Development and Validation of an On-Deck Helicopter Manoeuvring Simulation

Dr. Robert G. Langlois, Assistant Professor, rlangloi@mae.carleton.ca
Amanda R. Feldman, Graduate Student, mandyfeldman@rogers.com
Darren R. Linn, Graduate Student, dlinn82@hotmail.com
Mechanical & Aerospace Engineering, Carleton University, Ottawa ON Canada
Dr. Atef R. Tadros, Director of ASIST Engineering, atef_tadros@indaltech.com
Indal Technologies Inc., Mississauga ON Canada

Abstract

This paper describes an ongoing multi-phase project to develop and validate the capability for performing detailed analysis of shipboard helicopter manoeurvring and traversing operations. The first phase of the project involves developing a four-degree-of-freedom interactive transient-dynamic simulation of shipboard helicopter handling. In the simulation, aircraft motions result from commanded force inputs provided by the Indal Technologies Inc. (ITI) Aircraft/Ship Integrated Secure and Traverse (ASIST) shipboard helicopter handling system. A detailed tire model is used to accurately represent complex tire-deck interactions. The second phase involves designing and commissioning a single-degree-of-freedom scale-model experimental motion platform, a scale-model ASIST system with two degrees of aircraft actuation, and a scale-model reconfigurable dead load test vehicle representative of a variety of maritime helicopters. The third phase involves comprehensive qualitative and quantitative validation of the simulation using both full-scale data without ship motion and scale-model data including the effect of ship motion. This paper describes the derivation and implementation of the mathematical simulation model, the design of the experimental motion platform, validation activity, and an overview of immediate and long-term applications of this technology.

Introduction

The proposed paper focuses on the safety and ease of shipboard helicopter on-deck handling operations. Shipboard aircraft handling equipment such as the Indal Technologies Inc. (ITI) Aircraft/Ship Integrated Secure and Traverse (ASIST) shipboard helicopter recovery and on-deck handling system, shown in Figure 1, provides the capability to secure, straighten, and traverse helicopters on small ships in severe sea conditions. The usual process is to remotely align the aircraft with a deck-mounted track, then to traverse it forward to the ship's hangar. The same process is reversed prior to launch.

The helicopter/ship dynamic interface simulation program *Dynaface*® [1] has been developed by ITI over the past 15 years to support the analysis and design of helicopter handling systems and the safety of embarked helicopter operations. While *Dynaface*® is effective for analyzing the touchdown transient and on-deck securing phases of shipboard operation, it does not currently address the transient motions during aircraft straightening and traversing along the ship deck and into the hangar. This aspect of dynamic interface analysis is now being investigated in detail as part of a project sponsored jointly by ITI, Materials and Manufacturing Ontario (MMO), and Carleton University (CU).

This research project includes three phases: the development of a two-dimensional planar manoeuvring simulation, the development of a dynamic interface analysis experimental motion facility, and comprehensive validation of the results of the previous two phases. Once completed, the newly developed capability will be used to perform detailed analysis of embarked helicopter manoeuvring and traversing operations. The first phase involves developing an accurate planar model of shipboard he-

---

[1] Presented at the American Helicopter Society 59th Annual Forum, Phoenix, Arizona, May 6-8, 2003. Copyright © 2003 by the American Helicopter Society International Inc. All rights reserved.

Figure 1: Indal Technologies Inc. ASIST system

licopter handling using the ASIST system with attention primarily focussed on tire/deck interaction and the ASIST manoeuvring control system. The validated simulation will then be used to analyze on-deck handling and to develop efficient manoeuvring sequences. In the second phase of the project, an experimental facility is being developed such that the effect of motion on the manoeuvring sequences can be investigated using a scale-model dynamic interface analysis motion platform and a scaled dead load test vehicle. The motion platform will be used for validating the planar simulation, assessing its performance in the presence of motion, and for validating an extension to Dynaface® to include the manoeuvring capability developed with the planar simulation model. In addition, the motion platform must be flexible so that it can be used to explore a variety of dynamic interface issues beyond validating the simulation models.

In general, the interactive planar simulation must model the force profiles applied by the operator to the helicopter-mounted ASIST securing probe by the ASIST rapid securing device (RSD); complex low-speed tire behaviour; and planar helicopter dynamics including the possibility of a castoring or steerable nose or tail wheel. Modelling a slow moving tire, as in this application, requires accurate methods for modelling relaxation length and cornering force generation. This means using non-steady-state properties to predict the behaviour of the tires, thereby making the tire model the most complex part of the simulation.

The second phase of the research project involves the design and construction of a scaled one-degree of freedom motion platform with two degrees of aircraft manoeuvring actuation. The experimental motion platform must be capable of simulating various magnitudes of ship motion to study the effects of motion on the manoeuvring of a helicopter using a physical model of a helicopter and a physical model of the ITI ASIST system. Ship motion in general is fully three-dimensional thereby having six degrees of freedom. A challenge in this project is to use a single degree of ship actuation to capture ship motions in multiple directions to the extent possible. The associated helicopter model must be capable of representing a 1/10th-scale model of a typical maritime helicopter, which contains a full suspension system and an adjustable frame to represent different helicopter configurations, as well as both nose and tail steerable or castorable wheel designs.

Comprehensive validation of the planar simulation will occur in four stages: qualitative testing; scale-model experimentation on the experimental motion platform without motion; full-scale experimentation using the ITI integrated test facility, a functioning ASIST system, and a dead load test vehicle representative of an in-service shipboard helicopter; and scale model experimentation on the motion platform with motion. For qualitative testing by an experienced ASIST operator, a joystick and virtual reality interface is being implemented.

