Physical Modeling of Helicopter Rotorwash Environments for Enhanced Crew Training

Jeffrey D. Keller, Daniel A. Wachspress, Todd R. Quackenbush
Continuum Dynamics, Inc.
Ewing, New Jersey
jeff@continuum-dynamics.com, dan@continuum-dynamics.com, todd@continuum-dynamics.com

ABSTRACT

Military rotorcraft operations have grown in mission capability such that these aircraft are critical components in numerous combat and non-combat missions. Simulation provides a valuable tool for training aircrews and ground personnel during mission rehearsal of rotorcraft operations, which at times can involve coordination between multiple personnel. A critical aspect of ensuring that personnel receive effective training is the inclusion of physics-based models that account for the effects of rotorcraft operations, in particular, the effects of rotorwash, on the simulated environment. These effects have become more critical with the use of heavy lift rotorcraft and tiltrotors, which may potentially introduce a significant rotorwash hazard to ground personnel. It is highly desirable to identify enhanced models for rotorwash effects in simulation to yield highly effective training environments. This paper describes initial work on an advanced simulation capability for modeling helicopter rotorwash effects in a dynamic virtual training environment. The central element is a real-time, physically-based rotorwash model that is used to capture interactions between the helicopter and environment. A proof-of-concept rotorwash physics engine has been developed that simulates the response of dynamic objects (including rigid bodies and flexible objects such as cables) due to flight operations near the ground and ship flight decks. By using a physics-based approach, it is possible to represent the dynamic environment and provide proper training cues over a broad range of operational scenarios. The paper discusses the rotorwash physics engine development that combines an advanced rotorcraft flow model with a commercial off the shelf (COTS) multi-body physics engine. Results from representative applications are provided, including an application that presents regions of potential rotorwash hazards in a simplified manner for ground personnel training.

ABOUT THE AUTHORS

Jeffrey D. Keller is an Associate with Continuum Dynamics, Inc. in Ewing, New Jersey, where he has been since 1997. His professional interests include air vehicle aerodynamics and flight dynamics modeling and aircraft flight controls development, and he has led several flight dynamics and simulation projects for unmanned aircraft systems and shipboard dynamic interface environments. He received a Ph.D. from the Department of Mechanical and Aerospace Engineering at Princeton University in 1998 and also received B.A. and M.Eng. degrees in Aeronautical Engineering from Rensselaer Polytechnic Institute in 1990 and 1991, respectively.

Daniel A. Wachspress is a Senior Associate with Continuum Dynamics, Inc., where he has been directly involved in the research, development and implementation of rotorcraft computer models for over twenty years. He is the chief architect for numerous analysis and simulation tools for rotorcraft and has led the development of real-time rotor wake models for real-time simulation applications. He earned B.S.E. and M.S.E. degrees in Mechanical and Aerospace Engineering from Princeton University in 1980 and 1982.

Todd R. Quackenbush is a Senior Associate and Director of Business Development with Continuum Dynamics, Inc. He has led research and development efforts involving all aspects of modeling rotorcraft aerodynamics and dynamics, including extensive studies of rotor design optimization and unsteady airload computations. He earned B.S.E. degree from Princeton University in 1980, M.S. degree from Massachusetts Institute of Technology in 1981, and Ph.D. from Princeton University in 1986.

Physical Modeling of Helicopter Rotorwash Environments for Enhanced Crew Training

Jeffrey D. Keller, Daniel A. Wachspress, Todd R. Quackenbush
Continuum Dynamics, Inc.
Ewing, New Jersey
jeff@continuum-dynamics.com, dan@continuum-dynamics.com, todd@continuum-dynamics.com

INTRODUCTION

This paper describes initial development of a high-fidelity, real-time rotorwash and dynamic environment physics engine for enhancing realism in distributed training environments. The primary objective has been to demonstrate a proof-of-concept physics engine built primarily upon two software components: (1) the Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) developed for modeling rotorcraft aerodynamics and wake dynamics, as well as the associated flow fields, and (2) the open-source multi-body dynamics engine Open Dynamics Engine (ODE). This proof-of-concept CHARM/ODE physics engine can account for the interactions between the helicopter rotor wash and the surrounding environment, which may contain multiple simulated (dynamic) objects. Emphasis has been placed on modeling the physics of the dynamic environment, in particular the rotorwash/jet wash from V/STOL aircraft using first-principles since physically-based models will permit simulation of a broad range of operational scenarios and environmental conditions.

An important motivation for a real-time rotorwash physics engine is to enhance the realism in training environments, in particular where multiple personnel performing mission rehearsal require close collaboration and can influence one another, e.g., a simulated Vertical Replenishment (VERTREP) operation requiring collaboration between aircrew and ground personnel. Including the effects of rotorwash are important, in particular for heavy lift rotorcraft and tiltrotors, which may potentially introduce a significant rotorwash hazard to ground personnel. It is highly desirable to identify enhanced models for rotorwash effects in simulation to yield highly effective training environments in these cases, and thus, potentially contribute to increased positive transfer of training.

By using a physics-based modeling approach, it is possible to properly represent the dynamic environment due to these interactional effects and provide proper cues to trainees. These cues can include both physical cues and synthetic aids to the aircrew and flight deck personnel. Presentation of these cues can be provided through simulation of the dynamic environment (i.e., representing the proper behavior of objects in the virtual environment subject to wind and rotorwash/jet wash effects), as well as through the use of visualization aids that include representation of the relative flow field and/or simplified "hazard" metrics that provide reinforcement to trainees to avoid certain areas during rotorcraft operations.

