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# THEORY, TESTING AND ANALYSIS OF SHIPBOARD AIRWAKE FOR ROTARY WING AIRCRAFT INTERFACE APPLICATIONS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

**Dean William Meyer**

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## DEDICATION

This thesis is dedicated to the amazing team
at the Dynamic Interface department of the
Rotary Wing Aircraft Test Directorate,
Naval Aircraft Warfare Center, Aircraft Division,
Patuxent River, Maryland,
who truly epitomize what unleashed raw talent
can accomplish.

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# ABSTRACT

This research is intended to be a summary and sanity check for the diversified efforts taking place to advance the fields of ship airwake analysis. The target audience includes the managers and operators who will reap the benefits of the advancements in these fields. Without appreciation for the complexity this highly technical science and practical understanding for the immense advantages it has to offer, those of us elevated from cyclic and collective operators to money managers will fail to properly support the critical military phases of research.

Quantum leaps have taken place in associated technologies and hardware capabilities. The scope of embarked helicopter operational capabilities is similarly expanding and advancing. The primary dangers and limitations of these operations continue to revolve around the nearwake wind effects as they interface with the aerodynamic phenomena associated with rotary wing airframe configurations. Dynamic Interface is the field of technical evaluation that encompasses analysis of these effects and their interactions. It directly feeds into the field of Simulation, which then feeds back into theory and design.

The author seeks to contribute the operator perspective to methods of analysis and practical applications while describing evolution and current status of associated technologies. Conclusions and recommendations are also made on the future of the field.

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## GLOSSARY

| | |
|---|---|
| AGARD | Advisory Group for Aerospace Research and Development |
| ARL | Aerodynamics Research Laboratory |
| ART | Advanced Rotorcraft Technology |
| ASW | Anti-Submarine Warfare |
| BEM | Blade Element Model |
| BRC | Base Recovery Course |
| CERWAT | Center of Excellence for Rotary Wing Aircraft Technology |
| CFD | Computational Fluid Dynamics |
| DARPA | Defense Advanced Project Research Agency |
| ELP | Elevated Landing Platform |
| EMI | Electro-Magnetic Interference |
| FCLP | Field Carrier Landing Practice |
| FLOPS | Floating Operations Per Second |
| FTM | Flight Training Manual |
| FQ&P | Flying Qualities and Performance |
| GENHEL | General Helicopter Flight Dynamics Simulation |
| HQR | Handling Qualities Rating |
| HIFR | Helicopter In-Flight Refueling |
| LAMPS | Light Airborne Multi-Purpose System |
| LTE | Loss of Tailrotor Effectiveness |
| MLSF | Maritime Logistics Supply Force |
| MFS | Manned Flight Simulator |

| | |
|---|---|
| NATOPS | Naval Air Training and Operating Procedures Standardization |
| NAVAIRSYSCOM | Naval Air Systems Command |
| NAVSEASYSCOM | Naval Sea Systems Command |
| NAWCAD | Naval Air Warfare Center, Aircraft Division |
| NPGS | Naval Post Graduate School |
| NTSC | Naval Training Systems Command |
| NVG | Night Vision Goggles |
| OPNAV | Naval Operations Command |
| OSD | Office of the Secretary of Defense |
| PIO | Pilot Induced Oscillations |
| PRS | Pilot Rating Scale |
| RAST | Recovery Assist, Secure and Traverse |
| RDM | Rotor Disk Map |
| RWATD | Rotary Wing Aircraft Test Directorate |
| SAMS | Ship Airwake Measuring System |
| SWATH | Small Waterplane Area Twin Hull |
| S&T | Science and Technology |
| TTCP | The Technical Cooperative Program |
| URY | Uncommanded Right Yaw |
| VAR | Vibration Assessment Rating |
| VMC | Visual Meteorological Conditions |
| VSTOL | Vertical Short TakeOff and Landing |
| WST | Weapon Systems Trainer |

# CHAPTER I

## INTRODUCTION

Helicopters have been operating off ship platforms for several years. Their operations greatly enhance the capabilities of the ship and battle group by providing extensions of the ship's primary combat mission or support functions. The matrix of combinations of platforms, aircraft, missions, environmental conditions and operational techniques is staggering. The bread and butter of helicopter aviation is the flexibility associated with this field of relatively unrestricted aviation.

As technology and helicopter airframe capabilities have advanced, the dangers associated with these missions have increased. The airframes have consistently increased in gross weight limitation from their original design parameters. Aircraft are now operating with night vision devices to expanded landing spots with reduced obstruction clearances. With the development of recovery assistance devices, the ships are recovering their assets during heavier weather with significantly increased pitch and roll parameters. The United States Navy has assigned the responsibility for testing and evaluating criteria of this operational environment to the Dynamic Interface department of the Rotary Wing Aircraft Test Directorate at the Naval Air Warfare Center, Aircraft Division, in Patuxent River, Maryland.

Dynamic Interface encompasses the fields of engineering analysis associated with these operations. The department is directly responsible for determining the safe operating parameters for the myriad of aircraft and vessel combinations. Perhaps their principal mission and most direct input into fleet operations is the determination and description of wind envelopes for each flight deck platform. The pilots and flight deck controllers on all aviation capable ship platforms use these envelopes to minimize potential for mishaps associated with the wind environment over the decks.

There are several categories of hazards associated with the wind effects over the deck. Higher wind velocities are associated with heavier seas, both of which contribute to increased workload for the pilot as he attempts to keep a stabilized relative position over a moving target. The wind vector affects closure rates during the approach to the deck, and influences the power required to maintain a hover. Ambient winds are greatly influenced by the ship's hull, superstructure and the sea surface itself. Turbulence effects exacerbate the problem. Wind envelopes also determine safe parameters for engaging and disengaging the rotor systems.

Understanding these effects requires a combination of technical analysis and subjective reporting on real-time flight experience. The Dynamic Interface department is attacking both sides of the issue. Teams of engineers go to sea with fleet experienced test pilots who are trained to use specialized evaluation techniques to observe and document flight phenomena. They accurately record airflow characteristics over the flight deck as well as motion of the flight deck. The data collected is scientifically reduced and analyzed for incorporation into fleet operational and procedural guidelines. Without their organized participation, safe helicopter operations would be a hit and miss business, which is clearly unacceptable for both the aircrew and operational readiness of the battle group.

The Dynamic Interface department concurrently analyzes all other aspects of the helicopter/ship interface, including flight deck ground movement, support systems, ship equipment compatibility, lighting effectiveness, clearance dimensions, field of view, personnel safety issues, and more. They actively liaison with other Naval departments and foreign Navy programs to keep U.S. maritime operations up to speed with the state of the art technologies.

In these days of emphasis on Systems Engineering techniques for total warfare system optimization, the Dynamic Interface plays a vital role in providing key inputs for other fields associated with shipboard helicopter operations. Information they collect is heavily applied in the world of flight simulation. In the future, wind envelopes and operational parameters will be determined inside a building, greatly reducing the hazard to aircrew and equipment, as well as affording significant savings to the government. Furthermore, the information is already being utilized by preliminary ship and helicopter designers to effect advancements that will improve the next generation of maritime helicopter combatant operations.

# CHAPTER II

## BACKGROUND

### Helicopter Aerodynamic Phenomena

As mentioned in the previous chapter, there are several aerodynamic phenomena of helicopter flight that are influenced by the wind effects in the flight deck environment. The following descriptions are offered to provide a background in order to understand the importance of Dynamic Interface research initiatives.

### Tail Rotor Effects

Due to the physics of motion that require actions to have equal and opposite reactions, the helicopter fuselage wants to spin underneath its whirling rotor system in the opposite direction of the rotor's rotation. To counteract the torque imposed through the rotor mast, the tail rotor is employed as an "anti-torque" device. It imparts a force at the end of the tail boom moment arm that balances the rotor system moment. The moment of the main rotor system varies as collective pitch of the blades is varied to meet lift requirements. If uncorrected by pilot variation of the tail rotor anti-torque inputs, the heading of the fuselage would yaw back and forth. Some corrective assistance is provided to the pilot by flight control channel mixing and stability augmentation.

There are limitations to the amount of push or pull that the tail rotor can produce. For American helicopters, left pedal (rudder) is applied to counter increased main rotor system demand. A certain maximum thrust is created at full pedal deflection and tail rotor blade pitch. If any additional demand is requested from the main rotor, the helicopter will yaw to the right uncontrollably. In this scenario, tail rotor thrust required exceeds tail rotor thrust available.

In some regimes, the downwash from the main rotor can influence and disturb airflow through the tail rotor. If the helicopter is translating to the left, the tail rotor is receiving a relative wind from its left. When translating in the direction its wash, the tail rotor can be moved through a region of disturbed air that its own thrust had created. This scenario is similar to the wingtip vortices phenomenon encountered by the main rotor system in descending flight. In any case where the tail rotor encounters such a disturbance, it cannot generate effective thrust. This is known as loss of tail rotor effectiveness (LTE), which results in Uncommanded Right Yaw (URY). Again, the result is loss of yaw control.

The tail rotor configuration is the primary limiting design feature affecting operational capability of helicopters over the flight deck. The tandem rotor configuration of the H-46 airframe avoids the anti-torque yaw control problem by driving two main rotors in opposite directions of rotation. The fuselage absorbs the impinged moments as the systems counteract each other. Heading is controlled by concurrently (but not necessarily equally) increasing lift on opposite sides of the forward and aft main rotor systems, resulting in a pivot about any point of the longitudinal axis. Avoiding tail rotor limitations allows the H-46 to operate in significantly larger wind envelopes. Helicopters are rarely authorized to operate with tailwinds to single spot ships. In most cases, the H-46 tandem rotor aircraft is the only configuration permitted to operate with wind vectors reported aft of the abeam relative headings.

Rotor Blade Flapping

Most of the helicopters currently operating in the U.S. Navy utilize a "fully articulated" main rotor system. The blades twist about their longitudinal axis to change their pitch to meet lift requirements. They are allowed to "lead" and "lag", pivoting slightly forward or aft in the plane of rotation about their root end attachment at the mast hub. They are also allowed to "flap" above and below their plane of rotation. The extent of flapping is dependent upon lift requirements requested by cyclic and collective positions as the blade translates around its plane of rotation, as well as the elastic characteristics of the blade itself.

When the rotor system is at rest, the blades hang with a certain amount of static droop below the plane of rotation. At full rotational speed, the blades' weight and centrifugal force align the blades within the plane, with minor flapping excursions. When the rotor system is at low rotational speed during startup (engagement) or shutdown (disengagement), the centrifugal force is not strong enough to overcome flapping forces. The collective is fully reduced to minimize pitch and lift on the blades and to minimize flapping.

## Translational Lift

Helicopters require a certain amount of lift and associated power demand to hover. They require less power to generate that required lift as forward airspeed or relative velocity through the rotor system is increased, up to a certain "bucket" airspeed, beyond which power requirements increase. The term "bucket" is derived from the shape of the power required curve when plotted against airspeed. A sample curve is presented in Figure 1.

In order to create lift, the overall rotor system imparts thrust downward by drawing air through it. There is "induced drag" associated with accelerating that airmass through the system and power requirements associated with overcoming that drag. The shape of the power required curve at the low airspeed end is driven by a reduction of induced power required as airspeed increases. As forward airspeed builds, more air is imparted through the system due to the airframe velocity through the air, and less power is required to draw the air through. Eventually, at higher airspeeds, parasite and profile drag considerations overcome the reductions in induced power required, and power requirements increase [1].

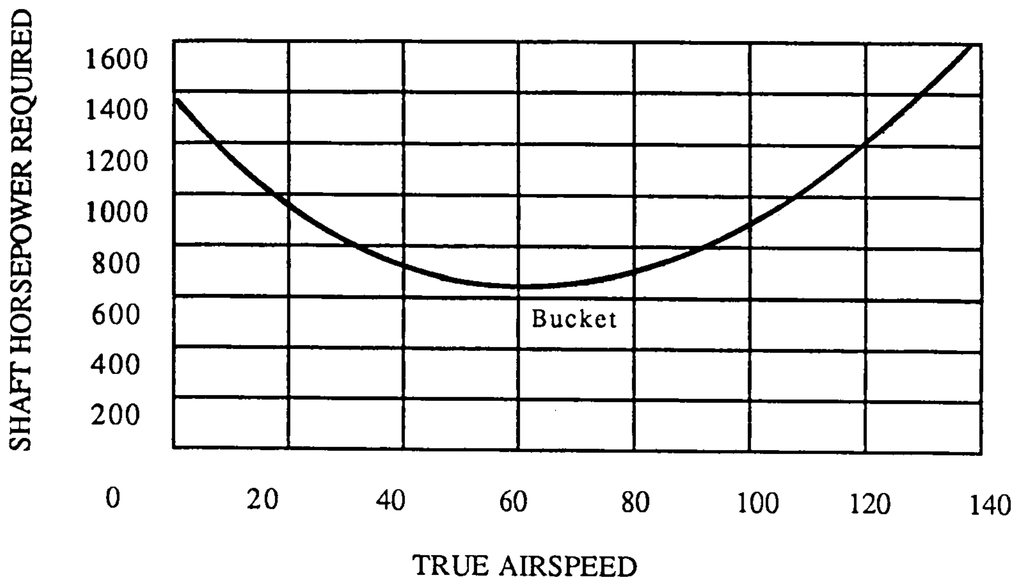



Figure 1. Level Flight Shaft Horsepower Required.

American helicopter main rotor systems rotate counter-clockwise when viewed from above. With a forward velocity component of the airframe, or in a hover with a relative wind from the nose, the blades in the forward right quadrant of the plane of rotation are advancing into that wind. The resultant angle of attack creates additional lift on the blade, which due to the rotation and a phenomenon known as "gyroscopic precession," is realized in the forward left to left abeam sectors of rotation. This lift requires countering with a small amount of left cyclic input to keep the rotor system and aircraft level [2]. Another leftward cyclic requirement is generated by sideward forces and moments about the longitudinal axis imparted by the tail rotor thrust. For American helicopters, the tail rotor thrust vector is to the right (tail rotor wash to the left). Since the tail rotors are mounted higher than the center of gravity, the thrust results in a right roll that must be countered with left cyclic. Higher gross weights require more lift and anti-torque, resulting in higher positive rolling moments and increased left lateral cyclic requirements. For these reasons, left lateral cyclic flight control margins (amount of control input remaining to the mechanical limit) become a limiting factor over the flight deck.

Tipover

Static tipover is a simple function of airframe weight distribution and landing gear configuration. If the center of gravity is laterally displaced beyond the gear, a rolling moment will be created that may topple the aircraft. The center of gravity is laterally displaced relative to the gear when the ship and flight deck roll. The angle of the flight deck may allow the aircraft to slide before it tips. Inertia of the airframe created by roll and sway of the ship also contribute to the tipover moment. It is for these reasons that the helicopters are chained to the deck until ready to commence flight operations [1].

The tipover situation is compounded by the thrust vector when the rotors are engaged. In the U.S. Navy, only the H-65 Coast Guard helicopter rotor system generates "negative pitch," which in effect "presses" the helicopter against the deck for increased friction and protection from sliding in heavier seas. Other helicopters still have some fraction of lift generated even when the collectives are fully reduced and set for "flat pitch." This lift vector contributes a rolling moment about the point of contact at the landing gear.

If the helicopter is airborne and contacts the deck with a lateral relative motion, the inertia of the airframe creates another contributory moment for tipover. If the lateral translation is toward an inclining deck, there is less potential for the landing gear to skip off the deck to alleviate the danger. There is a limited amount of lateral cyclic that can be applied to redirect the thrust vector in countering the developing roll. In most cases, it cannot be directed sideward enough to put the lift vector outside the landing gear and create an opposite rolling moment. Therefore, the preferred method of recovery when this scenario begins to develop is to fully bottom the collective and hope that gravity forces are sufficient to arrest the roll.

## Wind Effect Influence on Aerodynamic Phenomena

The helicopter flight characteristics and associated hazards described above are exacerbated by the wind effects encountered in the ship environment. Winds may be accelerated, blanked out or sustain drastic directional changes as they transit over the ship structures. The swirling of the air mass increases the workload of the pilot as he attempts to maintain a hover. The increased flight control activity decreases reduced margins in the directional pedal and lateral cyclic channels. Sideward wind components across the deck also reduce these margins and may contribute to LTE and URY.

During engagement and disengagement, main rotor blade flapping can be dangerous. If the blade flaps upward excessively and then flexes downward in elastic response, the blade can cause a strike hazard to ground personnel and the airframe fuselage. Ship motion and wind effects over the flight deck contribute to the amount of flapping. Updrafts created by the hull or downdrafts coming over the superstructure affect lift on the blades in various quadrants of the plane of rotation. The airflow around the ship and the extent of influence on the rotor system is not well understood. The massive blades of the H-53 have been observed to come down within a matter of inches from the flight deck.

The H-46 community has a history of blade strikes to the center fuselage area, experiencing an average of one "tunnel strike" every two months. Damage is sometimes beyond the operational level repair capability of the attached maintenance crew, especially for Navy combat logistics support detachments on Maratime Logistics Supply Force (MLSF) ships. A tunnel strike can put one of the detachment's two aircraft out of commission for the remainder of the deployment.

Swirling and unpredictable airmass movement constantly affects the translational lift effects felt in the rotor system. This not only increases required cyclic activity to maintain a level attitude, but it also increases required collective activity by varying the power requirements for maintaining altitude.

Static and dynamic tipover concerns are also exaggerated due to wind effects. Crossdeck winds contribute to relative lateral motion and reduce margins available to arrest such motions. Updrafts climbing over the hull may add lift and rolling moment when the aircraft is tied to the deck. The winds created on the bow of the amphibious helicopter carriers are particularly treacherous for lighter aircraft such as the UH-1. Any Air Boss who has experienced the discomfort of sliding on the deck will know not to position or recover such aircraft toward the bow when the winds are strong.

For the reasons presented, it is essential to pursue analysis of wind effects in the flight deck environment (ship airwake). By understanding the nature of flow and particular characteristics of each class of flight deck, the operators will know what wind conditions and flight regimes to avoid.

## Shipboard Helicopter Operations

This section is intended to give the non-pilot an appropriate level of appreciation for the demanding nature of shipboard helicopter operations. As in other communities of Naval Aviation, shipboard flight deck operations present the greatest hazard and require the most skill of the helicopter aviator. The repetitious maneuvers are made to look routine by the experienced pilots, when in fact each approach and landing is composed of wide-ranging and complex combinations of configuration and environmental factors.

Approach

During the approach, the pilot is advised of the winds presently observed over the flight deck, as indicated by the ship's anemometer measuring system. It is important to note that those systems are severely limited in accuracy because they are attached to the ship [2]. The extent of those limitations will be discussed later. The forecast winds give the pilot information to consider for determining power requirements and making applicable adjustments to the approach profile.

Most often, the approach will be made into the true wind. This technique will afford the pilot better directional stability and reduced power requirements. It will also allow him an advantage to use that wind to control or arrest his closure rate to the deck. With the headwind, a nose up pitch input or lateral cyclic input in a sideflare will quickly check the approach speed. Sometimes, however, operational necessity demands that the battle group proceed in a direction that does not produce optimum winds over the deck. With a tailwind (or if the headwind is blanked out by the superstructure), the pilot must arrest the closure with increased nose up or roll attitude and application of more power. When the helicopter attitude is deviated further from level, more power is required to generate the same vertical lift component that was produced in the hover. More power is also required in a tailwind situation because the airmass is carrying the airframe toward the deck, and blowing it across the deck in the hover. If the closure rate is too high, the pilot may not be able to arrest the inertia of the airframe with the thrust that the rotor system can generate, or do so within the safe operating performance limitations of his airframe.

