TRIM ANALYSIS OF A TACTIC OPERATIONS TRANSPORT HELICOPTER CONCEPT

Y. Kemal Yillikci, ykyillikci@thy.com, Turkish Technic

Tarkan Sancakdar, tsancakdar@thy.com, Turkish Technic

Giray Yillikci, gyillikci@itu.edu.tr, Istanbul Technical University

Istanbul, Turkey

Abstract

In this study a six degrees of freedom vehicle dynamics model of a single rotor helicopter configuration is constructed to analyze trim its conditions. The considered helicopter is familiar with the S-64 Skycrane helicopter and it is assumed to be a derivative of the UH-60 Black Hawk military utility helicopter. It is primarily considered to carry several standard container loads and these containers are considered to be distributed at different locations along the route of a described mission. This presumed load carrying and off-loading mission would result with a highly adverse travel of the center of gravity (cg) of the helicopter both due to changes in vehicle weight as well as the positions of the remaining loads. Since existing propulsion, hub and rotor system of an existing helicopter it is not possible to balance-*trim*- the helicopter with available rotor hub forces and moments, three auxiliary rotors; two on the main landing gear leg booms and one near the tail rotor are considered. An initial investigation for effects of these auxiliary thrusts is conducted.

1. INTRODUCTION

Concept exploration studies for Utility Transport VTOL vehicles mainly starts with a wide spectrum of operational capability and diversified mission requirements which are expected to be accomplished by a single vehicle. On the other hand, derivatives of an existing helicopter can be productive and more mission suitable if the requirements are narrowed by focusing more on certain specific applications.

The military fields dozens of types of helicopters, with different, even overlapping capabilities and primary tasks: to convey troops, vehicles and other heavy equipment; strike enemies; evacuate battle and disaster casualties; conduct intelligence, surveillance and reconnaissance; coordinate with artillery and other ground units; join other vehicles for search and rescue; fast-line spec ops people to extract bad guys; and more.

They're indispensable. But their crews are always at risk of accidental crashes or hostile fire. Here, as elsewhere, the transition to robotic controls – in Manned/Unmanned (MUM) rotorcraft- is under way [1]. Some systems are optionally manned, others can interoperate with manned aircraft, but the goal is the same, to keep the warfighter out of harm's way.

Boeing, a team of Lockheed Martin Corp. and Kaman Aerospace Corp., Sikorsky and a team of Northrop Grumman and Bell Helicopter are among the half dozen or so manned/unmanned teaming power hitters competing for United States of America Department of Defense contracts for airframes, avionics, guidance modalities, video, communications, electronic signals intelligence, and intelligence, surveillance and reconnaissance suites or weapon systems. The current Armed Aerial Scout drone helicopter program is a major inducement.

Considering Sikorsky UH-60 Black Hawk. In service since 1980 with countless upgrades, the 20,000-pound UH-60 is ubiquitous and a proven theater workhorse. Competencies range from airborne warning and control system tasking to networking duties to hauling a 105-millimeter howitzer and its 10-man crew.

Utilizing it as a MUM platform can be a practical application. Why not "fly-by-wire" as jet pilots do, replacing mechanical linkages with digital controls? Sikorsky hopes, in conjunction with the US Army's Manned-Unmanned Resupply Aerial Lift (MURAL) program, to do just that with an UH-60M by 2012. FBW is a vital feature of the production-ready configuration of an optionally piloted aircraft [1].

Working with an existing airframe can be relatively simple integration of unmanned capabilities with existing operational conditions. The UH-60M has an external sling load capacity of 9,000 pounds.

1.1 Midsize MUM "Skycrane"

In view of above new MUM applications authors started to investigate technical and operational feasibility of a derivative of UH-60 helicopter modified to a "Skycrane" configuration similar as S-

64 Skycrane [2]. Sikorsky S-64 Skycrane which was designed by Igor Sikorsky and made its first flight in 1962 and it is still in service as mainly used in firefighting by its capacity of carrying 22,000 pounds of fire retardants tank as shown in Figure 1. It is aimed to develop a conceptual design study for a UH-60 Skycrane derivative with a target to carry around 13,000 pounds of external load. The considered MUM configuration features conventional single main rotor-tail rotor configuration with additional auxiliary thrusts. Primarily, different load configurations are aimed to be transported with stringent hover requirements. Transportation and unsymmetrical disposal of payloads are expected as one of the major capabilities of the proposed MUM configuration which would require additional control forces and moments additional to main rotor hub control forces and moments. For this purpose it is first aimed to analyze; trimming the proposed MUM configuration, with adverse center of gravity (cg) dislocations around the mean location of cg both in lateral and sideward directions.