A notional implementation of the real-time, physics-based dynamic winds and rotorwash engine for distributed aircrew training is shown in Figure 1, illustrating the rotorwash/dynamic environment engine within a generic, multi-seat training environment. The ultimate goal of this research and development is to provide an interactive and easy-to-use modeling engine for representing the physical environment and associated dynamic response characteristics subject to inputs and actions taken by (multiple) trainees. This paper provides an overview of the underlying technology, development of the proof-of-concept tool, and demonstration results for several scenarios relevant to rotorcraft operations.

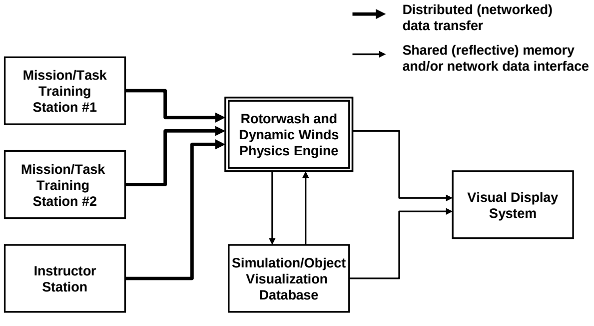

Figure 1. Illustration of Rotorwash Physics Engine in a Distributed Simulation Environment

ROTORWASH AND DYNAMIC ENVIRONMENT MODELING

Development of modeling and simulation tools to capture the effects of rotorwash and jet wash from helicopters and V/STOL aircraft on the dynamic virtual environment requires the ability to predict the unsteady flow field in the vicinity of the aircraft interactively, subject to operator inputs. The requirement for interactive modeling of the rotorwash flow field is critical for application to training systems, since trainees will naturally attempt to effect changes to the simulated environment, requiring immediate feedback from their actions and the actions of other "players" in the simulation. Modeling the induced flow field from helicopters and V/STOL aircraft is a challenging undertaking, especially when constrained by real-time computational requirements for interactive simulations. This section provides an overview of current methods available for rotorwash modeling, with emphasis on real-time free wake methods.

Background

A range of modeling techniques have been applied to predict the flow field in the vicinity of a rotor for engineering analysis ranging from simplified momentum-based models to high-end computational fluid dynamics (CFD) solutions. For real-time simulation applications, finite-state (dynamic) inflow models (Peters and He, 1995) historically have been used in rotorcraft simulation for predicting the induced velocity. These models have seen widespread use throughout the rotorcraft flight simulation community due to their inherent robustness and minimal computational requirements. Finite-state inflow models, however, gain these benefits at the expense of fidelity in modeling the vortex-dominated flow fields in the vicinity of operating rotorcraft, as well as their ability to capture dynamically evolving flow fields. Thus, while there are many computational benefits to use of finite-state inflow models, these models are not suitable for modeling rotorcraft downwash and outwash as part of a generic rotorwash physics engine for use in a distributed training environment where an unlimited range of operational conditions may exist.

By contrast, rotorcraft free-wake induced velocity models determine the flow field at the rotor and in the region surrounding the aircraft by computing the evolution of the rotorcraft wake, which is allowed to evolve due to the influence of the rotor, fuselage, wake (i.e., self-induction effects), ground plane/flight deck, and external unsteady wind disturbance (including ship or ground structure wake effects). While free wake methods have historically been restricted to high-end rotorcraft aeromechanics analysis, significant work has been performed since the late-1990's to develop real-time solutions and computational modules for free wake methods to permit this modeling technology to be accessible to pilot-in-the-loop (interactive) simulation applications (Quackenbush et al., 2002). The result of this work has been a modular, real-time offshoot of the CHARM free-wake methodology. Development, application, and validation of this real-time CHARM module have been reported in the literature (e.g., Wachspress et al., 2003). The wake module has been integrated with several rotorcraft flight simulation environments and has been shown to yield comparable or improved flight dynamics predictions without "tuning" that has been necessitated by using simpler (finite-state) models for the rotor induced velocity (Spoldi and Ruckel, 2003; Kothmann et al., 2004; Horn et al., 2005). Given its physical fidelity, modeling accuracy, and fast computational run-time, the CHARM real-time free wake module provides the critical foundation for developing a rotorwash/dynamic winds physics engine for enhancing realism in virtual training environments.

For the present application, the CHARM module provides the foundation for a rotorwash physics engine that captures the effects of helicopter and V/STOL aircraft operations in a dynamic virtual simulation environment. This initial development has focused on establishing the modeling basis and application to real-time rotorwash and jet wash predictions that are used to drive dynamic object simulations and to define flow field hazard metrics for enhanced training applications.

Benchmarking of Rotorwash Real Time Modeling

During the development of the CHARM methodology, extensive validation and real-time benchmarking has been performed, focusing on performance metrics, flight dynamics response characteristics, empennage interference effects, ground effect, and outwash predictions (Wachspress et al., 2003, 2008; see also references cited previously). For the present application, the principal concern is the ability to predict rotorcraft downwash and outwash velocity components, in particular in ground effect conditions, in a real-time computational environment. In addition to providing accurate rotorwash predictions, an additional requirement for this application is to provide induced flow field evaluations at many locations surrounding the aircraft, which is required for providing dynamic (motion) updates to objects within a richly populated virtual environment and/or flow field visualization objects and rotorwash hazard indices.

In general, the model fidelity of free-wake induced velocity solutions increases with the number of vortex elements (N) used to represent the wake structure. Correspondingly, the computational requirements also increase with the number of vortex elements, typically scaling as N^2. The CHARM methodology uses a combination of efficient representation of the wake (vortex sheet) trailing from each blade as vortex filaments representing constant vorticity contours (CVC) with advanced numerical algorithms (hierarchical multipole methods). These algorithms have been shown to yield a computational overhead that scales as N log N (Quackenbush et al., 1996).

