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AN INTEGRATED TIME-VARYING AIRWAKE IN A UH-60 BLACK HAWK SHIPBOARD LANDING SIMULATION

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ABSTRACT

A non-stationary (time-varying) ship airwake model developed using computational fluid dynamics techniques was implemented in a blade-element model of a helicopter in order to represent the complex interactions between the rotorcraft and the turbulent field. The integrated simulation was used to simulate shipboard landings in varying wind and sea conditions at the Vertical Motion Simulator facility at NASA-Ames Research Center.

BACKGROUND

In support of the Dynamic Interface Modeling and Simulation System (DIMSS) task in the Navy's Joint Shipboard Helicopter Integration Process (JSHIP) program, a real-time, piloted simulation experiment was conducted in the Vertical Motion Simulator (VMS) facility at NASA Ames Research Center. The purpose of the experiment was to develop and evaluate the capability of simulation to conduct dynamic interface testing, in order to establish the operational envelope for helicopters landing on ships in various wind conditions and sea states.

The experiment simulated a UH-60 helicopter landing on an LHA ship, and incorporated an unsteady (time-varying) ship airwake model computed by Computational Fluid Dynamics (CFD) techniques.

THE VERTICAL MOTION SIMULATOR

The VMS is the world's largest R&D motion-base flight simulator. To study a variety of different aircraft, the VMS uses interchangeable cabs. For this particular study, an interchangeable cab was created to emulate the UH-60 helicopter. Barco rear-projection displays were installed to give a wide-angle out-the-window view approximating that seen from the cockpit of a Black Hawk, and a close representation of its instrument panel was generated using computer graphics.

A DEC Alpha simulator host computer ran the Open VMS operating system. The simulation also included an Evans and Sutherland ESIG 4530 computer-generated "out-the-window" display system; graphical displays generated by Silicon Graphics computers, simulating the aircraft instruments; a hydraulic control loader system to simulate the control inceptors; and an ASTi sound simulation system. For this study, two other items were integrated into the simulator: a CATI PC-based XIG "out-the-window" display system, for comparison with the ESIG 4530; and a dynamic seat.

The Evans and Sutherland ESIG 4530 was upgraded to include an "ocean wave" simulation capability. The waves were specified in terms of modal period and significant wave height. A graphical model of an LHA ship was developed for the simulation, and a real-time version of the CARDEROCK Ship Motion Program (SMP) was integrated into the simulator host computer to provide realistic ship motion. A Landing Safety Enlisted (LSE) man, with limited hand-signaling capability, was also programmed into the ESIG.

UH-60 MODEL

The UH-60 helicopter was simulated using a blade-element model originally developed by Sikorski Aircraft and documented under contract from NASA.[1] The helicopter model consists of a main rotor model, aerodynamic models of the fuselage, horizontal and vertical tail surfaces, and tail rotor, as well as a simulation of the engine, drive train, flight controls, and landing gear. The blade-element main rotor model used five "equal annuli" segments on each of the four blades. All calculations for the helicopter flight model, including the airwake, were performed at an update rate of 100 Hz.

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CFD AIRWAKE MODEL

The CFD airwake model consisted of a matrix of time histories at each of 56,661 grid vertices in the region around the ship. The airwake model data were developed by NAVAIR's Advanced Aerodynamics Branch, at Patuxent River Naval Air Station, using a Navier-Stokes formulation of the viscid flow equations in the vicinity of the ship.[2] This simulation produced time-varying values for the three components of the airwake velocity at each of the spatial points. Each of these time histories consisted of 30 seconds of data, sampled every 0.1 second, for a total of 300 points. Therefore, the total number of data values was 50,994,900.

STORING THE DATA

Each of the floating-point data values in the CFD airwake model required 4 bytes of storage in the computer. This would constitute a total file size of nearly 204 Megabytes if the data were stored as a binary file. However, binary files are not computer-portable. In order to make the data computer-portable, a special format was developed that would be readable on any system, but would be the same size as a binary file.

The data were inspected, and it was determined that the values were always less than 300 feet per second. It was also decided that an accuracy of 0.01 feet per second would be acceptable. Therefore, if the values were multiplied by 100 and truncated to an integer, the result would always be less than 32767. This meant that the data could be scaled and stored in memory as a signed 4-byte integer; and it could be written to a disk file under FORTRAN Z4 format, consisting of four ASCII characters. Thus, the data could be transported in files of the same size as binary files; but, since these files actually consisted of ASCII characters, they would be totally computer-portable.