For the tail rotor configured helicopter, crossdeck winds and tailwinds are more critical. The following classic wind-related hazard can bite even the most experienced pilots. While most single spot platforms land aircraft on the approach lineup line, helicopter carrier decks and expanded capability amphibious platforms have landing spots oriented along the ship centerline. The approach to all of these spots is usually oblique, on a heading approximately 45 degrees either side of the ship's heading, or Base Recovery Course (BRC). An expanded capability LPD flight deck and associated types of approaches to the expanded spots is presented in Figure 2. A typical approach technique used to such decks involves yawing the aircraft to line up with the spot or ship centerline on very short final, usually while transitioning over the deck edge. When approaching starboard to port, this requires application of additional left pedal to stop right yaw at the same time power is applied to arrest closure and meet hover torque requirements. The pedal application commands increased tail rotor pitch, which demands additional torque from the power plant. If the aircraft is heavy and the approach is aggressive, or closure rates are high due

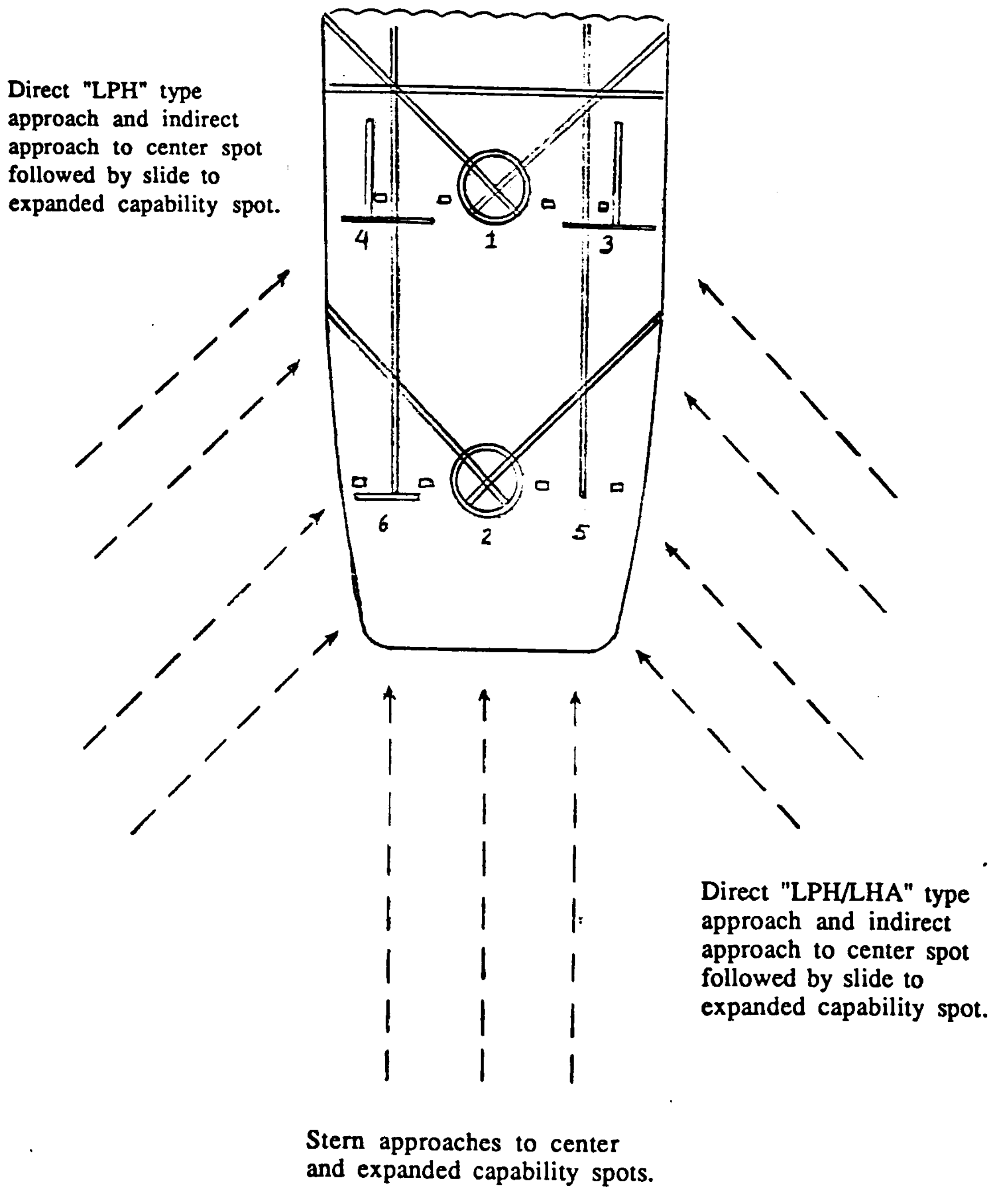



Figure 2. Expanded capability LPD flight deck with approach profiles to expanded spots.

to an overshooting crosswind, the pilot may exceed torque limitations of the airframe. Typically, tail rotor aircraft are prohibited from approaching or operating over the flight deck with tail winds.

For most airframes, pilot field of view from the cockpit is improved out his door compared to that available dead ahead, due to interference from the instrument panel. This is another advantage in using the oblique approach angle. Furthermore, the offset approach lines also afford increased waveoff potential because the aircraft will not have to deviate its flight path to avoid the ship's superstructure.

The H-46 tandem rotor configuration allows for approaches to be made with far less consideration for the wind direction. While the loss of translational lift is equally important, the lack of tail rotor concerns allows for extensive use of sideward flight. When approaching sideways (in a sideflare), the H-46 can also take advantage of the significant "barn door" profile drag of its fuselage to accurately arrest closure and establish a hover over the intended landing or external load pickup spot.

## Hover

Once over the flight deck, the pilot must stabilize the aircraft over the deck for landing or maintaining a steady relative position to allow the deck crew to attach an external load. The rotor tip path to obstruction clearances can be as low as fifteen feet [3]. Drifting about the deck in the hover can be dangerous. The pilot works to keep his stable relative position using outside visual reference to the deck and superstructure. Ship motion cues are picked up visually and the aircraft is primarily flown by "seat of the pants" proprioceptive cues.

The flight deck is not changing attitude about a fixed reference point. Ship motion is discussed in detail later in the text. The most active channels are usually roll and heave. Flatbottom amphibious ship flight decks often translate through the water on a corkscrew- shaped path. With all the degrees of motion combined, if the pilot attempts to keep the helicopter in an absolute fixed relative position in relation to the landing spot, he may find himself off the side of the ship when it rolls the other way. The results of this improper technique are demonstrated by the sequence presented in Figure 3. The proper technique involves maneuvering the airframe through a shifting position in space to keep it on a similar course with the deck at a consistent relative altitude [4]. The influences of swirling and gusting winds further contribute to the high workload in a hover.

Performing the mission at night, unaided or with night vision devices, when depth perception and visual cues are greatly reduced, also increases the workload. The pride of the community in accomplishing such a feat is expressed in the following statement.

"Fixed wing aircraft are for pilots who are interested in aviation, but are afraid to try it." (Author Unknown)

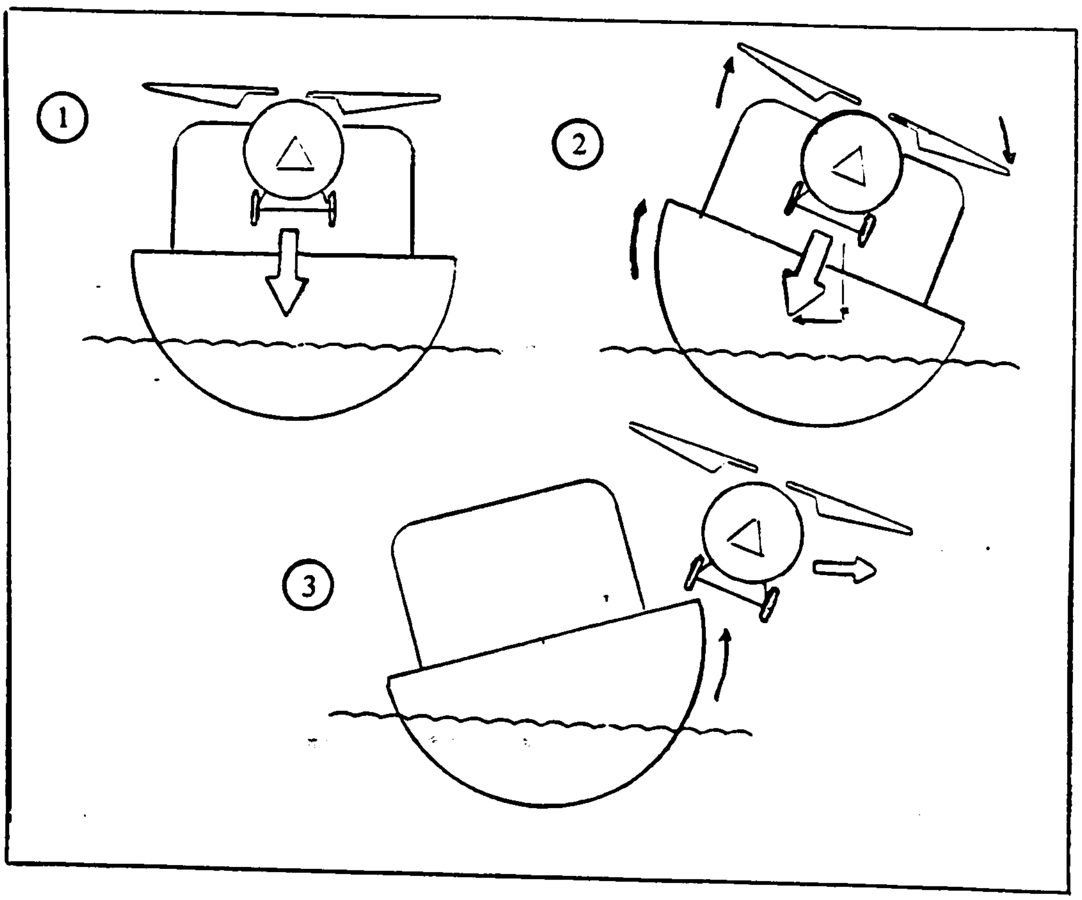



Figure 3. Results of keeping a strict relative position reference with the ship superstructure during ship roll.

Many smaller aviation capable ships can receive external loads from helicopters (Vertical Replenishment, VERTREP) with the aircraft oriented directly athwartships to provide adequate obstruction clearance. Rarely can the ship find a heading to generate optimum headwinds for this orientation. The H-46 operates over these decks comfortably. Personnel are routinely lowered by the external rescue hoist to a ten by ten square foot area between obstructions on a small combatant. During VERTREP, the majority of the flying is performed in winds from some relative position other than off the ship's bow.

### Landing

When the pilot is ready to land, he or she will normally wait and time the descent to meet the deck when it is relatively level. During daylight, they may even reference wave swell conditions near the ship to set down during an anticipated quiescent period in order to allow the ground crew time to attach chocks and chains before roll picks up again. Sometimes a landing can be accomplished by holding position and allowing the ship deck to heave up to the landing gear. Modern helicopter landing gear are designed to absorb significant vertical impacts. Older generation helicopters with gear that are not designed to withstand such loads, including skid configured aircraft, usually operate off larger, more stable platforms. The newer aircraft also incorporate landing assistance equipment (Recovery, Assist, Secure and Traverse, RAST) that haul the aircraft down to the deck with a cable and lock it to a grid with a pendant device. That capability substantially increases tolerance of the ship motion. The launch and landing phases are evaluated along with the approaches during Dynamic Interface testing and are factored into the determination of safe operating wind envelopes.

Emergency Procedures

All helicopters with primary missions of maritime operations are multi-engine configured. However, for many years, the majority of those aircraft could not effectively stay airborne in the event of failure of one of those engines. Recent engine upgrades have improved single engine performance capabilities in the aircraft that previously were most limited. Modern aircraft can hover with one engine out unless ambient conditions are prohibitive (extremely hot temperatures) or they are operating near maximum gross weight. Keeping some airspeed on the airframe gains the most benefits in reducing power requirements to conditions where flight can be maintained. During a single engine recovery, when the aircraft has no alternate landmass airfield available, the ship will prepare for recovery by making its best speed to generate maximum winds over the deck. Failure to understand the airwake effects behind the ship (downdrafts, blanked areas or significant turbulence) on short final while single engine can result in impacting the stern vice making the deck. Such misjudgments have been documented as contributory factors to fatal mishaps.

During flight control system failures affecting airframe controllability, such as hydraulic system or flight control computer failures, it is essential for the ship to establish the most stable wind and flight deck motion environment. Presently the pilot relies on the experience of the Officer of the Deck to know which heading will produce those conditions with the given combination of winds and sea state. Engineering analysis of the airwake and ship motion may provide a formula to quickly determine optimum ship heading and speed.

Technology regarding the operational environment of the helicopter must progress with the technology of designing and flying it. In 1909, Wilbur Wright was quoted as follows [5].

> "Like all novices, we began with the helicopter (then in childhood), but soon saw that it had no future. The helicopter does with great labor only what the balloon does without labor, and is no more fitted than the balloon for rapid horizontal flight. If its engine stops it must fall with deathly violence for it can neither float like the balloon nor glide like the aeroplane. The helicopter is much easier to design than the aeroplane but it is worthless when done."

Mr. Wright was obviously wrong. Without the helicopter in maritime aviation, logistics transport would come to a relative standstill, there would be no means of projecting combat troop power ashore, and the battle group would crawl the oceans in constant fear of death by submarine attack.

# CHAPTER III

## SHIP AIRWAKE

The current limiting factor in the scientific field of aerodynamics is the understanding of turbulence. Although the Navier/Stokes equations governing airflow around simple structures include expressions for turbulence factors and have been defined for several decades, computer technology has still not developed the capacity to process the volume of information necessary to solve those equations for a completely accurate solution or practical real-time application. The scope of that volume and the equations themselves are presented and discussed in the chapter on simulation. Furthermore, the theories addressing turbulence are not yet adequately understood or defined for airflow around complex structures such as those found in the ship flight deck environment. This chapter primarily focuses on the analysis techniques employed to research the problem up to the current day (1992).

### Definition

Ship airwake is the term given to the environment of airflow over the vessel that is influenced by its profile. Depending on ambient wind velocity and size and shape of the ship, the area of influence may extend far behind the ship. For the purpose of helicopter Dynamic Interface, the region of influence is considered to be on the order of one ship length behind the ship, and primarily in the direction the wind is heading. The area directly over the ship's flight deck back to one quarter of the ship length behind the ship is most heavily influenced by the ship profile and is referred to as the "nearwake" [6].

## Ocean Aerodynamics

Laminar flow aerodynamics are fairly well understood. The boundary layer of flow over a relatively smooth surface is also understood well enough for practical applications. To a certain extent, flow over rough surfaces can be modelled using mean local velocities. Airflow in the boundary layer over the ocean surface can be effectively approximated using mean velocities. For the scale of the ocean airmass and for moderate sea states generated by average winds, the boundary layer over the ocean surface is determined to be on the order of 250 meters [7]. The majority of the heights of ship flight decks and superstructures are in the bottom 20 percent of that layer. Freestream velocity in the atmosphere above the boundary layer is typically 25 percent higher than what the ships will encounter [8]. Mean velocity gradient follows a shear layer profile (nearly logarithmic) from zero at stagnation points directly at the surface, to ambient winds uninfluenced by the waves at the top of the boundary layer. The ship deck heights are typically in a range involving the steepest portion of that mean velocity gradient.

Until recently, concerns for turbulence generated by the roughness of the ocean surface were not taken into consideration. Turbulence is characterized by irregularity and randomness, which necessitates the use of statistical analysis and time-averaging when quantifying its values [9]. It is a characteristic of the flow of the fluid, not of the fluid medium itself. Turbulence results when the Reynolds number (a scaling factor measure of the characteristic dimension of the surface and flow region, as well as mean velocity and viscosity) gets large enough for that medium. The influence of the Reynolds number becomes critical when attempting to relate miniature wind tunnel model analysis to full scale applications [10].

As opposed to freestream aerodynamics analysis for standard flight, turbulence intensities in the shear profile boundary layer over the ocean can be increased by up to a factor of thirty [7]. Turbulence intensity is described as the variation, or standard deviation, of the along-wind velocity divided by the mean along-wind velocity. Turbulence intensity is also driven by surface roughness, which uses dimensions also considered in the Reynolds number. The scaling of roughness measures the characteristic dimension of the surface (wave height) against the height of the obstacle in the flow. Originally the sea surface contribution to turbulence was considered to be an insignificant factor regarding the nature of the ship airwake. Further analysis shows that in strong winds (on the order of 50 knots) over typical flight decks (30 to 40 feet above the surface), the turbulence intensity is indeed very high and will influence the nature of the ship airwake. Wind tunnel analyses of the past had underestimated turbulence intensities by as much as a factor of three [8, 9].

The turbulence longitudinal scale length factor is also a function of surface roughness and height of the flight deck. It describes the length of the region encompassing the most energetic vortices. For the operating conditions described above, this dimension equates to approximately 300 feet [9]. For most ships, the relationship of flight deck height of above the water to ship length is fairly consistent. The length factor coincides with the accepted significant airwake region length dimension of one ship length. Considering that a standard approach path follows an approximate three to six degree glideslope, the geometry of the profile places the helicopter within the region of significant turbulence intensity described by the turbulence length factor, which is also behind and below the major superstructure of the vessel.

In analyzing the turbulence, a significant characteristic is the spectral function, which describes how the energy of the turbulence is distributed amongst the frequencies of velocity variation. This characteristic will determine the amount of influence of the turbulence on the air vehicle operating in it. High frequency variations may effect the efficiency of the rotor system in creating lift. Low frequencies may increase profile drag forces on the fuselage profile [6].

In summary, significant factors to the environment in which the ship flight deck will operate include mean wind speed and sea state. Those two factors will determine the turbulence intensity, length scale factor and spectral function characteristics of the airflow over the ocean surface.

## Ship Superstructure Influence on Airwake

Influence of the ship superstructure further complicates analysis of the ship's airwake. The hull, hangar and island tower structures are considered "bluff bodies" that significantly distort the flow field. To a lesser extent, the airwake is also affected by the presence of guns, radar antennas, catwalks, railings and other equipment that clutter the external skin of the ship. Whereas the turbulence in the shear profile boundary layer is somewhat quantifiable, the separated flow behind bluff bodies is not even partially defined to the level that it can be modelled.

Empirical research and analysis of simple bluff bodies in wind tunnels can determine some of the basic characteristics of the flow on a macroscopic level. It had been assumed that separated flow created turbulence whose intensity was highest immediately behind the obstruction and tapered down rapidly downwind. Test results have shown that the opposite can be true. There can be a zone of near stagnant air immediately behind the obstruction, with increasing turbulence intensity and mean velocities proceeding downwind [7].

Generally, for a simple bluff body immersed in a shear gradient profile flow field with one face perpendicular to the airflow, the forward face will have a stagnation point at approximately two thirds of the height of the body. Flow above that point goes upward, and flow below travels downward. Flow around the new boundary layer attached to the body is accelerated. The majority of the flow energy will roll together at the base of the body and create a horseshoe shaped trailing vortex shed off the sides of the body [6]. Figure 4 presents the patterns of airflow experienced near a cubic bluff body immersed in sheared turbulent flow. The aft face of the body will have significant shedding, resulting in transverse and vertical velocity components much larger than those forward of the body. This flow description pertains to that observed for a body in boundary layer whose thickness is substantially larger than the object height, as is the case for the ship. A relatively thinner boundary layer will produce slightly different flow and separation characteristics. For example, with the thin layer, turbulence intensities are higher closer to the body, as was originally assumed in early research [7].

Since the ship does not always face directly into the wind and because the airwake obstructions are moving, the characteristic flow over the flight deck will be even more confused and dynamic. The flight deck height above the water will be changing as the ship heaves and pitches in response to the wave swells, which will cause

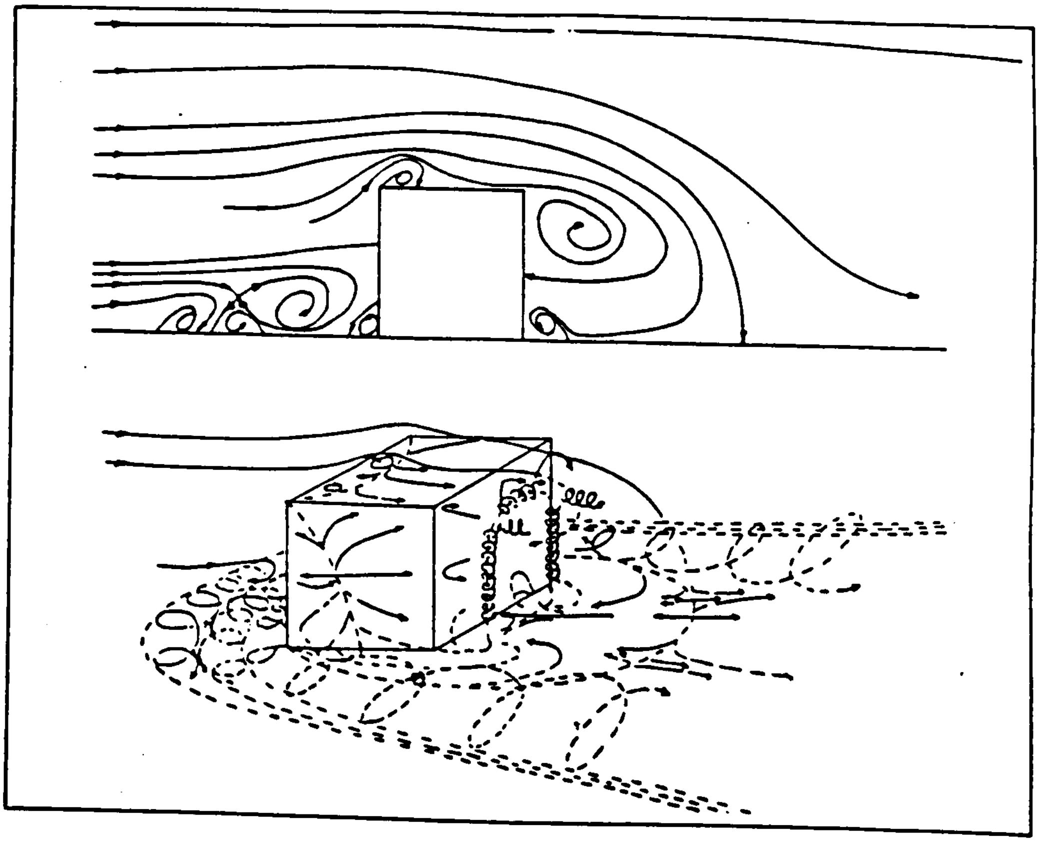


Figure 4. Airflow experienced near a cubic bluff body in sheared turbulent flow [11].

constant minor variation of the level of turbulence intensity approaching the superstructure surrounding the flight deck.