This paper describes the development of the project, including the design, quantitative and qualitative analysis, and validation activity for each of the project phases. The paper is structured such that the derivation and implementation of the planar helicopter simulation is described first; followed by the motion platform design and associated analysis. The remaining three sections describe validation activity, intended short- and long-term applications for the research, and concluding remarks respectively.

Planar Manoeuvring Simulation

Essential elements of the planar manoeuvring simulation are described in this section. Attention is focussed on the core governing equations that are carefully structured to allow the extraction of joint reaction forces at the castoring point required by a joint friction model, and such that only ordinary differential equations result, thereby permitting efficient computer implementation without requiring the solution of complex differential-algebraic equations.

Dynamic Helicopter Model

The generic helicopter on which the model is based is shown in Figure 2. It consists of two bodies representing the fuselage and the rotatable wheel assembly interconnected by a revolute joint; and three suspension stations each having either single or dual wheels. The geometry of the system is completely arbitrary with no implied assumptions of symmetry.

Figure 2 illustrates the four degrees of freedom included in the helicopter model, where the generalized coordinates q_i are: the linear x position of the helicopter centre of mass (CM) (q_1); the linear y position of the helicopter CM (q_2); the orientation of the helicopter (q_3); and the orientation of the optionally castorable wheel assembly relative to the helicopter body (q_4).

Kinematic analysis of the system allows the inertial frame accelerations of the helicopter body and castor assembly to be related to the generalized coordinates and their first and second time derivatives

$$\left\{\begin{array}{c}A_{Hx}\\A_{Hy}\\\alpha_H\\A_{Cx}\\A_{Cy}\\\alpha_C\end{array}\right\} = \left[\begin{array}{cccc}1&0&0&0\\0&1&0&0\\0&0&1&0\\1&0&B_{43}&B_{44}\\0&1&B_{53}&B_{54}\\0&0&1&1\end{array}\right]\left\{\begin{array}{c}\ddot{q}_1\\\ddot{q}_2\\\ddot{q}_3\\\ddot{q}_4\end{array}\right\} + \left\{\begin{array}{c}0\\0\\0\\b_4\\b_5\\0\end{array}\right\} \quad (1)$$

where,

$$\begin{aligned}B_{43} &= r^c_{B/C_y}\mathrm{C}(q_3+q_4) + r^c_{B/C_x}\mathrm{S}(q_3+q_4)\\ &\quad -r^h_{B/H_y}\mathrm{C}q_3 - r^h_{B/H_x}\mathrm{S}q_3\\ B_{44} &= r^c_{B/C_y}\mathrm{C}(q_3+q_4) + r^c_{B/C_x}\mathrm{S}(q_3+q_4)\\ B_{53} &= r^c_{B/C_y}\mathrm{S}(q_3+q_4) - r^c_{B/C_x}\mathrm{C}(q_3+q_4)\\ &\quad -r^h_{B/H_y}\mathrm{S}q_3 + r^h_{B/H_x}\mathrm{C}q_3\\ B_{54} &= r^c_{B/C_y}\mathrm{S}(q_3+q_4) - r^c_{B/C_x}\mathrm{C}(q_3+q_4)\\ b_4 &= -r^h_{B/H_x}\mathrm{C}q_3\dot{q}_3^2 + r^h_{B/H_y}\mathrm{S}q_3\dot{q}_3^2\\ &\quad +r^c_{B/C_x}\mathrm{C}(q_3+q_4)(\dot{q}_3+\dot{q}_4)^2\\ &\quad -r^c_{B/C_y}\mathrm{S}(q_3+q_4)(\dot{q}_3+\dot{q}_4)^2\\ b_5 &= -r^h_{B/H_x}\mathrm{S}q_3\dot{q}_3^2 - r^h_{B/H_y}\mathrm{C}q_3\dot{q}_3^2\\ &\quad +r^c_{B/C_x}\mathrm{S}(q_3+q_4)(\dot{q}_3+\dot{q}_4)^2\\ &\quad +r^c_{B/C_y}\mathrm{C}(q_3+q_4)(\dot{q}_3+\dot{q}_4)^2\end{aligned}$$

and C and S represent the cosine and sine functions respectively. For subsequent analysis, Equation 1 can be written more compactly as

$$\left\{\ a\ \right\} = \left[\ B\ \right]\left\{\ \ddot{q}\ \right\} + \left\{\ b\ \right\} \quad (2)$$

where individual terms are identified by comparison with Equation 1.

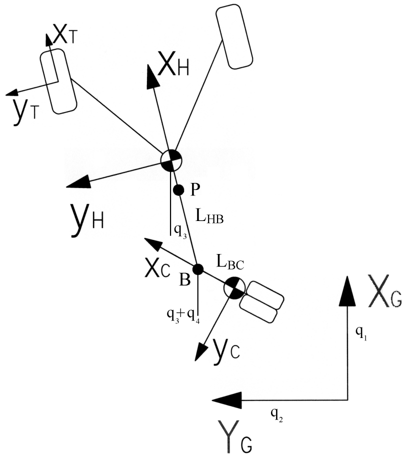

Figure 2: Schematic of the dynamic helicopter model

The applicable forces were next considered and the Newton-Euler method was used to derive the equations of motion using the full set of accelerations. This formulation was selected so that the reaction forces at the castor joint would naturally result and could be used to drive a joint resistance model. The resulting matrix equation is