For the present application, it is necessary to determine the rotorwash flow field at a finite number of points (M) off the rotor blade and wake, in addition to the N control points associated with the wake geometry. These additional M flow field evaluation points coincide with critical locations (aerodynamic control points) for evaluating the aerodynamic loads on physical objects within the visual database and/or flow visualization graphical primitives. While these additional requirements would cause conventional free wake methods to computationally scale as 2N(M+N), calculations have been performed to assess timing requirements of the CHARM module for a model problem representative of this application.

Calculations were performed for an isolated H-60 helicopter (22,000 lbs gross weight) hovering in ground effect with the rotor plane 25 feet above the ground, as illustrated in Figure 2 (note that the fuselage has been added for visualization but was not included in the calculation). Calculations were performed on an Intel Xeon 3 GHz processor, and processor times were recorded for various levels of wake resolution and number of flow field evaluation points. Representative results are shown in Figure 3, which plots the fraction of real-time required by the calculation as a function of the number of flow field evaluations points for two levels of wake resolution. Note that a real-time fraction of 1.0 corresponds to the point when unsteady wake-induced rotorwash calculations equal the wall clock time; in practice, it is desirable to have real-time fractions slightly less than 1.0 to allow for other overhead (e.g., module interface and run-time communications). The wake flow field solution was updated at approximately 17 Hz, which is equivalent to the blade passage frequency for the H-60 and provides sufficient bandwidth for piloted simulation applications. It was observed that with an adequate fidelity wake resolution (400 wake elements), nearly 10,000 flow field evaluation points could be evaluated in real-time. This wake resolution corresponds to five turns of free-vortex wake (tip filament only), as illustrated in Figure 2, which is sufficient to model the flow field within a 100ft-by-100ft-by-25ft cubic area surrounding the helicopter. This volume, which is approximately 2 rotor diameters in width and length and extends from the rotor disc all the way to the ground, was determined to be of sufficient size to contain objects of interest for a typical operational scenario.

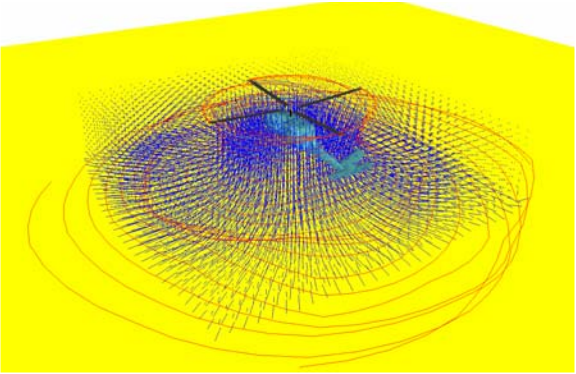

Figure 2. Illustration of Wake (400 elements) and Flow Field (10^4 evaluation points) for CHARM Real Time Benchmarking

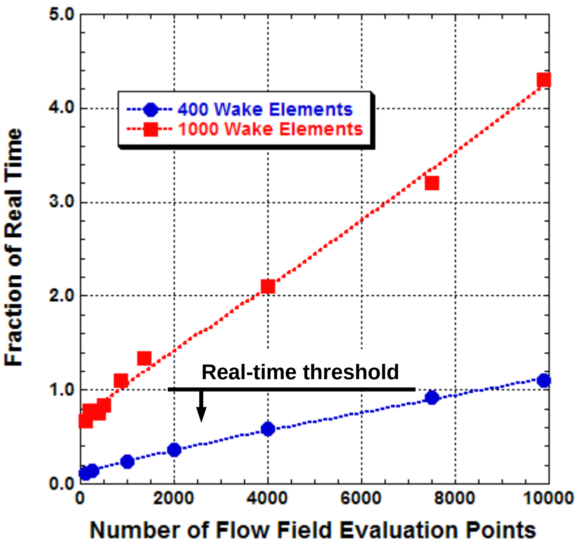

Figure 3. CHARM Module Computational Timing for Wake and Flow Field Evaluation Point Resolution

The critical parameters that control real-time operation are the number of vortex elements and evaluation points. The required number of vortex elements is typically determined by the operational flight condition, with more elements required for low speed flight operations. The number of evaluation points is determined by the visualization database requirements. Figure 4 illustrates snapshots for different evaluation point mesh resolutions. It is anticipated that most applications should require no more that approximately 1000 evaluation points, which will permit modeling of detailed dynamic object databases and flow visualization schemes. Thus, these results show promise for implementation of the CHARM module within a real-time rotorwash physics engine for dynamic object and flow visualization applications.

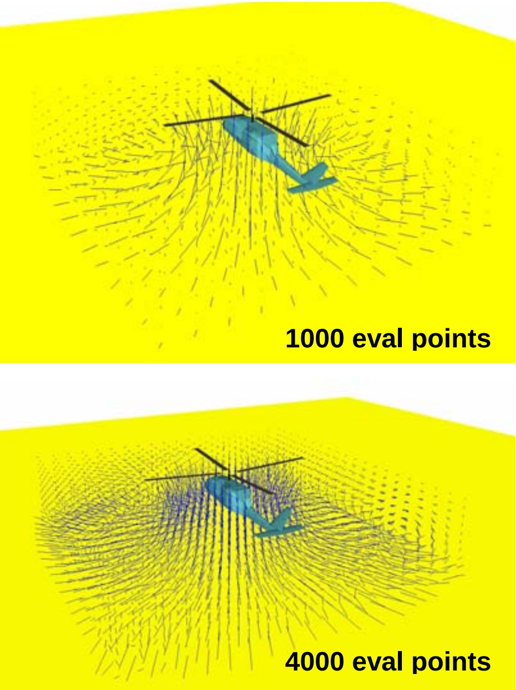

Figure 4. Illustration of Flow Field Grid Resolutions for CHARM Rotorwash Evaluation

