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Low airspeed systems for the naval SH-60 Seahawk aircraft

James Joseph Maune

To the Graduate Council:

I am submitting herewith a thesis written by James Joseph Maune entitled "Low airspeed systems for the naval SH-60 Seahawk aircraft." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

R. B. Richards, Major Professor

We have read this thesis and recommend its acceptance:

Fred Stellar, U. Peter Solies

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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LOW AIRSPEED SYSTEMS

FOR THE

NAVAL

SH-60 SEAHAWK AIRCRAFT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James Joseph Maune

May 2001

DEDICATION

This Thesis is dedicated to my wife Gina and parents James and Audrey Maune. Their untiring devotion, limitless patience, sacrifice and gentle persuasion have always pushed me back on the path I originally intended. I owe every personal achievement and professional success to them.

ABSTRACT

Pitot-static systems have long been used to measure helicopter airspeed. The Pitot-static system is inaccurate at low airspeeds (below 40 knots) due to the limited sensitivity of the sensor and interference of rotor down wash. Additionally, the Pitot-static system only measures unidirectional airspeed and unlike its fixed wing counterparts the helicopter is not limited to flight in one direction. With the changing roles of the US Navy Seahawk it is imperative that the pilot and aircrew have all the information necessary to safely complete the mission and prolong the life of the aircraft and dynamic components. With the addition of a dipping sonar to the remanufactured SH-60B aircraft (designated SH-60R) and the conduct of combat search and rescue mission in the Navy's Seahawks the aircraft will spend more time in a hover and will be flown more aggressively than in the past. This thesis examiness the advantages of incorporating a low airspeed system into the modern helicopter, in particular the SH-60 Seahawk. The author examines the low airspeed sensors and systems currently available and gives a brief description of each system's operation. The author examines the challenges of installing a low airspeed sensor onto the SH-60 Seahawk. The author has determined that either a laser velocimeter or an analytical neural network system would be the best approach for a low airspeed system for the SH-60 Seahawk. The author recommends a combined approach be taken to develop both the laser velocimeter and analytical neural network, and incorporate the best system after further flight testing.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND NOMENCLATURE

AADS	Airspeed and Directional Sensor
AFCS	Automatic Flight Control System
ALMDS	Airborne Laser Mine Detection System
ATO	Airborne Tactical Officer
AMCM	Anti-Mine Counter Measures
AOA	Angle of Attack
APU	Auxiliary Power Unit
ASU	Anti-Surface Warfare
CAS	Calibrated Airspeed
CFIT	Controlled Flight into Terrain
COMREL	Communications Relay
CRT	Cathode Ray Tube
CSAR	Combat Search and Rescue
d	diameter of obstruction
DELTA	Digital Electronic Low True Airspeed
DSP	Digital Signal Processor
DTIC	Defense Technical Information Center
DTU	Data Transfer Unit
EAMED	Eventide Airborne Multipurpose Electronic Display
EMCON	Emissions Control
EMI	Electromagnetic Interference
EPU	Electronic Processor Unit

ESM	Electronic Surveillance Measures
F	Frequency of vortex formation
FOV	Field of View
fps	feet per second
FRS	Fleet Replacement Squadron
GBS	Ground Based System
GPS	Global Positioning System
HADS	Helicopter Air Data System
HIFR	Helicopter In-flight Refueling
HIADC	Helicopter Integrated Air Data Computer
HUMS	Health Usage Monitoring System
IDW	In Downwash
IFR	Instrument Flight Rules
IMD	Integrated Maintenance Diagnostics
IMC	Instrument Meteorological Conditions
ISAR	Inverse Synthetic Aperture Radar
ISD	Integrated Self Defense
kt	knot (1 nautical mile per hour)
ktas	knot true air speed
lb	pound (force)
LBA	limits of the basic aircraft
LIDAR	Laser radar
LTE	Loss of Tail Rotor Effectiveness

MEDEVAC	Medical Evacuation
MIO	Maritime Interception Operation
MMR	Multi-Mode Radar
N	Newton (metric unit for force- forcer which imparts to a mass of one kilogram mass an acceleration of one meter per second)
NAVAIR	Naval Air Systems Command
NEO	Non-combatant Evacuation Operation
nm	nautical mile
NATOPS	Naval Air Training & Operation Procedure Standards
NSWS	Naval Special Warfare Support
NVD	Night Vision Device
OADS	Omnidirectional Air Data Systems
OAI	Omnidirectional Air Speed
OASIS	Organic Surface Influence Sweep
OBS	On Board System
ODW	Out of Downwash
OEI	One Engine Inoperative
OGE	Out of Ground Effect
Ω	rotational speed (radians per second)
ONR	Office of Naval Research
ORD	Operational Requirements Document
OTH	Over the Horizon
p	pressure (pounds per square foot (psi))

ρ	air density
ρ_0	air density sea level standard
q	dynamic pressure
r_d	dynamic range
RMS	Root Mean Square
S	Strouhal number
SAR	Search and Rescue
SBIR	Small Business Innovative Research
shp	shaft horsepower
SO	Sensor Operator
SOM	Self Organizing Map
TAS	True Airspeed
UAV	Unmanned Aerial Vehicles
UUV	Unmanned Undersea Vehicle
URY	Unanticipated Right Yaw
US	United States
USS	United States Naval Vessel description (ex. USS CROMMELIN)
USW	Undersea Warfare
v	flow velocity (feet per second)
VBSS	Visit Board Search and Seizure
VERTREP	Vertical Replenishment
VMC	Visual Meteorological Conditions
VRS	Vortex Ring State

INTRODUCTION

Modern naval helicopters use traditional Pitot-static systems to measure airspeed. Pitot-static systems are inaccurate at low airspeeds (below 40 knots), due to pressure fluctuations from main rotor down wash and sensitivity of the Pitot-tube. SH-60 helicopter pilots currently have no instrument capable of measuring and displaying the helicopter's speed in the air mass below 40 knots. In the absence of visual cues (such as at night or during restricted visibility), an inadequate airspeed reference can result in loss of situational awareness by the pilot which can result in loss of aircraft and aircrew. Some initial research was conducted on low range airspeed sensors in the late 1960's and early 1970's but their incorporation was never made a requirement for the SH-60 helicopter. Those low range airspeed systems that were incorporated into helicopters were mainly used for correcting for winds for unguided rockets and primitive autopilot systems. Those systems did not take advantage of the improved situational awareness in power management and flying qualities a cockpit display of low airspeed would provide. This thesis justifies the incorporation of a low airspeed system into the SH-60 Seahawk, lists some requirements of a low airspeed system, and conducts an analysis of current low range airspeed systems and recommends an approach to be taken.