$$\left[\begin{array}{cccccc}m_H&0&0&0&0&0\\0&m_H&0&0&0&0\\0&0&I_H&0&0&0\\0&0&0&m_C&0&0\\0&0&0&0&m_C&0\\0&0&0&0&0&I_C\end{array}\right]\left\{\begin{array}{c}A_{Hx}\\A_{Hy}\\\alpha_H\\A_{Cx}\\A_{Cy}\\\alpha_C\end{array}\right\} = \left\{\begin{array}{c}F_1\\F_2\\F_3\\-F_{B_x}+F_{tt_{x1}}+F_{tt_{x2}}\\-F_{B_y}+F_{tt_{y1}}+F_{tt_{y2}}\\F_6\end{array}\right\} \quad (3)$$

where,

$$\begin{aligned}F_1 &= F_{P_x} + F_{B_x} + F_{mlt_{x1}} + F_{mlt_{x2}}\\ &\quad +F_{mrt_{x1}} + F_{mrt_{x2}}\\ F_2 &= F_{P_y} + F_{B_y} + F_{mlt_{y1}} + F_{mlt_{y2}}\\ &\quad +F_{mrt_{y1}} + F_{mrt_{y2}}\\ F_3 &= \vec{r}_{P/H}\times\vec{F}_P + \vec{r}_{B/H}\times\vec{F}_B + \vec{r}_{mlt/H_1}\times\vec{F}_{mlt_1}\\ &\quad +\vec{r}_{mlt/H_2}\times\vec{F}_{mlt_2} + \vec{r}_{mrt/H_1}\times\vec{F}_{mrt_1}\\ &\quad +\vec{r}_{mrt/H_2}\times\vec{F}_{mrt_2} + M_B\\ F_6 &= \vec{r}_{B/C}\times -\vec{F}_B + \vec{r}_{tt/C_1}\times\vec{F}_{tt_1}\\ &\quad +\vec{r}_{tt/C_2}\times\vec{F}_{tt_2} - M_B\end{aligned}$$

and where m_H and I_H are the helicopter mass and mass moment of inertia respectively. Subscript P refers to the probe, mlt refers to the main left wheels, mrt the main right wheels, and tt the steerable or castorable wheels. Subscripts 1 and 2 refer to the left and right tires in dual-tire applications. Moment M_B is the bearing resistance at the castor joint. Equation 3 can be expressed more compactly as

$$\left[\ M\ \right]\left\{\ a\ \right\} = \left\{\ F\ \right\} \tag{4}$$

To develop the final dynamic model, Equation 2 is substituted into Equation 4 resulting in

$$\left[\ M\ \right]\left(\ \left[\ B\ \right]\left\{\ \ddot{q}\ \right\} + \left\{\ b\ \right\}\ \right) = \left\{\ F\ \right\} \tag{5}$$

Next, Equation 5 is manipulated to get all of the unknowns onto one side. The generalized accelerations are kept on the left and everything else is moved to the right hand side

$$\left[\ M\ \right]\left[\ B\ \right]\left\{\ \ddot{q}\ \right\} = \left\{\ F\ \right\} - \left[\ M\ \right]\left\{\ b\ \right\} \tag{6}$$

At this point there are six equations with six unknowns. The four generalized accelerations are unknown, along with the x and y reaction forces on the castor joint. The $\{F\}$ vector is then decomposed into the known forces $\{F_k\}$ and the unknown forces $\{F_u\}$

$$\left\{\ F\ \right\} = \left\{\ F_k\ \right\} + \left\{\ F_u\ \right\} \tag{7}$$

Equation 7 is substituted back into Equation 6 and the unknown forces are moved to the left hand side

$$\left[M\right]\left[B\right]\left\{\ddot{q}\right\} - \left\{F_u\right\} = \left\{F_k\right\} - \left[M\right]\left\{b\right\} \tag{8}$$

The forces must then be separated from the position vectors by creating a position matrix $[C]$

$$\left\{\ F_u\ \right\} = \left[\ C\ \right]\left\{\begin{array}{c} F_{B_x} \\ F_{B_y} \end{array}\right\} \tag{9}$$

where,

$$\left[\ C\ \right] = \left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \\ -r^h_{B/H_y} & r^h_{B/H_x} \\ -1 & 0 \\ 0 & -1 \\ r^c_{B/C_y} & -r^c_{B/C_x} \end{array}\right] \tag{10}$$

$[C]$ is then merged with the matrix product $[M][B]$ to put all six unknowns into one vector on the left-hand side

$$\left[\ \left[\ M\ \right]\left[\ B\ \right] \quad -\left[\ C\ \right]\ \right]\left\{\begin{array}{c} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \\ \ddot{q}_4 \\ F_{B_x} \\ F_{B_y} \end{array}\right\} = \left\{\ F_k\ \right\} - \left[\ M\ \right]\left\{\ b\ \right\} \tag{11}$$

Matrix Equation 11 contains six independent equations with six unknowns that are solved in the simulation using a numerical equation solver. An analytical solution was found, but proved to be impractical for implementation based on the anticipated solution efficiency using the complex analytical expressions.

The forces that drive the equations of motion can be broken down into two categories, operator applied forces and tire reaction forces. The operator applied forces are generated by the RSD model and are applied to the helicopter through the probe attached to the helicopter body.

RSD Model

The RSD model interprets input from the ASIST control system joystick and generates the force profile that should be applied to the helicopter probe. The deflection in the probe is used to generate the force and the physical limitations of the real RSD system are considered. These limitations restrict the velocities and forces that the RSD is able to apply to the probe.

The simulation has also been configured to run without the RSD model being used, by applying force profiles specified in an input file directly to the probe. This feature is useful during validation and for analysis where repeating inputs exactly, which would be very difficult with a joystick, is necessary.

Tire Model

During manoeuvring, the helicopter tires roll at relatively low speed compared with conventional vehicle applications. The low speed effectively complicates the tire model. When modelling a slow-moving tire, as in this application, accurate methods of modelling relaxation length and cornering force generation are needed. This means using non-steady-state properties to predict the behaviour of the tires, thereby making the tire model the most complex part of the simulation. Smiley and Horne [2] present accurate methods for modelling the non-steady-state properties of a rolling aircraft tire.

