UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

AEROSPACE ENGINEERING

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Period: 6/1/2016 to 5/31/2019

Project Title: A Surrogate Based Framework for Helicopter/Ship Dynamic Interface

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Section I: Project Summary

1. Overview of the Project

Helicopters have to operate in a complex environment during shipboard landing, illustrated in Fig. 1, making it a challenging task for the pilots. Conducting flight trials in this environment is expensive, therefore an accurate helicopter/ship dynamic simulation capability is highly desirable.

Our overall objective is the development of a high fidelity physics-based simulation capability, and its application to simulate approach to landing, hover over the deck and actual landing on the moving deck.

The overall objective was accomplished in three distinct stages. First stage consisted of developing a mathematical model for the principal components of the problem: (1) a coupled rotor/fuselage/landing gear model, (2) a flight control system for stability augmentation and trajectory tracking, (3) a high-fidelity ship airwake modeling capability, and (4) a dynamic ground effect model. In the second stage, computationally efficient reduced order models (ROM)/surrogates were developed for the ship airwake model. In the third stage, all the components were integrated into a global simulation framework.

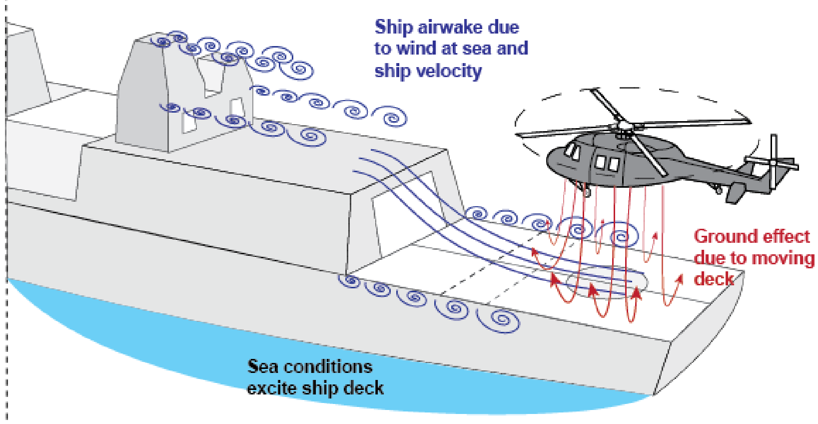


Fig. 1 Illustration of a typical helicopter ship landing environment

2. Activities and Accomplishments

The helicopter/ship dynamic interface problem is a long-standing issue for air-sea operations. The modular nature of the framework developed in our project has growth potential beyond the computationally efficient simulation of the helicopter/ship dynamics interface. Since additional components such as a pilot in the loop can be added late. Such a modified framework can be used for piloted simulation. Another benefit is that it can be combined with refined control techniques to model automated landing of rotary wing vehicles, as well as unmanned vehicles.