Information found in this thesis was collected from a wide variety of sources. Technical reports and industry proposals were available to the author from the Naval Air Systems Command (NAVAIR), the aviation system acquisition organization of the United States Navy. The author spoke with many of the experienced engineers and they shared some of their extensive personal libraries of reports and articles on the subject. What information was not locally available was provided by the Defense Technical Information Center (DTIC) which catalogues and collects technical reports specifically for later use and reference. Many of these technical reports provided very necessary information about a system's development from proposal to implementation.

Information on helicopter air data systems and Pitot-static systems was available from a variety of academic textbooks and flight test manuals. Finally, the author's experience with naval aviation as a designated helicopter pilot provides the fourth general source of information on which this thesis is based.

This thesis is organized in five Parts. In Part I, the author justifies the requirements and discusses the benefits of a low airspeed sensor. It examines the reasons why the currently used Pitot-static system is inadequate and numerous potential uses for a low airspeed system. The author defines some requirements for a low airspeed sensor since there currently exists no formal requirements in any SH-60 Operational Requirements Documents (ORD) [Ref 1, 2, 3, 4]

In Part II, the author discusses the various different low airspeed systems he discovered as part of his research. He describes the basic principles of operation for each system, the accuracies achieved through flight test data (where available), and the strengths and weaknesses of each system. Due to the data of some of the more modern systems being proprietary, the discussions of those systems are limited to what was permitted to be published by the contractor.

Part III includes a basic description of the SH-60 series aircraft and their basic missions. The author describes how a low airspeed sensor would benefit pilots of these particular military helicopters. It also discusses the particular problems in installing such a system on said helicopters.

In Part IV, the author conducts an analysis of six particular low airspeed systems (PACER LORAS, TAO Systems DELTA, BAE Systems HADS, an analytical approach, Honeywell's LIDAR and Optical Air Data systems laser velocimeter).

In Part V, the author concludes on which system would be the most appropriate for the SH-60 helicopter and recommends its incorporation. He also makes some recommendations on the future research and development of low airspeed systems in general.

PART I

REQUIREMENTS AND JUSTIFICATION FOR

LOW AIRSPEED SENSOR

IN NAVAL HELICOPTERS

1.0 GENERAL

Since the earliest days of helicopter aviation Pitot-static instruments have been used for the determination of airspeed. From the beginning there were obvious limitations to their use such as the inherent unidirectional nature, the inability to accurately measure airspeed below 40 knots, and the undesirable influence of pressure fluctuations due to rotor down wash. But despite inherent limitations the Pitot-static system has been the standard for helicopter airspeed measuring devices. Early helicopters were often limited to day visual meteorological flight conditions (VMC) and the helicopter pilot learned to adapt by estimating airspeed and direction from visual cues. In fact, pilots learn how to hover over a spot from using these visual cues and adjusting the flight controls to minimize movement. The more experienced the helicopter pilot, the more he uses his other senses (inertial cues, noise) to augment his visual cues to hover. But despite all his experience, it is difficult to maintain a hover with no visual references (at night or during Instrument Meteorological Conditions (IMC)). Modern helicopter pilots rely on instrumentation and automatic flight control systems to augment human sensory inputs to safely hover the aircraft. Because the Pitot-static system provides no information on helicopter drift in a hover, helicopter designers needed a device to inform the pilot of this movement during conditions of reduced visual reference. Doppler radar has been used as the source of input to provide the pilot ground speed information. Multiple beam Doppler systems can measure drift in all three axes. A limitation to Doppler radar is the lack of returned energy from a low sea state such that Doppler shift can not be adequately measured. In more modern helicopters, these systems are being replaced by Inertial Navigation Systems (INS) and Global Positioning System (GPS) and often combination systems.

The most important reason for incorporation of a low airspeed system is to improve safety by increasing pilot situational awareness. The basis of this thesis is that a low airspeed system should be a requirement in SH-60 naval helicopters. Its incorporation will require a paradigm shift in the helicopter community. Helicopters fundamentally differ from fixed wing airplanes and require devices unique to their operational environment. Accepting an inadequate instrument to measure airspeed and direction during low airspeed operations increases risk and inhibits the helicopter pilot from ever fully learning the helicopter's low speed characteristics and apply proper power management techniques. The low airspeed sensor can be compared to the Angle of Attack (AOA) gauge used on carrier aircraft and on airliners. Once limited for use on relatively few aircraft, through years of experience they have proven their worth and have become the standard gauge for aircraft carrier approaches. Today one will not find a carrier qualified aircraft without one. The impact of current Pitot-static systems on safety of flight was first officially recognized by a Helicopter Operations Study conducted by Commander Military Airlift Command, US Air Force (Ref. 5) which recommended that an airspeed indicator specifically designed for helicopters be qualified and procured. A properly installed low airspeed sensor with helicopter pilots trained in the techniques of power management would provide the benefits of improved situational awareness and increased safety. The installation of a low airspeed system would improve safety, save lives and aircraft.

Modern naval helicopters like the SH-60B Seahawk, SH-60F and HH-60H all have missions that would benefit from a low airspeed system. All Seahawk models have Search and Rescue (SAR) as a primary or secondary mission. The aircraft has the requirement to perform this mission at night or during instrument meteorological conditions. The rescue portion often requires the helicopter to remain in a hover for prolonged periods of time to effect the rescue. During Maritime Interception Operations (MIO) (such as those missions performed on a daily basis in the Arabian Gulf) and Visit Board Search and Seizure (VBSS) operations the helicopter crew is required to orbit the merchant ship being boarded at low speed or hover for prolonged periods to observe and ensure the safety of the boarding party. The helicopter may be required to perform combat maneuvering for Combat SAR (CSAR) where power management is critical. A low airspeed device would also be useful during confined area landings to provide the pilots with an accurate source velocity for planning ingress and egress routes into the landing zone. Accurate knowledge of velocity at low airspeeds would aid in automatic approaches to a coupled hover as performed in normal SAR operations or during Dipping sonar operations in the SH-60F/R. The device would also be useful during shipboard take-off and landing, single engine approaches and wave-offs. Helicopters towing sonars or minesweeping rigs can use the low airspeed system to maintain accurate airspeeds to avoid exceeding tow cable stress limits and to steer precise sweep tracks. A built-in low airspeed sensor would also aid the test community for sensor calibration and test data collection. Even the safe completion of vertical replenishment would be aided by use of this sensor by ensuring wind limits and sideward and rearward airspeed limits are not exceeded. The sensor would also back-up the current Pitot-static system during normal flight operations (greater than 40 kts).

Information was formally requested from the Naval Safety Center on helicopter accidents for the last 10 years that occurred during low speed flight, during take-off or landing, and during confined area exercises to support this research. Information was also requested for mishaps that involved settling with power and Vortex Ring State (VRS). The Safety center replied that the information requested would require rather detailed research and they did not have the available staff to perform such request. They offered the author an opportunity to visit the safety center and conduct the research himself, but it was their consensus that such research was unlikely to reveal much. Such mishaps have occurred and have been documented but normally are not attributable to a single cause. They also mentioned that a low airspeed sensor would not be a bad thing to have, but finding mishaps identifiable to low airspeed conditions would be difficult to find. Due to budget and time constraints the safety center research was abandoned.