In this study, a trim analysis approach for a proposed new Tactic Operations Transport Helicopter (TOTH) which would be referred afterwards as ***"MUM SkyCrane"*** configuration is introduced as based on the conventional six degrees of freedom flight dynamics model developed with the use of MATLAB and SIMULINK software tools. An illustrative concept of the considered MUM Skycrane is shown in Figure 2.

The considered helicopter is familiar with the S-64 Skycrane and as being a derivative of the UH-60 Black Hawk military utility helicopter. It is primarily considered to be carrying several standard container based loads and these containers are considered to be distributed at different locations along the route of a described mission. This planned load carrying and off-loading mission would result a highly adverse travel of the center of gravity (cg) of the helicopter both due to changes in vehicle weight as well as the positions of the remaining loads. Since existing propulsion, hub and rotor system existing UH-60 helicopter it may not possible to balance-trim- the helicopter with its available rotor hub forces and moments under these adverse loading and cg placements conditions.

Therefore three auxiliary rotors; two at ends of main landing gear leg booms and one at around two thirds distance between the main rotor and the tail rotor are utilized.

As being the initial stage of the technical and operational feasibility of the proposed configuration fixed values of thrusts are utilized by these three auxiliary rotors for different loading weights and cg locations.

Container or box types of loads are carried by helicopters as 'slung-load 'applications. Only S-64 Skycrane can transports container type loads as attached to its fuselage. Slung load operations are high risky and difficult to operate missions for utility helicopters. Tyson *et al* [3] review slung load operations and vehicle dynamics, handling qualities and dynamic stabilities of the slung-load and the helicopter transporting it.

2. MODELING THE MUM SKYCRANE

6 DOF vehicle dynamics of the proposed MUM Skycrane is developed as based on UH-60 helicopter configuration. References such Howlett [4], Hilbert [5] and Ballin [6] provide well documented mathematical formulation along with validations with test flight data for UH-60 Black Hawk military utility helicopter. In this study a 1st level dynamic simulation model is constructed as based on certain formulations given by Pathfield [7] and the notation used for formulation and model construction is shown on the illustrative description of the considered configuration as given in Figure 3.

2.1 The Formulation of Helicopter Forces and Moments in Level 1 Modeling

Analytic expressions for the forces and moments on the various helicopter components are derived. The forces and moments are referred to a system of body-fixed axes centered at the aircraft's center of gravity/mass, as illustrated in Figure 3. In general the axes will be oriented at an angle relative to the principal axes of inertia, with the x direction pointing forward along some convenient fuselage reference line. The equations of motion for the six fuselage degrees of freedom are assembled by applying Newton's laws of motion relating the applied forces and moments to the resulting translational and rotational accelerations. Expressions for the inertial velocities and accelerations in the fuselage-fixed axes system are derived as based on classical rigid body dynamics, with the resulting equations of motion taking the classic form as given below.

Force equations

$$\dot{u} = \frac{X}{M_a} - g\sin\theta - qw + rv$$

$$\dot{v} = \frac{Y}{M_a} - g\cos\theta\sin\phi - ru + pw \qquad (1)$$

$$\dot{w} = \frac{Z}{M_a} + g\cos\theta\cos\phi - pv + qu$$

Moment equations

$$I_{xx}\dot{p} = \left(I_{yy} - I_{zz}\right)qr + I_{xz}(\dot{r} + pq) + L$$

$$I_{yy}\dot{q} = (I_{zz} - I_{xx})pr + I_{xz}(r^2 - p^2) + M \tag{2}$$

$$I_{zz}\dot{r} = \left(I_{xx} - I_{yy}\right)pq + I_{xz}(\dot{p} - qr) + N$$

where u, v, w and p, q, r are the inertial velocities in the moving axes system; θ, ϕ, ψ are the Euler rotations defining the orientation of the fuselage axes with respect to earth and hence the components of the gravitational forces. I_{xx}, I_{yy}, etc. are the fuselage moments of inertia about the reference axes and M_a is the aircraft mass. The external forces and moments can be written as the sum of the contributions from the different aircraft components; thus, for the rolling moment