2.1 Development of the Coupled Rotor/Fuselage /Landing Gear Model

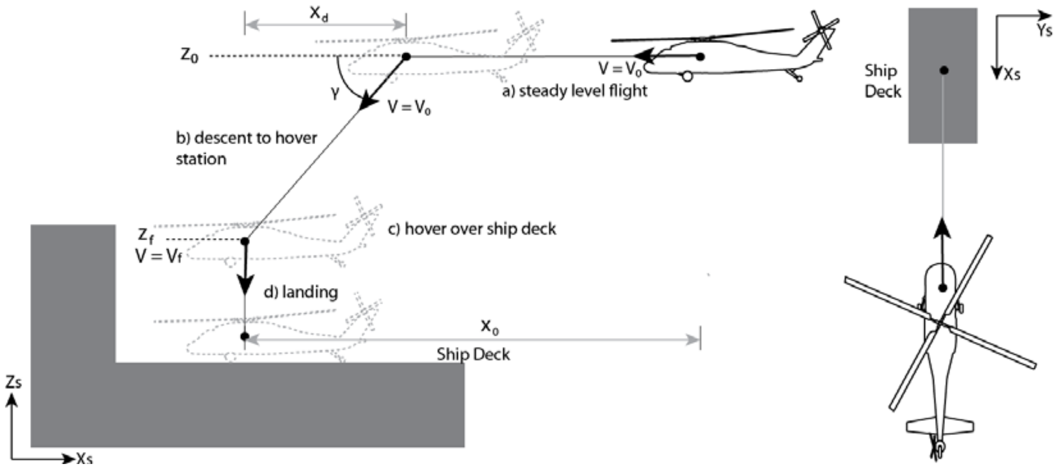
Development of a model for the coupled rotor/fuselage/landing gear is a principal ingredient of the framework. Initially it was supposed to be based on the RCAS code [1]. However, RCAS was replaced by the HeliUM2 code [2], a high fidelity coupled rotor/fuselage code developed for flight mechanics applications. HeliUM2 was developed at the University of Maryland by Professor Roberto Celi and his PhD students. Professor Celi (he was Friedmann's Ph.D. student) provided the source code and assisted us in modifying this well-documented FORTRAN code. The code was extensively modified for the current study. The primary modifications are:

(a) Integration of a high fidelity wind over deck (WOD) model.
(b) Introduced a capability for simulating a prescribed approach trajectory, starting from level flight, followed by inclined descent and hover at a given height above the ship deck, and landing as illustrated in Fig. 2.
(c) A gain-scheduled LQR controller was incorporated allowing the helicopter to follow the specified approach and landing trajectory. Such a controller is essential since helicopters are unstable and the controller mimics a stability augmentation system.
(d) Ground effect and landing gear models were introduced to simulate the helicopter dynamics during an actual touchdown on to the ship deck.
(e) Integration of Systematic Characterization of the Naval Environment (SCONE) data for simulating ship deck motion.

Two different ground effect models, a steady correction factor based model and a dynamic inflow based finite-state model, were implemented. The steady ground effect model is based on the image rotor concept and is valid only for heights greater than 0.5R, where R is the rotor radius. A finite-state ground effect model based on the He-Peters dynamic inflow model was implemented in order to account for dynamic ground effects in close proximity to a moving deck. Model predictions of rotor power consumption in-ground-effect to out-of-ground-effect ratio at various heights from a static and level ground are compared against experimental results in Fig. 3. The Landing gear is modeled as a massless spring-damper system, shown in Fig. 4. The standard UH-60A configuration with two main gears and a tail gear, shown in Fig. 5, is used. Gear reaction forces in the plane of the deck are due to surface friction. ***The modified code is designated "HeliUM2-umich".***

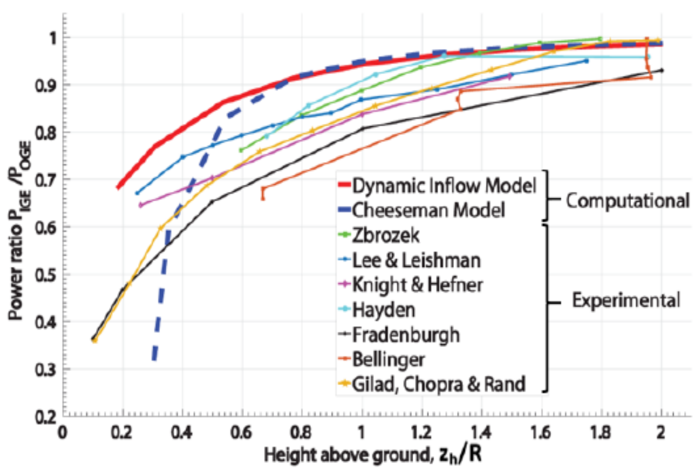
2. 2 Wind over Deck Model and Its Coupling with HeliUM2-umich