A three-degree-of-freedom tire model has been constructed using the properties outlined by Smiley and Horne. No motion in the vertical direction is considered in the planar simulation, but the vertical tire deflections are automatically calculated such that they are consistent with the helicopter weight distribution. In the longitudinal direction, a rolling resistance model is applied. The lateral direction is much more complex and involves calculating the relaxation lengths and cornering power generation. This unyawed relaxation length is defined as the distance the tire must roll in order for the lateral deformation to drop to a fraction $1/e$ of its initial value. The relaxation length L_S is calculated using Equation 12.

$$L_S = (2.8 - 0.8P/P_r)(1.0 - 4.5\delta_0/d)W \qquad (12)$$

where,

P	is the instantaneous tire pressure;
P_r	is the rated tire pressure;
δ_0	is the vertical tire deflection for the pure; vertical loading condition;
d	is the outside diameter of the free tire; and
W	is the width of undeflected tire

The lateral deformation is what creates the cornering force in the tire and can be generated (cornering power generation) by giving the tire a velocity in the lateral direction. This is done by calculating the yawed relaxation length in a similar manner as the unyawed relaxation length. The transient periods are so short in many other simpler applications that relaxation lengths are often ignored in the tire model.

Computer Implementation

The simulation model combines the three parts described above: the dynamic helicopter model, the RSD model, and the tire model, and numerically integrates the resulting equations. Figure 3 illustrates the simulation process. All of the physical helicopter properties are input, along with the simulation parameters, which include the simulation time, initial position, force profiles (if the joystick is not being used), etc. Next, the initial forces and displacements are calculated based on the initial conditions. Then the numerical integrator moves the solution forward in time. Currently a fourth-order Runge-Kutta numerical integrator is implemented to propogate the solution. The numerical integrator needs to be accurate as well as fast enough to drive the simulation in real time. As the simulation runs, information is gathered and output to a file for subsequent postprocessing and analysis.

Experimental Motion Platform

The scaled one-degree-of-freedom motion platform with two degrees of aircraft manoeuvring actuation is capable of simulating various magnitudes of ship motion to study the effects of motion on the manoeuvring of a helicopter using a physical model of a helicopter and a physical model of ITI's ASIST system. The experimental motion platform has several uses regarding the on-deck helicopter manoeuvring simulation study: the qualitative and quantitative testing of the two-dimensional planar manoeuvring simulation with and without motion; comprehensive validation of securing simulation software; development of manoeuvring algorithms; and experimental investigation of other helicopter dynamic interface issues.

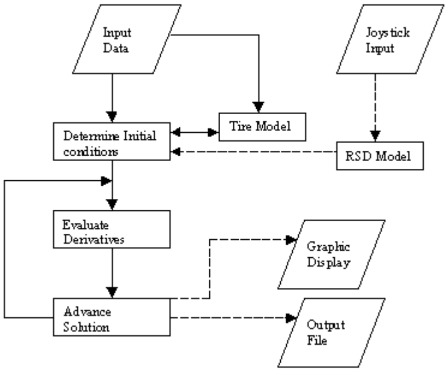

Figure 3: Flow chart of simulation

Motion Requirements

The experimental motion platform was designed to represent the motions of a $\frac{1}{10}$-scale model of a typical frigate where the motions must be scaled using the following scaling laws:

$$(\theta_{r,p,y})_{\frac{1}{10}} = (\theta_{r,p,y})_1 \qquad (13)$$

$$(\dot{\theta}_{r,p,y})_{\frac{1}{10}} = \sqrt{\frac{1}{R}}(\dot{\theta}_{r,p,y})_1 \qquad (14)$$

$$(\ddot{\theta}_{r,p,y})_{\frac{1}{10}} = \frac{1}{R}(\ddot{\theta}_{r,p,y})_1 \qquad (15)$$

$$(r_{x,y,z})_{\frac{1}{10}} = R(r_{x,y,z})_1 \qquad (16)$$

$$(\dot{r}_{x,y,z})_{\frac{1}{10}} = \sqrt{R}(\dot{r}_{x,y,z})_1 \qquad (17)$$

$$(\ddot{r}_{x,y,z})_{\frac{1}{10}} = (\ddot{r}_{x,y,z})_1 \qquad (18)$$

where R is the scaling ratio, $R = \frac{1}{10}$.

The most intense motions that will be simulated during the manoeuvring of the model helicopter correspond to an upper sea state 5 condition. The desired scaled motions for the motion platform are shown in Table 1.

Table 1: Scaled motions of a $\frac{1}{10}$-scale model of a typical frigate operating in an upper sea state 5 condition.

Motions	Displacement	Velocity	Acceleration
Roll	20.4 deg	40.1 deg/s	84.2 deg/s^2
Pitch	5.4 deg	19.2 deg/s	74.1 deg/s^2
Yaw	13.0 deg	2.4 deg/s	20.6 deg/s^2
Surge	285.8 in	69.3 in/s	265.8 in/s^2
Sway	85.4 in	42.5 in/s	132.2 in/s^2
Heave	44.5 in	60.2 in/s	211.0 in/s^2

Due to technical design and budgetary considerations, attention was focussed on the motions of greatest importance. These are roll and pitch motions and will be scaled appropriately, as shown in Table 1. Surge, sway, and heave are less important and will be produced along with the angular motions, which will be discussed subsequently. However, these secondary motion components will not reach the full magnitudes of the motions shown in Table 1.