While this thesis focuses on low airspeed sensors for naval helicopters, low airspeed sensors have applications for the commercial helicopter industry. Civilian helicopter pilots would benefit from low airspeed sensors during steep differential Global Positioning System (GPS) approaches, confined area landings for medical evacuation helicopters and rooftop landings for corporate helicopters. An accurate low speed velocity source would enhance the safety of many of these confined area approaches and landings especially with constantly changing wind conditions at these locations.

The purpose of this section is to justify the requirement and benefits of installing a low airspeed system on modern Naval helicopters. First, the basic theory of

Pitot-static sensors and their limitations is discussed. Next, the author explains how these systems improve pilot situational awareness. A low airspeed system allows for the visualization of the wind envelope for engagement and disengagement of the rotor system and improves safety during shipboard take-offs, landings, and wave-offs. The incorporation of a vortex ring state warning device requires accurate measurements of airspeed (below 40 knots) and vertical descent rate to predict when a helicopter encounters vortex ring state based on theoretical models. The successful incorporation of such a device relies on the installation of a low airspeed sensor. The author also describes the benefits a low airspeed data system would provide for structural and exceedance monitoring in the Integrated Maintenance Diagnostics (IMD)/ Health Usage Monitoring System (HUMS). Finally, the author proposes some of the requirements for a low airspeed system for a naval helicopter based on previous low airspeed sensor research and his experience as a naval helicopter pilot.

1.1 THE PITOT-STATIC TUBE

Consider an instrument consisting of two concentric tubes A and B as sketched in Figure I-1, called a Pitot Static tube. The mouth of A is open and is aligned directly into the airstream, while the end of B is closed on to A, causing B to be sealed off.

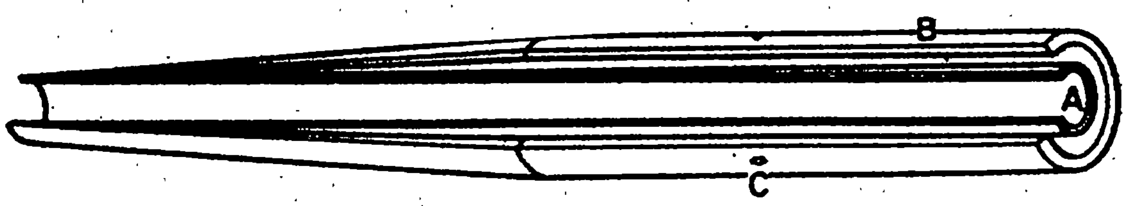


Figure I-1
SIMPLE PITOT-STATIC TUBE
Source: Houghton, E.L. & P.W. Carpenter, *Aerodynamics for Engineering Students*, 4th edition 1993. John Wiley & Sons Inc. New York.

Some very fine holes are drilled in the wall of B, as at C, allowing B to interact with the surrounding air. The right-hand ends of A and B are connected to the opposite sides of a manometer. The instrument is placed into a stream of air, with the mouth of A pointing directly upstream, the flow being of speed v (fps) and the static pressure p (psi). The air flowing past the holes in C will be moving at a speed very little different to v and its pressure will, therefore, be equal to p, and this pressure will be transmitted to the interior of tube B through the holes C. The pressure in B is, therefore, the static pressure of the stream. [Ref. 6]

Air entering the mouth of A will be brought to rest. The pressure at A will therefore be equal to the total head of the stream. As a result a pressure difference exists between the air in A and that in B, and this may be measured on the manometer. Denote the pressure in A by p_A, that in B by p_B, and the difference between them by Δp. Then

$$\Delta p = p_A - p_B \qquad \text{(eq 1.1)}$$

But, by Bernoulli's equation (for incompressible flow)

$$p_A + \tfrac{1}{2}\rho\,(0)^2 = p_B + \tfrac{1}{2}\rho\, v^2 \qquad \text{(eq. 1.2)}$$

$$p_A - p_B = \tfrac{1}{2}\rho\, v^2 \qquad \text{(eq. 1.3)}$$

$$\Delta p = \tfrac{1}{2}\rho\, v^2 \qquad \text{(eq. 1.4)}$$

This term is commonly referred to as dynamic pressure, q.

Solving for v:

$$v = (2\Delta p/\rho)^{1/2} \qquad \text{(eq. 1.5)}$$

The value of ρ, which is constant in incompressible flow, may be calculated from the ambient pressure and temperature. The manometer typically used in helicopters consists of a correlated capsule, with static pressure applied to the casing surrounding the capsule and the total pressure from the Pitot-tube admitted into the interior of the capsule. The pressure difference causes the capsule to expand, and this expansion is transmitted by a mechanism to the pointer on the airspeed indicator dial. The airspeed indicated by the pointer on the dial is termed "indicated airspeed". When converting the observed pressure difference into airspeed, the correct value for the air density can be calculated and used in equation 1.5. A simple mechanical instrument can not be expected to perform this calculation so, the airspeed indicator is calibrated on the assumption that the air density (ρ) is always standard sea level conditions (ρ_0). [Ref. 6]

The Pitot-static system provides only unidirectional airspeed information. The Pitot-static system measures only the component of airspeed that is parallel to the mouth of the Pitot-tube. For the SH-60 helicopter, the impact tubes are mounted rigidly on the nose of the helicopter and the static ports are located on both of the sides of the aircraft. The Pitot-static system measures only the component of wind that is parallel to the aircraft attitude line, with many undeterminable affects produced by the cross-wind or sideslip, gust velocity, and helicopter angle-of attack. An additional disadvantage of this system is that the static source is under the adverse pressure variation due to rotor wash. The Pitot-static system is also susceptible to water intrusion and time lag (since pressure changes are not instantaneous).

In a Pitot-static tube the velocity is determined as a result of the pressure differential sensed. Since the differential pressure is proportional to the velocity squared, very low velocities are difficult to measure with any accuracy. In order to discuss the sensitivity of the Pitot-tube, a helicopter is considered to be operating at a slow airspeed.