A high fidelity WOD code was developed and coupled with the modified HeliUM2-umich code. Airwake due to WOD is obtained from unsteady detached eddy simulation (DES) of flow over a full-scale SFS2 ship model having a 40-ft-high double-level ship structure causing significant flow separation and turbulence over the deck. The ship model is depicted in Fig. 6, together with the coordinate system used. A mesh constructed using hexahedral elements is used with a specified near-body resolution and it coarsens 40 times in each direction as it approaches the boundary. The near-body mesh is shown in Fig. 6. The final mesh consists of 1.95 million cells. The CFD simulation employs the commercial finite-volume solver FLUENT applied in the pressure-based mode. Velocity inlet and pressure outlet boundary conditions are used due to the low Mach number ($M \approx 0.05$). Sixty seconds of simulation data is stored in tabular form and used for the ship airwake simulation in HeliUM2-umich.



(a) **Side View (b) Top View**

Fig 2: Illustration of descent trajectory (figure not to scale)



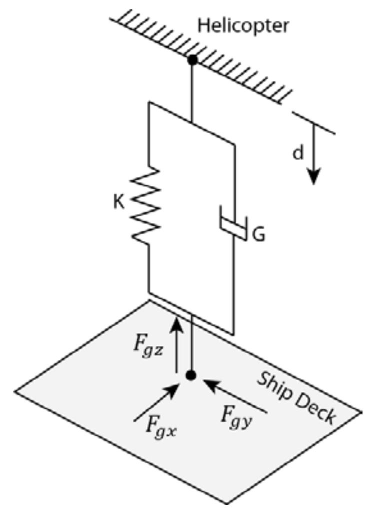
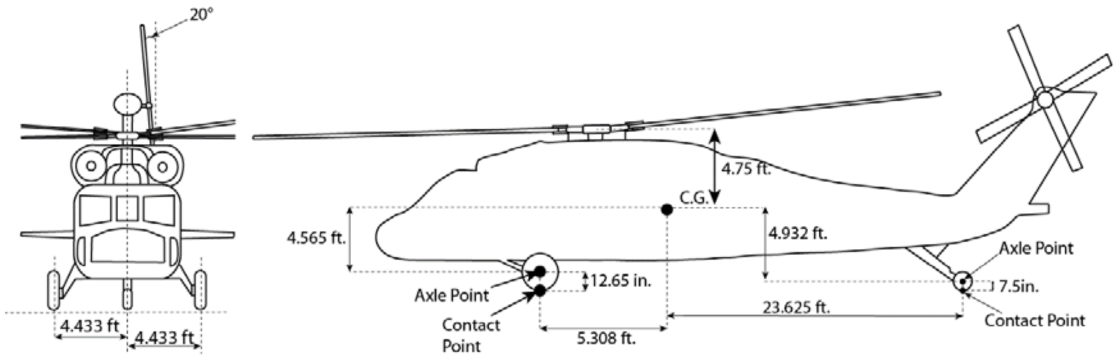


Fig. 3: Rotor power reduction due to static ground effect **Fig. 4: Landing gear model**