Another issue was the media on which to store the data. Compact disks (CD-ROM's) were the media of choice, since several sets of data could be stored on each one. The following compact disc specifications were adopted to minimize the difficulties in transferring the data:

(1) The media type should be CD-R, not CD-RW.

(2) The logical format should be ISO 9660, but may use the Joliet extensions (long file names).

(3) The CD should not be CD-XA format.

LOADING THE DATA

Due to the size of the data files, it was found that special techniques had to be implemented in order to minimize the time required to change data files. This was necessary because the experimental test plan called for frequent changes of wind azimuth (requiring a change of the data file). The technique used was developed specifically for the Open VMS operating system. It is based on the use of a Global Data Section, which is a section of memory that is allocated and named, and filled with data to be used by other programs.

A pre-processor was written that would read the data, convert it from INTEGER*4 to REAL*4 and scale it by a factor of 100, and then output it to a file in the special binary format required for the Global Data Section. Whenever a different wind azimuth was desired, a simulation engineer would run a program that would create a Global Data Section using the desired data file. A command issued within the simulation would map an array in the code to the data in the Global Data Section. By using this technique, the time to change from one azimuth to another was reduced from about 20 minutes to a matter of seconds. Although this technique is dependent on specific Open VMS utilities, similar techniques could be developed for other operating systems.

COORDINATES

In developing and implementing the airwake model and integrating it with the simulation, a number of different coordinate systems are involved:

CFD Wind Coordinates

The CFD data were generated using a set of coordinates originating at deck level, on the centerline of the ship, at the most forward part of the bow. The x-axis points aft, parallel to the centerline; the y-axis is toward the starboard side of the ship; and the z-axis is upward, perpendicular to the deck. This forms a right-handed coordinate system. The velocity components are positive when they blow along the positive axes; in other words, a wind blowing from bow to stern, port to starboard, and upward, has all positive components.

CFD Grid Coordinates

The CFD grid coordinates are different from the coordinates in which the velocities are represented. The grid coordinates also originate at deck level at the bow on the centerline; however, the coordinates form a lefthanded system: the I-axis points aft, the J-axis points to port, and the K-axis is upward.

The CFD grid is non-uniform; that is, the blocks of the grid have different sizes, depending on the location. Basically, the grid blocks get larger as the distance from the ship gets larger, as shown in Figure 1.

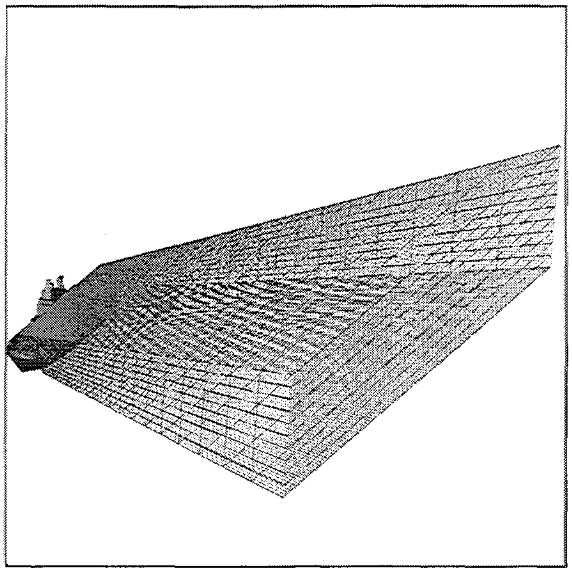

Figure 1. Non-uniform CFD Grid

Earth Axes

The Earth Axes used in the simulation are local North, East and Down. Their origin, initialized to an arbitrary location relative to the ship, is used for the location of the aircraft.

Ship Axes

The ship axes used in the simulation originate at the C.G. of the ship, pointing forward, starboard, and downward.

Aircraft Axes

The aircraft axes originate at the aircraft C.G., pointing forward, right, and downward.

Blade Axes

The helicopter blade axes are the axes in which the data are used in the rotor model. These axes are tangential, radial and perpendicular to the blade. For the airwake code, the transformation to this axis system was simplified by ignoring flapping and lagging angles.

INTEGRATING THE AIRWAKE MODEL INTO THE SIMULATION

For the airwake velocity components to affect the simulated aircraft, the velocity components need to be turned into forces and moments at the center-of-gravity (C.G.) of the vehicle. To do this, the airwake components were calculated at each of the aerodynamic centers of the helicopter. These consist of the fuselage aerodynamic center, the horizontal and vertical tail, the tail rotor, and at each of the main rotor blade segments.