Rotorwash Predictive Model Validation

As noted above, the CHARM model has undergone extensive validation during its development. Recent work has focused on correlation of CHARM predictions with a compilation of flight test and experimental data for several rotorcraft (Ferguson, 1994). Representative results are shown in Figures 5 and 6 that correlate predicted and measured outwash as a function of height above ground level (HAGL). Figure 5 shows mean and peak outwash predictions, compared with flight test data, at various heights above the ground one rotor diameter from the rotor center of a CH-53 Super Stallion (70,000 lb gross weight) helicopter hovering with the rotor 37 ft above the ground. Figure 6 shows similar predictions for a XV-15 tiltrotor (25,000 lb gross weight). These predictions were made using model settings configured for real-time operation. The correlations establish the ability of the real-time wake model to capture not only the mean velocities but also the peak (fluctuating) velocities, in particular near the ground. Note that the peak outwash correlation worsens as the height above ground increases. Additional correlation results (Wachspress et al., 2008) indicate that the prediction improves as the wake resolution in increased just beyond what is currently achievable in real-time. As computer processing speeds increase, it is anticipated that the real-time correlations will become more favorable.

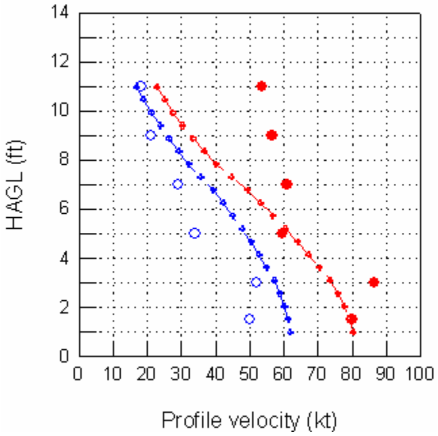

Figure 5. Comparison of Mean (blue) and Peak (red) Outwash Velocity for CH-53 Helicopter (Data shown with circles; prediction with dotted lines)

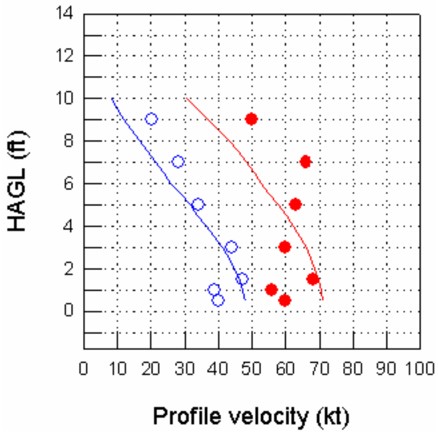

Figure 6. Comparison of Mean (blue) and Peak (red) Outwash Velocity for XV-15 Tiltrotor (Data shown with circles; prediction with solid lines)

ROTORWASH PHYSICS ENGINE DEVELOPMENT

A proof-of-concept tool has been developed for describing behaviors of dynamic objects within a simulated virtual environment due to the effects of rotorwash and winds. This tool is built from coupling the CHARM real-time free wake module with and an open-source physics engine (Open Dynamics Engine or ODE). The CHARM/ODE rotorwash physics engine models the downwash and outwash from the rotorcraft and the effect of this induced flow on the objects dynamic response. A description of a proof-of-concept rotorwash physics engine is provided below.

Multi-body Physics Models

Development of the proof-of-concept rotorwash physics engine requires modeling of the object dynamics subject to the aerodynamic forces and moments induced by the flow field from the operating aircraft and environment. In addition to modeling the aerodynamic loads, it is also necessary to model contact and reaction loads due to object-object and object-ground collisions, as well as approximations for modeling flexible bodies that account for distributed mass/stiffness characteristics as equivalent lumped masses, spring rate, and damping factors. Many different methods and formulations to the underlying equations governing the dynamic response and constraint reactions have been investigated (e.g., Catto, 2007; many more examples can be found in the literature). Accordingly, this breadth in modeling methods for general multi-body dynamic formulations is paralleled by the broad range of “off the shelf” multi-body physics engines that are available to the engineering and gaming communities. While several suitable candidate physics engines are available, the present application used ODE (Smith 2006). ODE is an open-source library for simulating articulated rigid body dynamics suitable with built-in collision detection for use in virtual reality environments. While fundamentally a rigid, multi-body physics solver, non-rigid (flexible) objects may be approximated by selection of joint constraints and model parameter (i.e., mass properties and joint parameters).

Note that use of an off-the-shelf physics engine software library has been pursued primarily to accelerate development. The ODE library includes an extensive application programming interface (API) for joint modeling, collision detection, and reaction load determination. Although ODE uses a robust integration scheme that is fast and stable, it should be recognized that these benefits are achieved by using a lower-order integration method that may not have sufficient accuracy for general engineering simulations. While sufficient for demonstration purposes, ongoing work is required to quantify accuracy of the existing modeling methodology and numerical implementations within ODE (through detailed verification and validation studies), and updates of the underlying algorithms (i.e., higher order integration methods) should be examined as needed.

CHARM Module Integration

Development of the rotorwash physics engine requires coupling of the CHARM model with the ODE multi-body physics library. This coupling occurs through the aerodynamic forces on the objects, which depend on the relative velocity between the object and induced flow field.