(a) Front View **(b) Side View**

Fig 5: Illustration of the landing gear configuration used

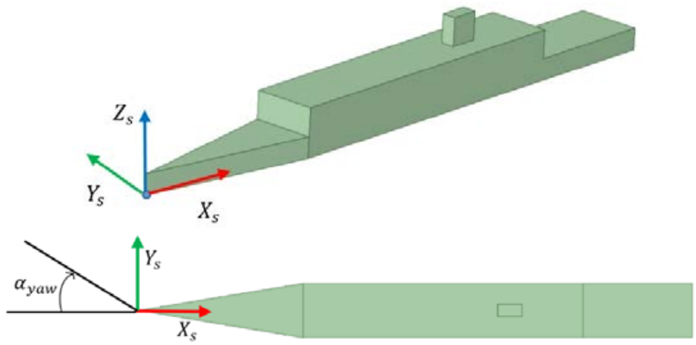


Fig. 6: SFS2 ship geometry and illustration of positive sideslip angle α_{yaw}

Simulations were performed for a 30 knot wind with sideslip angles $\alpha_w = \{0^0, 30^0, -30^0\}$, where α_w is illustrated in Fig. 6. The WOD solution from FLUENT is mapped onto a 4-dimensional orthogonal array, shown in Fig. 7, using MATLAB. This array has a uniformly distributed grid and is selected based on Refs. [3] and [4]. At each time step of the HeliUM2-umich time-marching simulation, the WOD solution is accessed via a computationally efficient interface which provides the WOD velocities corresponding to the current blade position. These velocities are taken into account at the individual blade sections in a manner similar to inflow. The HeliUM2-umich code is modified such that the rotor experiences the WOD as it enters the domain of interest, shown in Fig. 7. Only one-way coupling between the code and WOD components is considered, since downwash from rotor does not affect the ship airwake.

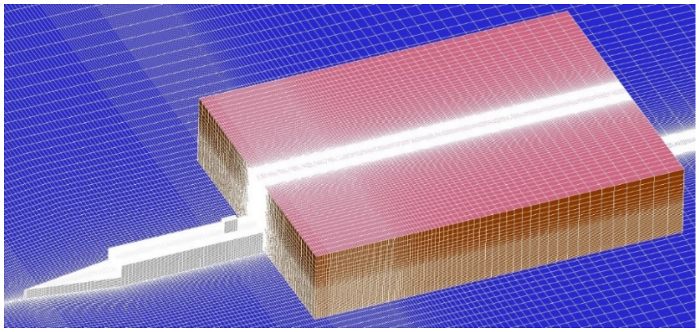


Fig. 7: Near body mesh and domain of interest

2.3 Typical Results Illustrating Helicopter Response to WOD for Approach and Hover

Approach simulations for various yaw angles were performed with WOD included only in the rotor aerodynamics. The initial altitude was 312 ft. The WOD was modeled for 30 knot winds at $\alpha_{yaw} = \{0^{o}, 30^{o}, -30^{o}\}$, where α_{yaw} is shown in Fig. 6. Figure 8 shows time histories of the helicopter Center of Gravity (C. G.) position coordinates and the control inputs during approach and hover. The solid vertical line represents the time when the rotor hub enters the domain of interest shown in Fig. 7. The controller is effective in maintaining the desired trajectory profile, even with WOD effects included. However, there are slight drifts in the final vehicle position, notably, in the lateral and vertical positions. The high frequency oscillations in the control inputs indicate that greater control effort is required when the WOD approaches at an oblique angle compared to the headwind case. The associated WOD velocity components experienced by the vehicle are higher. Furthermore, the control inputs for $\alpha_{yaw} = -30^{o}$ and $\alpha_{yaw} = 30^{o}$ cases are not symmetric. Therefore, response should be examined for portside and starboard WOD conditions in establishing ship-helicopter operating limits (SHOLs).

