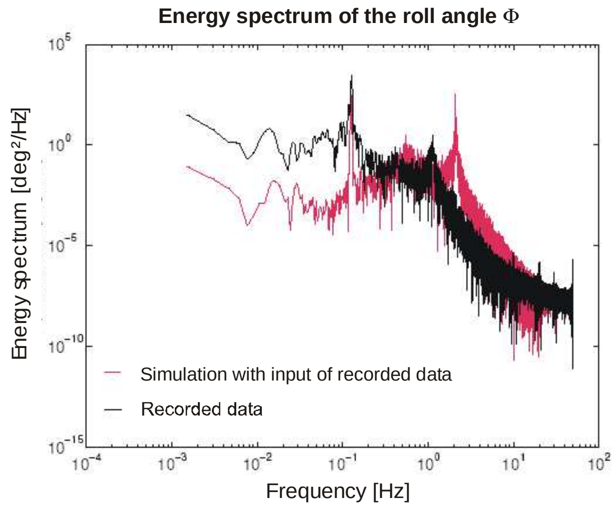

Fig 5: Simulated (pink) and measured (black) energy spectrum of the yaw angle Ψ

The picture reveals a similar trend of both graphs. The pendular period matches that one of the simulation, whereas the two oscillations of the container differ highly. The motion about the longitudinal is pictured in the energy spectrum at a period of $T_{\Phi meas}$ = 0.9 s (see Fig 5). This deviation is a result of changes in flight mechanical and aerodynamical characteristics due to technical and bodily adjustments of the Helipod during time. Its values of aerodynamic derivatives and inertias that have never been actualised since the construction of the Helipod was finished in 1994, which are input to the simulation. The frequency of rolling oscillation of the container has already been detected in previous surveys (Ref 2).

Trajectory of the Helipod The trajectory of the probe was displayed by projecting the vector of distance of the Helipod relative to the helicopter into the three planes of the geodetic coordinate system (top view, lateral view and back view). Moreover, the performance of the probe was observed during both a horizontal flight and a spiraling that are discussed in the following sections.

Horizontal flight In the top view the Helipod moves in an elliptical manner. Referred to the simulation of a average measuring flight the deflections reach a maximum at lateral 4 m, horizontal 0.8 m and vertical 0.5 m (see Fig 6).

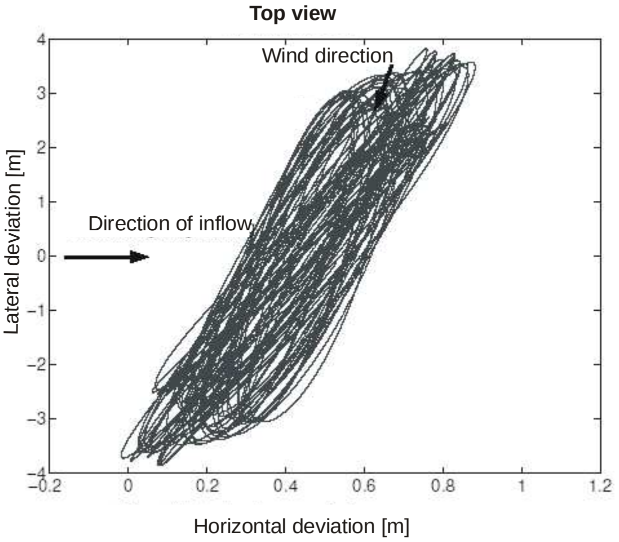

Fig 6: Modelled trajectory of a horizontal flight in top view

Spiraling In the simulation of the spiraling the helicopter flew a 180 ° turn at a constant speed of 40 m/s and a radius of 1000 m. Fig 7 displays the trajectory of the Helipod during that turn in top view.

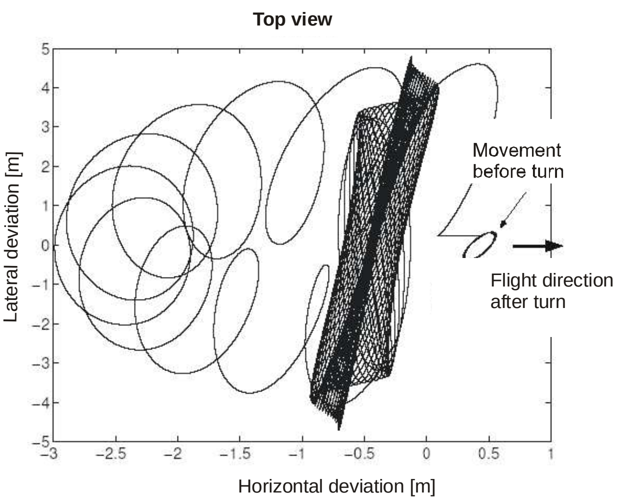

Fig 7: Modelled trajectory of the Helipod during a 180 ° turn in top view

Summary

In order to gain more insight into the behaviour of the meteorological helicopter-borne probe Helipod during a mission a simulation program was developed in Matlab/Simulink. This model contains the aerodynamical and flight dynamical characteristics of the probe and an elastic model of the towrope. In a module of the helicopter different manoeuvres can be chosen. Furthermore, environmental conditions can be simulated by a special input for wind values.
By means of the simulation the eigenfrequencies of the Helipod were detected. One major oscillation with a periodic time of about 8 s was found to match the period of a pendulum with a pendular length, which is equivalent to the rope extensions. Furthermore, two tilt oscillations about the longitudinal and the lateral axis were identified. Their time period was found to be $T_{K\Phi} = 0.48$ s and $T_{K\Theta} = 3.18$ s, respectively. The oscillations could be analytically confirmed.
In comparison with real measured data the pendulum oscillation is of the same frequency, whereas the other oscillations differ highly. The motion about the longitudinal has a period of $T_{\Phi meas} = 0.9$ s. The deviations arise from different moments of inertia that are implied in the cases of simulation and reality.
The trajectories of the Helipod during a horizontal flight and a spiraling were depicted in different points-of-view.

Future prospects

The simulation serves the purpose of a better understanding of the behaviour of the Helipod in flight. It is supposed to assist in measurement experiments in the future.
The DLR Braunschweig in Germany is developing an automatic flight regulation display, which informs the pilot of the helicopter about the best way to minimize the motion of a towed mass. The Helipod could be a major supporting component in this project.
Currently the measuring system Helipod is being expanded by a new board computer and navigation systems. It will be investigated if the inertial platform used so far becomes obsolete when the GPS attitude determination routines are coupled. This redundancy was theoretically shown by means of the presented numerical simulation.

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