Ultimately, during component selection, it was decided that it would be desirable to allow the motion platform to have a greater angular displacement for potential subsequent studies in more extreme conditions. Therefore, the motion platform was designed with the ability to produce angular displacements of up to 45 degrees with little incremental cost associated with this capability.

Motion Platform Design

The motion platform, shown in Figure 4, was designed to be easily adjustable and expandable to achieve different motion combinations. It presently uses a single degree of actuation to produce combinations of roll, pitch, sway, surge, and heave motions, yet is expandable in the future to include a second angular degree of freedom for separate pitch and roll actuation, if required.

The single linear actuator is positioned on the motion platform to produce roll motion. However, the helicopter model on the ship deck will experience roll, sway, and heave motions as the result of kinematic coupling between linear and angular motions depending on the location of the axis of rotation and the position of the model on the motion platform. The platform also has the ability to be horizontally rotated about the centre post (yaw angle) so the model can experience a combination of roll, pitch, sway, surge, and heave motions with the single linear actuator.

The motion platform consists of three components: the deck, the frame, and the rotating plate. The motion platform's deck is the top surface on which the scaled helicopter model will manoeuvre. The deck has been sized to allow the scale model helicopter to perform a full 360-degree rotation and to travel along the deck a distance of approximately four times the length of the model. This will allow ample room for the model's manoeuvring algorithms to be performed.

The deck is made of a lightweight foamboard, since an aluminum frame is used to support the deck and to house the linear actuator used for the traversing component of the ASIST model. The rotating plate allows the frame and deck to rotate about the centre post to allow a combination of pitch and roll motions. The rotating plate yaw orientation remains constant, while the frame and deck rotate about a centre pin on the plate. Four clamps are used to secure the frame at the desired orientation.

The platform is attached to the centre post by a universal joint to eliminate yaw but allow ±45 degrees of roll and ±11 degrees of pitch. A support post is required to prevent the platform from rotating about the nonactuated horizontal axis. The location of the axis of rotation is also adjustable to achieve different magnitudes of motions by placing the universal joint at different locations along the centre post. Additionally, the position of the posts and linear actuator are interchangeable thereby producing different combinations and magnitudes of motions.

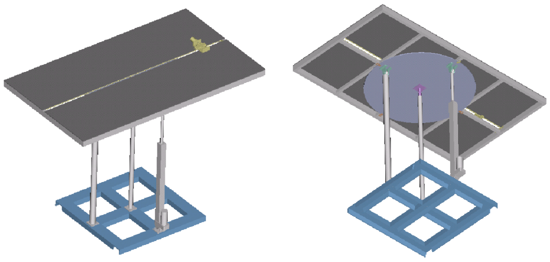

Figure 4: Top and bottom views of the experimental motion platform

Analysis

As mentioned above, the helicopter model on the ship deck will experience roll, pitch, surge, sway, and heave motions as the result of kinematic coupling between linear and angular motions depending on the motion platform orientation, the location of the axis of rotation, and the position of the model on the motion platform. Equations were derived to determine the linear and angular displacements, velocities, and accelerations at every point on the deck. Figures 5 and 6 show the front and top views, respectively, of the key reference points and coordinate systems on the motion platform, as well as the dimension variables referred to in the upcoming equations.

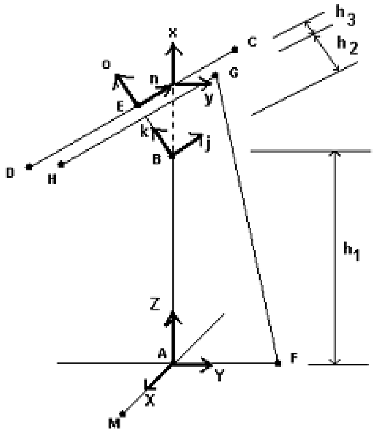

Figure 5: Front view of the motion platform showing points and coordinate systems used for analysis

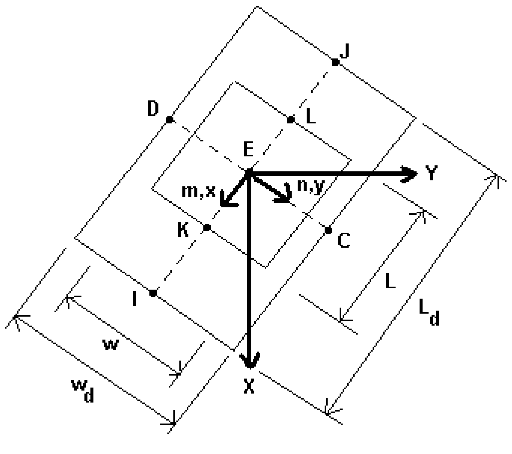

Figure 6: Top view of the motion platform showing points and coordinate systems used for analysis

By monitoring the global positions of the key reference points, as well as the point P, which represents the centre of gravity of the scale model helicopter, the required displacements, velocities, and accelerations of the linear actuator can then be determined. The global position of key points can be determined from

$$r_E^G = r_B^G + [T_{ijk \to XYZ}] \cdot r_{E/B}^L \tag{19}$$

$$r_C^G = r_E^G + [T_{mno \to XYZ}] \cdot r_{C/E}^L \tag{20}$$

$$r_D^G = r_E^G + [T_{mno \to XYZ}] \cdot r_{D/E}^L \tag{21}$$

$$r_I^G = r_E^G + [T_{mno \to XYZ}] \cdot r_{I/E}^L \tag{22}$$

$$r_J^G = r_E^G + [T_{mno \to XYZ}] \cdot r_{J/E}^L \tag{23}$$

$$r_P^G = r_E^G + [T_{mno \to XYZ}] \cdot r_{P/E}^L \tag{24}$$

where the superscripts L and G indicate a local coordinate system or global coordinate system with respect to point A, respectively, and

$$[T_{mno \to XYZ}] = R(x,\theta) \cdot R(z,\theta) \tag{25}$$

$$[T_{mno \to XYZ}] = [T_{ijk \to XYZ}] \cdot [T_{mno \to ijk}] \tag{26}$$

$$[T_{mno \to XYZ}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} \cos\lambda & -\sin\lambda & 0 \\ \sin\lambda & \cos\lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{27}$$

where θ is the roll angle of the platform with respect to the horizontal, and λ is the yaw orientation of the motion platform with respect to a zero heading.