The impact pressure of the Pitot-tube is equal to dynamic pressure q, and the sensitivity of this pressure to a change in airspeed V is obtained by differentiating equation (1.4):

$$\partial q/\partial V = \rho V \qquad \text{(eq. 1.6)}$$

When V =0 (ideal hover with zero wind) the sensitivity is zero. When V=1.0 kt, the change in force on a 1 cm^2 pressure transducer surface area is determined by calculating the change in pressure over the face of the pressure transducer:

$\Delta F = \Delta q\ A = \rho\ V\ \Delta V\ A$=(.002377 sl/$ft^3$)(1 kt)(1 kt)(1.0 cm^2)(6076 ft/nm)^2(h/3600 s)^2

(in/2.5440 cm)^2(ft/ 12 in)^2(lbf s^2/sl ft)= 7.288 * 10^{-6} lbs force/cm^2

7.288 *10^{-6} (4.448 N/lbf) = 3.242 * 10^{-5} N

The dynamic range of this sensor is defined as the pressure change at the high end of the airspeed envelope (Δp_{high}) divided by the pressure change at low airspeed end (Δp_{low}). Dynamic range for the Pitot-static tube is calculated as follows:

$r_d = (\Delta p_{high})/ (\Delta p_{low})$ = (100 lbf/ft^2)/(7.288 * 10^{-6} lbf/cm^2)(in/2.54cm)^2(ft/12 in)^2 =

$r_d = 1.477 * 10^4$

Since this transducer must also measure pressures in excess of 100 lbs/ft^2 during cruise flight, its dynamic range must be 1.477 * 10^4, which is beyond the capability of conventional airspeed sensing devices. The limited dynamic range of the Pitot-static system in addition to adverse flow effects and pressure lag result in the Pitot-tube being unreliable at airspeeds below 40 knots. [Ref. 7]

1.2 SITUATIONAL AWARENESS

Situational Awareness as used in this thesis is defined as the ability of the helicopter pilot to acquire information about the aircraft's movement in relation to the air mass, both in speed and direction, process the information and respond accordingly.

Below 40 KIAS, visual cues provide only information as to the motion of the helicopter with respect to the ground (not the air mass). The helicopter fly's in the air mass and reacts to changes in relative airspeed in very repeatable and predictable ways. Power required, pilot workload, error in holding position directly over a spot and the structural loads on the tail rotor, are all parameters which a pilot can influence if he knows his relative airspeed; or the relative wind conditions within which he is operating.

Some of the consequences of inadequate low airspeed situational awareness can be "Loss of Tail Rotor Effectiveness " (LTE), "Unanticipated Right Yaw" (URY), unplanned downwind/crosswind landings and takeoff's, inaccurate power predictions, exceeding flight limitations, and restrictions to training of avoidance/recovery techniques.

1.2.1 POWER MANAGEMENT SITUATIONAL AWARENESS

The slow speed flight characteristics of the helicopter are repeatable and predictable when they are considered within in the context of operating within the air mass. Often, as the helicopter enters slow speed flight the pilot uses another reference to substitute for inadequate low airspeed information. Doppler radar is often used to give the pilot a speed reference, but it provides the pilot ground referenced speed (i.e. ground speed). In some new aircraft when airspeed drops below some measurable Pitot-static value (approximately 40 KIAS) the airspeed display switches from Pitot-static airspeed to Doppler ground speed. Helicopter performance depends on airspeed relative to the air mass, not ground speed. [Ref. 8]

When asked to draw a sketch of the helicopter power required versus airspeed, the average helicopter pilot will draw a curve similar to Figure I-2. The pilot will note the high power requirement for hovering, the decrease in power required as the aircraft

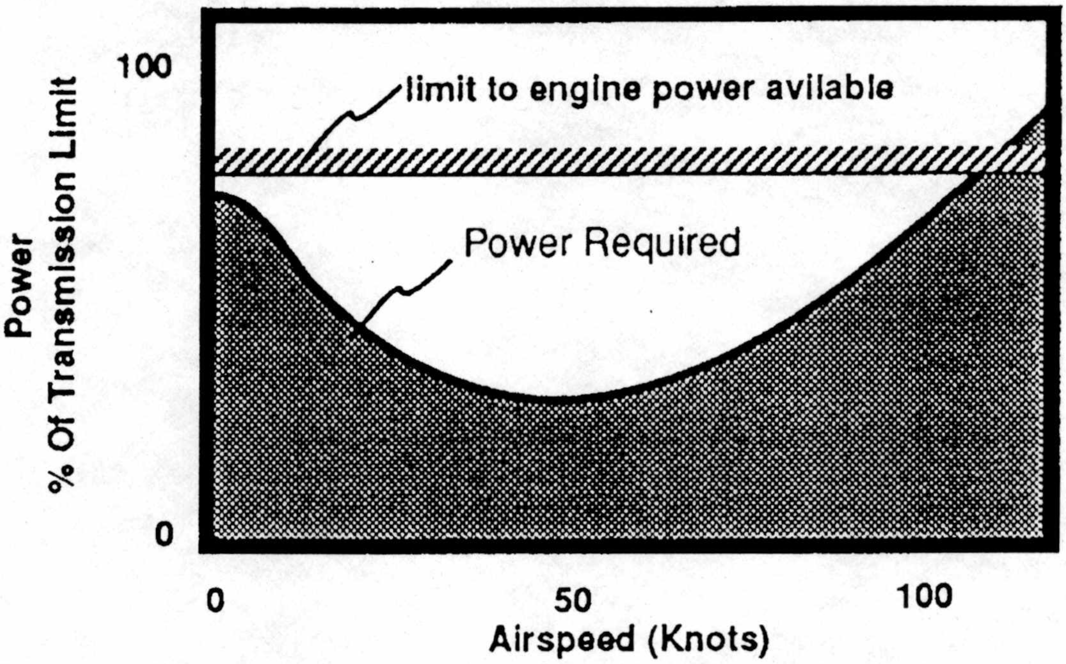


Figure I-2

TYPICAL HELICOPTER PERFORMANCE GRAPH
Source: Green, David L., *Special Scout Trainer (SST) An Examination of the Concept*, Starmark Corporation, 1994

passes through translational lift and accelerates, decrease to some minimum (or "bucket") airspeed and then increase again until maximum level forward airspeed. What is not normally noted or discussed is the power required to the left of the airspeed axis (negative airspeed with respect to the air mass). This region does not always constitute rearward flight, but can depict the case of hovering over a spot with a tailwind. The helicopter performance for forward and rearward flight or positive and negative airspeeds with respect to the air mass is depicted in Figure I-3. [Ref 8]

In Mr. David Green's FlightFile article in Rotor & Wing International [Ref 9] he presents a situation where a pilot does not possess full situational awareness to the helicopter performance problem of a downwind take-off.