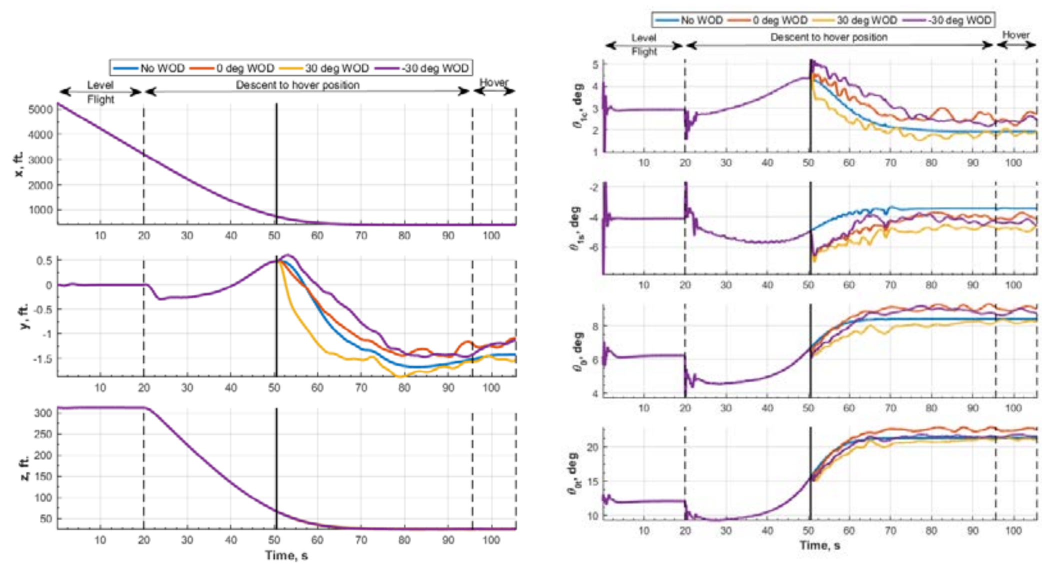


Fig. 8: Helicopter C. G. positions and control inputs during approach and hover; Positions are with respect to the ship frame shown in Fig. 6; Solid vertical line indicates time when hub enters the domain of interest shown in Fig. 7.

Two separate configurations were simulated. In the first configuration the effect of the WOD was included only in the rotor loads. In the second configuration the WOD effect was also included in the fuselage, empennage and tail rotor components, in addition to the main rotor. Helicopter approach was simulated only with a 30 knot starboard wind at -30°, since it represents the worst case scenario. Helicopter C. G. attitude angles and the control inputs are shown in Fig 9. Including WOD effects in all the helicopter components results in larger deviations and oscillations in the helicopter attitude angles. The angles change by approximately 4° when WOD is included in the additional components. The control inputs are also affected by accounting for WOD in the helicopter components with the tail rotor collective showing the maximum change of approximately 4°.

The combined influence of dynamic ground effect and WOD was illustrated by conducting hover and landing simulations with the deck excited in combined roll, pitch and heave motion, using SCONE data corresponding to the "moderate" heave displacement case. A 30 knot portside wind at -30° was considered. The WOD effect was included on the entire helicopter consisting of the fuselage, empennage, main rotor and tail rotor. The position coordinates of the CG during the hover and landing approach are shown in Fig. 10. The baseline case with no WOD and ground effect is included for comparison. The inclusion of WOD produces displacements of approximately 1.5 ft., 0.7 ft. and 1.5 ft. in the horizontal, lateral and vertical positions coordinates, respectively, relative to the ground-effect-only case. Note that the offset between the deck and CG position after the vehicle lands at t = 112.1 s corresponds to the z offset of 5.9 ft. between the CG and landing gear contact points. The control inputs generated by the FCS during the *hover* flight segment are shown in Fig. 10. High frequency oscillations due to WOD are evident in the control inputs. The combined effect of dynamic ground with deck motion induces offsets in the response, relative to the WOD-only case. A maximum change of approximately 0.5° is evident in the main rotor collective input. Ground effect decreases the rotor inflow, and the controller attempts to maintain rotor thrust, decreasing the collective to keep the angle of attack constant. A decreased collective results in a decrease in the rotor power consumption.