In order to look up the airwake velocity components, it was first necessary to locate each of the aircraft aerodynamic centers in the grid coordinates. The airwake data were extracted from the database at eight points adjacent to the aerodynamic center. The values were interpolated to the current time (modulo 30), and then interpolated on the spatial coordinates. Then the velocity components were related to the proper axis system.

In order to keep the number of table lookups reasonable for real-time computation, a different algorithm was used to interpolate to the blade-elements of the main rotor. For this, the five points extracted from the database were the rotor hub, and the center of the outermost segment of each blade, as shown in Figure 2.

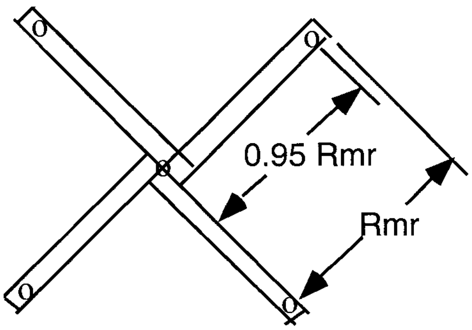

Figure 2. Main Rotor Data Lookup Points

The airwake velocity components at each of the other blade elements were found by interpolating along the blades. In this way, the total number of table lookups was kept to 432. This consists of one for each of the 5 points on the main rotor, plus one for each of the other 4 aerodynamic centers (giving 9 locations); times 2 for the number of time points to be interpolated for each point; times 8 for the number of adjacent points for the spatial interpolation; times 3 for the number of velocity components at each point. If the data were to be looked up for each of the twenty blade elements, it would have been necessary to perform 1152 lookups.

Although the CFD data had been computed with the ship stationary, it was allowed to steam along a straight course in the simulation. In order to simulate this situation correctly, it was necessary to separate the ambient wind from the airwake. This was done by solving for the ambient wind which, combined the ship speed and direction, would yield the desired wind-over-deck speed and azimuth corresponding to one of the sets of CFD data. The ambient wind was then added into the calculation of the airspeed of the aircraft, and the wind-over-deck was subtracted from the airwake data. The resulting airwake velocity perturbation components at each of the aerodynamic centers were then transformed to the proper coordinates (usually aircraft body axes; except that for the main rotor, blade axes were needed), and then added to the local velocity used to calculate the aerodynamics at that location.

Another option that was provided was the capability to simulate wind-over-deck speeds different from the CFD data. All the CFD data had been run at a speed of 30 knots. In order to simulate different wind speeds, it was necessary to scale both the magnitude and frequency spectrum (or time). Scaling the magnitude was simply a matter of multiplying the airwake velocity components by the ratio of the wind-over-deck speed divided by the nominal speed (30 knots). In order to scale the frequency spectrum, the independent time variable used to look up the data in the time history was scaled by the same factor.

SIMULATION VERIFICATION

The airwake velocity components integrated into the simulation were verified by comparison with the raw CFD data at specified locations. The total effect was evaluated by experienced UH-60 pilots in the simulator, and was found to be generally realistic and to produce a workload representative of a shipboard landing. One pilot said, "Better than a generic model," and another said, "...better than any training simulator." Some negative comments were also received, but they can be explained by some of the known errors that were present in the airwake model at the time of the evaluation, but that have since been corrected.

FREQUENCY ANALYSIS

In order to better understand the effects produced by the introduction of the time-varying airwake into the UH-60 math model, frequency analysis was performed using a software tool known as Comprehensive Identification from Frequency Responses[3] or CIFER®. Three cases were simulated: one in still air, one with 30 knots of wind-over-deck (but without airwake turbulence), and one with 30 knots of wind-over-deck and airwake turbulence. Each case with wind was run at the two wind-over-deck azimuths of 0 and 60 degrees.

Each simulation run was 30 seconds in length, in order to utilize the full 30 seconds of airwake data, thus preserving the low frequency data. Each run was made with the aircraft C.G. at an altitude of 10 feet over the deck of the LHA, hovering over landing spot #5 – just to port of the forward part of the "island" (superstructure) of the ship. For each run, a software flag was set to disable the integration of acceleration to velocity and velocity to position in the equations of motion. This effectively "froze" the aircraft in space, so that the forces and moments exerted on the aircraft by the airwake, and their resulting accelerations, could be analyzed without spurious transition to different locations during the run.