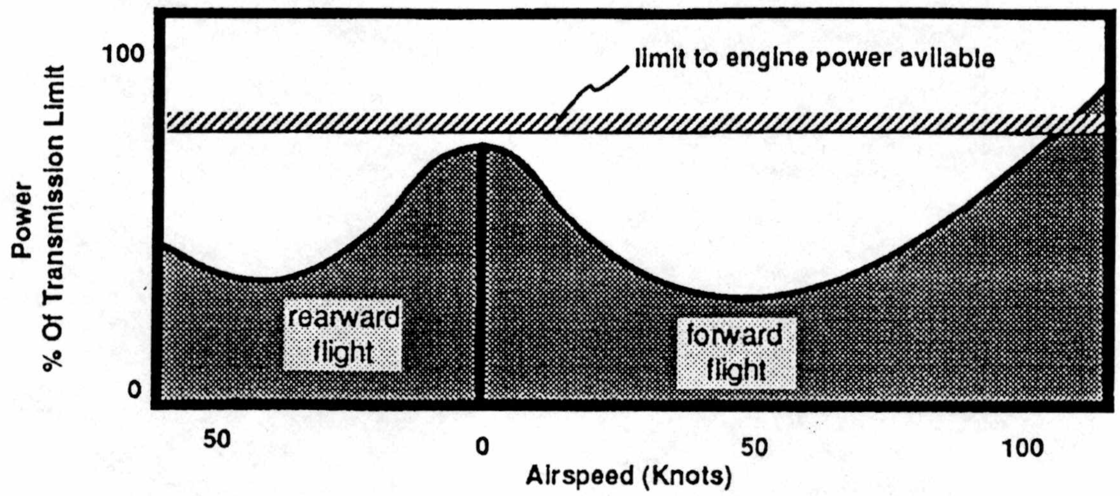


Figure I-3

HELICOPTER PERFORMANCE FOR FORWARD/REARWARD FLIGHT
Source: Green, David L., *Special Scout Trainer (SST) An Examination of the Concept*, Starmark Corporation, 1994

Mr. Green describes a situation where a typical helicopter does not have sufficient power to hover at near zero airspeed (or zero wind speed). But there is sufficient power available to hover with a tailwind or headwind. This can occur even in newer, more powerful helicopters at higher gross weights and during hot temperatures or high altitude (mountainous) operations.

The performance graph for this example is presented in Figure I-4. In Mr. Green's example the pilot is attempting to depart a landing zone in a forest clearing during a search and rescue operation but the terrain is such that he cannot remain in ground effect during the departure. Although he knows that he is departing downwind, he has no absolute knowledge of wind speed or direction. Due to the location of the landing zone and the height of the trees, he feels he has no alternative for takeoff heading or ground track. As he maneuvers the aircraft into an Out-of-Ground Effect (OGE)

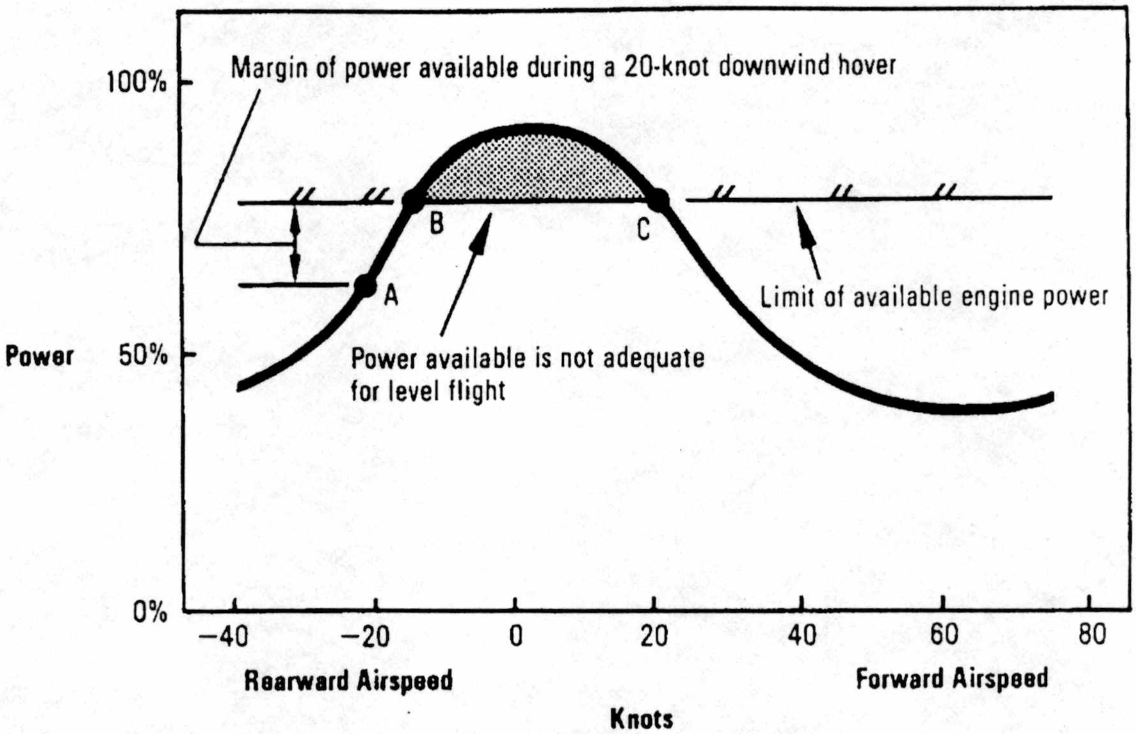


Figure I-4
HELICOPTER PERFORMAMCE EXAMPLE
Source: Green, David L., FlightFile Article, Rotor & Wing International, May 1980.

hover, he checks his power margin. Looking at the helicopter performance curve in Figure I-4, the helicopter is at Point A in the hover. In this case he reads 70% torque out of a maximum of 80% available as calculated based on environmental conditions. Judging that he has sufficient power available considering he is out of ground effect, he checks his engine instruments are all reading normally and proceeds to depart downwind by pushing the cyclic over gently. As the helicopter accelerates forward, the rearward relative airspeed (wind plus ground speed) decreases.

He is now proceeding to the right on the helicopter performance curve approaching Point B. As his ground speed increases he notes he must increase power (up collective) to sustain altitude and acceleration into forward flight. When he passes Point B, he has applied all available power and since the helicopter is at a point on the performance curve where power required exceeds power available the aircraft starts to settle. As the pilot pulls more up collective to avoid ground contact he is now losing rotor speed for continued flight. Whether or not his helicopter makes ground contact depends on his height in the initial hover (potential energy), the kinetic energy available in the rotor, and the width of the airspeed band the aircraft must eventually transition across (the region between Points B and C). Even though the example pilot has made downwind takeoffs from confined areas before and there had not been a problem, he mistakenly thought the 10% power margin during takeoff was sufficient. The pilot observed a fairly large margin of power available while in a high hover and out of ground effect. But what the pilot did not know was that a strong tailwind could greatly reduce the power required to hover. This unexpected reduction of power required subsequently confused his logic and caused him to take off through zero airspeed where he did not have enough power to hover at that condition. He lacked a true understanding of the environmental conditions and where he was on the power required curves. In essence, he lacked the situational awareness to safely depart from that landing site. [Ref. 9]

Just as hovering with a tail wind in the previous example, lateral flight has its own unique performance characteristics. A general rule that helicopter pilots follow is to hover in left crosswinds and not with right crosswinds. In order to understand this generalization, one must consider the helicopter performance curves for sideward flight for a typical U.S. built single-rotor helicopter having a conventional tail rotor depicted in Figure I-5. This figure characterizes a generic single rotor helicopter made in the USA (main rotor rotates counter clockwise). This figure shows that as the magnitude of a left