The CHARM module, described previously, has been coupled with the latest version of ODE (version 0.8.1), and this coupled CHARM/ODE rotorwash physics engine has been used to examine the response of rigid and flexible bodies due to the rotorwash field as a demonstration of capability. A simplified module interface was developed for this application, which permits variation of the relative winds to the aircraft and allows evaluation of the downwash/outwash flow field at points corresponding to the aerodynamic reference point on multiple bodies in the simulation. The updated CHARM API also includes functions for initialization, aircraft trajectory update, and induced velocity evaluation at specified aerodynamic control points, in addition to function (methods) for accessing wake geometry in support of flow visualization methods. In simulation results presented in this paper, the aircraft trajectory has been pre-defined, although this restriction is not required since the free wake module can compute the flow field for dynamically-changing (maneuvering) trajectories in real-time.

Input data for the rotorwash engine include:

- Geometric data (e.g., length, width, height) for the simulated objects
- Object mass properties
- Constraint/contact parameters (e.g., coefficients of friction and restitution)
- Aerodynamic data

These data can be defined as part of an object database. Aerodynamic data should include lift, drag, and moment data as a function of object angles of attack and sideslip, in general.

Determination of the aerodynamic loads requires definition of suitable aerodynamic data (coefficients). While aerodynamic data have been compiled from experimental investigations for a range of geometric configurations (e.g., Hoerner, 1965, 1985), a generic modeling approach is highly desirable. Given the nature of the rotorwash/flow field environment, the modeling approach should be capable of supporting flow conditions that typically fall outside the range of empirical data (e.g., large flow angles of attack and yaw angles). An approach to define aerodynamic characteristics at high angles of attack has been examined based on a Newtonian flow model. For Newtonian flow analysis, the aerodynamic lift, drag, and moment are related to the velocity component normal to the aerodynamic surface. This approach has been previously applied to thin airfoil sections of lifting wings (Stengel, 2004). For the present application, a generalization has been made for the aerodynamic loads of arbitrary bodies (in symmetric flow conditions) using the following relationships:

$$c_l = K_1 \sin^2 \alpha \cos \alpha \tag{1}$$

$$c_d = K_2 \sin^3 \alpha \tag{2}$$

where α is the local angle of attack, c_l and c_d are the aerodynamic lift and drag coefficients, respectively (see Figure 7), and K_1 and K_2 are modeling parameters. Note that the Newtonian flow approximation is appropriate for large angles (greater than 60 degrees). To provide data suitable for the complete range of angles, it is necessary to blend together small angle data and/or analytical predictions (i.e., slender body theory) with the Newtonian approximation at large angles. The modeling constants can be adjusted to match known aerodynamic characteristics at specific flow conditions (e.g., maximum lift and/or limiting cases as α approaches 0 or 90 degrees).

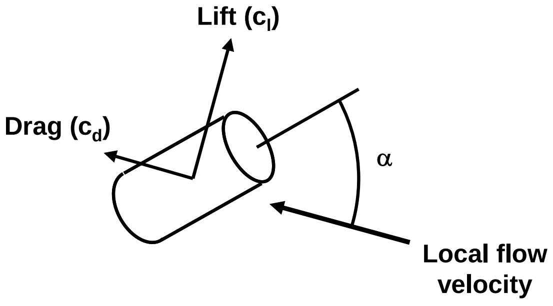

Figure 7. Aerodynamic Data Parameter Definitions for Coupled CHARM/ODE Engine

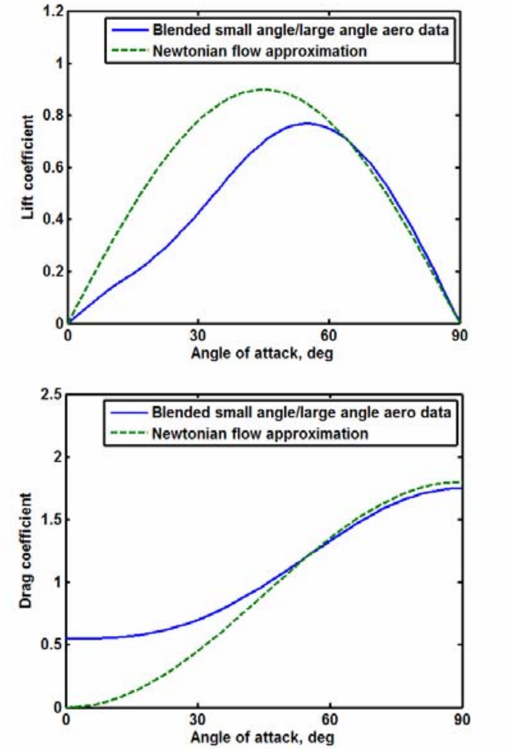

Figure 8. Representative Aerodynamic Data for Generic Cylindrical Body Based on Simplified Aerodynamic Theory

As an example, the aerodynamic loads on a generic cylindrical body are illustrated in Figure 8 using this generalized modeling approach. Note that these representative data are normalized by the projected area when the body is at an angle of attack of 90 degrees. These aerodynamic data coefficients provide a basis for initial assessment of rotorwash effects on dynamic object behavior modeling. While sufficient for initial demonstrations, more detailed object aerodynamic databases will be required for general applications. In addition, inclusion of unsteady aerodynamic effects (i.e., angular rate effects and effects of the time rate of change of the angle of attack and sideslip) should also be considered. General implementation of the rotorwash physics engine will likely require a combination of empirical aerodynamic data and analytical methods.

RESULTS

The proof-of-concept CHARM/ODE rotorwash physics engine has been used to simulate the dynamic response of objects due to the induced flow field from a helicopter operating in ground effect. Initial demonstration has examined modeling both simple rigid body objects (i.e., boxes with different mass properties) and a flexible cable. Demonstration simulation results have used a simplified aerodynamic (drag) model, and contact model/reaction force parameters (e.g., friction model, coefficient of restitution) have also been varied as part of the simulation study. Output from the modeling tool have included both quantitative and qualitative (visualization) results.