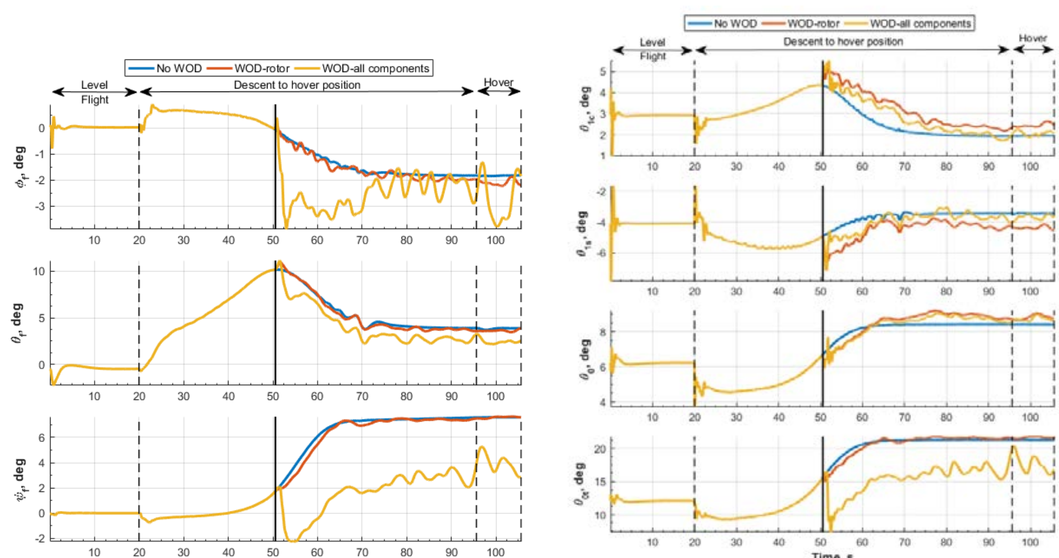


Fig. 9: Helicopter C. G. attitude angles and control inputs during approach and hover with WOD included in all helicopter components.

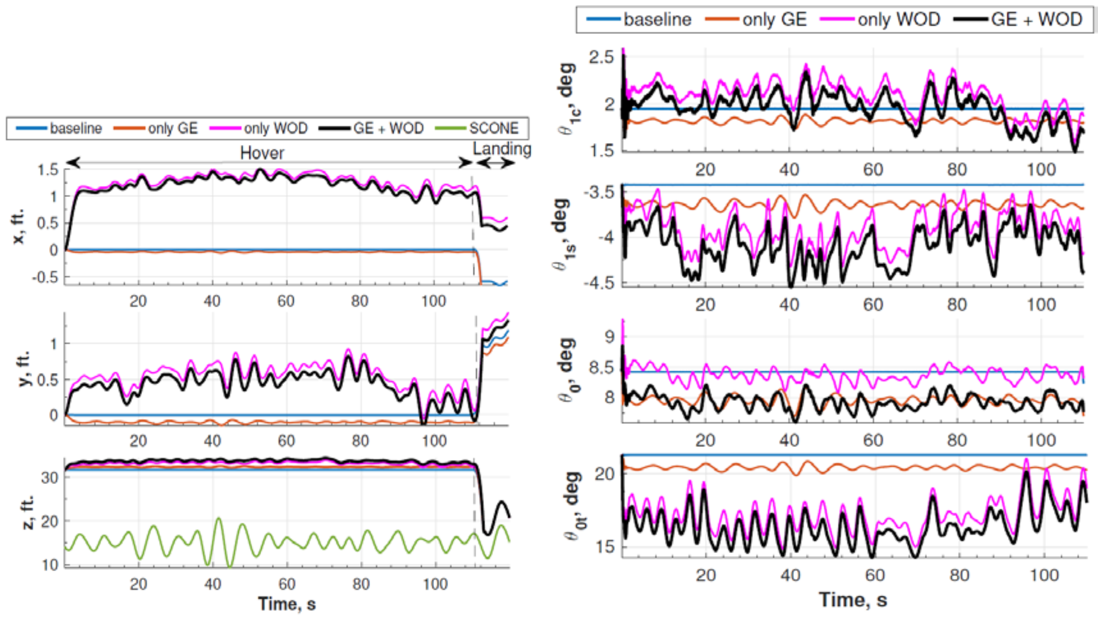


Fig. 10: Helicopter C. G. positions and control inputs during hover and landing segments; deck excited by combined pitch, roll, and heave motion based on SCONE data together with WOD.