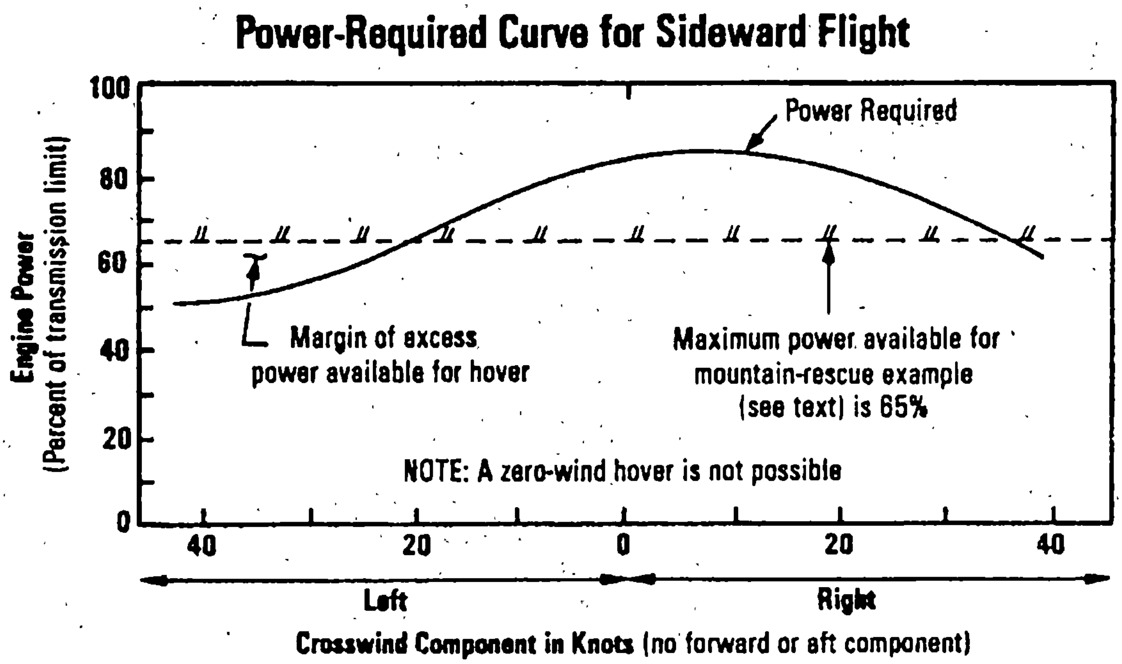


Figure I-5
HELICOPTER PERFORMANCE SIDEWARD FLIGHT
Source: Green, David L., FlightFile Article, Rotor & Wing International, June 1980.

crosswind increases, the power required to hover decreases. Similarly, when the wind increases from the right, there is a decrease in power required to hover, but it is considerably less than the reduction for left sideward flight. In slow speed flight the main rotor accounts for 80-85% of the total power required. The tail rotor is sensitive to helicopter wind direction and magnitude, as well as main rotor torque. Whenever there is a crosswind component, the required tail-rotor thrust changes as a function of the helicopter's weathercock characteristics. If the helicopter is stable it will turn into the wind and the power required by the tail rotor will vary greatly in sideward flight. [Ref. 10]

For left sideward flight, the tendency for the helicopter to weathercock into the direction of flight requires the application of more right pedal (decreased thrust and tail-rotor power required). Conversely, moving to the right (or operating with a right crosswind) requires left pedal and increased thrust and increased tail-rotor power required. When operating near or above the altitude where a zero-wind hover can be performed, unusually high tail-rotor-power demands may be required in right sideward flight and it is possible to exceed the design limitations of the tail rotor. At high gross weights and density altitudes, nonlinear fin-to-tail rotor and main-to-tail rotor wake interactions may become significant in varying flow through the tail rotor and further exaggerate the performance differences in left and right sideward flight. Finally, since the helicopter uses bank angle during high-speed lateral flight, the tail-rotor's thrust vector is directed downward in right sideward flight (working opposite to main-rotor thrust) and upward in left-sideward flight (acting in the same direction as main rotor thrust). [Ref. 10]

In his FlightFile article in the June 1980 edition of Rotor & Wing International [Ref. 10], Mr. Green presents the dangers of a right crosswind hover. In his example, a helicopter is attempting a mountain rescue where a no-wind hover is not possible where the helicopter can produce only 65% indicated torque. The task is to search along an east-west road, locate an injured camper, and hoist him to safety. With the wind from the north at 25 knots, the pilot's flight manual indicates a no wind hover is not possible. With the knowledge that the best approach is using a left crosswind, the pilot starts his search heading to the east. When the camper is spotted, the pilot decelerates the helicopter to a high hover and hoists the camper aboard. With the camper secured, the pilot notes that 58% indicated torque is required to hover and he still has an adequate margin of 7%. If the pilot had attempted to hover into the wind, the power required would have been 62% and 76% with a right crosswind (or 11% more than available).

Still facing east, the pilot desires to go to the nearest medical facility to the south. There is a gradual up slope in the terrain to the north and some tall pine trees straight ahead. The pilot is flying from the right seat in the helicopter, so his field of view is greatest to the right. Because of these factors, he begins a right lateral drift with a subsequent gradual turn to the right. In essence he turned downwind, and commanded a zero sideward aircraft speed. When he rolled the aircraft, he observed the helicopter accelerating over the ground and misinterpreted these visual cues as the desired acceleration through the air mass, but he was actually decelerating quickly and placed the aircraft near the zero-airspeed point on the power curve. As the power required exceeded the power available the helicopter begins to settle into the trees. With a better situational awareness, if the pilot had rolled left (holding pedals fixed) and turned into the wind to depart the aircraft would have yawed left sideward as left sideward airspeed increases permitting a safe departure. [Ref. 10].

A low airspeed sensor would give the pilot information where he is on the omni-directional power required curves. It will give accurate wind information and let them know what the rotor "sees" and reacts to for actual helicopter performance. With the advent of glass displays, a power required versus power available routine could be easily incorporated into a display to give real-time performance information to the pilot. Doppler airspeed while useful to navigation does not give the information the pilot needs for predicting aircraft performance.

1.2.2 FLYING QUALITY SITUATIONAL AWARENESS

Just like helicopter performance characteristics, low airspeed flying qualities are omni-directional. Azimuthal differences in handling quality ratings for shipboard landing exist. Figure I-6 depicts a map of the pilot ratings observed for a light helicopter during ship interface operations. Cooper Harper ratings (Figure I-7) are typically used in the flight test environment to measure pilot workload completing various tasks.