Other values of interest are the linear actuator stroke, velocity, and acceleration required to produce the desired ship motions. The linear actuator stroke Δ required for a specific roll angle is given by

$$\left| r_{G/F}^G \right| = \left| r_G^G - r_F^G \right| \tag{28}$$

$$\Delta = \left| r_{G/F}^G \right| - \text{original length} \tag{29}$$

The linear actuator velocity is determined by the following equations:

$$v_{G/F}^G = \dot{\theta} \cdot \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\sin\theta & -\cos\theta \\ 0 & \cos\theta & -\sin\theta \end{bmatrix} \cdot r_{G/B}^L \tag{30}$$

$$v_{actuator} = v_{G/F}^G \cdot (r_{G/F}^G)_{UNIT} \tag{31}$$

The linear actuator acceleration is determined by the following equations:

$$a_{G/F}^G = \ddot{\theta} \cdot \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\sin\theta & -\cos\theta \\ 0 & \cos\theta & -\sin\theta \end{bmatrix} + \dot{\theta}^2 \cdot \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\cos\theta & \sin\theta \\ 0 & -\sin\theta & -\cos\theta \end{bmatrix} \cdot r_{G/B}^L \tag{32}$$

$$a_{actuator} = a_{G/F}^G \cdot (r_{G/F}^G)_{UNIT} \tag{33}$$

A Matlab program was used to implement these hand-derived equations to determine the linear and angular motions of the model placed at any point on the deck, the equilibrium forces acting on the motion platform, and the linear actuator motion required to produce the desired motions.

For any peak roll displacement, velocity, acceleration, and yaw orientation of the deck, the Matlab program also provides the ability to display two-dimensional images of the motion platform orientation, shown in Figures 7 and 8, indicating the position of the platform at the indicated peak motion and location of the scaled helicopter model.

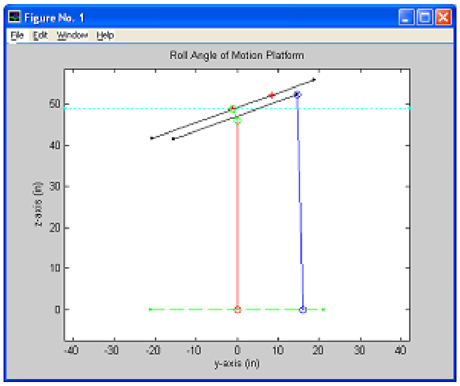

Figure 7: Front view of the motion platform plotted by Matlab

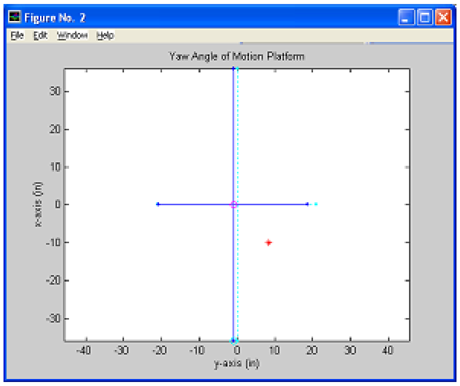

Figure 8: Top view of the motion platform plotted by Matlab

A model of the motion platform was also created using ADAMS, which is multibody dynamic simulation software that can simulate the full-motion behaviour of complex mechanical systems. This model, shown in Figure 9 was used to perform a dynamic analysis of the motion platform and measure the forces and moments acting on the components of the motion platform during the most extreme conditions. This data, along with the Matlab results, were used to size the components and compare alternative motion platform designs.

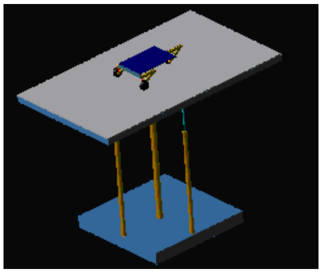

Figure 9: View of ADAMS dynamic model scale-model dead load test vehicle on the experimental motion platform

DLTV

The associated helicopter model, as shown in Figure 10, represents a $\frac{1}{10}$-scale model of a typical helicopter configuration, which contains a full suspension system and an adjustable frame to represent different helicopter configurations (nose or tail wheel and steerable or castorable wheel designs). Values that are measured on the DLTV during the manoeuvring simulations include: probe securing forces, DLTV position and orientation, and suspension deflection.

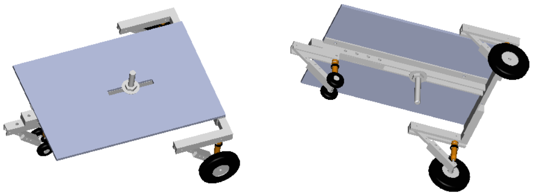

Figure 10: Top and bottom views of the DLTV

ASIST Model

The two degrees of on-deck aircraft actuation are: the longitudinal motion of the RSD and the lateral motion of the RSD claw (the actual securing point), which grips the helicopter-mounted probe. Using the translational scaling laws stated above, the motions of the model of the ASIST system were scaled to traverse the $\frac{1}{10}$-scale, approximately 20 pound, DLTV longitudinally at 3.8 in/s and move the claw laterally at 0.3 inches per second.