2.4 Non-intrusive Reduced Order Modeling of Ship Airwake Simulation Using POD and Artificial Neural Networks

In addition to generating the results presented in the previous section, we also had an objective to develop a reduced order model (ROM) that learns from a set of sample detached eddy simulation (DES) solutions (training data) at different conditions (more specifically, combinations of side-slip angle α_w and time *t*), at a significantly reduced computing cost. The reduced order model (ROM) is based on an artificial neural-network (ANN) to predict the proper orthogonal decomposition (POD) mode coefficients in the projection-based ROM. The basis generation pursues the dual POD approach of Wang et al. [5], which is computationally efficient. Two major characteristics of the method are: (1) as a non-intrusive method, it produces a model that avoids solving the governing equations at the online prediction stage, thus requiring extremely low computing cost, and (2) once the ROM is built, the ANN only takes flow parameters: sideslip angle α_w and time as inputs, and no CFD knowledge is required to perform predictions.

Given a set of DES data corresponding to various angles of sideslip, the first step in the ROM training is to obtain a set of low-order projection bases that are representative of the flow field captured by the data. The commonly used POD modes are adopted in the approach as the projection bases. Due to the large size of CFD solution, the memory requirement to perform a direct POD on the collection of data would be extremely high. Thus, a 2-stage POD based on the Schmidt-Eckart-Young theorem [6, 7] is used. In the first stage, a separate set of truncated POD bases is obtained for each condition using the corresponding training data. In the second stage, the truncated basis sets are combined and another POD is performed on the combination thus the most representative POD modes over all conditions are retained. Using *n* to denote the size of original size of CFD solution at a time instance, and *k* to denote the number of modes retained from the 2-stage POD, the resulting set of projection bases $\mathbf{V} \in^{\mathrm{n}\times\mathbf{k}}$ spans a subspace $\mathcal{V} \subset^{k}$. Then a reduced order approximation of the quantity of interest on the reduced space $\mathcal{V}$ is given by

$$\mathbf{q}(x,\alpha_w,t) \approx \mathbf{V}(x)\mathbf{q_r}\left(\alpha_w,t\right) \qquad (1)$$

where $\mathrm{q}_r \in^{k}$ is a vector of temporal coefficients for the POD modes.

Now using Eq. (1) we only need to compute the mode coefficients q_r to obtain the quantity of interest at any α_w and t. The computing cost is reduced from the mesh size O(n) to the number of mode coefficients O(k). The ANN is trained to learn the relation between the output q_r and the inputs α_w and t from the training data and predicts $\mathrm{q_r}$ at new conditions without performing any CFD computation.

In the current implementation, training cases consist of 10 high-fidelity detached eddy simulations (DES) covering side-slip angles from 0° to 45° with an incremental interval of 5° between each cases. The CFD simulations are performed in ANSYS FLUENT. The ANN is built using Keras [8], which is a high-level API for neural networks, capable of running on multiple backbends. The training is conducted by minimizing a cost function given by the mean squared error (MSE) between the truth given by training data and the prediction from ANN under the same conditions. The state-of-the-art Adam stochastic optimizer [9] is used to minimize the cost function. The ANN-related computations are performed on a NVIDIA GTX 1070 GPU. Table 1 lists the computing cost for the ROM. It is evident that a 54000-time acceleration is achieved for the online computation.

Table 1: Computing cost comparison between ROM and DES

Source	Offline			Online
	DES / case	Basis generation (10 cases)	ANN training	ANN Prediction / case
Cost	180 CPU hours	10 minutes	70 minutes	20 seconds (on GPU)

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3. Findings and Conclusions

A comprehensive simulation capability for helicopter ship landing denoted “HeliUM2-umich” was developed. The “HeliUM2-umich” simulation code represents a major enhancement of the original HeliUM2 code with provision for: WOD, dynamic ground effect, and landing gear model. The WOD is modeled using unsteady Detached Eddy Simulation of the flow over a Simple Frigate Shape Version 2 ship. The SCONE data was used to model ship deck motion. Approach and landing simulations for a UH-60 Blackhawk helicopter were performed in the presence of WOD and ground effect for several sideslip angles. The work was documented in detail in the 2 papers listed under Item 10, below.The principal findings are:

1. The control effort increased with increasing sideslip angle.
2. Time histories of helicopter response indicated that the response with respect to the yaw angle is not symmetric.
3. Increased control effort is required when WOD is included on the entire helicopter as opposed to including the WOD on the rotor alone.
4. Ground effect begins to influence the helicopter response as soon as the rotor hub enters the region above the ship deck. The steady model used is not accurate for $z/R < 0.5$; therefore, a dynamic inflow based finite-state ground effect model which displays good agreement with experimental data, in close proximity to the deck, was implemented.
5. Actual landing was demonstrated on level, inclined, and moving decks in the presence of WOD and ground effect for a UH-60A configuration.

4. Plans and Upcoming Events

5. Transitions and Impacts

No information to report

6. Collaborations

No information to report

7. Personnel

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Co – PI: Karthik Duraisamy, kdur@umich.edu, 734-764-5229

Assistant Research Scientist: Dr. Ashwani Padthe, 10 months

Post-Doctoral Fellow: Dr. Daniel Foti, 5 months

8. Students

Abhinav Sharma, Ph.D. student, graduated with a Ph. D. in September 2019, and has been supported by the project throughout the entire period.
Jiayang Xu, Ph.D. student, has been working on the project for two years (24 months) and now is supported by a different project, expected graduation fall 2020.

9. Technology Transfer

No information to report

10. Products, Publications, Patents, License Agreements, etc.

- Sharma, A., Xu, J., Padthe, A. K., Friedmann, P. P., and Duraisamy, K., "Simulation of Maritime Helicopter Dynamics During Approach to Landing With Time-Accurate Wind-Over-Deck," in *Proceedings of the AIAA SciTech 2019 Forum*, San Diego, CA, Jan 2019, AIAA 2019-0861, https://doi.org/10.2514/6.2019-0861
- Sharma, A., Padthe, A. K., Friedmann, P. P., "Simulation of Helicopter Approach and Landing on a Moving Ship Deck Using a Dynamic Ground Effect Model," accepted for publication in *Proceedings of the AIAA SciTech 2020 Forum*, Orlando, FL, January 6-10, 2020.

11. Points of Contact in Navy

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NOTE: Continued on next page

Section II: Project Metrics

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Metrics

Number of faculty supported under this project during the reporting period: 2

Number of post-doctoral researchers supported under this project during this period: 2

Number of graduate students supported under this project during this period: 2

Number of scientists/engineers/technicians supported under this project during this period: N/A

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: N/A

Number of publications (all) during this reporting period: 1+1

Awards received during this reporting period:

- 2019 Vertical Flight Society (VFS, previously AHS) Honorary Fellow Award, (May 2019)
- 2017 Dr. Alexander Klemin Award, American Helicopter Society (AHS), the Klemin Award is the highest honor the AHS bestows on an individual for notable achievement in advancing the field of vertical flight aeronautics, (May 2017)

Invited talks given:

Friedmann, P.P., “Vibration and Noise Reduction in Rotorcraft Using On-Blade Control: from Theoretical Concept to Flight Ready Hardware”, Department of Aerospace Engineering, Texas A & M University, October 25, 2018.

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None

14. ABSTRACT
A comprehensive physics-based simulation capability for the ship-helicopter dynamic interface was developed. Key features incorporated are: 1) a high fidelity flight dynamics model with coupled rotor-fuselage-landing gear dynamics, 2) a detached eddy simulation based wind-over-deck (WOD) model, 3) a finite-state dynamic ground effect model ,4) ship deck motion based on SCONE data, and 5) a LQR based Prescribed Trajectory Tracking Control System. The effects of WOD and dynamic ground effect due to a moving deck on the helicopter response were examined in detail. Controlled landing on level, inclined and moving decks in the presence of WOD and ground effects demonstrated.

15. SUBJECT TERMS
Helicopter flight dynamics, ship landing, ship-airwake - wind over deck (WOD), dynamic ground effect

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