The flow will attach, shed and recirculate about the faces of the superstructure with both the apparently randomly shifting mean velocity of the shear layer turbulence and profile/aspect of the front face to the wind due to ship motion. The variations cannot be assumed to follow an overall Gaussian distribution. It is estimated that the level of turbulence intensities experienced due to shedding with winds in excess of 30 knots precludes the use of data gathered with present day measuring equipment [12].

In past research it was also incorrectly estimated that placing a "splitter" shape ahead of the perpendicular bluff body face would eliminate the vortex shedding nature of the flow. It has since been discovered that the splitter results in increased vortex shedding, with turbulence intensities increased up to three to four time existing levels [12].

## Wind Tunnel Testing

Wind tunnel testing technology has advanced substantially over the decades of aviation and has been responsible for many of the advancements in aviation itself. Scaling effects, Reynolds number influence, compressibility effects and sidewall interference are much better understood. Test techniques have likewise advanced. Early researchers simply streamed smoke into the tunnel and visually observed the results. The complexity of the models as well as the measuring equipment have grown with the size and capabilities of the wind tunnels.

The technology advancements have, however, exceeded the degree of their application to the field of airwake analysis. The major research facilities are rarely found with a ship model in the tunnel. There are sufficiently complex models of all class ships available. A majority of this type of testing is accomplished at the Naval Postgraduate School research facility. Testing conducted presently still pursues definition of gross characteristics of the airwake, utilizes a limited number of models, and employs simpler test equipment. They have made significant strides, however, in creating flow representative of the ocean boundary layer and validating the influence of the shear boundary layer turbulence effects, as well as describing gross flow characteristics [7].

Wind tunnel measuring equipment ranges from tufts attached to the model to laser doppler velocimeters. Tufts are useful for understanding flow direction adjacent to the superstructure faces. Smoke can be injected into the tunnel immediately ahead of the model. The smoke gives adequate gross flow patterns, but quickly disperses and gives little indication of local velocities or recirculation. Another technique involves photography of the travel of helium filled bubbles illuminated by strobelights against dark backdrops. The bubbles dance well but still carry a certain amount of momentum and occupy space that is affected by several local velocities. It is also difficult to differentiate the bubbles and track them individually when a field is introduced over the model. Even when the bubbles are released in a stream, the photography does not show transient characteristics of flow. The inertia of the bubbles also tends to carry them past zones of recirculation. Hot-wire anemometers measure voltage changes required to keep a heated wire segment at a constant temperature as airflow velocity affects the temperature and resistance. They are considered accurate tools to measure flow velocity variation, but their capabilities are exceeded in the nearwake region. Cheaper pulsed-wire anemometers generate a thermal pulse at a pair of electrodes at a known separation and then measure time until the pulse is sensed to accurately determine local velocity. Orientation of the wire anemometers is varied to determine in-line, transverse and vertical local components. Laser anemometers and velocimeters are very accurate for very small local velocity components, but are also very expensive and complicated to use [7].

Effectively mapping a sufficient sample of the flight deck and airwake aft of the ship is detailed and time-consuming. Hours and hours are required to map a single platform configuration with a single aspect to the wind, for a single mean wind speed and sea state condition.

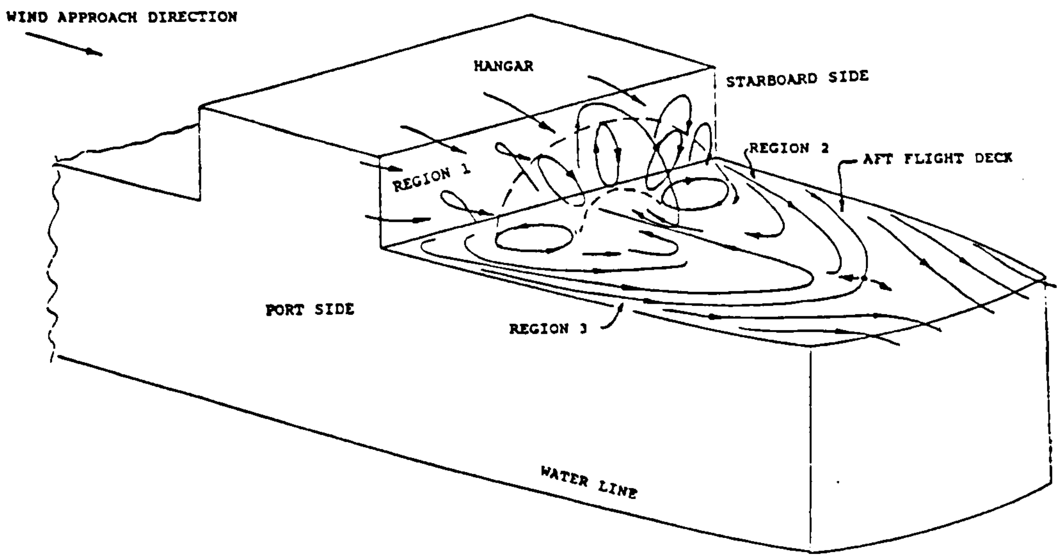
Dedicated support and increased funding are required to allow this critical phase of the research to continue advancing. Wind tunnel testing is the cheapest way to develop theories using actual wind, which can be used to determine prioritization of real-time airwake testing requirements. Real-time Dynamic Interface testing is much more expensive, labor intensive and difficult to schedule.

## Wind Tunnel Results

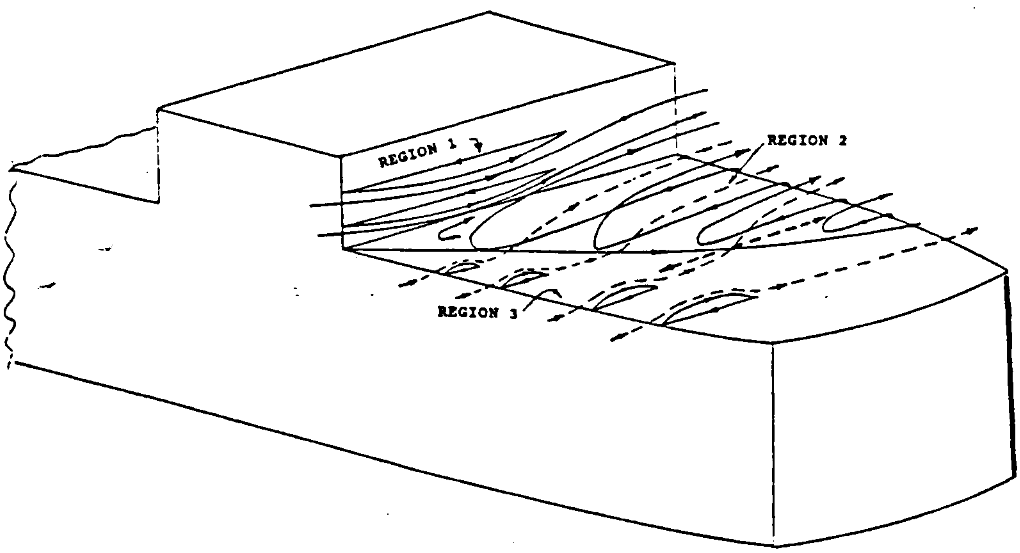
Professor J. Val. Healey of the Naval Postgraduate School has published results of testing with several findings that have direct application and are of concern to the operator. Under certain conditions during his wind tunnel testing, he observed large vortex zones detaching from the aft face of the hangar and building up to twice the height of the hangar. The zone then drifted diagonally across the flight deck and collapsed, before another zone was created and detached. The result was a flapping zone of turbulence that crossed the deck approximately every 2.5 seconds [7].

During helium bubble testing, bubbles were observed to climb over the leeside hull of the ship and actually cross the flight deck area into the direction of mean wind. Some bubbles would actually stop travel and reverse their direction in the recirculation zones [7].

Consistent observations are perhaps the most credible and useful. These are the data to be first validated by full scale analysis. Generally the transverse and vertical local velocities are relatively small compared to the in-line mean velocity. Those components over the flight deck seem to depend mostly upon relative wind heading. Transverse components never reach 20 percent of the centerline component for any wind vector. The vertical components are near zero for winds on the bow, and achieve a maximum for winds at 110 degrees relative. Flow visualizations in Figure 5 demonstrate the significant changes of flow over a single spot ship due to a change in the windline [7].




Winds off the bow.
(Headwinds)




Winds 315 degrees relative.
(45 degrees left of headwinds)

Figure 5. Airflow patterns over the U.S.S. Wabash for bow winds and winds left of the bow [7].

For winds close to the bow, the most substantial consistent vertical velocities are on the order of 15 percent of the in-line velocity in the region of approximately one eighth ship length behind the flight deck (for a flight deck on the fantail) [7]. This is useful to the pilot in that he will know where he is most likely to experience downdrafts when approaching the ship (which unfortunately happens to be on very short final just behind the stern). Pilots usually learn these characteristics associated with particular platforms the hard way. One good downdraft thrust toward the catwalk on short final to spot 5 behind the portside elevator on an LPH (helicopter carrier) with starboard winds will get enough of the pilot's attention to prepare him for subsequent approaches. Similarly, overshooting spot 4 in front of the elevator because of updrafts with port winds will get the attention of the ground crew.

Understanding the causes of these phenomena will teach us how to avoid or anticipate them. Identification of potential hazardous areas in the wind tunnel will save time during full scale testing by allowing the test team to focus on suspected worst cases. The conclusions offered by Dr. Val. Healey's research are to avoid box-shaped hangars, contour sharp edges, and lower the ship's hull height (freeboard). These conclusions are almost categorically in contrast to present ship configurations of the U. S. fleet. Russian vessels approximate these designs more closely, partially due to the heavy artillery configurations stacked along the deck. Their exhaust stacks and antenna arrays also appear to incorporate aerodynamic considerations. Until recently, ships were designed by marine architects solely to meet seaworthiness specifications. The aviation capabilities had been tacked on as an afterthought [7]. Now that the helicopter is recognized as a principal factor of the overall weapon system capability, ship designers in recent years have plugged the aviation considerations into the original design equation. Ship architects are now regularly attending and participating in maritime aviation research symposiums.

# CHAPTER IV

## SHIP AND HELICOPTER MOTION

### Ship Motion

Another aspect of the airwake analysis that is not completely understood is the motion of the ship platform through the water. While the physics of buoyancy, momentum and viscosity are known, the wave and swell action of the ocean surface has not been modelled with complete accuracy. This science again involves fluid dynamics and another complex set of Navier/Stokes type equations. Ships have been operating much longer than aircraft, and more effort has been put into understanding and solving this problem than has been applied toward the airwake problem. Naval architects conduct sophisticated tank analysis and operate with complex models in research labs much like the wind tunnels utilized for the aerodynamic arena. They too are challenged with understanding motion in a expanded matrix of environmental conditions, including wave height, wave period, relative ship and wave heading, prevailing current, class of vessel, ship loading, hull shape, and even wind effects [8]. Anyone who thinks winds are not a major factor in this equation should talk to the skipper of U.S.S. Eisenhower, whose carrier was blown out of the channel into another vessel in the last mile of a successful deployment.

The goals of this science are to design the optimum ship hull design for speed and stability, determine which speed and heading is most efficient for different sea states, and to predict quiescent periods as well as periods of maximum motion. There are some recognized cardinal rules that apply to the design of ships. It is known that minimum water drag occurs when length of the vessel is ten times the ship width [7]. However the mission of the vessel may often take precedence over economy of steaming costs. Amphibious Assault vessels have shallow draft and flat bottom hulls to allow for close approaches to shorelines. As previously mentioned, this configuration is perhaps the worst for stability of the flight deck, causing significant rolls and an overall corkscrew motion through the water, even in mild sea states. For the Anti-Submarine Warfare (ASW) vessel, speed and agility are of primary concern. The carriers generally provide speed and stability.

Ship architects are now employing systems engineering concepts to weigh the priorities of mission requirements, economy, weapons systems limitations and other factors in order to design configurations that will maximize benefits for the overall advantage. One of the next generation combatants configurations being looked at is the SWATH (Small Waterplane Area Twin Hull) for the frigate class. It promises significantly increased stability which would dramatically increase mission capability in areas of the world with higher sea states. Dr. Val. Healey analyzed that availability for helicopter operations to our present destroyers is reduced to 50 percent when wave heights increase from calm up to three to five feet. Operational capability is reduced to 10 percent when wave heights increase to eight to nine feet. Using sea state data for the Northern Atlantic operating areas, he estimated that on the average, helicopters could only operate within safe deck motion limitations for approximately ten percent of the time during the winter months [6]. The Beaufort sea state rating scale is presented in appendix A.

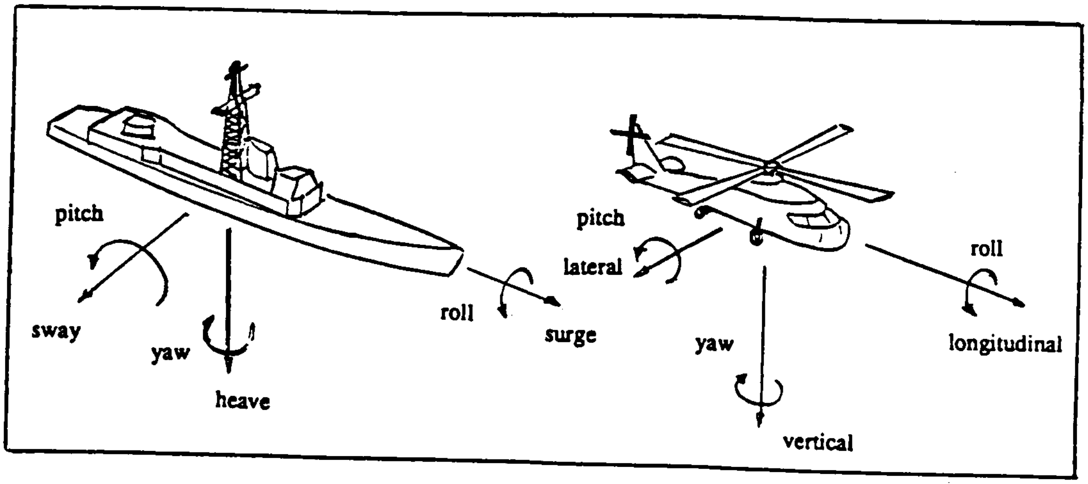



Figure 6. Characteristics of ship and helicopter motion.

Ship motion involves six degrees of freedom similar to those discussed in rotary wing aircraft motion as presented in Figure 6 [13]. Some of the motion factors are coupled, but can be separated using simple assumptions and transfer functions which will simplify the matrix of equations used to solve the resultant motion. Three dimensional fluid dynamic effects are simplified by "slicing" the hull into planar sections perpendicular to the centerline that can be analyzed using two dimensional potential-flow theories. This process is known as the "strip theory" [6]. The distribution of wave motion characteristics is more random than Gaussian, and has its own associated spectral function (frequencies of period and amplitude). The wave spectral function translates to a ship spectral function. The Strouhal number is utilized in analyzing the roll and factors ship roll oscillation, ship beam dimension, and free stream velocity [8].

Present data collection and reduction techniques employ statistical analysis and time averaging similar to the airwake problem. Dynamic Interface engineers record ship motion concurrently with flight operations to know precisely what conditions may have identified end points of the operational wind envelope. They also take samples in each new set of conditions to establish baselines of characteristic motion. The ship motion recorder is constructed of a combination of sensitive gyros and sensors for each degree of freedom. Data is recorded for the location that the recorder is mounted, and reduced to translate that motion geometrically to the flight deck arena. Often two recorders are used to validate the data.

Actual time histories of ship motion for each platform are plugged directly into flight and ship simulators, or are used to develop motion models. Data samples may range from continuous run for a matter of minutes, to lengthy time histories taken at anchored floating data collection stations [14]. The most common model presently employed for waves utilizes a large number of waves with different periods that are random in phase and relatively small in amplitude. The spectral function associated with wave motion shows lower energy levels in lower frequency waves, and higher energy levels in higher frequency waves [6]. Higher amplitude swells are observed to travel in sets. The period of the waves within the set will be fairly consistent and the amplitude will generally build toward the end of the set. The size of the set and period between the sets, as well as the character of the waves between the sets, seem to be random.

## Helicopter Motion

Perhaps the most understood aspect of the airwake and helicopter interface equation is the helicopter motion. As previously noted, there are six degrees of freedom associated with the motion. The translational motions are longitudinal, lateral and vertical. The rotational motions are pitch, roll and yaw. The rotor systems have the pitch rotation, lead-lag, and flapping degrees of motion discussed previously. The pilot manages all of these with the cyclic, collective and pedal inputs. Flight control inputs to maneuver in any one channel will require monitoring and correcting resultant coupled motions in most of the other channels. For example, collective application for altitude adjustment requires yaw compensation, which couples to roll and lateral motions, which changes the lift vector, which requires collective adjustment, and so on. The degree of coupling and corrective inputs will depend upon the authority of the stability augmentation and automatic flight control systems. At one end of the spectrum, older model AH-1

Cobras are heavily influenced by crosswinds and require constant rudder control inputs. Conversely, the AH-64 Apache pilot can perform an aggressive pop-up maneuver (rapid vertical climb to unmask from behind a treeline or ridge, momentary stabilization for a quick look or shoot, and return to the deck for cover) with a heading change of less than five degrees while his feet are resting on the deck off the pedal controls.

The helicopter motion and flight control systems have been modelled with great success for flight simulators. There are significant simulator limitations beyond the model that will be discussed later. Current rotor systems aerodynamics are modelled by integrating lift influences at local sections of the rotor blades or disk over the entire plane of rotation, then translating those forces through and moments about the rotor hub, and finally determining the resultant motion moment created about the helicopter center of gravity.

# CHAPTER V

## DYNAMIC INTERFACE

There are two primary categories of Dynamic Interface. Experimental Dynamic Interface involves the real-time, full-scale empirical data collection during actual engagement, launch, VERTREP, HIFR (Helicopter In-Flight Refueling), recovery, and disengagement, as well as other ground and flight evolutions on or over the flight deck. Analytical Dynamic Interface addresses simulation of ship and helicopter motion, dimensional analysis, interface of flight deck equipment, flight deck design and lighting systems. This field will be focused upon in the chapter on simulation. The Dynamic Interface department at the Patuxent River test center is aggressively involved in both fields.

### History

The first Dynamic Interface testing took place when a U.S. Army pilot landed the Sikorsky XR-4 helicopter on a clearing of the deck of the S.S. Bunker Hill, a merchant vessel, in 1943. The Naval Air Test Center (NATC) was established at Patuxent River during World War II, and became directly involved in helicopter testing before the end of the decade. A fly-off evaluation was conducted in 1949 in which the Sikorsky XHJS-1 and the Piasecki XHJP-1 (HUP) competed. The Piasecki aircraft won the competition largely due to its increased range of center of gravity [15].

Flying Quality and Performance (FQ&P) testing continued with the model HSS-1 in 1956 and HSS-1N in 1958. Carrier suitability testing was performed using the HSS-2 on the U.S.S. Lake Champlain (CV-39) in 1961. Helicopters were becoming truly maritimized and blade fold systems were evaluated. Dedicated takeoff and landing characteristics evaluations were performed using the YHSS-2. Results reported those characteristics to be excellent in winds up to 40 knots. The first wind envelope boundary was encountered at winds of 48 knots, 120 degrees relative, where the pilot reported unsatisfactory directional control [15].

The Dynamic Interface department was formally established in 1982 in conjunction with the establishment of the LAMPS MK III (Light Airborne Multi-Purpose System) program. Helicopters had become more recognized for the importance of their role in combat during the Viet Nam conflict. In 1983, the Naval Air Systems Command (NAVAIRSYSCOM) recognized Dynamic Interface for its principal role in development of safe operational envelopes and designated them as a lead activity. NATC was redesignated as Naval Air Warfare Center, Aircraft Division (NAWCAD), Patuxent River, in 1992. Dynamic Interface is presently a major department of the Rotary Wing Aircraft Test Directorate at NAWCAD Patuxent River. Since their inception, the department has conducted more than 150 test evolutions.

