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Executive summary

A Flight Dynamics Helicopter UAV Model For A Single Pitch-Lag-Flap Main Rotor

Model Extensions

Problem area
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A Flight Dynamics Helicopter UAV Model For A Single Pitch-Lag-Flap Main Rotor Model Extensions

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Abstract: The current model includes only the main and tail rotor modules, this to allow for an incremental model validation[1] procedure. We present hereunder some candidate model extensions that could potentially be added in the future, to increase the model representativity and validity. These additions exclude aeroelasticity aspects, but include issues on the fuselage, tail, further comments on the tail rotor, ground effects, engine control and transmission, fuel slosh, and atmospheric disturbances.

1 Model extensions

1.1 Fuselage

The following two paragraphs are derived from [54].

[1]The final step of any model development is model validation, through wind tunnel measurements and/or flight tests. It is indeed well known that about 80% of fidelity can be achieved with a physical model, the remaining 20% requires artificial tuning and corrections applied to the physical parameters of the model [55, 54]. But, due to time and space constraints, further aspects relative to model validation such as time- and frequency-domain system identification techniques will not be covered in this paper

The flow around the fuselage is characterized by strong nonlinearities and distorted by the influence of the main rotor wake [54]. Hence the associated forces and moments due to the surface pressures and skin friction are therefore complex functions of flight speed and direction [54]. Further it is important to note that in general the fuselage moments are destabilizing, stemming from the large planform and side area ahead of the vehicle CG.

For low speed sideways flight, the important fuselage characteristics are the sideforce, vertical drag, and yawing moment. While in forward flight, the three most important fuselage characteristics include drag, and pitching and yawing moments variations with incidence and sideslip [54]. The fuselage rolling moment is usually small, except for configurations with deep hulls where the fuselage aerodynamic center may be significantly below the vehicle CG [54].

For a simple analytical model see [34], for an alternative formulation including also pitch and yaw moments see [56]. Often only steady airloads effects on the fuselage are considered. It is however important to know, as mentioned in [54], that important unsteady separation effects also exist, but are rather complex to model.

An expression for rotor downwash over the fuselage, for typical single rotor helicopters, was provided in [75] as a polynomial in wake skew angle. The polynomial coefficients were empirically fit to data presented in [45], but in the case of our UAV, these would potentially need to be readjusted through flight tests.

For fuselage drag calculations, it is estimated that the fuselage may account for up to 50% of the total helicopter drag [24]. Vertical drag penalty in hover and corresponding drag coefficient may be derived from available lookup tables, or for instance from a chart in [62]. Additionally the presence of the fuselage just under the main rotor acts as a so-called pseudo-ground effect, resulting in some thrust recovery. This latter effect may be obtained from a chart in [62]. In forward flight, for parasite drag calculations, and the associated form factor and skin friction coefficients may be derived from [72, 62].

1.2 Tail

The following is mainly derived from [54].

The horizontal tail (called also horizontal fin) and vertical tail (called also vertical fin) form together the tail of a helicopter. Their role is to perform two principal functions. The first one in forward flight, the horizontal tail generates a trim load that reduces the main rotor fore-aft flapping, while the vertical tail generates a sideforce and yawing moment reducing the tail rotor thrust requirement, in order to increase the fatigue life of the tail rotor [54, 62]. The second aspect during maneuvers, and during wind gusts, the tail surfaces provide pitch and yaw damping and stiffness, and enhance pitch and directional stability [54].

The tails are basically wings, hence refer to [72, 2] for basic aerodynamics characteristics, and to [43, 75, 34, 56] for helicopter applications.

It is also well known that depending on the longitudinal and vertical position of the horizontal tail with respect to the main rotor, erratic longitudinal trim shifts may happen when the helicopter is transitioning from hover to forward flight [62]. This is the case when the main rotor wake impinges on the tail surface, for an overview of main rotor wake skew angle limits see [54].

Regarding the modeling of the main rotor downwash on the tail, good results were obtained by using flat vortex wake theory [7] (valid for small sideslip angles), as presented in [84, 74]. An alternative formulation is to represent the downwash as a polynomial in wake skew angle [75].

Finally the effect of the main rotor downwash on the tail boom should also be considered at low speed, since this may influence yaw damping [54].

1.3 Tail rotor

The tail rotor operates in an adverse aerodynamic environment, a strongly nonuniform flow field, due to the wake of the main rotor, main rotor hub, fuselage, and vertical fin which reduce the aerodynamic efficiency, and control requirement and increase the tail rotor loads and vibrations [46]. This is particularly true in low-speed flight, in-ground effect, sideways flight (potentially operating in the VRS), and in transition to forward flight [54].