One can see from this diagram that winds of certain magnitudes and azimuths present various difficulty levels for the task of shipboard landing and results in correspondingly higher pilot ratings. Additionally, night handing qualities were higher due to decrease in visual cues available. Accurately knowing these conditions will allow the helicopter pilot to plan the approach and landing with the minimum workload possible. This is especially critical during conditions of control degradations and system malfunctions such as Automatic Flight Control (AFCS) failures and flight control hydraulic problems where flying qualities can be substantially more difficult. [Ref.11]

Providing the helicopter pilot low airspeed information combined with knowledge of low airspeed handling qualities would allow the pilot to avoid potentially challenging regions of flight or provide opportunity to wave-off and plan a safer, reduced workload approach. A low airspeed sensor would help the helicopter pilot better anticipate the flying qualities for the given wind conditions. An improved knowledge of how the helicopter reacts to given wind conditions will help the pilot avoid known hazards (i.e. regions for unanticipated right yaw, etc.) and plan for safer operations. An integrated electronic display could be incorporated in the cockpit which would depict the flight envelope, labeling various regions with degraded flying qualities, and use the low airspeed source input to depict where the helicopter crew is operating with respect to the flight envelope. This type of "smart" display would improve pilot situational awareness.

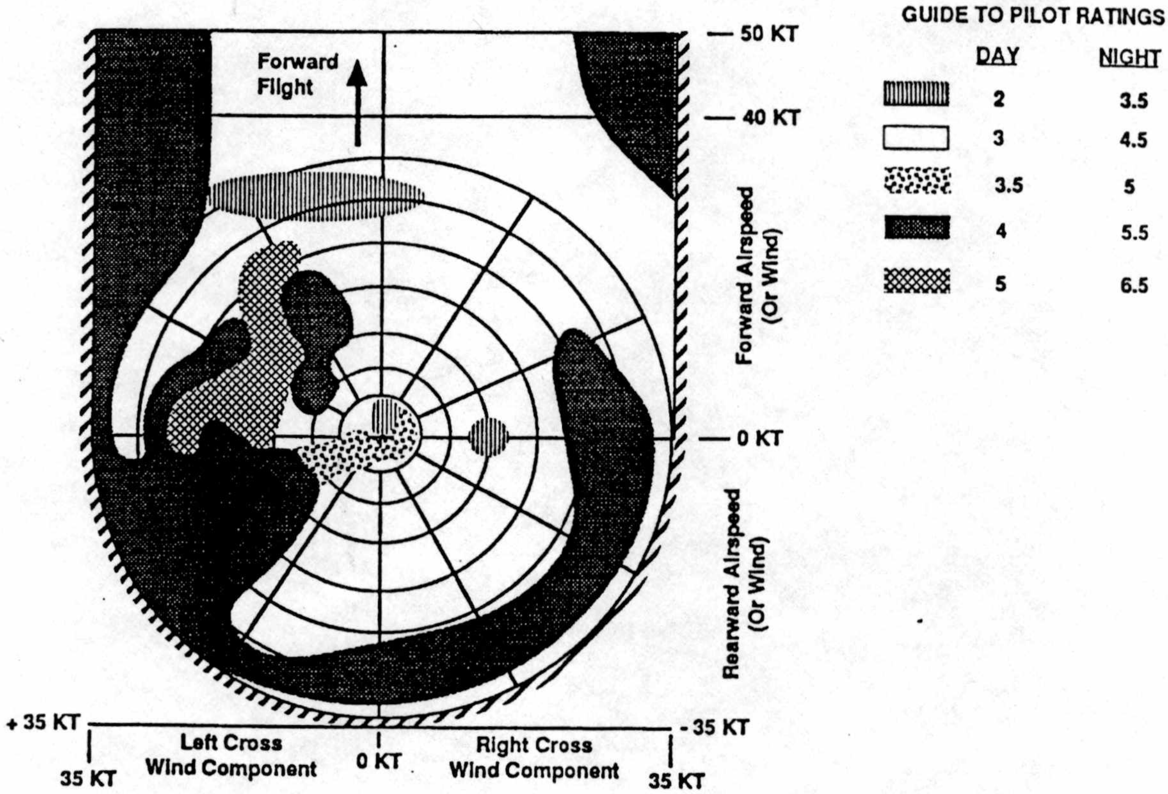
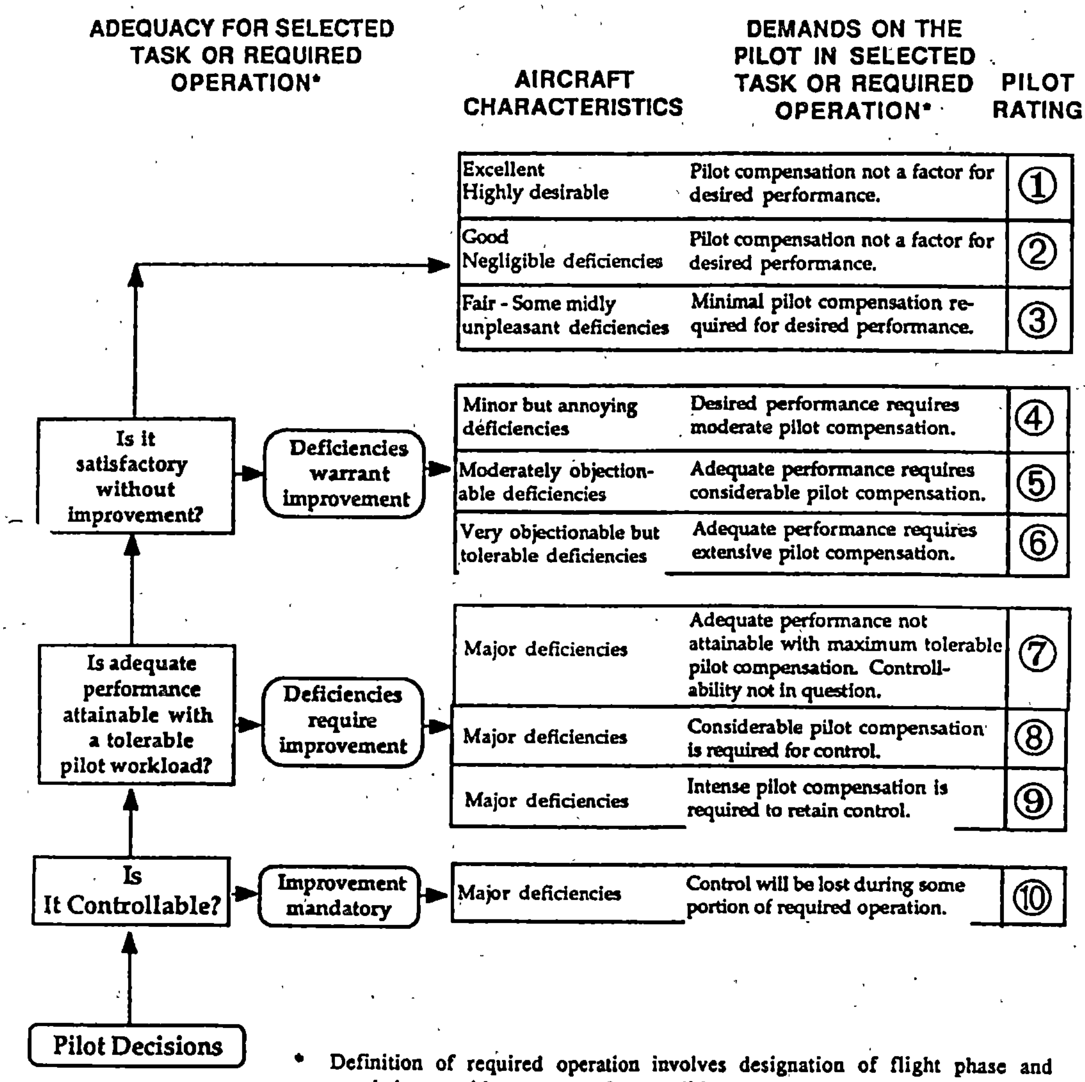