For each of these runs, the ship was stationary, with a heading of 0 degrees (North). The aircraft also had a heading of 0 degrees, with zero ground speed (hovering over the deck).

Figures 3 through 14 are Power Spectral Density (PSD) plots of the linear and rotational accelerations. Each plot shows three cases. The solid line shows the still air case, the dotted line represents the case with wind but not airwake, and the dashed line shows the case with the airwake. The series of plots on the left is for a wind azimuth of 0 degrees; the plots on the right are for a wind azimuth of 60 degrees. Note the peaks at 108 and 216 radians per second. These are the fundamental and second harmonic of n/rev: there are 4 blades, and the rotation rate is 27 radians per second (257.8 rpm).

In each case, the effect of adding steady wind does not significantly affect the frequency or energy content in the acceleration responses, except for some additional low frequency energy in some cases. The addition of airwake turbulence is significant in all cases, however, producing a substantial increase in total energy over a wide bandwidth. This effect contributes to pilot workload when landing on a ship in windy conditions. One pilot wrote, "Workload frequency (and magnitude, to a lesser extent) increased markedly in all axes to counteract turbulence."

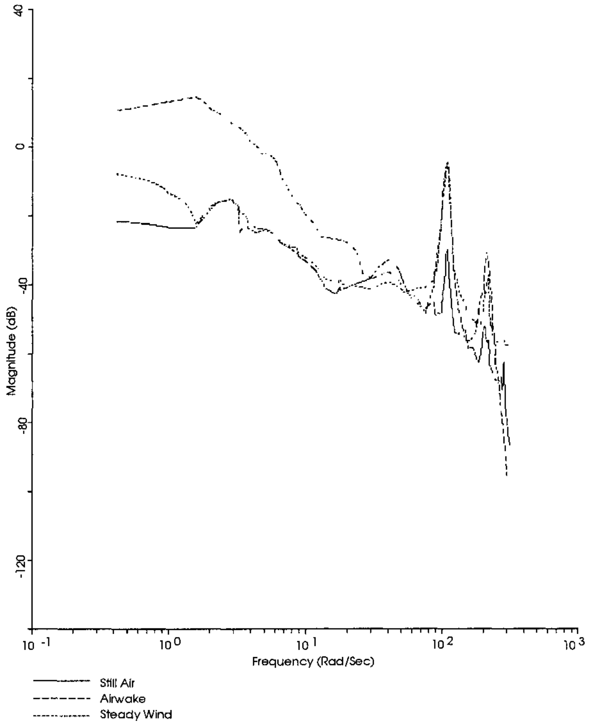

Figure 3. Rolling Acceleration - Wind Azimuth 0 Degrees