$$L = L_R + L_{TR} + L_f + L_{tp} + L_{fn} \tag{3}$$

where the subscripts stand for: rotor, R; tail rotor, TR; fuselage, f; horizontal tail plane, tp; and vertical fin, fn.

2.2 Integrated Equations of Motion of the Helicopter

Once the equations for the individual helicopter sub-systems have been derived a working simulation model requires the integration of the sub-systems in sequential or concurrent form, depending on the processing architecture. The general nonlinear equations of motion take the form

$$\dot{\boldsymbol{x}} = \mathbf{F}(\mathbf{x}, \mathbf{u}, \mathrm{t}) \tag{4}$$

where the state vector **x** has components from the fuselage $\mathbf{x}_f$, rotors $\mathbf{x}_r$, engine/rotors speed $\mathbf{x}_p$ and control actuation $\mathbf{x}_c$ sub-system i.e.

$$\boldsymbol{x} = \{\boldsymbol{x_f}, \boldsymbol{x_r}, \boldsymbol{x_p}, \boldsymbol{x_c}\}$$

$$\boldsymbol{x_f} = \{u, w, q, \theta, v, p, \emptyset, r\}$$

$$\boldsymbol{x_r} = \{\beta_0, \beta_{1c}, \beta_{1s}, \lambda_0, \lambda_{1c}, \lambda_{1s}\} \tag{5}$$

$$\boldsymbol{x_p} = \{\Omega, Q_e, \dot{Q}_e\}$$

$$\boldsymbol{x_c} = \{\theta_0, \theta_{1s}, \theta_{1c}, \theta_{0t}\}$$

where only first-order blade flapping dynamics is assumed.

SCAS inputs apart, the control vector is made up of main and tail rotor cockpit controls,

$$\boldsymbol{u} = \{\eta_0, \eta_{1s}, \eta_{1c}, \eta_{0t}\} \tag{6}$$

Written in the explicit form of eqn. 4, the helicopter dynamics system is described as instantaneous and non-stationary. Euler angle rated are also calculated as

$$\dot{\theta} = p + q\tan\theta + r\cos\phi\tan\theta$$

$$\dot{\phi} = q\cos\phi - r\sin\phi \tag{7}$$

$$\dot{\psi} = q\frac{\sin\phi}{\cos\theta} + r\frac{\cos\phi}{\cos\theta}$$

2.3 Trim Analysis of The Helicopter

The solution of eqn. 4 depends upon initial conditions - usually the helicopter trim state - and the time histories of controls and atmospheric disturbances. The trim conditions can be calculated by setting the rates of change of the state vector to zero and solving the resultant algebraic equations. However, with only four controls, only four of the flight states can be defined, the values of the remaining 17 variables from eqn. 4 are typically computed numerically. Generally the trim states are unique, i.e., for a given set of control positions there is only one steady state solution of the equations of motion.

Using small perturbation theory we assume that, during disturbed motion, the helicopter behavior can be described as a perturbation from the trim, written in the form

$$\boldsymbol{x} = \boldsymbol{x}_e + \delta\boldsymbol{x} \tag{8}$$

A fundamental assumption of linearization is that the external forces X, Y and Z and moments L, M and N can be represented as analytical functions of the disturbed motion variables and their derivatives [7]. Taylor's theorem for analytic functions then implies that if the force and moment functions (i.e. the aerodynamic loadings) and all its derivatives are known at any one point (the trim condition), then the behavior of that function in a series about the known point.

$$X = X_e + \frac{\partial X}{\partial u}\delta u + \frac{\partial X}{\partial w}\delta w + \cdots + \frac{\partial X}{\partial \theta_0}\delta\theta_0 + \cdots etc.$$