A leadscrew assembly, similar to the preliminary design shown in Figure 11, is used for both the RSD and claw actuation using an ACME thread screw shaft with a pitch of 3 threads per inch. Two stepper motors are used to actuate the physical model of the ASIST system.

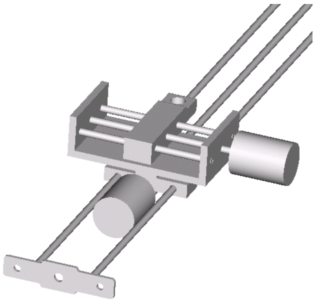

Figure 11: Model of the RSD for the ASIST system

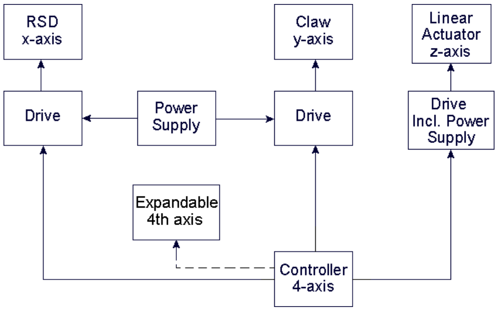

Figure 12: Schematic of the actuation components

Actuation Components

The motion system will contain three actuation axes: x, y, and z, as shown in Figure 12. The x- and y-axes describe the planar motion of the RSD, where the x-axis aligns with the longitudinal motion of the RSD (parallel to the ship's longitudinal axis) and the y-axis represents the lateral motion of the claw. Both axes will use size 23 stepper motors to activate the leadscrews. The z-axis contains the vertical linear actuator that will be used to produce the ship motions, which is a purchased leadscrew linear actuator powered by a brush motor. To reduce the cost of the system, all three initially-required actuators are controlled using a multi-axis controller. A four-axis controller was purchased to accommodate further expansion to include pitch motion. All three axes will interface with the operator through National Instruments (NI) Labview 6.1 software with additional NI Motion tools, which allow all instruments and controls to be virtual and displayed on the computer monitor.

There are three aspects of the project that determine the controls required for the planar motion system. First, the controller must allow input from a joystick to control the longitudinal and lateral motions of the RSD. Second, pre-programmed algorithms from the computer should be able to control the RSD. Finally, through the measurement of the position and orientation of the model, automation algorithms will be developed to determine the motions required for the RSD.

Validation

The validation of the simulation has been broken down into experiments involving ship motion and not involving ship motion. The validation done without ship motion will be broken down into three stages: qualitative testing; scale-model experimentation on the experimental motion platform; and full-scale experimentation on ITI's integrated test facility (ITF). The validation done with ship motion will be done on the experimental motion platform. A verification plan is outlined first.

Verification

The simulation is checked for programming errors. A set of inputs is run through the program and the results at specific moments in time are then compared with hand calculations. This will be done for a wide range of inputs. The entire simulation is then qualitatively scrutinized for a number of simple situations. These situations include a constant probe force inputs applied for different helicopter orientations. Similar simple situations will also be used as described subsequently in the context of the ITF-based validation process.

Qualitative Validation

An experienced ASIST operator will perform a number of manoeuvres with the simulation interfaced to a joystick and a graphics package (ITI's Dyna2D®). This will be done to get a general feel for the way the simulation reacts, compared with the actual ASIST system.

Scale-model Experimentation on the motion Platform Without Motion

The simulation will be validated first with a physical model of the helicopter and ASIST system on the experimental motion platform. The helicopter trajectory and orientation will be tested by running the helicopter through a few simple situations and manoeuvres. These are described in greater detail below. The experimental results will then be compared with the simulation results.

Full-scale Experimentation on ITI's Integrated Test Facility (ITF)

ITI's ITF is currently equipped with a full-scale dead load test vehicle (DLTV) that can represent a number of different helicopter configurations. Validation using results generated by the ITF has been broken down into three measurement phases. The complexity of the manoeuvres carried out increases with each measurement phase.

The ASIST system joystick control input values will be recorded while each test is being carried out by a proficient ASIST operator. This allows for all of the phases to be recorded on the ITF at one time and the validation results can be analyzed separately. The following data will be gathered from the ITF for each test:

- claw velocities, to test the simulation joystick model;
- probe forces, to test the ASIST model;
- helicopter position, to map the trajectory;
- helicopter orientation, to map the orientation through the trajectory; and
- tire deflections, to further validate the tire model.

Simple Situations

The ITF will be run through some simple motions first to catch any large discrepancies between the simulation model and reality. These simple situations will include, moving the helicopter: in a straight line; in a straight line along a curved track; and swinging the castor wheel laterally. These can also be used to help determine if the instrumentation is set up correctly.

Manoeuvre Components

A number of standard manoeuvring situations will be used for advanced testing. These manoeuvres can be broken down into three different manoeuvre components. The next validation step is to run the ITF through these components that are:

- *straightening* where the helicopter is straightened from an askew angle;
- *align probe* where the probe is aligned with the track from an askew angle; and
- *align castor* where the castor wheel is realigned from 180 degrees and 90 degrees.

Standard Manoeuvres

Standard manoeuvres, which are groups of two or three of the components defined above are used to straighten the helicopter from an askew landing orientation. Three conditions, as defined by ITI, must be met for the helicopter to be considered straightened. The conditions are: the probe must be centre on the track; the nose or tail wheel pivot axis must be on the track centreline; and the nose or tail wheels must be parallel to the centreline. These conditions must be met for a successful manoeuvre to have taken place.