Nearing the fiftieth anniversary of the first helicopter shipboard landing, Dynamic Interface has grown from proof of a concept to an internationally recognized state of the art engineering research team. Flight evolutions have progressed from a daytime experiment to night-time RAST assisted haul-down recoveries in high seas and Night Vision Goggle (NVG) operations to expanded capability flight decks.

## Scope of Testing

The United States is presently operating more than a dozen various manned and unmanned VSTOL (Vertical/Short TakeOff and Landing) vehicles to approximately 20 classes of air capable ships. A matrix of aircraft and ship types is presented in appencix C and a list of classifications of air capable ships is presented in appendix A. The matrix of aircraft and ship combinations alone is substantial. The actual at-sea portion of a single testing evolution usually involves one week with a dedicated platform and aircraft. As many as four aircraft have been evaluated simultaneously during a Dynamic Interface test period on a helicopter carrier. Conducting multiple aircraft evaluations considerably slows the envelope definition process. Each aircraft has its own peculiarities and configurations that make it susceptible to limitations in slightly different wind quadrants or velocities. When one aircraft has to re-evaluate a data point, the other aircraft must loiter before conditions can be adjusted for a new data point. The majority of the envelope expansion testing at lower velocity headwinds moves fairly quickly. Single aircraft evolutions can define the envelope for that airframe in a substantially shorter period, however deck availability is so limited that the team usually tries to involve several models.

During that week at sea, the success of testing is at the mercy of the weather. The last test period prior to this printing was cut in half due to poor weather. The test team arrived at the ship two days late and could not test the first night due to low cloud ceilings and low visibility. Visual Meteorological Conditions (VMC) and a visible horizon are required for Dynamic Interface testing. Then again, the weather could be too good to conduct meaningful testing. In 1991, an Australian crew went aboard the H.M.S. Darwin with an H-60 airframe variant for more than a month. During that period, they experienced only one day when the winds were higher than 15 knots. Even though it was a relatively small vessel, ship motion was minimal for the entire period. The ship can only generate so much relative wind over the deck by steaming. The crew had hoped to gain extensive airwake data and observations on aircraft strut dynamics during ship motion. American test teams attempt to schedule evolutions during Spring and Fall months, hoping there will be enough weather for envelope expansion, but not severe weather that would prevent flight operations.

When deployed, flight operations typically include a day period followed by a late afternoon launch that affords transition through dusk into darkness. The "pinky time" at sunset provides for safe buildup and proficiency with instrument scan before total darkness. Operations have also been conducted in total darkness. The last test period before this printing involved aided (NVG) and unaided testing at night in zero illumination conditions. The only horizon visible, even on goggles, was toward the beach from the city lights.

Including test preparation, buildup and data reduction, a test may cost on the order of 75 to 150 thousand dollars. Some of the funding comes from program offices for the helicopter model itself. Many of the older airframes such as the H-46 and UH-1 have limited funding available. Unless there is a clearly defined operational issue to evaluate, such as the blade strike problem for the H-46, program managers are more inclined to reserve their funds for evaluation of new equipment, such as avionics systems. The Dynamic Interface department receives a substantial portion of the funding directly and organizes testing based on fleet requirement priorities as well as deck availability. The primary goal is to explore sections of the envelopes that have not been investigated. Dynamic Interface also receives significant funding from the ship project management departments in NAVSEASYSCOM, who are equally interested in expanding the operational capability of their weapons platforms.

The cost of testing depends primarily on the number of aircraft involved and where they come from. Utilizing NAWCAD airframes drives the cost up significantly. Some of those airframes are extensively instrumented, which contributes substantially to the aircraft program overhead costs. Although they are desired because they allow for much higher quality quantitative data, those airframes are most often not available or utilized. The major cost factor affecting test center flight hours is the structuring of the funding. Under the current comptroller system, funding of operations, maintenance, overhead and personnel labor for the entire test facility is tied to the revenue generated by the aircraft test programs. Therefore, flight hour costs for the airframes, even for non-testing proficiency flying, is exorbitant. Presently in 1992, the average cost per flight hour for helicopters is well over two thousand dollars. Utilizing fleet squadron assets affords great savings because only the consumable fluids and maintenance costs are the primary factors of the flight hour cost equation. Using fleet aircraft, six to ten hours of testing can be performed for for every hour using NAWCAD airframes. Fleet squadron commanders, however, are understandingly reluctant to release their operational assets to the test team, especially when their pilots cannot participate in the flying and log the hours. On th eother hand, utilization of fleet assets is sometimes perceived as taking revenue away from the test center.

There are four categories of flight testing. Category A is the most benign and usually involves evaluation of avionics systems or navigation equipment. Category B involves some minor degree of potential for hazardous situations. Category C testing is reserved for FQ&P testing and operational envelope expansion. Prototype aircraft testing is classified Category D. Since exploration of the wind envelope may involve exceeding performance limitations or limits of controllability, Dynamic Interface testing is classified as Category C and requires participation of designated test pilots [16]. Testing may also include certain degraded configurations of flight control systems that are not authorized for fleet operators during shipboard operations.

The test pilots are trained to recognize trends and apply proper safe build-up techniques. They are also trained extensively on the mechanics of stability and control, as well as data collection methods. Even though the test pilot is conducting engineering level evaluation, his fleet experience and operator perspective are equally important. He must report upon the tasks performed in a manner that would apply to all fleet operators, including the best and worst (or least experienced) pilots.

The primary limiting factor for scheduling Dynamic Interface testing has historically been ship availability. Requests are made months in advance and money is promised. Often, the money fails to get committed, or operational requirements take precedence and redirect the asset. Ship equipment casualties have also prevented participation. Recently, there seems to be a more informed mindset of the ship schedulers regarding the importance of such testing and benefits to be gained by the fleet.

With the fleet scale-down, certain platforms and airframes may be deleted, which will reduce the number of combinations requiring testing. The next generation of the battle group is planned to consist of only five or six classes of ships, and there are moves to narrow the helicopter fleet down to one or two models. The monetary savings realized by completely eliminating operation, maintenance and logistics support of an airframe are tremendous. This is being balanced against the operational capabilities lost by discontinuing operations with the airframe whose design and configuration were optimized for its mission. Money is rapidly becoming the operative factor in all military procurement and operational decisions.

## Method of Testing

Once the Dynamic Interface department gets funds committed for a test evolution, the preparation schedule begins. A test plan is generated and routed through the participants, Safety representatives, and Directorate management. Most of the test plans follow a generic format for wind envelope expansion testing and can be generated on surprisingly short notice. Specific airframes, platform peculiarities and points of specific ancillary testing are described in detail. No testing may be performed that is not addressed and approved in the test plan.

### Envelope Expansion

Wind envelope expansion test preparation begins with proficiency flights at the test center. Flight simulators may also be utilized, including the Manned Flight Simulator (MFS) at NAWCAD

Patuxent River, which is especially beneficial for evaluation of lighting packages. The Dynamic Interface engineers can create unlimited experimental deck configurations for the pilot to evaluate before he has to actually rely on them. The pilots will also requalify for ship operations by completing a series of FCLP's (Field Carrier Landing Practice approaches). Those who are not current will also log proficiency time on NVG's. If available and affordable, the aircraft will use the Elevated Landing Platform (ELP) ship deck in Lakehurst, New Jersey. Finally, albeit rarely, the pilots will regain shipboard operation currency at an available platform to comply with OPNAV instruction and specific NATOPS procedural requirements.

Preparation at the test center includes hover ladder performance flights to determine average torque requirements for the aircraft at different altitudes in a stabilized hover. Those values serve as relative baselines for comparison to evaluate the power demands and fluctuations encountered over the dynamic ship environment. The pilots may also perform low airspeed flights in the runway environment if the aircraft has incorporated a new configuration that may affect aerodynamic flying qualities. The aircraft flies formation on a calibrated ground pace vehicle at incremental relative headings and airspeeds during minimum wind conditions. These flights provide baseline flight control positions and establish critical azimuths for which the pilot might expect end points to testing during the Dynamic Interface flights. These test techniques are described in further detailed in the Naval Test Pilot School Flight Test Manuals, FTM 105 and FTM 106 [17, 18].

A presail conference is conducted with ship personnel to review the test profile and discuss ship standard operating procedures. Administrative preparations are made and the team embarks upon the ship. Depending on weather and passenger carrying capability, the engineers and maintenance support crew may embark pierside or fly onboard with the aircraft.

The first flight period involves requalifying pilots who are not current for shipboard operations. Build-up requirements dictate that day envelope expansion is accomplished before night flying, and that night testing will only be conducted to conditions previously flown during the day. NVG operations will only be conducted to conditions found satisfactory during unaided testing. Flight control degradation shall be incremental, if applicable, and conducted only to conditions found satisfactory for full up control. Headwinds are usually tested before tailwinds. In general, conditions are established to build up from the more benign to the more hazardous.

Depending upon the amount of maneuvering required, conditions may be altered by shifting relative wind headings for a constant velocity or by increasing wind velocity along a constant wind heading, with the latter being preferred. The most common criteria for establishing an end point is reaching limited flight control margin remaining, usually in the left pedal or left cyclic. It is easier to observe the trend toward a decreasing control margin during subsequent approaches into increasingly stronger winds versus shifting headings. Fifteen percent flight control travel remaining, based upon the average control position, is generally accepted as the minimum criteria tolerable. Contacting the flight control stop during any portion of the maneuver is also considered an end point. Other criteria for designating an end point include excessive power requirements, inadequate field of view, excessive flight control workload or potential for the fleet pilot to encounter any other hazardous condition.

It is preferable to conduct testing with a fully instrumented aircraft. Special instrumentation will more accurately record flight control positions and operational performance parameters. The engineers will then be afforded the luxury of playback to observe indicator excursions that the crew might miss. During daylight hours, copilots will record parameters on kneeboard data cards. A sample data card is presented in appendix B. Average flight control position and activity, maximum and average torque, aircraft fuel weight and remarks are recorded for each event. The aircraft will generally refuel at least every hour and a half in order to keep the operating weight up to be representative of the worst conditions that the fleet operator may encounter. Remarks may include excessive attitudes or wind effects encountered such as downdrafts.

The pilots are not required to record data on data cards during night evolutions, so that both pilots may continuously monitor instruments and external cues. Day and night operations are also recorded on cockpit voice-actuated portable tape recorders connected to the internal communication system. Most of the evolutions, including NVG operations, are recorded on videotape. Engineers simultaneously record data for each event from the ship flight control tower, bridge and combat control. Ship's heading, winds, ship pitch and roll, time of event, atmospheric conditions, observations from the flight deck and information passed over the radio by the pilots are also recorded.

For each event, the pilot assigns a qualitative rating based upon the overall difficulty of the maneuver or limiting criteria described above. The assessment is quantified with a PRS (Pilot Rating Scale) value of one through four, as described in table 1. Quantification allows for data correlation and definition of the wind envelope. Other countries use similar qualitative judgements with different scale value systems. At the last AGARD (Advisory Group for Aerodynamic Research and Development) symposium and TTCP (The Technical Cooperative Program) workshop in Bedford, England, representatives from participating countries were asked to develop a common scale.

If a pilot classifies a maneuver as a PRS-2, the copilot will usually fly the event to provide a second opinion. When a PRS-3 is assigned, the conditions for that event will be studied more carefully. The crew may elect to reduce the winds for those conditions and work up to them again in smaller increments, or return to an adjacent wind heading increment of known satisfactory conditions to re-evaluate. Winds are usually increased in increments of 10 knots and headings are adjusted by increments of

30 degrees. The crew may investigate neighboring regional conditions around the PRS-3 by building back up to it in smaller increments such as 5 knots or 15 degrees heading variation. Perhaps the rating was assigned for a suspected transient condition (high roll, heavy salt spray, unexplained aerodynamic vibrations). The crew may attempt to fly the point again. Usually, the PRS-3 conditions will not be reflown, especially at night. PRS-4 rated conditions are never re-evaluated.

Table 1
Dynamic Interface Pilot Rating Scale

| PRS No. | Pilot Effort Adjective | Remarks |
|---|---|---|
| PRS-1 | Slight | No problems; minimal pilot effort required. |
| PRS-2 | Moderate | Consistently safe launch/recovery operations under these conditions. These points define the fleet limits recommended by NAWCAD. |
| PRS-3 | Maximum | Landings and takeoffs successfully conducted through maximum effort of experienced test pilots under controlled conditions. These evolutions could not be consistently repeated by fleet pilots under operational conditions. Loss of aircraft or ship system is likely to raise pilot effort beyond capabilities of average fleet pilot. |
| PRS-4 | Unsatisfactory | Pilot effort and/or controllability reach critical levels and repeated safe landings and takeoffs by experienced test pilots are not probable even under controlled test conditions. |

When a pilot encounters conditions producing a higher PRS value assignment, he will comment more thoroughly on the flight control and/or performance characteristics experienced. Flight control activity (amplitude and frequency) will be described and another qualitative rating assigned based upon the Cooper-Harper Handling Qualities Rating Scale presented in appendix A [19]. They can also assign a Vibration Assessment Rating (VAR), Pilot Induced Oscillation (PIO) tendency rating, or Turbulence rating according to the scales presented in appendix A [17].

Pilot workload usually depends on a combination of factors including ship motion, turbulence levels, field of view, and deck visual cues available. Although hard number quantitative data is recorded (control positions and torque values, etc.), the pilot opinion is considered the principal factor in defining the operational envelope [20]. The British employ a similar pilot qualitative rating combined with a rating scale based on defined torque ranges [21].

## Airwake Analysis

Many creative techniques have been employed in attempts to visualize the airwake. Smoke has been utilized and gives an appreciation for gross velocity and overall turbulence intensity. However, as in the wind tunnels, the smoke dissipates and spreads too rapidly to observe local flow effects or downstream effects. The Dynamic Interface team engineers have resourcefully resorted to the even simpler technique of blowing soap bubbles off the top of the hangar and watching where they go. The highest level in that technology is the chemical combination process required to make bubbles that hold together in more than 25 knots of winds. Actually the bubbles are quite effective in giving flow indications of small portions of the airwake. They show some surprising recirculation and stagnation patterns. The bubble paths appear random, however, over the relatively massive flight deck, even when hundreds of samples are observed [22].

The importance of airwake analysis data collection during Dynamic Interface testing can also be expressed by noting the inaccuracy of the ship's wind indication system [3]. Most ships utilize two anemometers, primarily to have one available as a backup in the event of equipment failure. One wind vane is usually mounted forward on the ship and the other aft in the vicinity of the flight deck on single spot platforms. The tower operator will have the capability to select which measuring instrument is making inputs to the indicator he uses to base flight operations restrictions upon. Though the two systems are calibrated for position and instrumentation error, and sometimes biased to give similar indications in a known wind, there will usually be some disparity between the indications in the majority of wind quadrants. The dual system can cause confusion if the pilot house and the tower operator are observing different vane indications. The tower operator may request an adjustment for acceptable winds while the bridge is already observing an indication within the operational envelope.

Even though they are mounted to the highest positions on the superstructure, the vanes are being influenced by ship airwake. Wind tunnel analysis and handheld anemometers prove that the winds over the flight deck most likely will have no close correlation to winds sensed by the vanes. In fact, the wind heading may shift around the entire compass with wild velocity excursions as readings are taken around various positions at deck level. For the majority of the approach (entry to short final), however, it is estimated that the superstructure vanes give a more legitimate approximation. The ship anemometers are used to determine that particular vessel's envelope. Since that envelope does apply to a class of ships, the engineers will validate the calibration of the indication system. It is assumed that there will not be significant variation between ship indication systems that might cause operations to be conducted outside the intended envelope. The envelope is described with a safety margin for such considerations. It is also noted that even if the winds experienced during the approach do not have an exact correlation for reported winds, the test pilot is making his qualitative judgement for whatever those winds are and attaching the rating to the observed wind indication. If there are significant turbulence effects that would be large enough to affect the aircraft, the pilot will more than likely recognize them at some point during the build-up process. Pilots can also scan the sea surface for cues of predominant wind direction.

It is recognized, however, that the indication system is severely limited. Full-scale real-time observation airwake analysis is necessary to better understand the airflow and the data is vital to validate other phases of research. No credibility can be attached to wind tunnel test results or CFD (Computational Fluid Dynamics) models unless actual full-scale data can validate it. This aspect of the problem is just beginning to catch up with the analytical incentives.

Some modern aircraft incorporate their own low airspeed sensing or doppler motion detection systems. These systems may help to evaluate or record wind conditions approaching the ship, but would not be useful to the pilot over the deck because he or she then shifts to an external scan. Judging from results presented in wind tunnel analysis and pilot observations, the turbulence shifts over the deck would most likely exceed the sampling and display rates of those systems and the information displayed would not be useful.

In the last year, new wind measuring equipment has been designed and is now being utilized to gather data. Based upon an Australian design, the American Dynamic Interface department contracted construction of two anemometer masts, called SMAS (Ship Airwake Measuring System). Each mast is collapsible and mounted on wheels to facilitate repositioning around the flight deck. Sensitive, calibrated, and extremely light, styrofoam Gill anemometers are mounted to the mast at approximately 10, 20 and 30 feet. Three vane systems are oriented orthogonally at each station to record longitudinal, transverse and vertical velocity components. Data is usually recorded for up to five minutes, at sample rates of approximately 20 Hz (data taken every .05 seconds) [9]. Ship motion data is taken concurrently.

The mast is positioned over a matrix of points about the flight deck for each set of wind conditions. Using two masts, one wind condition can require up to several hours to record depending upon the number of positions on the flight deck evaluated. Not only is the data recording extremely labor intensive and time consuming, the reduction of it is very complicated, and requires extensive geometric triangulation and synchronization. This system, however, is the state of the art in real-time, full-scale data collection and needs to be employed extensively.

## Rotor Engagement and Disengagement

Blade flapping during transient low rotor speed periods in engagement and disengagement became a serious concern for helicopters only after they started operations at sea. Most Army helicopters still do not employ rotor brake systems. Winds are usually much steadier over airfield surfaces and land-based aircraft start or shut down much further away from obstructions that would disturb the airflow. The rotor brake not only slows the rotor system down rapidly to minimize low rpm time, it holds the system steady while the engines are brought on line to flight idle, which allows for a rapid acceleration from static conditions.

Still, the rotor brake alone has not been completely effective in eliminating blade strikes to the fuselage, particularly in the H-46.

Other aircraft generally have larger clearances between the rotor system and fuselage. Static droop of the aft rotor system on the H-46 brings the blades to within a couple feet of the spine of the fuselage. Engineers attempted to increase the size of the shim in the droop stop to increase the static droop clearance, but problems were encountered when the extra thickness prevented the stops from seating during shutdown. The CH-46E incorporated a secondary throttle detent position to select immediately after the rotor brake is released that more rapidly accelerates the rotors. Even with these fixes, the fleet still experiences tunnel strikes.

The Dynamic Interface team has employed several methods to attack this problem. H-46 aircraft have been deployed for dedicated engagement and disengagement evaluation. The process of establishing wind conditions and monitoring startups and shutdowns takes more time than envelope expansion. There are also more conditional variables involved in each event beyond the wind conditions that the fleet pilot could experience. Most of those include the same variables seen in the hover, such as ship motion and varying wind effects. Additionally, the different orientations of the helicopter as it is spotted on the deck (usually along one of the two approach lineup lines or along the ship's centerline) and the rotational position of the rotor blades at start must be considered. Even though the blades are spread into the same position each time the aircraft is spotted for the first launch, subsequent shutdowns and launches without blade fold may put the rotors in a new position. It is standard operating procedure to rotate the system slightly from the spread position to verify that the valve and lock mechanism is unlocked on the aft main transmission mast. There is no standardization to that amount of offset. Furthermore, in the final rotation of disengagement, there is no way to predict where the rotor blades will end up. The wind effects present in that last few seconds of rotor blade rotational movement may vary significantly over several sequential shutdowns for the same predominant wind.

Collection of a significant amount of data is again, labor intensive and time consuming. There is also an undetermined amount of wear and tear on the airframe during all those rotor brake applications and drive train engagements. What concerns the engineering team and owner of the aircraft even more is the fact that in the course of testing for a tunnel strike, one may actually be encountered. The test team devised a "greasy board" skid plate to fit over the synch shaft to deflect a low flying blade. Although the device served to protect the tunnel, it was not known what extent of damage the blades underwent during the impact. This potentially destructive method of testing has drawn serious objection and has not been utilized for some time.

Data are usually taken concurrently with other phases of testing at the beginning and end of each flight evolution. It is difficult to accurately assess the minimum blade to tunnel clearance and overall maximum blade flap even with videotape documentation. During the "greasy board" testing, styrofoam "chicken sticks" were mounted to the board for the blade to chop off so the clearance could be measured [22].