All six forces and moments can be explained in this manner.

$$\frac{\partial X}{\partial u} = X_u \,, \frac{\partial L}{\partial \theta_{1c}} = L_{\theta_{1c}}, etc.$$

The linearized equations of motion for the full six degrees of freedom, describing perturbed motion about a general trim condition is written as

$$\dot{\boldsymbol{x}} - \boldsymbol{A}\boldsymbol{x} = \boldsymbol{B}\boldsymbol{u}(t) \tag{9}$$

Following from eqn. (9), the so-called system and control matrices are derived from the partial derivatives of the nonlinear function F, i.e.

$$\boldsymbol{A} = \left(\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{x}}\right)_{x=x_e}$$

and

$$\boldsymbol{B} = \left(\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{u}}\right)_{x=x_e}$$

3. RESULTS AND DISCUSSIONS

Results for trim conditions of the proposed MUM Skycrane configuration are obtained by the numerically linearized solution of eqn. 4. Center of gravity and auxiliary thrust application locations are shown in figure 4. The reference cg location is defined, as is point 1, with values given in Ref. 5;

Xcg= 350 in.
Ycg= 0 in.
Zcg= 248 in.

As Case 1, lateral controls are given as percentages of pilot cyclic stick position versus forward flight speed (between 0 and 20 knots) are shown in figure 5. Reference lateral cyclic controls (solid line) are compared with subcases;

(i) Cg is moved forwards +Y direction with a value of ΔYcg = 30 inches (point 2) (line with square).
(ii) Cg is moved forwards +Y direction with a value of ΔYcg = 30 inches (point 2), and 200 lb. auxiliary thrust is applied in +Z direction (point 6) as opposite direction to new cg placements (line with plus).
(iii) Cg is moved forwards +Y direction with a value of ΔYcg = 30 inches (point 2), and 400 lb. auxiliary thrust is applied in +Z direction (point 6) as opposite direction to new cg placements (line with diamond).

As Case 2, lateral controls are given as percentages of pilot cyclic stick position versus forward flight speed (between 0 and 20 knots) are shown in figure 8. Reference lateral cyclic controls (solid line) are compared with subcases;

(i) Cg is moved forwards -Y direction with a value of ΔYcg = 30 inches (point 3) (line with square).
(ii) Cg is moved forwards -Y direction with a value of ΔYcg = 30 inches (point 3), and 200 lb. auxiliary thrust is applied in +Z direction (point 5) as opposite direction to new cg placements (line with plus).
(iii) Cg is moved forwards -Y direction with a value of ΔYcg = 30 inches (point 3), and 400 lb. auxiliary thrust is applied in +Z direction (point 5) as opposite direction to new cg placements (line with diamond).

As Case 3, lateral controls are given as percentages of pilot cyclic stick position versus forward flight speed (between 0 and 20 knots) are shown in figure 9. Reference lateral cyclic controls (solid line) are compared with subcases;

(i) Cg is moved forwards +Y direction with a value of ΔYcg = 30 inches (point 2), and 400 lb. auxiliary thrust is applied in +Z direction (point 6) as opposite direction to new cg placements (line with plus).
(ii) Cg is moved forwards -Y direction with a value of ΔYcg = 30 inches (point 3), and 400 lb. auxiliary thrust is applied in +Z direction (point 5) as opposite direction to new cg placements (line with diamond).

As Case 4, longitude controls are given as percentages of pilot cyclic stick position versus forward flight speed (between 0 and 20 knots) are shown in figure 10. Reference longitude cyclic controls (solid line) are compared with subcases;

(i) Cg is moved forwards +X direction with a value of ΔYcg = 50 inches (point 4) (line with square).
(ii) Cg is moved forwards +X direction with a value of ΔYcg = 50 inches (point 4), and 400 lb. auxiliary thrust is applied in +Z direction (point 7) as opposite direction to new cg placements (line with plus).

(iii) Cg is moved forwards +X direction with a value of $\Delta Ycg = 50$ inches (point 3), and 400 lb. auxiliary thrust is applied in -Z direction (point 7) as opposite direction to new cg placements (line with diamond).