Rigid Body Object Modeling

The proof-of-concept CHARM/ODE rotorwash physics engine has been used to simulate the dynamic response of a simple isolated object subject to the rotorwash field of an H-60 helicopter hovering 15 feet above the ground/flight deck. Properties for the simulated object, including the initial position relative to the rotor center, geometry, mass, and contact parameters, have been varied. Outputs from the CHARM/ODE modeling engine include object trajectory and rotorwash flow field data, which may be plotted for comparison. For these results, the CHARM/ODE engine has also been coupled with a simplified visualization tool (packaged with the ODE library) to provide an animation of the object dynamic response. A snapshot from this simplified visualization tool is shown in Figure 9, which illustrate the response of a relatively large object (6 sq. feet projected area). Object trajectories (time histories) are shown in Figure 10, illustrating the sensitivity of the object response to variations of its mass. For this set of simulation parameters, the heaviest object simply tips over before coming to rest, while the lightest object is thrown into the air and tumbles to the ground with multiple ground impacts (note that ground contact is indicated by the cusp in the height above ground time history shown in Figure 10).

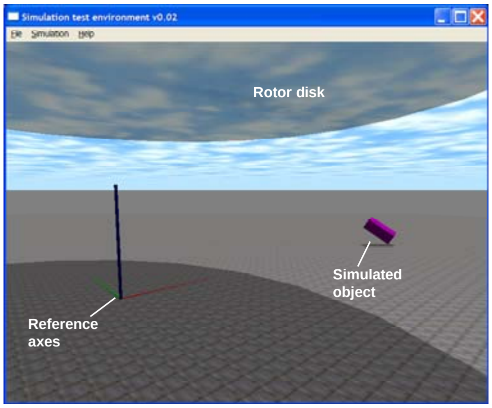

Figure 9. Snapshot from Simplified Visualization Tool for CHARM/ODE Engine Illustrating Single Object Response

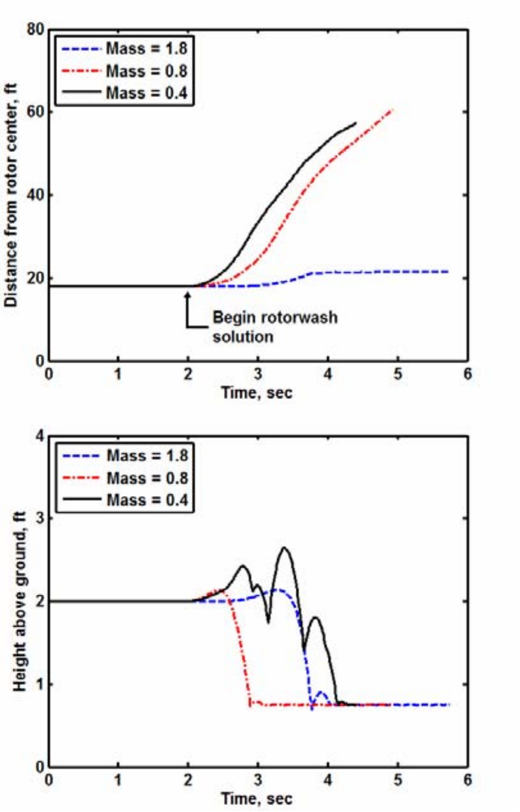

Figure 10. Parameter Variation Effects on Object Trajectories Computed with CHARM/ODE Engine

To illustrate the CHARM/ODE engine in modeling rotorwash effects during representative shipboard launch/recovery operations, the CHARM/ODE engine has been integrated within a representative 3D visualization environment, built upon the OpenSceneGraph rendering library. This visualization tool allows inclusion of ship and helicopter geometries, as well as permitting modeling of the background and scene lighting for self-shadowing effects. Example calculations have been performed that model the interactions of multiple rigid bodies with the rotorwash from the helicopter, hovering above the flight deck of an LPD-class ship. Snapshots from a demonstration calculation, where the H-60 helicopter is hovering 15 feet above the flight deck in an 18-knot cross wind (wind direction oriented 45 degrees to the starboard side of the ship), are shown in Figure 11. These snapshots show the initial response of the individual objects (the response is asymmetric with the upwind objects initially "feeling" the rotorwash effects) and dynamic behavior that include object-object and object-ship collisions.

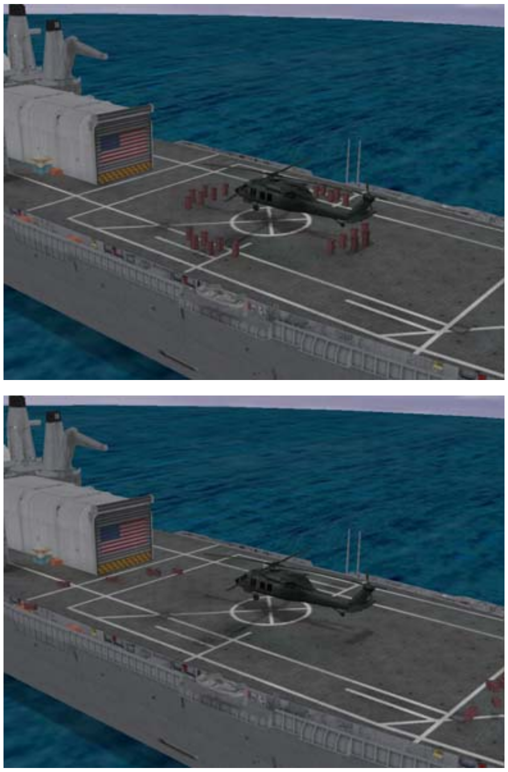

Figure 11. Snapshots from OpenSceneGraph Visualization Tool for CHARM/ODE Engine in Representative Shipboard Scenario

Flexible Object Modeling

Application of the CHARM/ODE engine to modeling the effects of rotorwash on the response of a flexible body (cable) suspended from the bottom of a helicopter has also been examined. Use of ODE to model ropes/cables has been previously investigated (Garrido, 2004); for the present investigation, the cable is modeled as a series of rigid body elements connected by universal joint constraints (to eliminate the rotational degree of freedom between individual segments). In addition, the connection to the helicopter is modeled as a ball joint connection (see Figure 12). Twenty rigid body segments are used to model the cable, with each segment length equal to 0.5 feet (total cable length is 10 feet). Rotorwash effects are applied following the approach used for the rigid body simulations described in the previous section. Note that while this modeling approach is approximate, it provides a reasonable representation of the cable dynamics, as shown below.