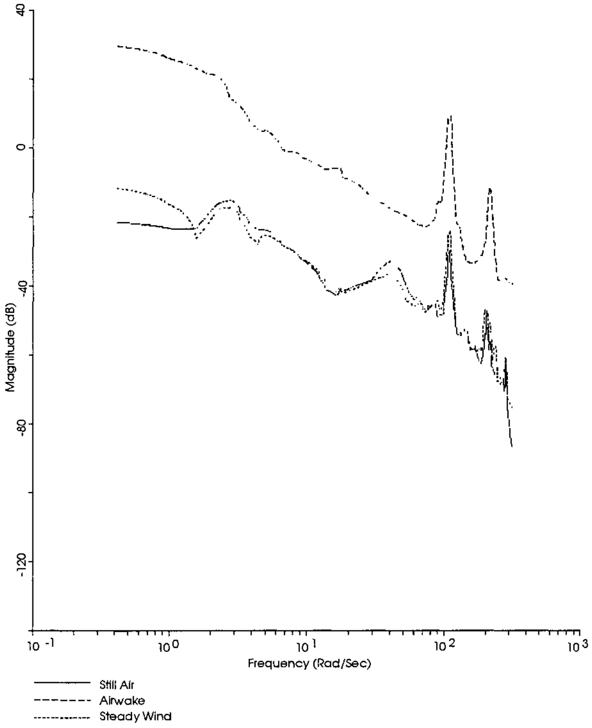

Figure 4. Rolling Acceleration - Wind Azimuth 60 Degrees

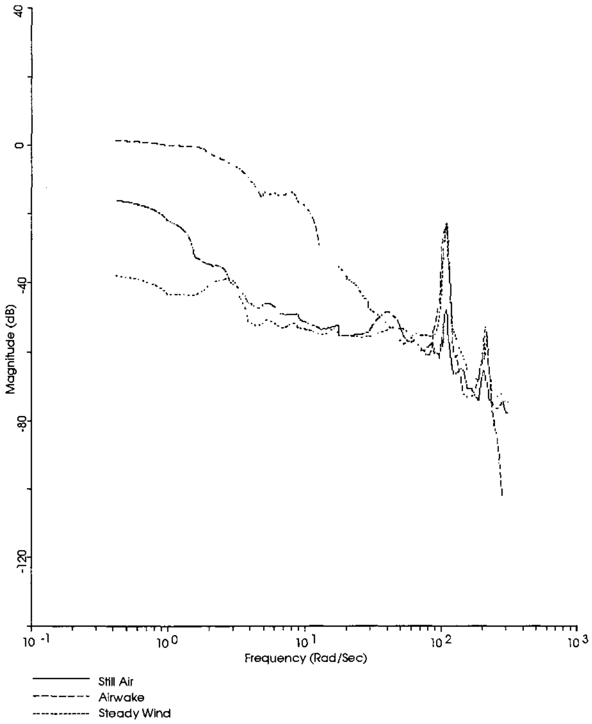

Figure 5. Pitching Acceleration - Wind Azimuth 0 Degrees

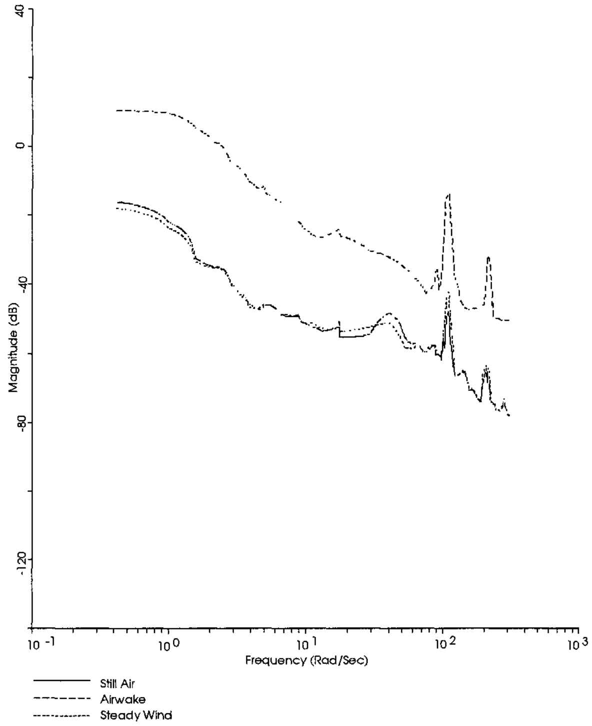

Figure 6. Pitching Acceleration - Wind Azimuth 60 Degrees

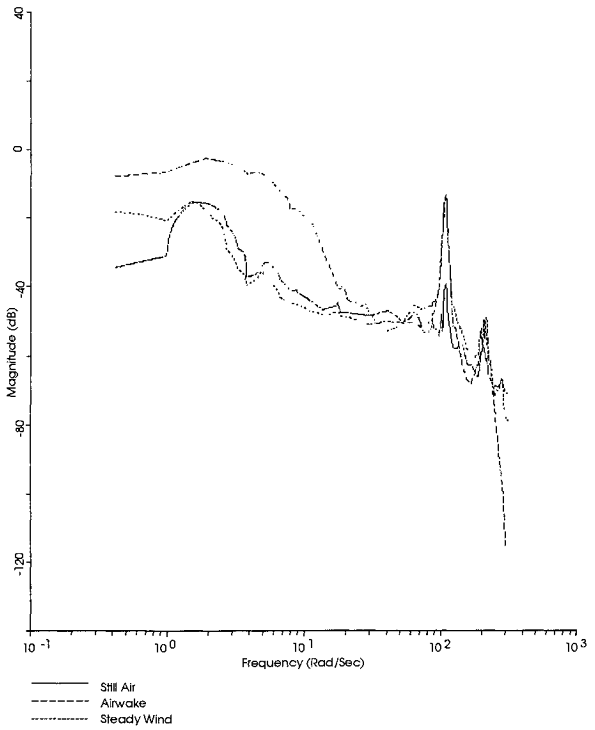

Figure 7. Yawing Acceleration - Wind Azimuth 0 Degrees

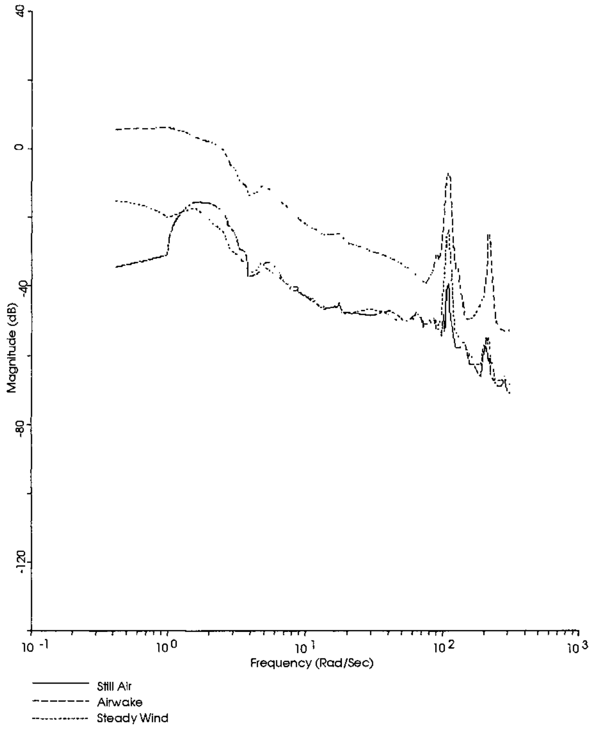

Figure 8. Yawing Acceleration - Wind Azimuth 60 Degrees

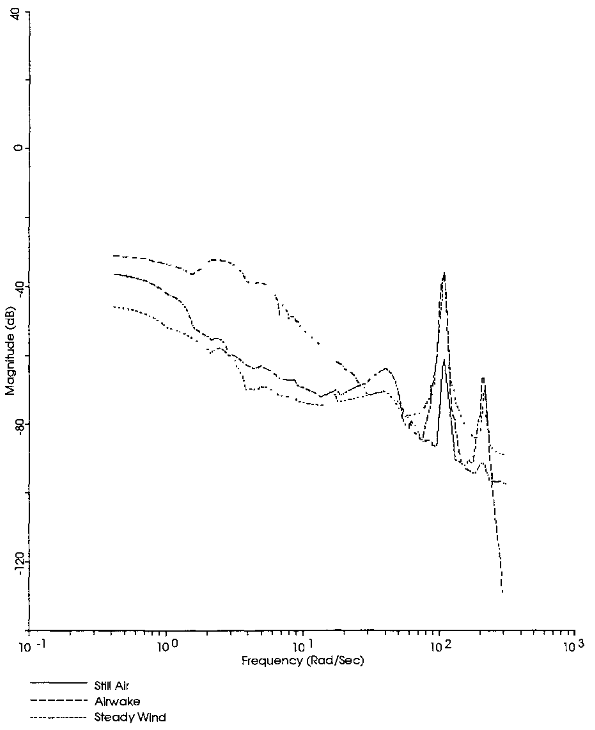

Figure 9. Longitudinal Acceleration - Wind Azimuth 0 Deg.

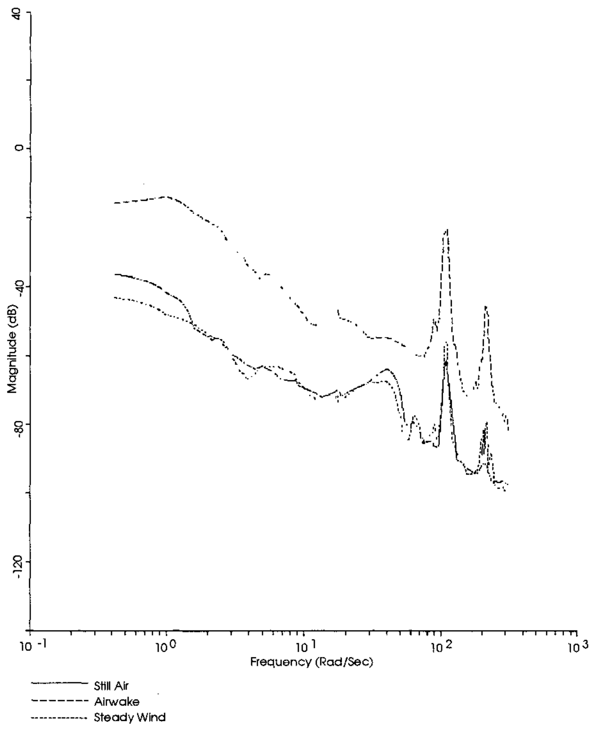

Figure 10. Longitudinal Acceleration - Wind Azimuth 60 Deg.