Modeling of the main rotor downwash on the tail rotor can be done using flat vortex wake theory, as outlined in the previous section.

Further a vertical tail blockage factor k_{bl} can be added, as in [4], to account for vertical tail interference

$$k_{bl} = (1 - b_{t_1})\frac{u_{TR}^2}{v_{bl}^2} + b_{t_1} \quad \text{for} \quad u_{TR} \leq v_{bl} \tag{1a}$$

$$k_{bl} = 1 \quad \text{for} \quad u_{TR} > v_{bl} \tag{1b}$$

Where the transitions velocity v_{bl} and tail blockage constant b_{t_1} can be derived from flight tests.

1.4 Interactional aerodynamics

Interactional aerodynamics refers to the interaction between several vehicle components. This phenomena is inherently related to a.o. the geometry of the helicopter configuration, the physical relationships between the elements, the relative wind direction and magnitude, and the rotor downwash velocity [70]. It is safe to say that this presents a formidable modeling problem, see [70, 26, 11, 5, 52, 54, 10, 25] and references therein.

1.5 Ground effects

Ground effects can be divided into three domains: static ground effect, dynamic ground effect, and the ground vortex. Static ground effect had already been taken into account in the current model.

1.5.1 Dynamic ground effect

When a helicopter is hovering above a heaving, rolling and pitching surface (such as a ship deck), the lifting rotor is subjected to a so-called dynamic ground effect. The static ground effect models cannot capture the unsteady aerodynamics due to such dynamic ground effect. In [79, 80] the generalized finite-state dynamic inflow [58] was extended to include dynamic ground effects. For the case of helicopter hover above an inclined ground plane or ship deck, in which not only the magnitude but also the distribution of rotor induced velocity are changed, see [82, 41].

Now in some operations, a helicopter has to partially hover above a building top or a ship deck (thus not completely above the ground surface), the case is known as hovering with partial ground effect. Further details about this problem can be found in [81].

1.5.2 Ground vortex

It is well known that when a lifting rotor is operated close to the ground at low advance ratios, under certain conditions, a horseshoe ground vortex forms under the rotor [70].

The earliest identification of the ground vortex phenomenon occurred in [44], followed by theoretical investigations in [20, 38, 28], and experimental results in [71, 18, 17].

The ground vortex is produced by the interaction of the rotor downwash, the ground, and the velocity of translation. And estimates of the ground vortex strength indicated that it is at least an order of magnitude stronger than the blade tip vortex [18, 17]. Additionally its position relative to the helicopter depends on helicopter forward speed [70]. For example, for a full-size helicopter, the ground vortex does not seem to exist from hover to about 5kts. It appears to form at about 5kts, several rotor diameters in front of the helicopter and in the direction of flight [71]. The consequence of such a ground vortex is that such characteristics as the control required to trim the helicopter and the effectiveness of the tail rotor as well as engine performance[2] can be markedly changed [18].

1.6 Engine, ECU and transmission unit

The propulsion system dynamics can have a profound effect on the helicopter flight dynamics. Dynamic interface problems involving the engine/fuel control and the rotor/drive train/airframe have been encountered in the ground or flight testing of helicopters for a long time [15].

In flight, the power required by a helicopter varies continuously, due to required changes in forward speed, due to maneuvers, due to power recovery following autorotative flight, and due gusts, which result in rapid thrust variations [53, 73, 1]. Fast main rotor RPM compensation by a governor mechanism, i.e. an Engine Control Unit (ECU), is thus required since any discrepancy between the required and the available main rotor torque will cause the rotor to decelerate or accelerate.

For example, assuming a constant rotor RPM may result in poor heave axis dynamics, and poor yaw response to pitch input dynamics, when compared to flight test data [49]. Also specific problems can also be related to the fact that main rotor and drive train systems may have lightly damped torsional dynamic modes, which may be within the bandwidth of the ECU. Further highly responsive engines have the potential of destabilizing the lag dynamics of the main rotor, or may cause large resonant responses in lag through fast rotor speed excitation. This is especially true when the lag mode is only lightly damped, as is the case for hingeless rotors which are usually not equipped with lag dampers [53].