In order to gather more data over a shorter period, attempts have been made to gather fleet operator input. The problems with collection of this empirical data include format standardization as well as accuracy and variance of the qualitative observations. The author recently assisted the Dynamic Interface department in generating a data card for fleet squadrons to utilize when they deploy. The detachments were very receptive to the request and data is expected to start arriving within the next few months. The data card attempts to record all significant parameters affecting the event in meaningful dimensions that will eliminate distortion due to observer quantification variance. A copy of the card is presented in appendix B.

## Data Reduction and Presentation

Depending on availability of manning and equipment, data reduction may begin during the deployment. This provides the advantage of identification of areas to reinvestigate while the assets are still in place. Suspect data can be validated or discounted. Utilization of fully instrumented aircraft greatly enhances quality of data and speed of reduction. Some flight recorders can be directly downloaded into computer data reduction programs that generate final plots and displays. Other recorders merely store the data on audio tape that must be fed into multi-channel strip chart machines.

These strip charts must be manually reduced by engineers for data presentation. That process may take weeks. The engineers must also review the audio tapes from the portable cockpit recorders to collect the pilots observations and qualitative assessments of the events. PRS values are usually passed over the radio for the engineer observer in the tower to record, and copilots record them on the data cards during daylight operations, but the audio tapes provide the commentary justifying the assessment. Those notes are often the key to qualifying the endpoints assigned. Even though the portable recorders are voice-actuated, review often takes longer than the actual flight evolution.

Following each flight, the pilots are required to complete a daily flight report to document the testing. A copy of the format is presented in appendix B. Quality and usefulness of this report depends directly upon the effort made by the test pilot. He can rely on the data cards and tapes to remind him of important data to present.

The primary data presentations generated include plots of flight control positions and polar plots of PRS numbers. It is often difficult to get wind conditions over the flight deck required to generate a complete plot. For example, if twenty knots could only be generated between 300 and 090 relative headings, the pedal flight control margin plot for twenty knots would be incomplete. A comprehensive data base accompanies the PRS value polar plot to account for all the variables involved in each event. A plot may show a PRS-2 at 20 knots of wind, and a PRS-1 for 30 knots on the same wind bearing. This could be an accurate assessment (because the higher winds eliminated recirculating vortex shedding effects or allowed for continued translational lift assistance) or be strictly due to transient high swells that caused excessive ship motion during the event with lighter winds. Therefore, the plot must be backed up with the data base. The data base also includes significant pilot remarks. Sample flight control position plots and a PRS polar plot are presented in appendix B. Dynamic Interface data base information is recorded in D-Base III and is available to all users upon request.

## Reporting and Application of Results

Following each test period, the Dynamic Interface engineers generate a series of reports summarizing the evolution and data observed. A message report is published usually within a week of completion. It outlines the scope of testing accomplished and offers general preliminary observations. Absolute conclusions are not offered until data are reduced. Quick response reports can be made for specific tasking, such as lighting system evaluation. Results are reported to the proper flight authorization branch at NAVAIRSYSCOM and eventually put out via message to operators of the airframe and class of ship involved. Few full technical reports are prepared since tests rarely generate a complete envelope and because the process is ongoing. Airframe and system modifications may require re-evaluation of defined envelopes.

Dynamic Interface is not responsible for air capable ship flight deck certification. Certification involves inspection of flight deck systems such as communications, refueling systems, sprinkler systems, visual landing aids and lighting packages, as well as equipment including firefighting gear, personnel protective attire and VERTREP retrograde material. Separate NAVAIRSYSCOM (Naval Air Systems Command) department personnel conduct these inspections and assign the ship one of the classifications presented in appendix A. Flight deck dimensions, classification and capabilities are described in the HOSTAC RESUME [4]. A sample from the RESUME is presented in appendix C.

Wind envelopes are presented in the Shipboard Helicopter Operating Procedures Manual, NWP-42, [23] and the individual aircraft NATOPS operating procedure manuals. Day and night launch and recovery envelopes, engage/disengage envelopes, pitch and roll limitations and other operating restrictions are presented for aircraft and ship class combinations. The wind envelope boundaries presented are not all defined by endpoints experienced during testing. Only the boldfaced lines indicate hard endpoints, whereas other portions of the envelope may be based solely upon maximum winds that could be generated during testing. It may be safe to operate outside that envelope, but those conditions have never been tested. NAVAIRSYSCOM guidance advises the fleet to use "best judgement" when operations must be conducted in environments outside the described envelope, especially regarding ship motion [24]. The NWP-42 contains several matrices that specify what airframes are authorized to operate from which vessels. Sample wind envelopes and a matrix are presented in appendix C.

Standard OPNAVINST 3750 series safety instruction hazard reports are generated to identify any hazardous conditions experienced during testing that may have immediate application to fleet operations. During one test evolution, ship roll became sufficient to cause the mainmount of an H-60 to lift off the deck when the aircraft was tied down. During another test it was discovered that the ground clearance below the bottom of an external fuel tank was less than the height of the RAST trap mechanism on the deck. It was determined that during free-deck landings in conditions of increased roll, substantial potential existed for the pilot to drift to a landing position where the tank could be punctured by the trap. These observations are examples of the field of analytical Dynamic Interface.

Data can also be used to conduct preliminary evaluations of proposals before flight testing is required. There is presently high level interest in assessing the capability of the H-60 to perform the VERTREP mission of the H-46. Navy H-46 assets are below desired strength and are suffering steady attrition with no replacement in sight. Previously anticipated Marine Corps assets are now tied to the success of the V-22, which will not be delivered for operational use for a minimum of six more years. The H-60 contractor reported that the airframe was capable of operating at more than its present authorized maximum gross weight, with adequate pedal control margins in the worst possible wind conditions that could be encountered. Dynamic Interface data did not substantiate the contractor claim and brought attention to the fact that left lateral cyclic control margins were also a concern. The data provided by the contractor reported the mean flight control positions taken in the controlled and stabilized environment of the runway during low airspeed testing. From Dynamic Interface testing, we know that there can be substantial variation about the mean position due to turbulence effects in the airwake. Wind tunnel and airwake analysis also show that while conducting VERTREP, the H-60 would be operating in the region of reduced margins (right quartering tailwind) more than the contractor had predicted. These factors may be more important than the simple performance and dimensional comparisons of logistical transport capability.

## Summary

Funding availability is becoming a primary limitation for Dynamic Interface testing. Continued testing is crucial to keep up with advancements in other technologies that depend on these results. Unfortunately, this field is not regarded as a "big ticket item" that money managers want to support or tack their name on. The application of results is generally viewed as limited, primarily due to a historically consistent inadequate appreciation for the importance of helicopter operations at the highest levels. Proper support of this science could open doors to advancements of technology with wide spread applications, including design, construction, simulation, boundary layer control for VSTOL vehicles, and ultimately real-time solution of the Navier/Stokes equations for improved aerodynamics and fluid dynamics.

# CHAPTER VI

# SIMULATION

The field of simulation has witnessed the greatest advancements and stands to reap the most direct application of future advancements. This chapter will present a brief history of the evolution of flight and airwake simulation, discuss present technology and limitations, analyze practical applications of present technology, and make observations about the future of simulation.

## Flight Simulator Development

The first helicopter fleet training device technically evaluated by an engineering team was the SH-2F Weapons System Trainer (WST), Device 2F 106 [15]. It incorporated two mono-chromatic visual monitors, had seats for the pilot, copilot and instructor, and had motion capability. Visual displays and motions had significant lag from flight control inputs. The visual displays were also very two-dimensional which limited assessment of closure rate. It was an effective cockpit trainer for teaching the pilot proper instrument scan and emergency procedures. The motion dramatically increased the workload for the pilot, but gave confusing proprioceptive cues out of synchronization with the visual display. Still, it was state of the art and the author remembers the thrill of getting an opportunity to fly it. We "launched" from the local airfield at NAS Norfolk, Virginia, and proceeded to fly low altitude down what we perceived to be one of the local interstates toward the town. The graphics showed lane dividers and streetlights, but the road followed a constant heading and the town never came into the picture.

That was ten years ago in 1982. The instructor could program some environmental factors such as pressure altitude and wind vectors. We challenged each other during approaches to the runway by inserting an instantaneous 180 degree, 50 knot wind shift on short final. The simulator had a carrier deck and a frigate with programmable ship velocity and sea state. With the lags in cues, limited field of view and poor synchronization, flying around the ships was extremely challenging and the trainer was not recommended for shipboard landing instruction. We enjoyed a strong sense of accomplishment when, after several attempts, we were able to crash the helicopter somewhere near the aft end of the ship (motion was not active). We did not enjoy the degree of motion sickness generated by the confusing sensory cues. Finally, after a significant learning curve to overcome the deficiencies, we were able to successfully recover to the small deck in benign conditions.

At the same time, NASA Ames was attempting to simulate and program the airwake influence into the picture for the same trainer. Ship airwake and turbulence levels were qualitatively evaluated as excessive in both magnitude and frequency [15].

Great strides have been made in the flight simulator arena for most airframes. The Lamps Mark III SH-60B flight simulator, ironically is one of the least advanced. The airframe is of the newest generation with state of the art software, but the simulator has no day visual image capability, the night scenes are two-dimensional, and closure rates are difficult to judge due to lack of texturing. The older CH-46 and CH-53 aircraft have much improved visual graphics and motion packages. They employ a wide range of environmental conditions, including a fairly realistic fog simulation. Day visuals incorporate a full spectrum of color. Airfields and local operating areas are accurately modelled and incorporate navigation aids. Some obstacles are modelled as "hard" obstructions that will freeze the simulation when impacted, and some can be flown through. The pilot can fly the helicopter through the hangar or watch stanchions swing through the picture while he performs a pedal turn under the airfield water tower. Mission capabilities have been expanded to include aerial refueling and formation nap-of-the-earth terrain flight. The pilot can fly a route, record it, and have the simulator create a wingman to fly the same route whom he or she can fly formation on. Visual monitors have been expanded to include side window pictures and a chin bubble screen. Five years ago the monitors were providing 106 degrees of lateral field of view, 23 degrees of vertical field of view, and visual fidelity providing up to 8000 edges per scene [6].

State of the art simulators now place the cockpit frame inside a larger spherical dome for a completely surrounding visual presentation. This allows the pilots to improve or adjust the field of view by moving their head. The AH-64 Apache simulator at McDonnel Douglas has impressive fidelity that even simulates blowing grass in a low hover. Water and skies are textured to look more real than animated. Their simulator visual package allows the pilots to hover down inside a grass hut through a hole in the ceiling and then perform a pedal turn while looking outside the hut through its windows as they swing by. While standing on the platform next to the cockpit inside the dome, the observer will have to hang onto the railing to keep from falling over. Even though the platform never moves, the visual graphics are realistic enough to convince the observer's brain that he or she is actually moving.

Modern helicopter simulators can fly combat missions against foreign national assets, both rotary and fixed wing, realistically matching performance capabilities and limitations of the airframes. Pilots can even fly combat against each other by linking the simulators through computer phone networks. The simulators are being utilized to optimize procedures based upon performance parameters, including air-to-air combat maneuvers.

A joint Army/Navy program in work to update helicopter flying quality Military Specification, MILSPEC 8501A, is heavily employing simulation incentives [15]. The simulators are developed under certain specifications themselves, and are then challenged against the specifications and truth data for the actual airframes.

Flight simulators employed by the military are extremely cost effective in accomplishing training. The cost per hour to operate fleet flight simulators is in the low hundreds range, compared to the expensive cost of flying and maintaining actual airframes. Instructors can be available around the clock. The simulator world also boasts an outstanding safety record for training pilots, even though there actually was one fatal mishap involving a simulator whose motion system malfunctioned and threw it through a wall.

The ultra-modern MFS facility at Patuxent River is utilized for training pilots to fly prototype aircraft while the airframes are still on the drawing boards. This capability provides the tremendous advantage of allowing the pilots to make inputs into the design process and improve flight control systems before first flight. The MFS is also used for engineering analysis of flight control systems and has the unique capability to operate several airframe cockpits off a single motion pedestal. The cockpits are mounted on rollers and stored in adjacent rooms. Switching to a completely different aircraft involves disconnecting the computer umbilical cord, swapping the portable cockpits, and reconnecting the canon plugs. One enthusiastic team accomplished the swap in under 20 minutes.

The MFS facility was also used extensively to analyze last year's V-22 mishap. Engineers were able to recreate the flight control system misconfiguration discovered in the mishap aircraft, and validate the controllability limitations suspected to have contributed to the crash.

The new T-45 primary Navy jet trainer program is already using simulators to teach the next generation of instructors how to fly it while the aircraft is still being evaluated prior to production

[25]. The FAA, DARPA (Defense Advanced Research Project Agency), and the U.S. Army Program Manager for Training Devices are all pursuing new standards for simulation validation criteria. Part of the LHX (AH-65 Comanche) contract recently won and lost by Sikorsky/Boeing included the requirement to validate design concepts through simulation before prototype production began [26].

The Navy has recognized the significant contribution simulators make to fleet readiness. They established the Naval Training Systems Center (NTSC) in Orlando, Florida, to manage the field. NAWCAD test pilots work closely with NTSC engineers to validate the trainers by evaluating both accuracy of simulation and specification compliance. Representatives from both centers interact with contractors to prioritize implementation of new capabilities and keep the trainers up to state of the art standards.

## Current Flight Trainer Limitations

Even with the awesome visual imagery and networking capabilities of the day, flight simulators have plenty of room to advance. Fortunately, the most complicated advancements are tied to computers, whose technology is advancing at warp speed. The Georgia Tech simulation department breaks the simulator down into the following subsystems: Cockpit, audio, motion, control, math model, environment, ground handling, mission equipment, system latency and visual system. Desired characteristics are identified for each subsystem and a rating scale assigned. Each subsystem's performance is rated during a series of critical tasks to evaluate the overall simulator fidelity [26]. This process identifies systems most in need of improvement.

Priorities for improvement can be based upon the performance of the subsystems for the critical tasks with regard to how well they accomplish the desired training. For example, the fidelity of the ship motion model may not be completely representative, but even with a strictly sinusoidal motion the pilot will be adequately tasked to learn how to hover in a stable relative position over the flight deck.

The newest strides in fidelity involve more simple mechanical and electrical fixes. Simulators will soon incorporate seat shakers to give more proprioceptive motion cues. Often pilots sense flight regimes or maneuver the aircraft based upon vibration level changes in the airframe, such as those felt in the H-60 when transitioning through translational lift. Fleet and test center aircraft are presently in the process of making audio recordings of the cockpit environment to incorporate into the simulator. Blade slapping and rotor rpm changes also cue the pilot to certain flight regimes. With the increased capacities of monitor fidelity, engineers are constantly upgrading the visual packages to provide more texturing and improve depth perception cues. Even the padeyes on the flight deck are being accurately modelled into the picture [3].

One physical limitation that will be difficult to overcome is the lack of g-force onset and sustained g-forces felt in turns and aggressive maneuvers. These proprioceptive cues help the pilot maintain balanced flight and avoid overstressing the aircraft. On the hydraulic ram pedestal motion trainers, the pilot may feel the motion as he enters the turn, but eventually the ram motion will dampen out and he will feel and inaccurate lean in his seat until the ram levels the trainer for the next maneuver. The huge motion simulator at RAE Bedford in England slings the entire cockpit enclosure approximately 20 meters in the each of the primary axes. Huge rams and tracks are employed to enable a g-force range from below zero to more than two g's for up to a few seconds [3].

EMI (Electro-Magnetic Interference) has been a factor in degraded simulator performance. Last year a test team evaluating the CH-46E trainer was continually frustrated while trying to measure pedal motion and response against truth data and the specifications. The engineers kept fine-tuning digital filters to try to balance the pedal bias, but each time the system was brought on line a new set of measurements were observed. Finally the troubleshooters traced the problem down to an unshielded wire bundle at the data transfer bus that was absorbing varying amounts of interference voltages from a cooling fan coil. The stray voltages were affecting the bias balance each time the baseline conditions were established at startup. Shielding the bundle eliminated the problem.

The following list presents simulator deficiencies identified by test pilots during V-22 shipboard compatibility evaluation conducted at the MFS facility at Patuxent River. The deficiencies are listed in order of priority [3].

Inadequate aural cues
Excessive throttle lag and torque response delay
Turbulence model needs fine-tuning
Ship deck not always modelled as hard surface
Water cues inadequate at ship waterline (no splashing)
Superstructure needs more detail (scaling of doors, etc.)
Visual system update rate slow (slow computer speed)
Ship and aircraft pitch rates not in phase on ship deck
Flight deck surface needs more texturing (padeyes)
Ship motion model not adjustable
Recommend addition of chin bubble visual
Excessive lag between motion/visual during cyclic inputs

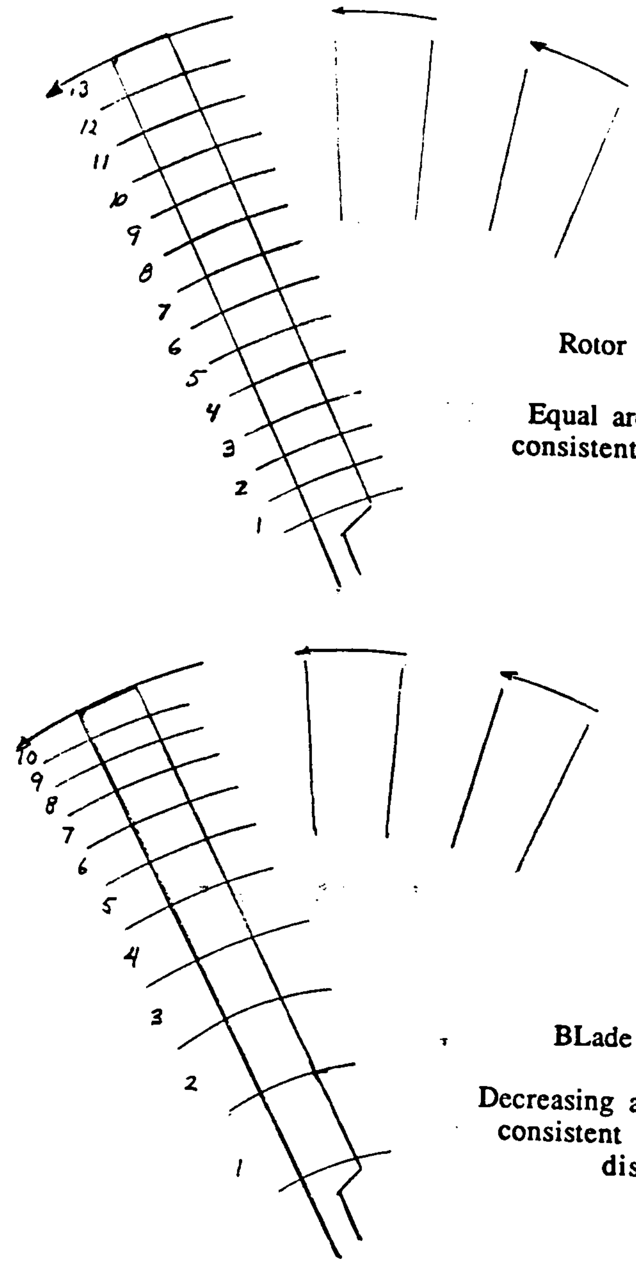
## Helicopter Motion Simulation

Most computer programs model helicopter motion by analyzing the aerodynamic forces requested of the rotor systems depending upon positioning of the flight controls. As described previously, local lifting forces over the rotor system plane are added or integrated for their contribution to the total forces and moments transferred through the mast about the center of gravity of the airframe. Airframe inertia contributions are also considered. Other factors modelled into the rotor system contribution include blade lead/lag, flap, elasticity, coupling, offset, compressibility effects, ground effects, harmonics and more [6]. Special considerations were applied to the tandem rotor configuration of the H-46 to account for the overlapping entrainment sections where the fore and aft system cross over each other.

Early models for the rotor system were called Rotor Disk Map (RDM) programs. The rotor tip path plane was divided into concentric rings with incrementally increasing diameters. The aerodynamic forces were averaged over the blade segment based upon the mean velocity of the point half way out spanwise for that segment, and were considered applied at the same location, as depicted in Figure 7. The forces were summed for all segments of the individual blade, which had equal spanwise and chordwise dimensions, as well as for the other blades. Samples were taken at a frequency representative of the operating rotational speed and often enough to accurately represent forces created about the entire plane of rotation. Model accuracy improved with sampling rate.

The Blade Element Model (BEM) is a variation of the RDM model that changed the diameters of the rings (spanwise length of each segment) such that each would inscribe an equal amount of area as it rotated about the plane, as described in Figure 7. The segments become smaller proceeding from the hub outward to the blade tip [27]. Unlike the RDM program, the BEM theory recognizes that the mass distribution over the blade is not similar to the aerodynamic lift distribution. Segments further away from the rotor hub are travelling at much higher speeds, and achieve increasingly higher lifting forces. The RDM model also assumes that

10 degree arcs sampled at rotor RPM.