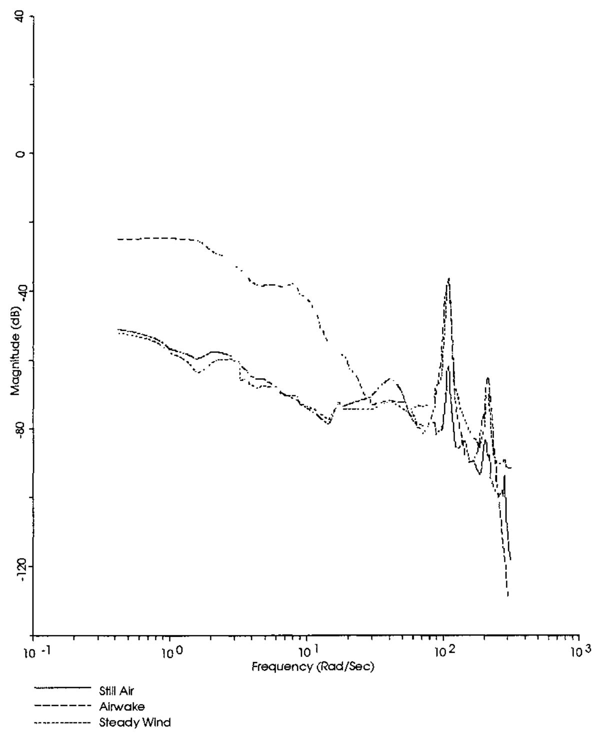

Figure 11. Lateral Acceleration - Wind Azimuth 0 Deg.

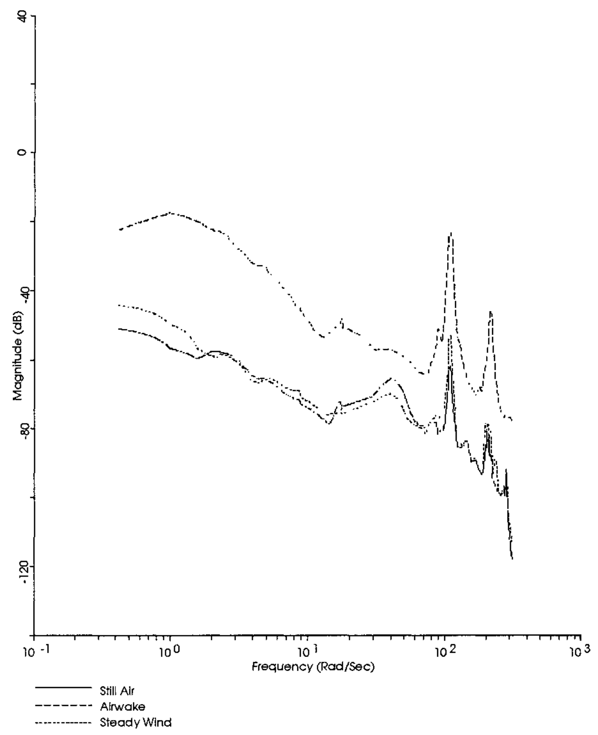

Figure 12. Lateral Acceleration - Wind Azimuth 60 Deg.