Finally the advantages of variable rotor speed may be worth considering, since in principle optimal rotor speed for a certain flight condition will not be optimal for another one, i.e. being for example function of vehicle airspeed, altitude, load factor, and/or total mass. It has been shown that

[2] Such as engine inlet ingestion of its own exhaust [71]

performance benefits, i.e. in terms of maneuverability and agility, can be obtained, by varying the main rotor rotor speed during transient maneuvers [42].

We provided here only a very brief introduction on this subject, for further references see for example [6, 53, 1, 9].

1.7 Fuel slosh

Sloshing is the occurrence of any free liquid surface motion inside a container. Sloshing becomes complex during sporadic movements in partially filled liquid containers. Depending on the frequency of the disturbance and the container shape, the free surface of the liquid will undergo a number of complex motions including non-planar, rotational, irregular beating, quasi-periodic and chaotic [69]. The problem of fuel sloshing has received extensive attention, especially in the spacecraft community (satellite and launcher dynamics).

As in the case of vibrations, there are passive and dynamic ways to prevent and lower the effect of fuel sloshing. It starts with proper fuel tank design, often including hydrodynamic damping through so-called baffles. Then the residual sloshing is often dealt with through modeling and adequate design of the flight control computer. Fuel sloshing can be modeled in several ways, the most common approach is to model the sloshing as a pendulum like motion.

For some UAVs, the sloshing phenomenon may particularly be important to consider, since in some cases up to 30% or 40% of the vehicle total mass may be subject to sloshing.

1.8 Atmospheric disturbances

Atmospheric disturbances may be added to a model as additive perturbations, and these come in three different forms: constant linear wind velocity, stochastic linear turbulence velocity, and stochastic rotational turbulence velocity. While linear disturbances will affect the vehicle aerodynamic velocity, rotational turbulence velocities will affect vehicle body roll, pitch, and yaw rates.

Now the main rotor is sensitive to atmospheric disturbances. Wind and wind gusts, induced by atmospheric variations, by local terrain or man-made structures, will change the aerodynamic conditions at the rotor, hence impact blade lift [37, 50].

A low altitude turbulence survey with a huge amount of data can be found in [77], see also [60] for an early description of a nonstationary[3] low altitude atmospheric turbulence. Further two atmospheric models have been extensively used in the aerospace community, to investigate fixed- and rotary-wing responses to atmospheric disturbances. The first one is the von Karman model [76], where an isotropic[4] turbulence model was assumed, which was validated by experimental measurements of low altitude turbulence in [33]. The second one is the Dryden atmospheric model [3]. The difference between the von Karman and Dryden models lies basically in a small variation in the high frequency content [36]. The Dryden model is most frequently used owing to its greater simplicity of implementation, i.e. by passing white noise through linear filters, [8]. On the other hand, the FLIGHTLAB atmospheric model [4] is based on the von Karman spectrum [76], and on results from [66, 68], where only the vertical turbulence velocity is modeled, since it is supposed to have the most important effect on blade aerodynamics.

The literature on transient and steady-state gusts (turbulence) modeling, and aircraft and helicopter response to gusts, is extensive to say the least. We refer the reader to the following influential contributions, for fixed-wing design and response to gusts see [83, 61, 40, 39, 23, 22], for rotary-wing an excellent *tour d'horizon* is provided by Gaonkar in [31, 29, 30], additionally for flapping response to gusts see [78], for coupled flap-torsion dynamics to stochastic vertical turbulence see [32, 47, 27], for flap-lag dynamics to stochastic vertical turbulence in hover see [63, 48], for flap-lag dynamics to stochastic horizontal turbulence in hover see [64] and in forward flight see [65], for the effect of deterministic gusts see [12, 13, 14], for hingeless response to random gusts in forward flight see [21, 22], for stochastic stability analysis see [51], for effects on handling-qualities see [37, 57], and for blade-fixed[5] atmospheric turbulence see [67, 68, 59, 35, 16, 19].

In the case of our UAV, due to its small scale compared to the large-scale turbulence, we will assume that the entire rotor disk experiences a spatially uniform turbulence velocity, identical to that at the rotor center, hence spatial gradients effects will be judged insignificant.

[3] A stochastic process whose probability distribution changes when shifted in time or space

[4] Statistical properties invariant with respect to direction

[5] Body-fixed atmospheric turbulence refers to the turbulence experienced by a point fixed on a non-rotating vehicle component such as the vehicles CG, while blade-fixed atmospheric turbulence refers to the turbulence experienced by a component of a rotating rotor blade [67]. Indeed the atmospheric turbulence velocities seen by non-rotating vehicle components and rotating blades may be substantially different

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