In all 4 cases, it is shown that lateral and longitude cyclic controls are improved with auxiliary thrusts application.

4. CONCLUSIONS AND REMARKS

Initial modeling and linearized trim analysis of the proposed MUM Skycrane configuration have shown that utilization of auxiliary thrusts can balance adverse cg dislocations in general. Further studies envisioned, to develop higher fidelity 6 DoF flight dynamic models, can be outlined as;

(i) Calibration of the Level 1 simulation model with available UH-60 data, for static application of these auxiliary thrust,
(ii) Introducing auxiliary thrusts as additional flight controls to the model,
(iii) Integration of a test bed remote controlled helicopter configured with the proposed auxiliary thrusts.

Once the flight dynamics model is well established; modification of an existing manned helicopter to a "Skycrane" configuration can be assessed in terms of technical and operational feasibility.

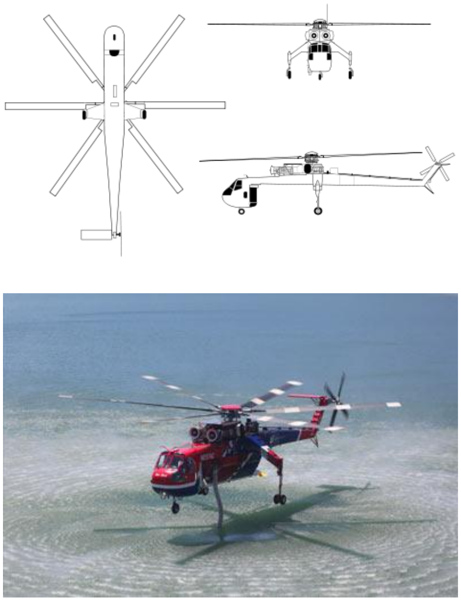

Figure 1. S-64 Skycrane Helicopter which is unique in with its configuration and still in use.

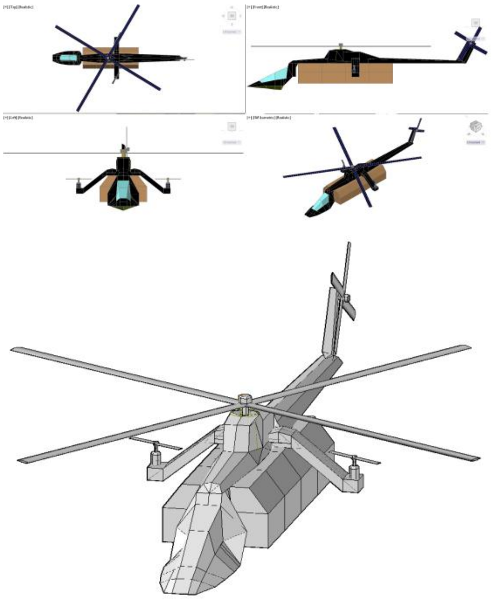

Figure 2. The considered *"MUM Skycrane"* Helicopter Configuration.

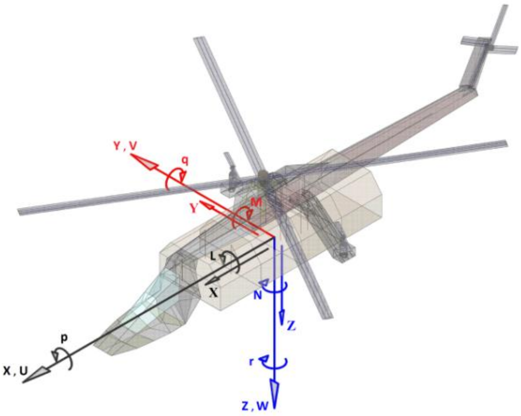

Figure 3. Notation used in 6 DOF Flight Dynamics Model of the proposed *"MUM Skycrane".*