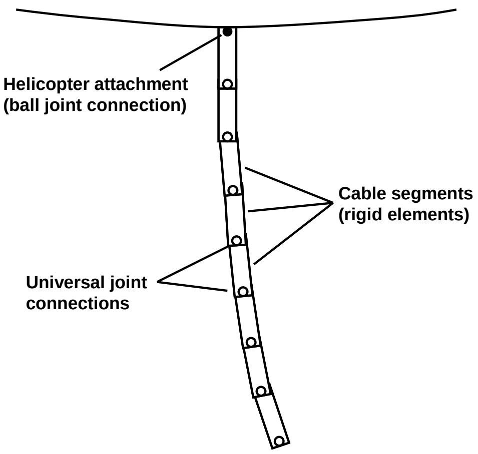

Figure 12. Illustration of Flexible Cable Model in CHARM/ODE Engine

Simulations have been performed for an H-60 helicopter hovering 25 feet above the flight deck in symmetric hover and hovering in a cross wind condition (18-knot winds oriented 45 degrees to the starboard side). Snapshots from the OpenSceneGraph visualization tool for the cable simulation in an 18-knot cross wind are shown in Figure 13. Motion of the cable is apparent between the successive frames from the visualization tool.

Figure 13. Snapshots from CHARM/ODE Engine Modeling Rotorwash Effects on Flexible Cable

Quantitative results from the cable simulation are shown in Figure 14, which illustrate the cable tip deflection as a function of time. The effects of rotorwash on the cable response can be seen by comparing the solid and dotted lines in Figure 14. Note that the cable response (no rotorwash) follows a damped oscillation with frequency of 0.34 Hz, which is in very good agreement with the theoretical value of 0.343 Hz for a 10-foot cable (Kreyszig, 1988), verifying the ODE cable model approach. The solid lines in Figure 14 illustrate the influence of the unsteady rotorwash flow field, showing substantial deflection. Note that the cable properties for this demonstration (2-inch diameter, approximately 5 lbs/foot) do not necessarily correspond to a physical case and have been selected to provide a reasonable demonstration of capability.

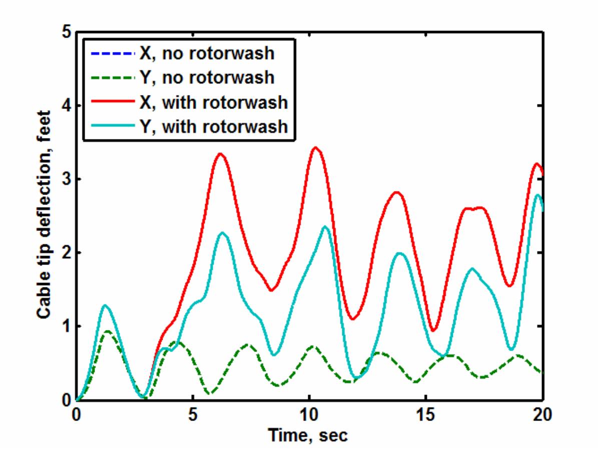

Figure 14. Predicted Cable Tip Deflection from CHARM/ODE Engine

Rotorwash Hazard Visualization Applications

Another benefit of directly computing the rotorwash flow field in real-time is the ability to present these data to trainees as synthetic cues describing regions of significant rotorwash hazards. Engineering-based flow visualization methods (e.g., flow vectors, streamlines), however, generally provide more detail of the underlying flow field structure than necessary, making it difficult to interpret (assimilate) details of moderately complex flow fields, which are quite common for rotorcraft operations. Recent work on the development of simplified representations of the ship airwake flow field has demonstrated a benefit of including flow visualization for pilot training applications when presented in an appropriate format (Aragon and Long, 2005). This work has motivated the development of an analogous rotorwash "hazard metric" that may be used to drive visualization aids in a real-time virtual environment based on the CHARM/ODE engine.

Using previous assessments of rotorwash effects on personnel and equipment (Ferguson, 1994) as a basis, a rotorwash hazard metric has been defined based on the force required to overturn a "standardized" human. This metric can be derived based on a weighted average of the rotorwash field at several vertical stations above the flight deck. Comparison of this weighted average to pre-defined thresholds is performed to convert the rotorwash to a hazard index (0 = no hazard up to 3 = severe hazard with substantial risk for overturning flight deck personnel). Evaluation of the weighted average metric at a grid of points on the ground surrounding the helicopter allows the effective rotorwash hazard to be presented in the visual environment. One presentation is shown in Figure 15, which illustrates the "avoid" region as a transparent red curtain, which approximately corresponds to the region where forces on an immersed body exceed a pre-determined threshold (for this example, the threshold is 30 pounds). Note that for the simulation conditions in this example, objects in this region have been observed to be thrown across and over the flight deck, while objects initially outside the hazard region are knocked over but do not move very far. Although additional work would be required to tailor the flow visualization metrics to a particular application, this example provides a proof-of-concept verification that information useful for training personnel on rotorwash hazards may be provided using a rotorwash physics engine with embedded flow field visualization methods.