Rotor Disk Map Model

Equal area blade segments; consistent mass distribution.

BLade Element Model

Decreasing area blade segments; consistent aerodynamic force distribution.

Figure 7. Rotor systems division for helicopter motion models.

the aerodynamic center and mass center of the rotor system are coincident. This is not the case for systems that incorporate a lead/lag degree of freedom. BEM uses approximately 10 degree arcs sampled at optimum rotor rpm [28].

Sikorsky developed the GENHEL (General Helicopter Flight Dynamics Simulation) model. Frequency response techniques (dynamic stability) were used to validate the model. NASA Ames adapted the GENHEL model to the UH-60A helicopter airframe and further validated fidelity improvements over other programs. NAWCAD Warminster is working with this model to incorporate airwake effects. NAWCAD Patuxent River is working to install the GENHEL program into a system at the MFS, and Australian engineers are utilizing it at their Aerodynamics Research Laboratory (ARL). GENHEL performs more integration of blade movement calculations, but is considered a somewhat rigid computer program to work with. The Advanced Rotorcraft Technology (ART) company is currently developing a more flexible version of the GENHEL model that will be used by Georgia Tech [3].

Validation of the model involves paralleling motion results with truth data. Even if the model is accurate, the flight simulator may not be effective if its hydromechanical motion package is limited. Most of the yanking and banking felt inside the trainer cockpit is accomplished over the span of a few inches of hydraulic ram motion. Pump volume capacities and pressure tolerances must be closely monitored and calibrated. Also, due to the difference between real-time cues and simulator cues, simulator motion that exactly corresponds to actual motion may not seem realistic to the pilot.

## Airwake Simulation

Scientists have been pursuing modelling of airflow for decades. The governing Navier/Stokes equations involve complex matrix computations of 60 time-dependent variables. In the equations below, **x**, **y** and **z** represent cartesian coordinate directions, with associated velocities of **u**, **v** and **w**. **V** represents the velocity vector (and magnitude). **P** is pressure and **F** is force. $\rho$ is density, $\mu$ is viscosity, and $\lambda$ is the second coefficient of viscosity for a homogenous fluid.

$$D/dt = (d/dt) + u(d/dx) + v(d/dy) + w(d/dz)$$

$$\overline{V} \cdot V = (du/dx) + (dv/dy) + (dw/dz)$$

$$\rho(Du/dt) = Fx - (dP/dx) + (d/dx)\,[2\mu(du/dx) + \lambda V \cdot \overline{V}] + (d/dy)\,[\mu(dv/dy + dv/dx)] + (d/dz)\,[\mu(dw/dx + du/dz)]$$

$$\rho(Dv/dt) = Fy - (dP/dy) + (d/dy)\,[2\mu(dv/dy) + \lambda V \cdot \overline{V}] + (d/dz)\,[\mu(dv/dz + dw/dy)] + (d/dx)\,[\mu(du/dy + dv/dx)]$$

$$\rho(Dw/dt) = Fz - (dP/dz) + (d/dz)\,[2\mu(dw/dz) + \lambda V \cdot \overline{V}] + (d/dx)\,[\mu(dw/dz + du/dx)] + (d/dy)\,[\mu(dv/dz + dw/dy)]$$

While the terms, axes systems and parameters seem simple enough, the derivations and computations demand more than present technology computers are capable of. Using certain assumptions of physical properties, Fast Fourier Transforms (FFT) and linear relationship simplifications, the equations can be simplified and solved for local velocities around simple structures. The computers, however, cannot manage the information and interaction computations required for an entire flow field solution. Even the simplified calculations have demanded months of continuous run of the most sophisticated computers available [10].

Air flow modelling is required not only to accurately simulate the environmental turbulence encountered at the ship, it is also necessary in order to accurately model the influence of the helicopter's downwash upon itself. While overall tubulence intensity variation is low enough not to cause appreciable aircraft oscillation, the overall downwash impingement on various sections of the airframe profile can affect its attitude. Navier/Stokes calculations of the individual blade vortex and overall rotor system vortices are being performed with increasing accuracy and efficiency [29].

Incorporating the massive computer demand for the airwake analysis and simulation will add to the computational through-put delay already present in the system as it handles the load of helicopter motion and visual presentation. It would be less taxing on the overall system to input a modelled airflow instead of calculating one from the conditions existing in the simulator. This further demonstrates the importance of the SAMS data collection being performed by the Dynamic Interface personnel.

At a working review conference for the CH-46 simulator just last year, the contractor asked for data to model the wind effects around the islands of the LPH or LHA amphibious ships. They had been tasked to develop a training tool to instruct students on the dangers of wind effects over the landing zones due to turbulence off the ship's island superstructure. The engineers were amazed and disappointed to hear that no useful data were available. They attempted to simulate vortices by generating a relative local velocity shift in a tapering spiral emanating orthogonally from the corners of the island. These vortices were filtered to wash out in the main flow stream and bend toward the direction of flow. The resulting simulated vortices were unrepresentative and failed to even reach the landing zones. The efforts were abandoned and, at the suggestion of the author, a simpler method was adopted to accomplish the intended training. A variable downdraft or updraft generation capability was afforded to the instructor that he could apply at a point on short final where, according to his own fleet experience, he felt that one might be encountered. Even if the programmed downdraft were not completely representative, the students would recognize that some aberration occurred and the instructor could debrief them on the potential for such wind effects. The goal of the training was accomplished.

It is still desirable to pursue a completely realistic simulation. The Technical Research division at RWATD Patuxent River sponsors several Small Business Innovation Research (SBIR) programs, some of which are pursuing the airwake model. Georgia Tech researchers at their Center of Excellence for Rotary Wing Aircraft Technology (CERWAT) are presently working to validate a stochastic ship airwake model using existing airwake data from a DD-963 class destroyer and statistical analysis programs. Their goal is to implement a working model into their simulator within the next year [30].

## Computer Technology

Computer capability advancements have provided for increased helicopter motion and visual system fidelity. Studies showed that time delays between sensory cues to the inner ear and the eyes on the order of one half second or more caused motion sickness for the pilots. NATOPS General Flight and Operating Instructions, OPNAVINST 3710 [31], recognizes the associated fatigue and performance degradation caused by "simulator sickness," and cautions pilots not to fly within a 12 hour period following simulator training. Inability to handle response delay was dramatically demonstrated in last year's V-22 mishap, when the flight control system phase lag and throughput delay combined to create an aircraft motion response delay of more than a full second in the roll channel. As the pilot fought to interpret the problem, the aircraft oscillated three times and then cartwheeled across the taxiway. Even when they were anticipating a control system aberration, test pilots recreating the V-22 misconfiguration scenario in a simulator were unable to control the aircraft. State of the art visual and motion response systems are presently operate at 100 milliseconds of delay.

State of the art image generators are capable of generating up to 15,000 textured and shaded polygons at a 30 Hz rate, with 60 Hz update speed and full spectrum of color. Monitor resolutions are up to 2048 x 2048 lines without jagged edges. Moving targets are now crisp and depth perception cues are greatly improved. Imagery can accurately simulate and rapidly update complex weather phenomena such as variable-density fog and haze [25]. One has to only go as far as the nearest mall video arcade to witness the technological explosion that has taken place in this field.

Computers are still relatively limited for Navier/Stokes equation solution applications. Even the relatively simple Australian model for compression of the landing strut involves 70,000 lines of FORTRAN code and two million bites of memory [13]. In the late 1970's, one author speculated that the computer capability would exist in the mid 1980's [32]. The article noted that then current computers were taking up to an hour to solve the simplified two-dimensional Reynolds number averaged Navier/Stokes equations. More complicated solutions were estimated to require a computer that could work one billion FLOPS (Floating Point Operations) per second, with a working memory of 30 million words. The IBM 360 computer of the day would require a month to reach a solution, and the Control Data 7600 would require a day. By the mid 1980's, computer capabilities had not reach their goals, and the new estimates placed required capacity at 10 billion FLOPS per second on 64-bit operands, with a 200 million 64-bit word working memory. Such requirements exceeded the capability of the NASA Ames Illiac IV super-computer, which then represented the state of the art, by 200 to 300 times, with 10 times the memory capacity. By the late 1980's, the fastest Cray super-computers were only computing up to 13 million FLOPS per second [33] Today's supercomputers are rapidly approaching the necessary computation capabilities and storage volume capacities.

## Future Development

Whereas the cost of operational real-time analysis and wind tunnel research have continued to rise, the costs of computer analysis and simulation have consistently declined, due to advancements in technology. Computations that required a massive mainframe to perform are now being accomplished on the parallel processors in most personal desktop computers. Fully parallel neural network logic processors may hold the key to management of the large volumes of computations required to model the airwake. Incentives are also in progress to incorporate artificial technology programs to enhance software configuration control. It can be used to identify what parameters of the program are affected when an airframe configuration or environmental factor are adjusted.

The Secretary of Defense recently reported a priority shift in his acquisition strategy of the 1990's from production to development. The Office of the Secretary of Defense (OSD) directed all services to submit their Science and Technology (S&T) plans of action for incorporation into the 1994 Defense Budget [34]. With the funding reductions currently being felt in the military, it makes sense to fund the incentives with the greatest potential for advancements. The field of airwake analysis is such an incentive. Once the technology is achieved, the applications will be limited only by the imagination of the users. The benefits of this technology are expected to rival those gained during the development of the space industry.

# CHAPTER VII

## CONCLUSIONS AND RECOMMENDATIONS

Advancements in operational capabilities for rotary wing aircraft at sea rely heavily upon the advancements in the technologies associated with ship airwake analysis. The related technologies include the fields of ocean surface aerodynamics, bluff body turbulence, ship motion, helicopter motion, simulation, and computer technology. Testing encompasses wind tunnel analysis, helicopter flying qualities and performance evaluation, dynamic interface and computer analysis. Practical applications of the fields include expanded operational envelopes for launch/recovery and engagement/disengagement, more realistic training capabilities, improved ship and helicopter interface design features and safer operations. The ultimate result of those applications is increased combat readiness of our Battle Groups. Research applied to the solution of the ship airwake will also help to solve the full Navier/Stokes equations and unlock the doors to the design and technology of the next generations of aircraft.

The audience that fully appreciates the scope of ship airwake analysis is primarily technically oriented. In the past, insufficient priority has been placed on the various ship airwake research efforts, and there has been a lack of organized collation of the results of those efforts. In the coming decade of budget restrictions, military drawdown and defense project reprioritization, sponsors may sacrifice proper support for these initiatives in efforts to pursue "bigger ticket" programs. Understanding the airwake will allow optimized utilization of the assets we already have, as well as afford the best use of new assets.

Fourteen countries were represented at the AGARD symposium in 1991. Attendees represented all aspects of airwake analysis, including scientists, research engineers, dynamic interface test and evaluation personnel, designers, simulation experts, and military operators. This level of cooperation and organization is necessary to solve the problems and advance the technology. If any of these fields of research stagnate, the advancement of shipboard helicopter operations stagnates.

U.S. military representation at the AGARD symposium was minimal. Military presence in this field should be substantially increased. In order to effectively compete for declining available funds, management representatives in each of the diverse fields should unite and push NAVAIRSYSCOM to establish a separate Program Management Activity with senior military officer representation. Dynamic Interface department personnel at RWATD should have a military department head. That officer should be a dynamic interface experienced test pilot. Such presence would improve communication with other military organizations outside the test and evaluation world, as well as commands who control necessary assets and facilities who are not accustomed to dealing with Civil Service department personnel.

There is a great deal of information already gathered in these fields that can be immediately applied to shipboard flight operations, simulation improvement, and advancements in ship flight deck/helicopter interface design features. Dedicated military participation will better direct proper application of that material. Increased familiarity with this field will enable accurate user interpretation of contractor claims and provide great savings by preventing unnecessary testing. User involvement in the design phase will improve development of new products and eliminate mistakes that are often discovered later in operational testing.

The present restructuring of the Navy testing community is consolidating many of the teams in the diverse fields attacking various portions of the airwake problem. Research departments from Warminister, PA, Lakehurst, NJ, Indianapolis, IN, and possibly Orlando, FL, are being co-located at the NAWCAD facility at Patuxent River. Colocation will enable direct and convenient communication which will enhance interfacing between researchers. Now is the time to organize and implement military participation into the infrastructure.

Opportunity is knocking to significantly increase Naval Battle Group combat readiness and effectiveness through advancements that can be made in helicopter operation capabilities. Dedicated military support and participation in the field of airwake analysis will open the door for those advancements.

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# APPENDICES

# APPENDIX A
# SCALES AND CLASSIFICATIONS

# BEAUFORT SCALE
# WITH CORRESPONDING SEA STATE CODES

| Beaufort number | Wind speed: knots | Wind speed: mph | Wind speed: meters per second | Wind speed: km per hour | Seaman's term | World Meteorological Organization (1964) | Estimating wind speed: Effects observed at sea | Estimating wind speed: Effects observed on land | Hydrographic Office: Term and height of waves, in feet | Hydrographic Office: Code | World Meteorological Organization: Term and height of waves, in feet | World Meteorological Organization: Code |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | under 1 | under 1 | 0.0-0.2 | under 1 | Calm | Calm | Sea like mirror. | Calm; smoke rises vertically. | Calm, 0 | 0 | Calm, glassy, 0 | 0 |
| 1 | 1-3 | 1-3 | 0.3-1.5 | 1-5 | Light air | Light air | Ripples with appearance of scales; no foam crests. | Smoke drift indicates wind direction; vanes do not move. | Smooth, less than 1 | 1 | | |
| 2 | 4-6 | 4-7 | 1.6-3.3 | 6-11 | Light breeze | Light breeze | Small wavelets; crests of glassy appearance, not breaking. | Wind felt on face; leaves rustle; vanes begin to move. | Slight, 1-3 | 2 | Calm, rippled, 0-1/3 | 1 |
| 3 | 7-10 | 8-12 | 3.4-5.4 | 12-19 | Gentle breeze | Gentle breeze | Large wavelets; crests begin to break; scattered whitecaps. | Leaves, small twigs in constant motion; light flags extended. | Moderate, 3-5 | 3 | Smooth, wavelets, 1/3-1 2/3 | 2 |
| 4 | 11-16 | 13-18 | 5.5-7.9 | 20-28 | Moderate breeze | Moderate breeze | Small waves, becoming longer; numerous whitecaps. | Dust, leaves, and loose paper raised up; small branches move. | | | Slight, 2-4 | 3 |
| 5 | 17-21 | 19-24 | 8.0-10.7 | 29-38 | Fresh breeze | Fresh breeze | Moderate waves, taking longer form; many whitecaps; some spray. | Small trees in leaf begin to sway. | Rough, 5-8 | 4 | Moderate, 4-8 | 4 |
| 6 | 22-27 | 25-31 | 10.8-13.8 | 39-49 | Strong breeze | Strong breeze | Larger waves forming; whitecaps everywhere; more spray. | Larger branches of trees in motion; whistling heard in wires. | | | Rough, 8-13 | 5 |
| 7 | 28-33 | 32-38 | 13.9-17.1 | 50-61 | Moderate gale | Near gale | Sea heaps up; white foam from breaking waves begins to be blown in streaks. | Whole trees in motion; resistance felt in walking against wind. | | | | |
| 8 | 34-40 | 39-46 | 17.2-20.7 | 62-74 | Fresh gale | Gale | Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks. | Twigs and small branches broken off trees; progress generally impeded. | Very rough, 8-12 | 5 | Very rough, 13-20 | 6 |
| 9 | 41-47 | 47-54 | 20.8-24.4 | 75-88 | Strong gale | Strong gale | High waves; sea begins to roll; dense streaks of foam; spray may reduce visibility. | Slight structural damage occurs; slate blown from roofs. | High, 12-20 | 6 | | |
| 10 | 48-55 | 55-63 | 24.5-28.4 | 89-102 | Whole gale | Storm | Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced. | Seldom experienced on land; trees broken or uprooted; considerable structural damage occurs. | Very high, 20-40 | 7 | High, 20-30 | 7 |
| 11 | 56-63 | 64-72 | 28.5-32.6 | 103-117 | Storm | Violent storm | Exceptionally high waves; sea covered with white foam patches; visibility still more reduced. | | Mountainous, 40 and higher | 8 | Very high, 30-45 | 8 |
| 12<br>13<br>14<br>15<br>16<br>17 | 64-71<br>72-80<br>81-89<br>90-99<br>100-108<br>109-118 | 73-82<br>83-92<br>93-103<br>104-114<br>115-125<br>126-136 | 32.7-36.9<br>37.0-41.4<br>41.5-46.1<br>46.2-50.9<br>51.0-55.9<br>56.1-61.2 | 118-133<br>134-149<br>150-166<br>167-183<br>184-201<br>202-220 | Hurricane | Hurricane | Air filled with foam; sea completely white with driving spray; visibility greatly reduced. | Very rarely experienced on land; usually accompanied by widespread damage. | Confused | 9 | Phenomenal, over 45 | 9 |

## AVIATION FACILITY CERTIFICATION CATEGORIES FOR AIR CAPABLE SHIPS (HOSTAC RESUME)

| | |
|---|---|
| Level I, Class 1 | - Day and night IMC (Instrument Meteorological Conditions) landing facilities with service and organizational level maintenance. |
| Level I, Class 2 | - Day and night IMC landing facilities with full service but without maintenance facilities. |
| Level I, Class 2A | - Day and night IMC landing facilities with limited service but without maintenance facilities. |
| Level I, Class 3 | - Day and night IMC landing facilities without service and maintenance facilities. |
| Level I, Class 4 * | - Day and night IMC VERTREP/hover/facilities; hover height in excess of five feet. |
| Level I, Class 5 * | - Day and night IMC "high" VERTREP/hover/facilitie; hover height in excess of fifteen feet. |
| Level I, Class 6 | - Day and night IMC HIFR (Helicopter InFlight Refueling) facilities. |
| Level II, Class 1 | - Day and night VMC (Visual Meteorological Conditions) landing facilities with service and organizational level maintenance. |
| Level II, Class 2 | - Day and night VMC landing facilities with full service but without maintenance facilities. |
| Level II, Class 2A | - Day and night VMC landing facilities with limited service but without maintenance facilities. |
| Level II, Class 3 | - Day and night VMC landing facilities without service and maintenance facilities. |
| Level II, Class 4 * | - Day and night VMC VERTREP/hover facilities; hover height in excess of five feet. |
| Level II, Class 5 * | - Day and night VMC "high" VERTREP/hover facilities; hover height in excess of fifteen feet. |
| Level II, Class 6 | - Day and night VMC HIFR facilities. |
| Level III, Class 1 | - Day only VMC landing facilities with service and organizational level maintenance facilities. |
| Level III, Class 2 | - Day only VMC landing facilities with full service but without maintenance facilities. |
| Level III, Class 2A | - Day only VMC landing facilities with limited service but without maintenance facilities. |
| Level III, Class 3 | - Day only VMC landing facilities without service and maintenance facilities. |
| Level III, Class 4 * | - Day only VMC VERTREP/hover facilities; hover height in excess of five feet. |
| Level III, Class 5 | - Day only VMC "high" VERTREP/hover facilities; hover height in excess of fifteen feet. |
| Level III, Class 6 | - Day only VMC HIFR facilities. |

* There are three types of VERTREP/hover areas detailed in section 12.2 of HOSTAC RESUME

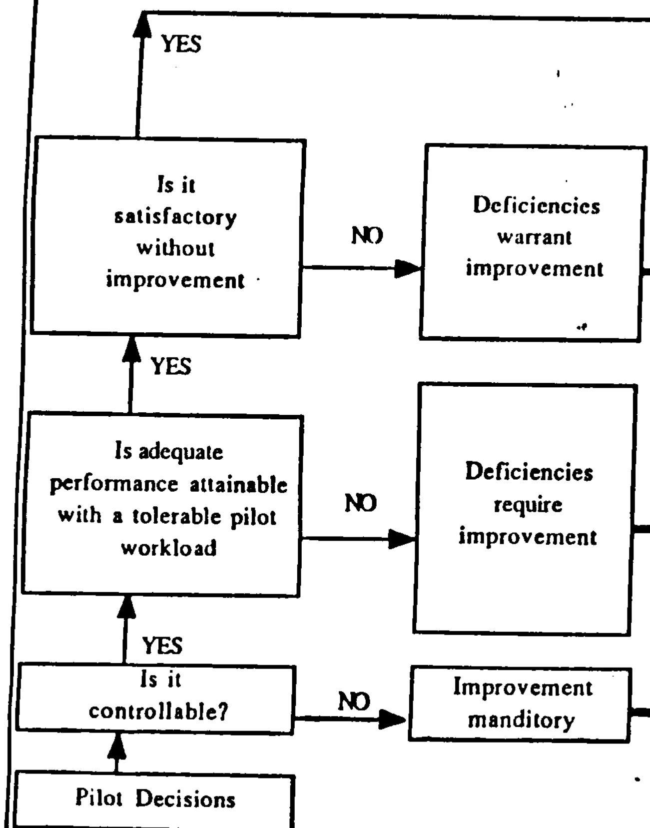
Type 1 - Minimum VERTREP/hover area

Type 2 / Special Type 2 - VERTREP/hover area (exceeding minimum requirements) with cargo staging/drop zone aft