Effect of Motion on the Manoeuvring Simulation

The study of the effects of motion on the manoeuvring of the helicopter uses the experimental motion platform with a physical model of the helicopter and ASIST system to simulate various magnitudes and types of ship motion during the manoeuvring of the scale-model helicopter. The resulting model trajectories under the influence ship motion will be compared to the model trajectories without motion. The results from the experimental motion platform can then be compared to the planar manoeuvring simulation and simple alterations can be made to the simulation to represent the ship motion, such as changing the direction of gravity. The alterations to the planar simulation may not result in a completely accurate model of the manoeuvring of the helicopter with ship motion, however it will be an approximation. Once the results of this project are incorporated into *Dynaface*® [1], a comprehensive, accurate, and fully-three-dimensional simulation will result.

The cases that were used to validate the manoeuvring simulation without ship motion will be repeated with motion generated by the developed motion platform. The data will be compared with the previously obtained data to determine the effect of motion. Six cases will be selected, based on roll angle and heading angle, for use during the study of the effect of motion on the manoeuvring of the helicopter.

Application

This ongoing multi-phase project is comprised of three distinct parts. While the combination of these three parts is aimed at both resolving the immediate need for analysis capability and demonstrating the potential for a significant technological advance with autonomous operation, each of the individual parts is suitable for a variety of applications beyond the immediate objective.

Manoeuvring simulations have traditionally been developed for four-wheel road vehicle applications at relatively high speed, with the force generated through the wheels. The specific simulation that is the subject of this work has addressed the more general case where the system is driven by forces generated externally and not necessarily coincident with the wheels. In the case of the ASIST system, the aircraft has three to six wheels and manoeuvring forces are applied to a retractable helicopter-mounted structural probe that is located near the vehicle's centre of mass. This technology could be applied to a variety of material handling applications where material is being towed on wheeled platforms or otherwise manipulated by external forces. For example, navies are looking for faster means to move cargo on deck to achieve faster replenishment at sea operation. Analysis and simulation of the proposed equipment for such application would be necessary for the design process.

Development of a motion platform and associated test vehicle constitutes a fundamental research tool that, in the current application, will be used for simulation validation and to support development of autonomous manoeuvring and traversing algorithms in the presence of ship motion. However, this general test facility could be used to investigate securing requirements in a variety of motion environments. Two immediate applications in Ontario include road and rail shipping of automobiles and rolls of processed steel and cabling. A recent tractor-trailer fatality in Ontario has been attributed to inadequate securing of such cargo.

Automation also has potential widespread applicability. The unique feature of the proposed work is that a successful on-deck manoeuvring algorithm for a helicopter must combine conventional path planning and error control strategies with a decision making approach as the optimal manoeuvring sequence is comprised of multiple manoeuvres dependent upon the initial position and orientation of the aircraft on the flight deck. The considerations involved in this aspect of the project have applications in other industries including manufacturing, automotive, and transportation.

In addition to the direct benefits to companies that become directly involved in the work, spin-off benefits must also be considered. ITI is a system integration company, where improved market share resulting from improved technology in its products will lead to expanded sales and spin-off benefits for the many Ontario manufacturing companies that are subcontracted to provide the material and manufacturing processes required for the production of ITI's products. While the overall project is aimed at one particular technical challenge, the elements of the proposed project make the technology transferable to other industrial applications in Ontario and beyond.

ITI markets its analytical services to navies and shipyards around the world. In the short term this research program will add to ITI's capabilities and opportunities to perform more extensive studies and provide software licences to its customers. In the long term the research program will facilitate the development of the TC-ASIST control system. TC-ASIST is being developed to target European markets with a sales volume potential of over $30,000,000.

Development of the motion platform to replicate embarked helicopter securing and manoeuvring in a controlled environment will set the foundation for future experimental research work relating to the dynamic interface problem, and thereby offering long-term benefits in terms of securing equipment design as well as the safety of personnel during embarked helicopter operations. Autonomous manoeuvring and traversing has the potential for raising the state of the art for embarked helicopter handling systems and will affect the direction of future developments.

Concluding Remarks

The vital role of helicopter/ship dynamic interface analysis has been steadily increasing as shipboard helicopters are required to operate in more extreme ranges of sea conditions, as interoperability requirements become more prevalent, and as the demands placed on the efficiency of on-deck operations - both in terms of minimizing the number of deck personnel and reducing the required time for on-deck operations increase. Simulation capability for investigating shipboard helicopter securing requirements is fairly mature with the availability of established helicopter/ship dynamic interface simulation programs such as *Dynaface*® [1]. The project described in this paper addresses the increasingly important shipboard manoeuvring and traversing aspect of embarked helicopter operation. It is expected that the helicopter manoeuvring simulation and associated dynamic interface experimental motion platform will lead to significant improvements in analysis capability and will contribute to optimization of manoeuvring algorithms, the possibility of autonomous manoeuvring and traversing, and refinements to helicopter securing methods that facilitate on-deck helicopter handling.

Acknowledgment

This project has been sponsored jointly by Indal Technologies Inc. (ITI), Materials and Manufacturing Ontario (MMO), and Carleton University (CU).

References

[1] R. G. Langlois and A. R. Tadros. *User's Manual for the Aircraft/Ship Dynamic Interface Simulation Dynaface Release 5.0.* Indal Technologies Inc., Mississauga, Ontario, Canada, January 1998. ITI Report No. 99/419 (dia5).

[2] R. F. Smiley and W. B. Horne. Mechanical properties of pneumatic tires with special reference to modern aircraft tires. Technical report, National Aeronautics and Space Administration, Langley Research Center, Langley Field, Virginia, USA, 1980. (dia24).

CURTISS-WRIGHT

Info

curtisswrightds.com

Email

ds@curtisswright.com

CURTISSWRIGHTDS.COM