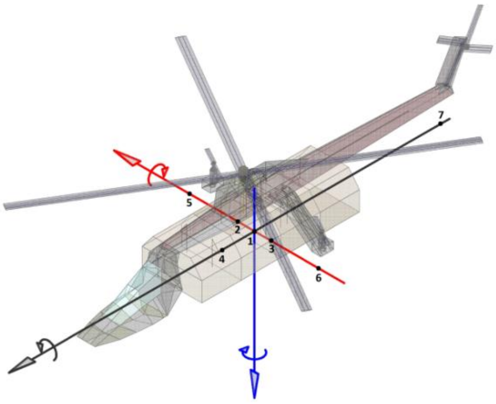

Figure 4. Center of Gravity (cg) locations considered for the trim analysis of the proposed *"MUM Skycrane".*

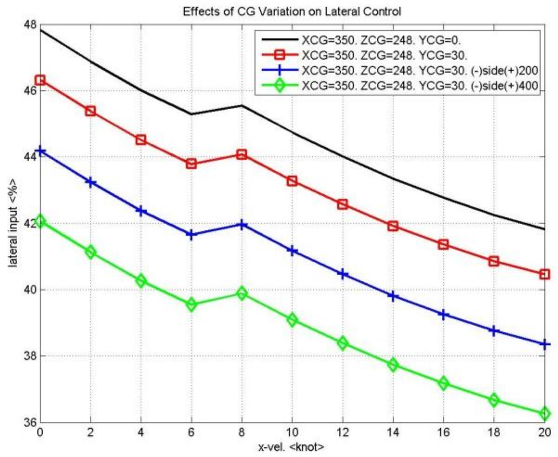

Figure 5. Comparison of lateral control inputs for Case1.

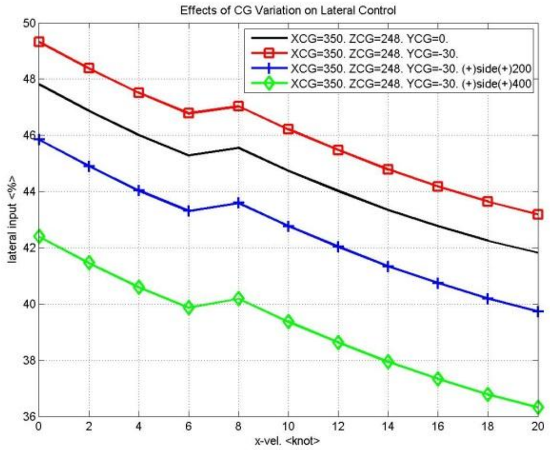

Figure 6. Comparison of lateral control inputs for Case2.

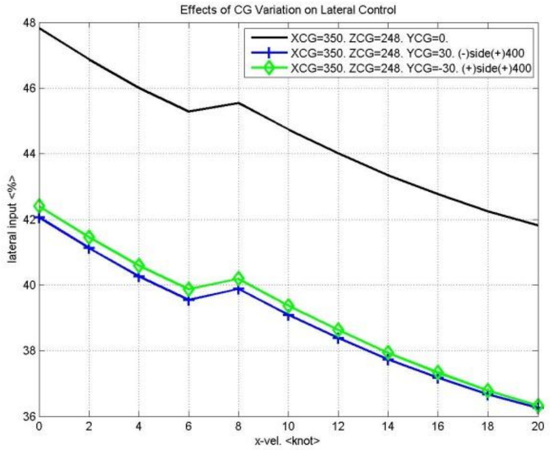

Figure 7. Comparison of lateral control inputs for Case3.

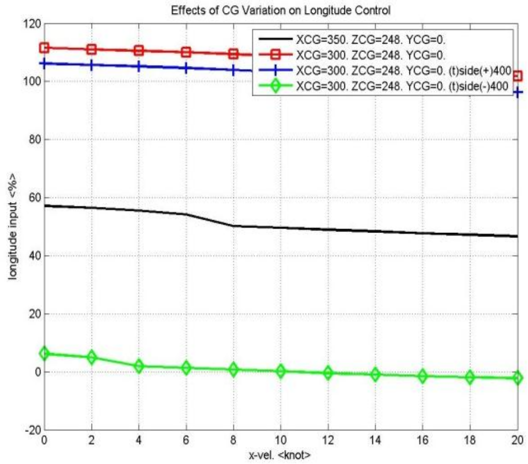

Figure 8. Comparison of longitude control inputs for Case4.

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