Type 3 - VERTREP/hover area (exceeding minimum requirements) with cargo staging/drop zone at center

# COOPER-HARPER HANDLING QUALITIES RATING SCALE

Adequacy for Selected Task or Required Operation*




| Aircraft Characteristics | Demands on the Pilot In Selected Task or Required Operation* | Pilot Rating |
|---|---|---|
| Excellent Highly desirable | Pilot compensation not a factor for desired performance | 1 |
| Good Negligible deficiencies | Pilot compensation not a factor for desired performance | 2 |
| Fair Some mildly unpleasant deficiencies | Minimal pilot compensation required for desired performance | 3 |
| Minor but annoying deficiencies | Desired performance requires moderate pilot compensation | 4 |
| Moderately objectionable deficiencies | Adequate performance requires considerable pilot compensation | 5 |
| Very objectionable but tolerable deficiencies | Adequate performance requires extensive pilot compensation | 6 |
| Major deficiencies | Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question | 7 |
| Major deficiencies | Considerable pilot compensation is required for control | 8 |
| Major deficiencies | Intense pilot compensation is required to retain control | 9 |
| Major deficiencies | Control will be lost during some portion of required operation | 10 |

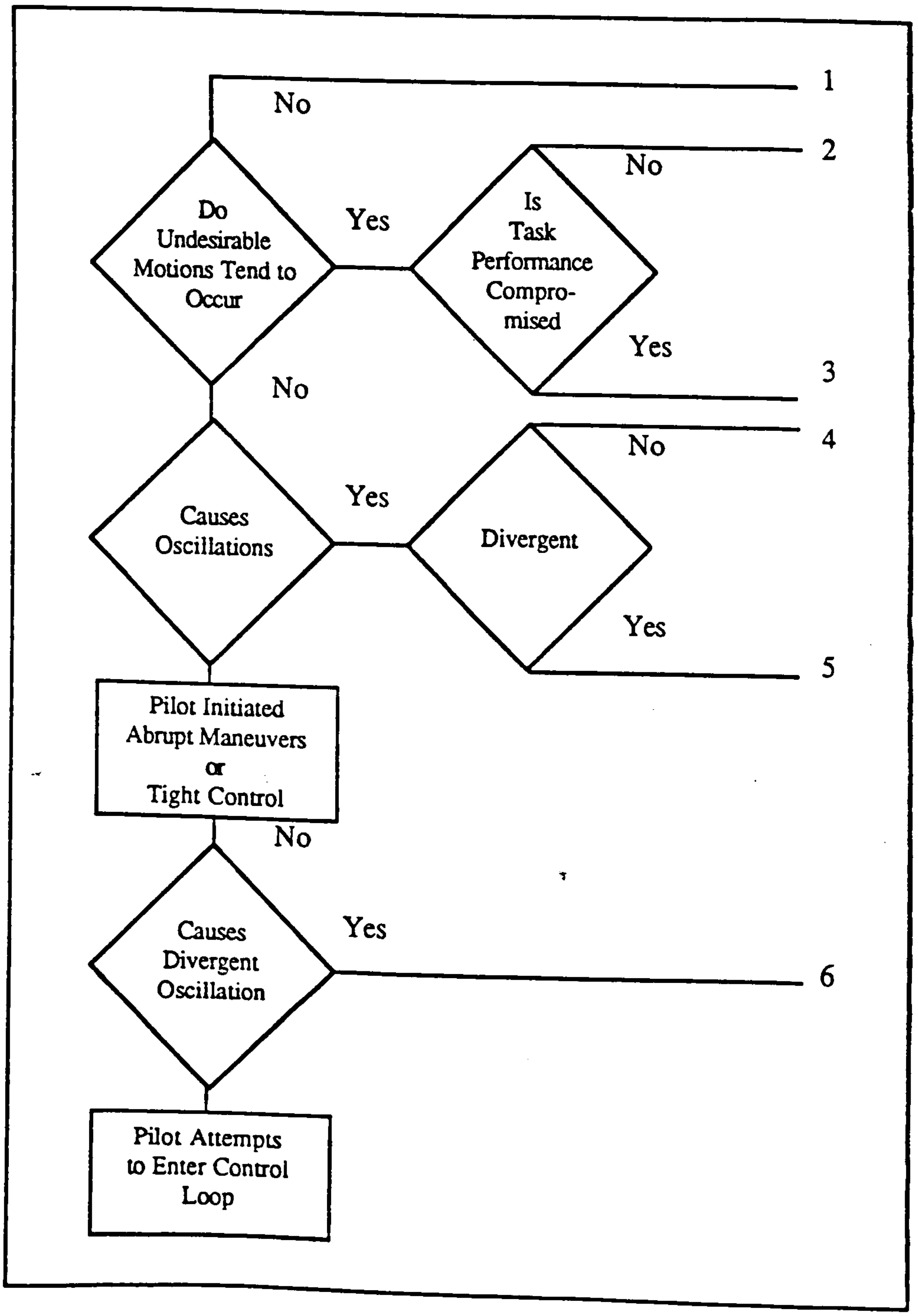
* Definition of required operation involves designation of flight phases and/or subphases with accompanying conditions

## VIBRATION ASSESSMENT RATING SCALE

| Degree of Vibration | Description (1) | Pilot Rating |
|---|---|---|
| No Vibration | | 0 |
| | Not apparent to experienced aircrew fully occupied by their tasks, but | 1 |
| Slight | noticeable if their attention is directed | 2 |
| | to it or if not otherwise occupied | 3 |
| | Experienced aircrew are aware of the | 4 |
| Moderate | vibration, but it does not affect their | 5 |
| | work, at least over a short period | 6 |
| | Vibration is immediately apparent to experienced aircrew even when fully | 7 |
| Severe | occupied. Performance of primary task is affected or tasks can only be | 8 |
| | done with difficulty. | 9 |
| Intolerable | Sole preoccupation of aircrew is to reduce vibration level. | 10 |

Note (1): Based upon the subjective vibration assessment scale developed by the Aeroplane and Armament Experimental Establishment, Boscombe Down, England.

# PILOT INDUCED OSCILLATION (PIO)
# RATING SCALE



# TURBULENCE RATING SCALE

| INTENSITY | AIRCRAFT REACTION | REACTION INSIDE AIRCRAFT |
|---|---|---|
| LIGHT | | |
| Turbulence | Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude. | Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encounter in walking |
| Chop | Turbulence that causes slight, rapid and somewhat appreciable changes in altitude or attitude | |
| MODERATE | | |
| Turbulence | Turbulence that causes changes in altitude and/or attitude, but with the aircraft remaining in positive control at all times. It usually causes variations in indicated airspeed. | Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult. |
| Chop | Turbulence that causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude. | |
| SEVERE | | |
| Turbulence | Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control | Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible. |
| EXTREME | | |
| Turbulence | Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. | |

| FREQUENCY | DEFINITION |
|---|---|
| Occasional | Less than 1/3 of the time |
| Intermittent | 1/3 to 2/3 of the time |
| Continuous | More than 2/3 of the time |

# APPENDIX B

# DATA

| | | | |
|---|---|---|---|
| Weather | | | Card No.<br>PTR BIS |
| Aircraft Type | BuNo. | Takeoff<br>Land | Date |
| Pilots | | T/O CG | |
| Cond | | | Gross Weight |
| External Config | | | |
| Remarks | | | |

| Event No | APPR | Wfuel | PRS | Qmax | Qavg | $\delta$lat | $\delta$ped | Rmks |
|---|---|---|---|---|---|---|---|---|
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**DYNAMIC INTERFACE ENVELOPE EXPANSION DATA CARD**

Month/Year:______________ Ship Hull Number/Name:______________

Acft BuNo/Side No:__________________ DCC 61: Y / N

Acft BuNo/Side No:__________________ DCC 61: Y / N

| DATE | SIDE NO | ENGAGE OR DISENGAGE ? | RELATIVE WIND SPD/DIR (REL TO SHIP CL) | HELO LINEUP (0-360 DEG) REL TO SHIP CL | DIST (FT) FROM NOSEWHEEL TO CENTER OF SPOT | SHIP MANEUVER REQUIRED? | HELO RESPOT REQUIRED? | SEA STATE | SHIP SPEED (KT) | MAX SHIP PITCH/ROLL DURING E/D | PRE-ENGAGE STATIC TIP FLAP (IN/FT) | MIN BLADE/ TUNNEL CLRNCE (AT TUNNEL) | LOCN/HT OF ANY BLADE FLAPPING LOWER THAN TUNNEL | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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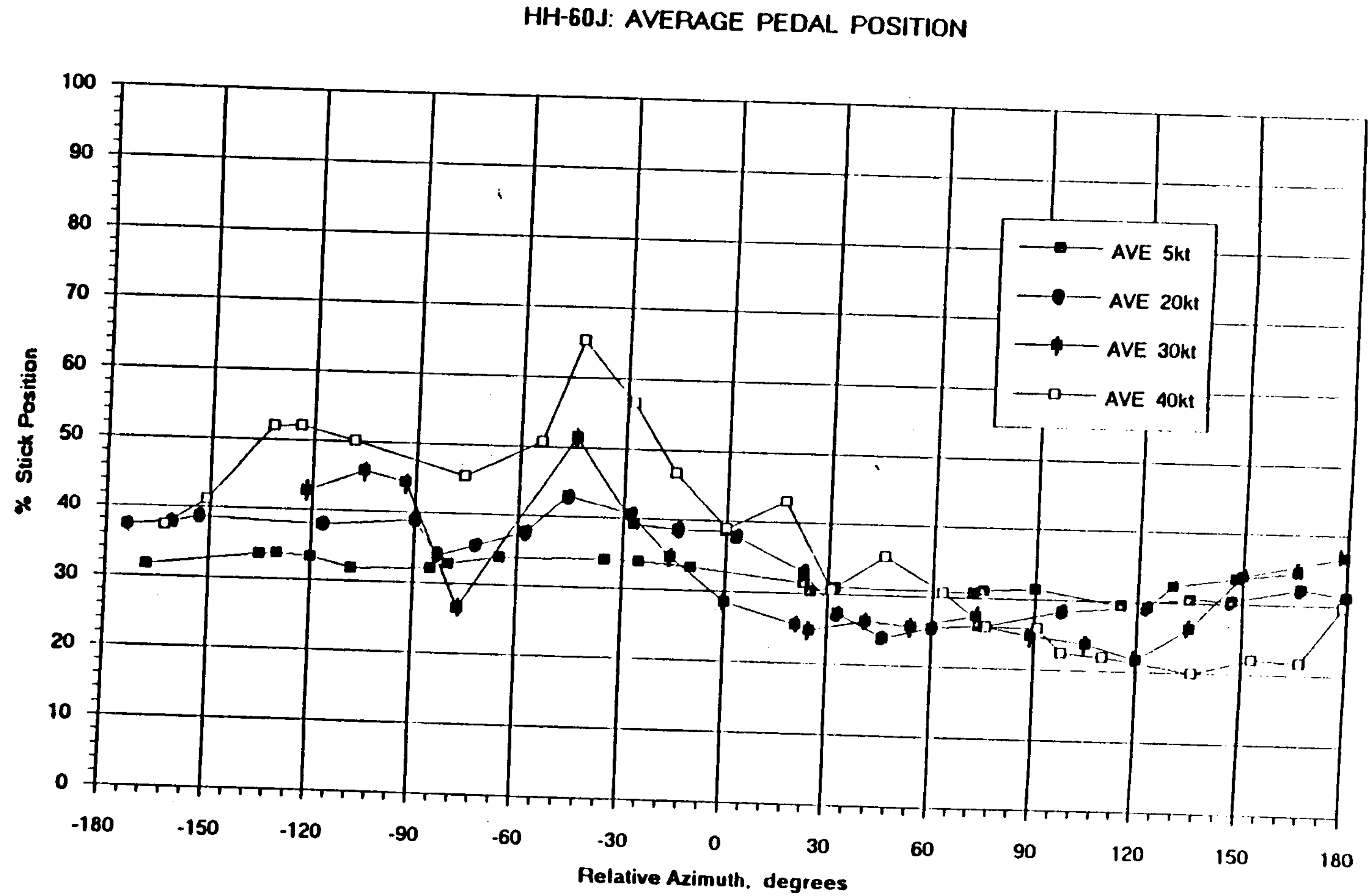
Please Return Completed Form to: Commander, Naval Air Test Center, Patuxent River, MD 20670 Attn: Mr. [illegible] Long (RW4[illegible])
Tel A/V 326 1336; Fax A/V 326-1140

## ENGAGE/DISENGAGE DATA CARD

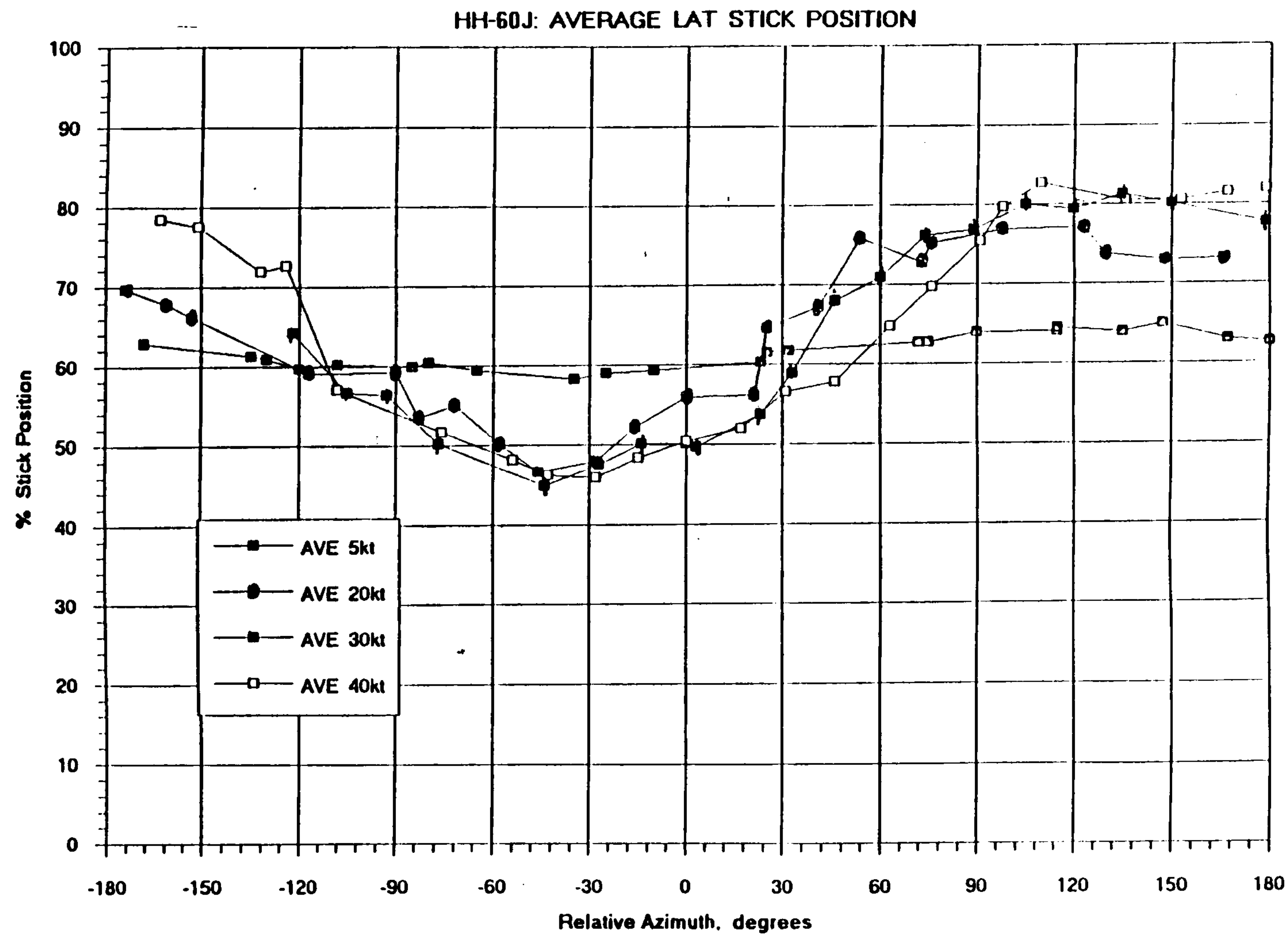
| | | | |
|---|---|---|---|
| Helicopter Type/Model /Series | | Side Number | |
| Pilot / Copilot | Date | T/O Time | Land Time |
| **Weather** | | OAT | Hp |
| Other: | | | |
| **Loading Conditions** | 0 Fuel GW | T/O Fuel GW | Land Fuel GW |
| | 0 Fuel CG | 0 Fuel CG | Land Fuel CG |
| **External Configuration** | | | |
| | | | |
| Special Instrumentation | | | |
| | | | |
| Changes since last Flight | | | |
| | | | |
| Purpose/Results | | | |

**DAILY FLIGHT REPORT**




Notes: Std Config, Avg Gr. Wt. 20,500 lbs, Avg CG, Std Day, Sea State 2, CGN Class, AFCS ON.

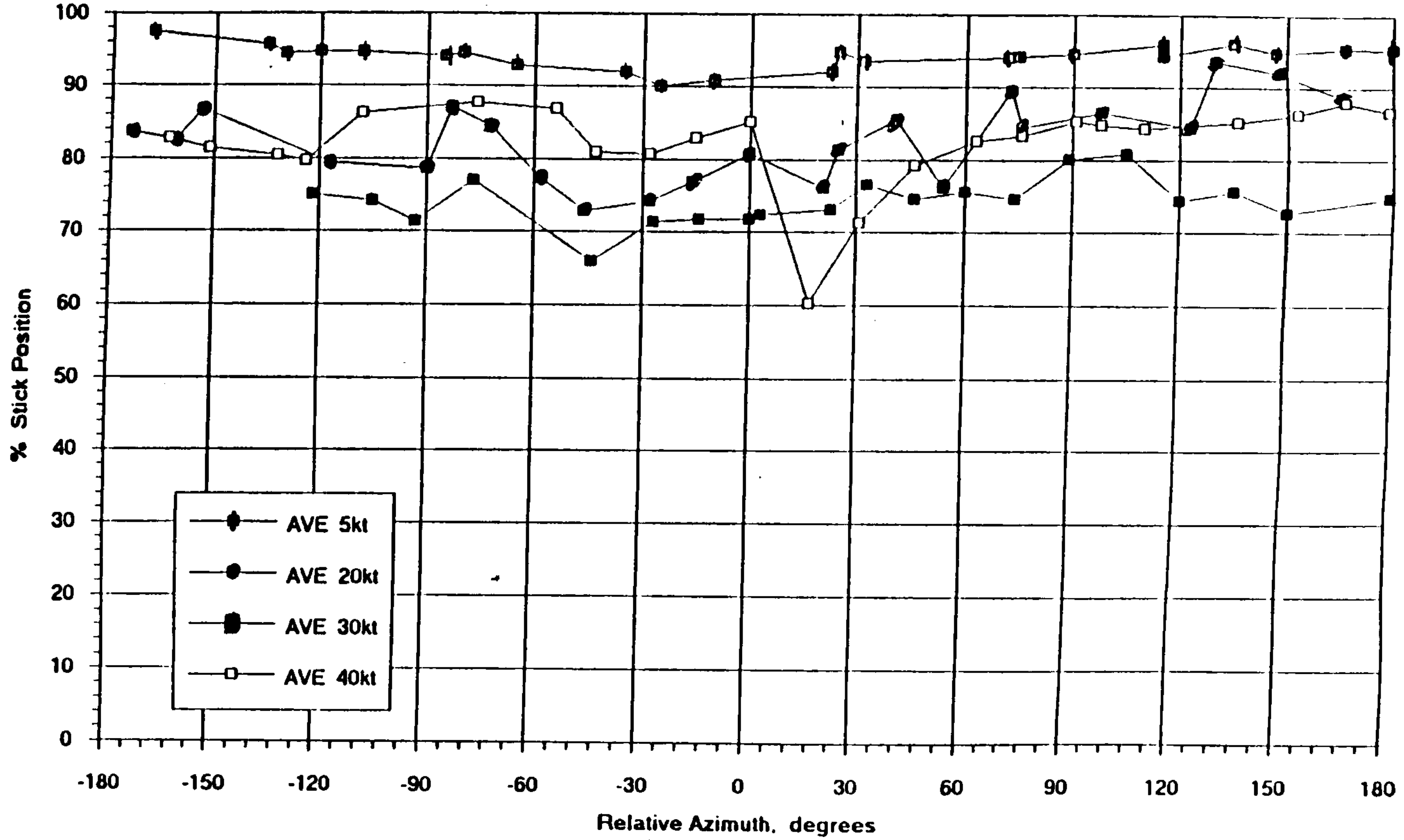
**TRIMMED PEDAL POSITION**




Notes: Std Config, Avg Gr. Wt. 20,500 lbs, Avg CG, Std Day, Sea State 2, CGN Class, AFCS ON.