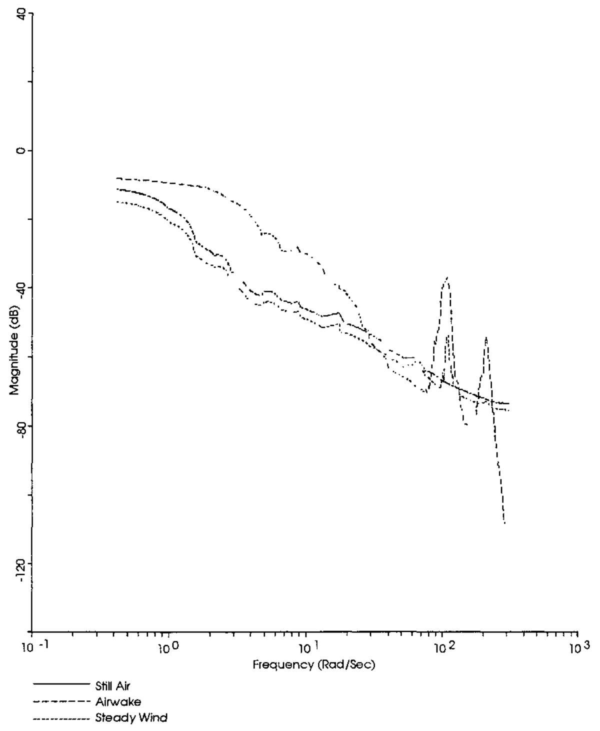

Figure 13. Vertical Acceleration - Wind Azimuth 60 Deg.

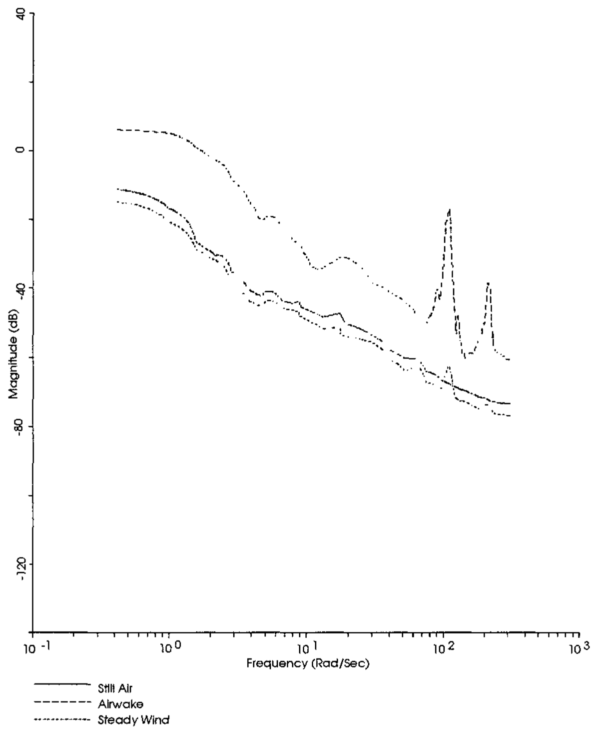

Figure 14. Vertical Acceleration - Wind Azimuth 60 Deg.

RECOMMENDATIONS

In order to validate this model, a series of flight tests should be conducted, in which the helicopter is mounted on a stationary test stand attached to the deck of a ship. Instrumentation should include measurements of the forces and moments acting on the airframe and test stand. The tests should be conducted in a variety of wind-over-deck conditions, with the controls fixed, rotor turning at normal RPM, and the collective set so that the total lift force approximates the aircraft weight. Frequency analysis could then be used to compare the test data with a simulation of the same conditions.

The volume in which the airwake is computed is necessarily bounded in order to keep the data storage requirements reasonable. In order to avoid transients at the boundary, the lookup algorithm held the function values at the boundary for positions outside the volume. Over the deck, the top of the volume was at about 51 feet above the deck, extending to 300 feet at 1000 feet from the ship. Although the experimental test plan called for the pilots to stay within the boundaries, they occasionally exceeded these limits in their familiarization flights. Since the volume over the deck was limited to 51 feet above deck height (but the island extends to about 80 feet above the deck), the pilots noticed that they did not reach a freestream airflow in a vertical ascent past the top of the island. In order to make the simulation more realistic, a heuristic fadeout should be applied to the airwake turbulence outside of the volume in which the CFD data are defined.

CONCLUSIONS

Significant techniques to simulate a helicopter flying through ship airwakes have been developed and demonstrated in piloted simulation. Subjective pilot evaluation has shown that the techniques produce a realistic environment, with appropriate increases in pilot workload. Frequency analysis of acceleration histories show that the simulated airwake produces much more frequency content and total energy than steady simulated winds.

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2. Polsky, S., and Bruner, C., "Time-Accurate Computational Simulations of an LHA Ship Airwake", AIAA-2000-4126, August, 2000.

3. Tischler, M.B., and Cauffman, M.G., "Frequency-Response Method for Rotorcraft System Identification: Flight Applications to BO-105 Coupled Rotor/Fuselage Dynamics," Journal of the American Helicopter Society, Vol. 37, No. 3, pp. 3-17, July 1992.