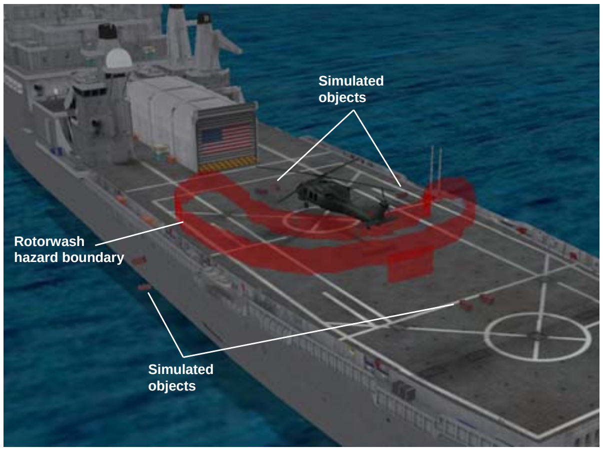

Figure 15. Illustration of Rotorwash Hazard Boundary Visualization with CHARM/ODE Engine

CONCLUDING REMARKS

A proof-of-concept rotorwash physics engine has been developed to enhance real-time, distributed training environments and expand applications for collective and collaborative training of aircrew coordination tasks during helicopter operations. A key enabling technology has been a real-time, free-wake model for determining the flow field due to rotorwash/jet wash from V/STOL aircraft. This modeling approach is derived from the CHARM methodology, a physically-based rotor wake and induced velocity (outwash) model that is the result of many years of development and validation. When coupled with a multi-body dynamics engine, the effects of rotorwash effects on the dynamic environment can be modeled, as well as allowing the generation of flow visualization aids to provide additional cues to enhance training effectiveness. Demonstration results have shown the ability to represent different scenarios for rotorcraft launch and recovery operations. Continuing development will focus on refinement to the core modeling methods and implementation within a server interface to permit straightforward integration within distributed (networked) training environments.

ACKNOWLEDGEMENTS

This paper is based upon work supported by the Naval Air Warfare Center Training Systems Division under Contract No. N61339-07-C-0070, Mr. John Hodak technical monitor. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Naval Air Warfare Center Training Systems Division.

REFERENCES

Aragon, C.R. and Long, K.R. (2005). “Airflow Hazard Visualization fro Helicopter Pilots: Flight Simulation Study Results.” American Helicopter Society 61st Annual Forum, Grapevine, TX, June 2005.

Catto, E. (2007). “Modeling and Solving Constraints.” Presented at Game Developers Conference ’07, San Francisco, CA, March 2007.

Ferguson, S.W. (1994). “Rotorwash Analysis Handbook Volume I – Development and Analysis.” DOT/FAA/RD-93/21, June 1994.

Garrido, R. A. (2004). “A Real Time Rope Model Suitable for Game Engine Usage.” Master’s Thesis, Naval Postgraduate School, September 2004.

Hoerner, S.F. (1965). *Fluid Dynamic Drag*. Hoerner Fluid Dynamics, Bakersfield, CA.

Hoerner, S.F. (1985). *Fluid Dynamic Lift*. Hoerner Fluid Dynamics, Bakersfield, CA.

Horn, J., Bridges, D., Wachspress, D., and Rani, S. (2005). “Implementation of a Free-Vortex Wake Model in Real-Time Simulation of Rotorcraft.” American Helicopter Society 61st Annual Forum, Grapevine, TX.

Kothmann, B. D., Lu, Y., et al. (2004). “Perspectives on Rotorcraft Aerodynamic Modeling for Flight Dynamics Applications.” American Helicopter Society 4th Decennial Specialist’s Conference on Aeromechanics, San Francisco, CA.

Kreyszig, E. (1988). *Advanced Engineering Mathematics, Sixth Edition*. John Wiley and Sons, New York, NY.

Peters, D. A. and He, C. J. (1995). “Finite State Induced Flow Models Part II: Three-Dimensional Rotor Disk.” *Journal of Aircraft*, Vol. 32, (2), pp. 323-333.

Quackenbush, T., Boschitsch, A., and Wachspress, D. (1996). “Fast Analysis Methods for Surface-Bounded Flows with Applications to Rotor Wake Modeling.” American Helicopter Society 52nd Annual Forum, Washington, DC.

Quackenbush, T.R., Wachspress, D.A., Keller, J.D., Boschitsch, A.H., Wasileski, B., and Lawrence, T. (2002). “Full Vehicle Flight Simulation with Real Time Free Wake Methods.” American Helicopter Society Specialists’ Meeting on Aeromechanics, San Francisco, CA, January 2002.

Smith, R. (2006). “Open Dynamics Engine v0.5 User Guide,” from http://www.ode.org, February 2006.

Spoldi, S. and Ruckel, P. (2003). “High Fidelity Helicopter Simulation using Free Wake, Lifting Line Tail, and Blade Element Tail Rotor Models.” American Helicopter Society 59th Annual Forum, Phoenix, AZ.

Stengel, R.F. (2004). *Flight Dynamics*. Princeton University Press, Princeton, NJ.

Wachspress, D.A., Quackenbush, T.R., and Boschitsch, A.H. (2003). “First-Principles, Free-Vortex Wake Model for Helicopters and Tiltrotors.” American Helicopter Society 59th Annual Forum, Phoenix, AZ, May 2003.

Wachspress, D.A., Keller, J.D., Quackenbush, T.R., Whitehouse, G.R., and Yu, K. (2008). “High Fidelity Rotor Aerodynamic Module for Real Time Rotorcraft Flight Simulation.” American Helicopter Society 64th Annual Forum, Montreal, Canada, April 2008.