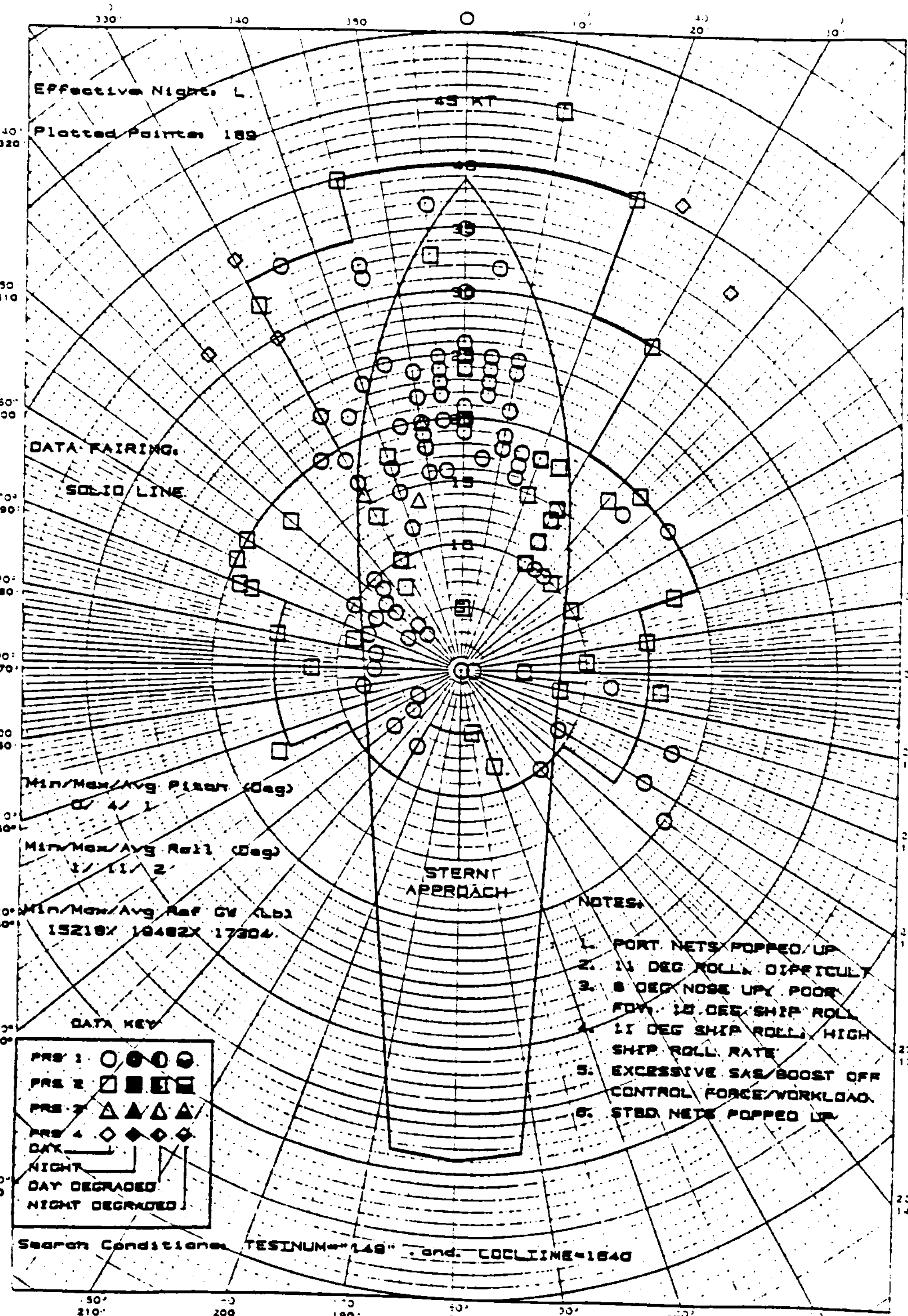
TRIMMED LATERAL CYCLIC POSITION

HH-60J: AVERAGE TORQUE POSITION



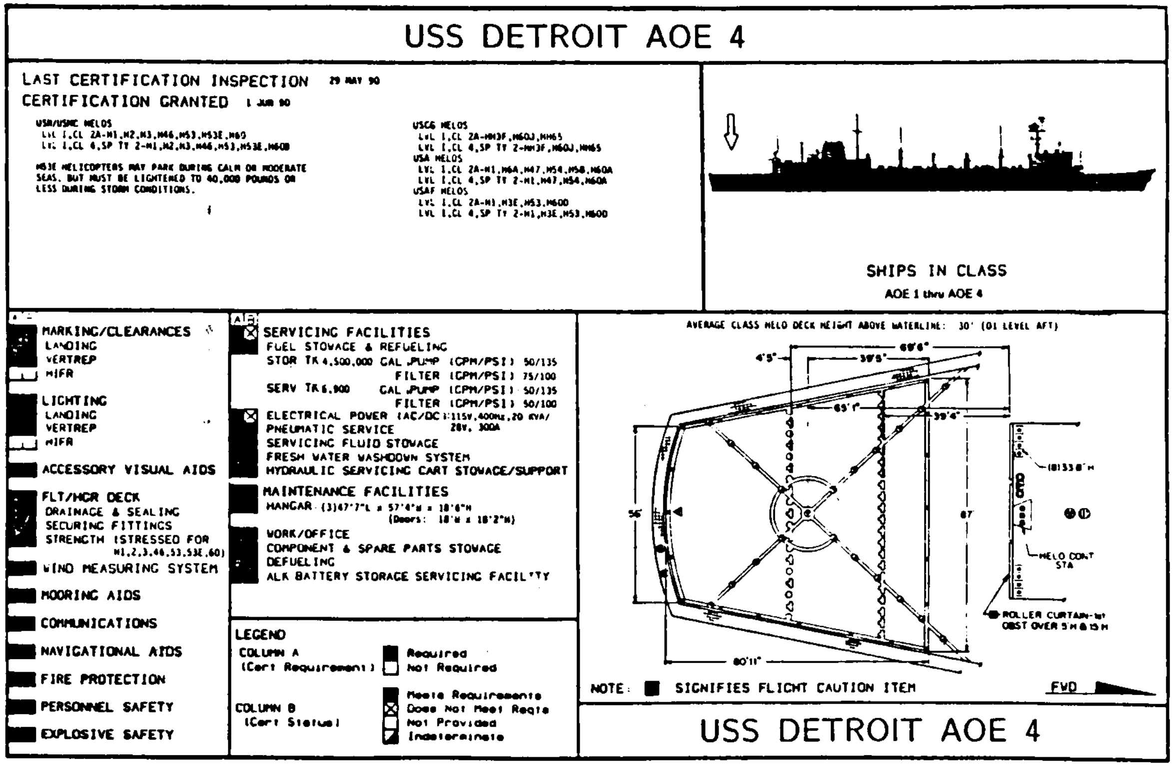

Notes: Std Config, Avg Gr. Wt. 20,500 lbs, Avg CG, Std Day, Sea State 2, CGN Class, AFCS ON.

AVERAGE HOVER-OUT-OF-GROUND-EFFECT TORQUE

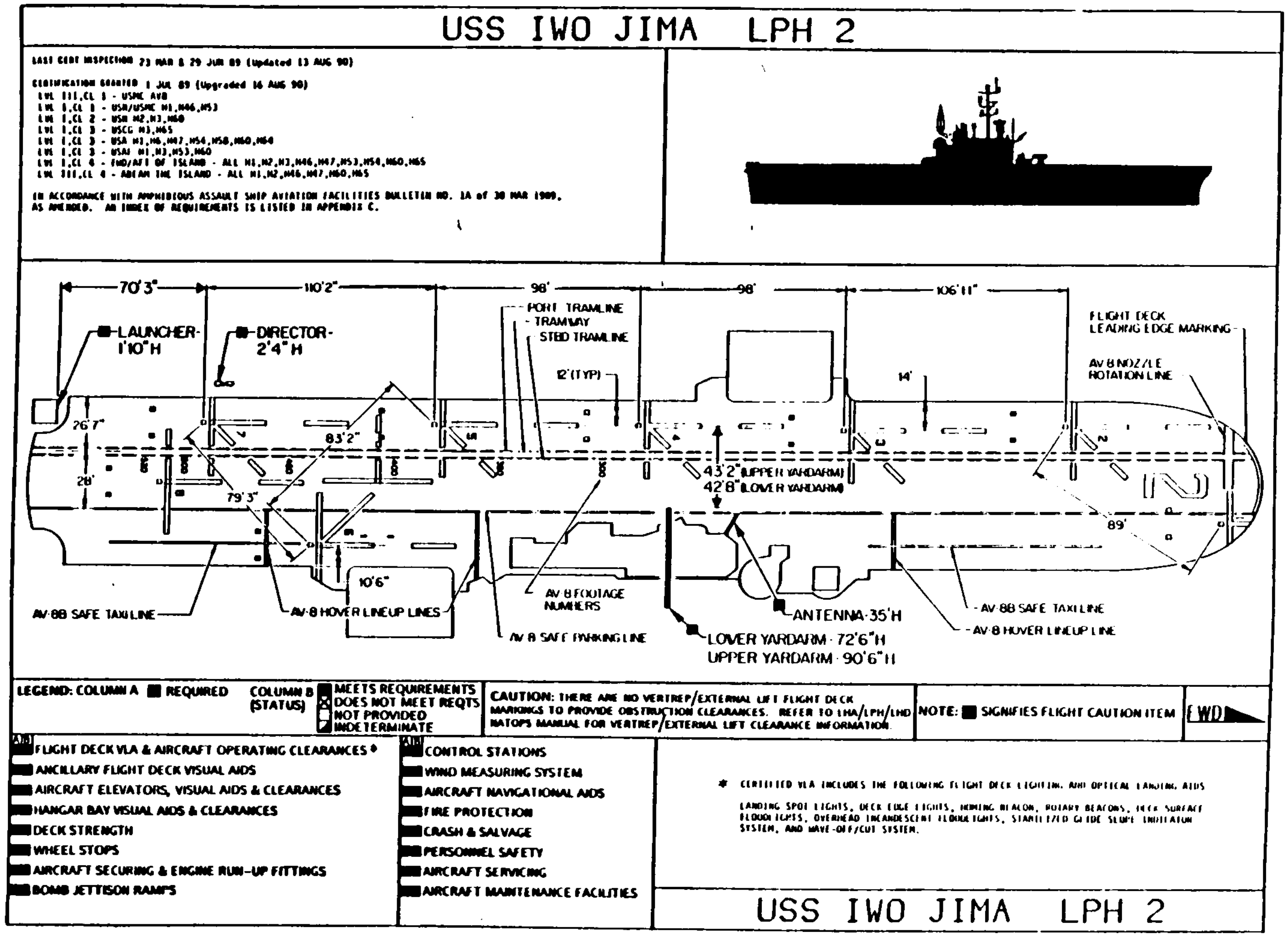



**DYNAMIC INTERFACE OPERATIONAL WIND ENVELOPE EXPANSION PRS POLAR PLOT**

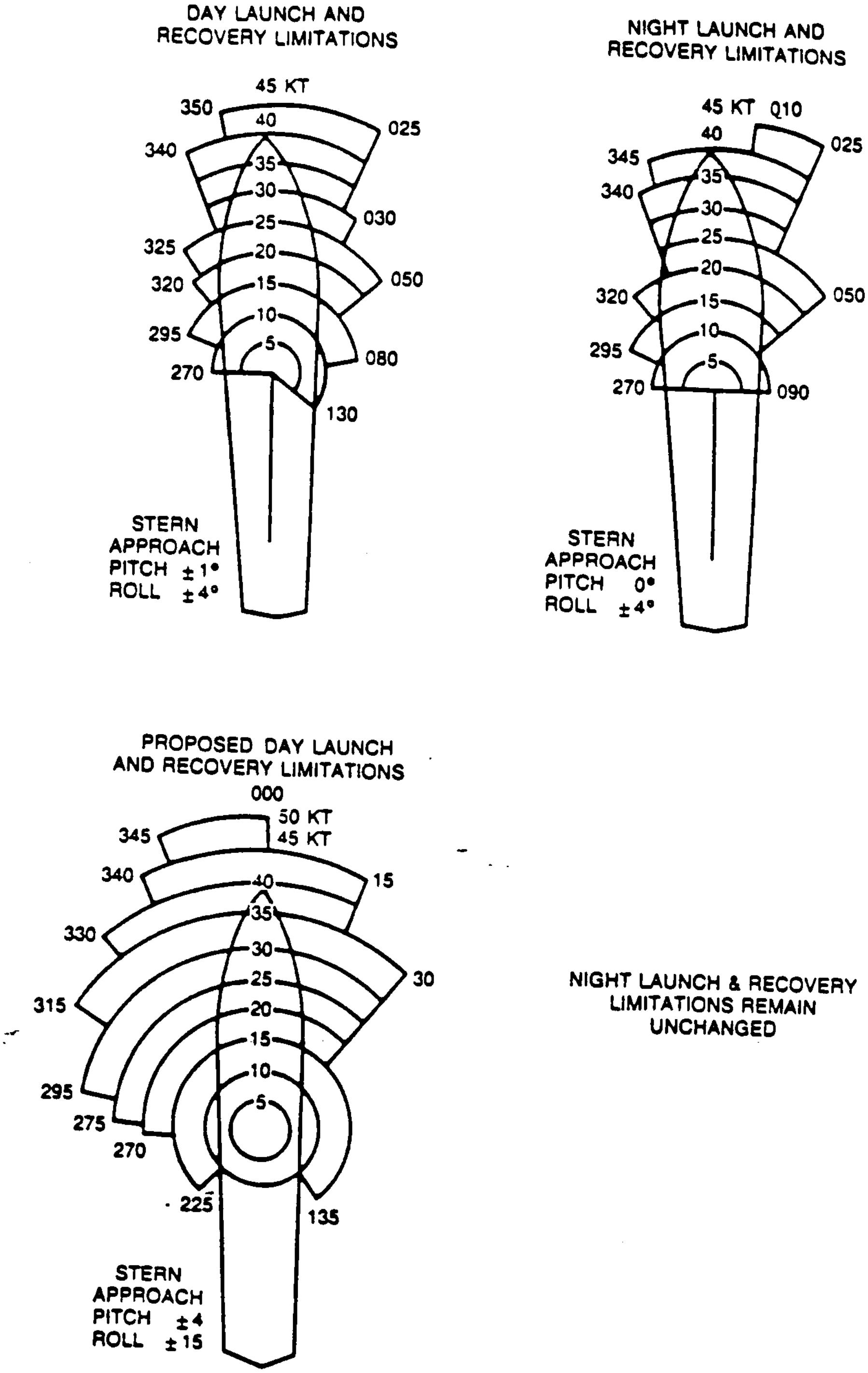
# APPENDIX C
# OPERATIONAL DIAGRAMS




**SAMPLE SINGLE-SPOT SHIP FLIGHT DECK**
**(HOSTAC RESUME)**




**SAMPLE MULTI-SPOT SHIP FLIGHT DECK**
**(HOSTAC RESUME)**




SAMPLE WIND ENVELOPE EXPANSION PROPOSAL

## SINGLE-CIRCLE AIR-CAPABLE SHIPS

| SHIP | OPERATING AREA ② | SINGLE SHIP OR CLASS | OPERATING LEVEL | LANDING HELICOPTER ① | | | | | | | | | | | | | | | VERTREP TYPE | VERTREP HELICOPTER ① | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | UH1 | SH2 | HH3 | SH3 | OH6 | CH46 | CH47 | HH53 | CH53E | CH54 | OH58 | SH60 | UH60 | AH64 | HH65 | | H1 | H2 | H3 | H46 | H47 | H53 | H53E | H54 | H60 | H65 |
| AD 15 | AL | C | III | | X | | | X | | | | | | | | | | X | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AD 18 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AD 19 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 4 |
| AD 37 | AL | C | II | X | X | X | X | X | 6 | | | | | X | X | X | | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AD 41 | AL | C | II | X | X | X | X | X | 6 | | | | | X | X | X | | X | 2 | 4 | 4 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 4 |
| AE 21 | AL | C | II | X | X | X | X | X | | | | | | X | X | X | X | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AE 23 | AL | C | II | X | X | X | X | X | X | | | | | X | X | X | X | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AE 27 | AL | C | I | X | X | X | X | X | 6 | | | | | X | X | X | X | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AFS 1 | AL | C | I | X | X | X | X | X | X | | | | | X | X | X | X | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AFG 3 | AL | S | I | X | X | X | X | X | X | | X | | 6 | X | X | X | X | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AO 98 | FV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AO 177 | AL | C | III | X | X | X | X | X | 6 | | 6 | 6 | 6 | X | | | | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AOE 1 | AL | C | I | X | X | X | X | X | 6 | | | | | X | X | X | | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AOE 4 | AL | S | I | X | X | X | X | X | X | X | 6 | 6 | 6 | X | X | X | | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AOR 1 | AL | C | I | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| AR 5 | AV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| ARS 8 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| ARS 38 | AV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| ARS 50 | AV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 5 | 4 | 5 | | | | 5 | 4 |
| AS 11 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| AS 18 | AV | S | III | | | | | | | | | | | | | | | | 2 | 5 | 5 | 5 | 5 | 5 | | | | 5 | 5 |
| AS 19 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| AS 31 | AV | C | III | | | | | | | | | | | | | | | | 2 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| AS 33 | AV | C | III | | | | | | | | | | | | | | | | 2 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| AS 36 | AV | C | III | | | | | | | | | | | | | | | | 2 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 |
| AS 39 | AV | C | III | | | | | | | | | | | | | | | | 2 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 |
| ASR 21 | AL | C | III | X | X | | | X | | | | | | X | | | | X | 2 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| ATF 159 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| ATF 160 | AV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| ATS 1 | AV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| BB 61 | AL | C | I | X | X | X | X | X | 6 | | 6 | 6 | 6 | X | X | | | X | SP2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| CG 16 | AV | C | III | | | | | | | | | | | | | | | | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | FV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| CG 21 | AL | S | I | X | X | | X | X | | | | | | X | X | | | | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | FV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| CG 26 | AL | S | I | X | X | | X | X | | | | | | X | X | | | X | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| | FV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 5 | 4 | 4 | 5 | 5 | 5 | 4 | 4 |
| CG 27 | AL | C | I | X | X | | | X | | | | | | X | | | | X | 1 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| | FV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| CG 47③ | AL | C | I | X | X | X | X | X | 6 | | 6 | | | X | X | | | X | 2 | 4 | 4 | 4 | 4 | 4 | | | | 4 | 4 |
| | AV | C | I | | | | | | | | | | | | | | | | 1 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | FV | C | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| CGN 9 | AL | S | I | X | X | X | X | X | 6 | | | | | X | X | | | X | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| CGN 25 | AL | S | I | | X | | X | X | | | | | | | | | | X | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | FV | S | III | | | | | | | | | | | | | | | | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 |

SAMPLE SHIP/AIRCRAFT INTERFACE MATRIX
(NWP-42)

# VITA

## VITA

Dean Wm Meyer was born in Quincy, Massachusetts, on January 22, 1958. He grew up on the Space Coast of Florida, attending schools at Patrick Air Force Base and Satellite Beach. His father's involvement in the Space Program at NASA and the engineering influence of the community inspired him to seek an engineering degree. He entered college on a Navy ROTC scholarship and completed an undergraduate degree in Mechanical Engineering at Georgia Tech. In the Spring of 1980, he began Naval flight training in Pensacola. That training culminated in the Summer of 1981, with the receipt of Naval Aviator Wings in the unrestricted aviation field of helicopter flying. Following two operational tours flying the H-46 in logistics and combat support, including the precision seat-of-the-pants mission of vertical replenishment, he transitioned to flying the venerable Huey for Search and Rescue support of operations on the U.S.S. Iwo Jima. In 1989 he was selected to participate in the United States Naval Test Pilot School training program. Following gruaduation and designation as a Test Pilot, he began a tour of service at the Rotary Wing Aircraft Test Directorate. During this tour he became involved in the world of Dynamic Interface, which inspired and supported completion of his degree of Master of Science in Aviation Systems at the University of Tennessee, Knoxville.