Figure I-6

HELICOPTER FLYING QUALILITIES DURING
DYNAMIC INTERFACE TESTING

Source: Green, David L, *Special Scout Trainer (SST) An Examination of a Concept*, Starmark Corporation 1994.



* Definition of required operation involves designation of flight phase and subphases with accompanying conditions.

Figure I-7

COOPER HARPER PILOT RATING SCALE

Figure I-8 characterizes the flying quality trends that are associated with the operation of a small helicopter in pursuit of precision flight task objectives during good visual conditions but incorporating no stability augmentation. It can be seen that again, various combinations of lateral and longitudinal airspeeds lead to varying degrees of workload for the pilot. Knowing the workload required and the region the helicopter is operating within, will improve flying quality situational awareness. [Ref. 11]

Fixed wing accidents that have been attributed to a "down-wind" turn are usually caused when pilots shift their speed reference from the cockpit airspeed indicator to looking at how fast objects on the ground were passing by. If he perceived that he was speeding up, the logical reaction was to throttle back, sometimes to such a low speed where the wing stalled, often with disastrous results. While helicopters do not "stall" while decelerating they encounter very different performance and handling characteristics. Some helicopter pilots have even reported loss of directional control under similar circumstances. A study of such incidents was the subject of an American Helicopter Society paper by Ms. Kelly McCool and Dr. Davis Haas of the Navy's David Taylor Model Basin. [Ref. 12, 13]

Their study was to explain the causes of "unanticipated right yaw" (URY) on the Navy's Kaman SH-2 Seasprite helicopter. Some of these incidents resulted in two or more revolutions of the helicopter around the vertical axis before the pilot was able to regain control. This phenomena has also been called "Loss of Tail Rotor Effectiveness" (LTE). Kaman Seasprite (SH-2) pilots have reported that the difficulty occurred during low speed turns to downwind. The SH-2 was often used for search and rescue operations and it was this flight regime where the phenomena could be encountered. [Ref. 13]

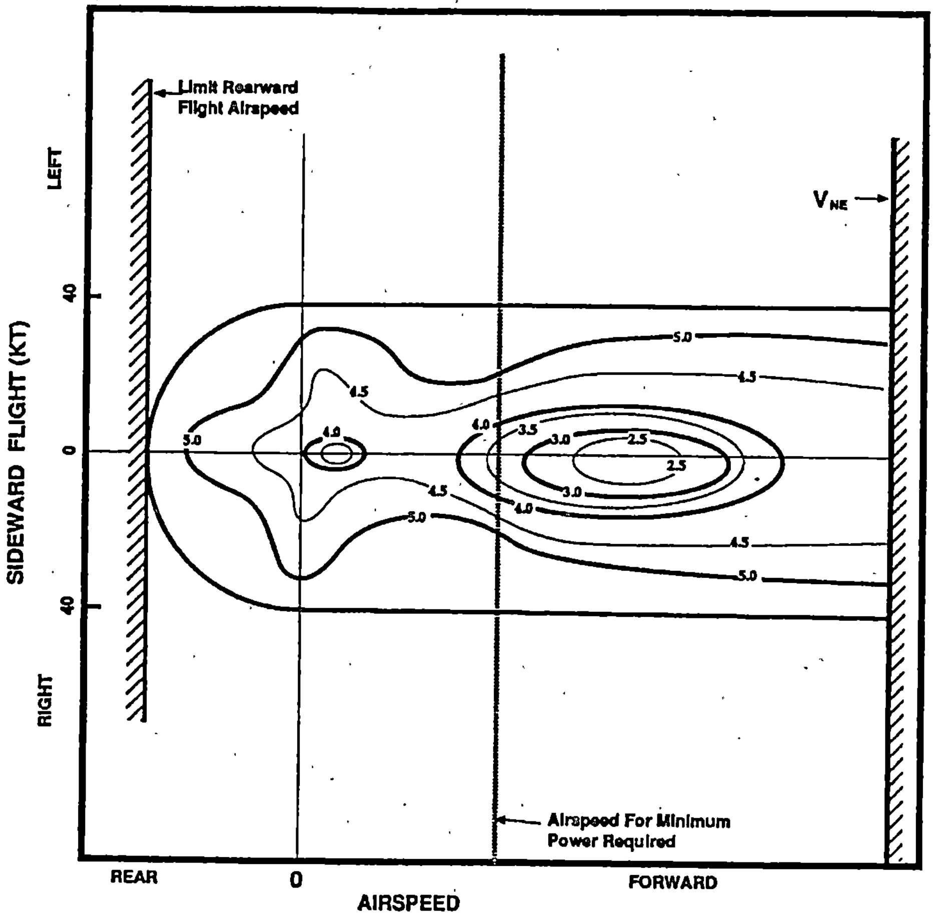


Figure I-8

FLIGHT HANDLING QUALITIES LIGHT UNAUGMENTED HELICOPTER

Source: Green, David L., *Helicopter Handling Qualities,* Paper presented at NASA Conference Publication 2219, Presented at Specialists Meeting on Helicopter Handling Qualities sponsored by the NASA Ames Research Center and the American Helicopter Society, NASA Ames Research Center, Moffett Field, CA April 14-15, 1982.

As the helicopter crew spotted something in the water, the pilot would fly a low-speed circling maneuver to get a better look. During the turn, the pilot would inadvertently transfer his speed reference from his airspeed indicator to the surface of the sea. Flying at a constant ground speed reference produces a variable airspeed. For example, with a 25 knot wind and the pilot maintaining a constant 40 knot ground speed in a 360° turn, the airspeed will vary from 15 knots to 65 knots, resulting in large varying changes in main rotor torque. [Ref. 12, 13]

Assuming that the pilot attempts to maintain as perfect a circle as possible to maximize visibility, large sideslip angles will result during the crosswind portions of the maneuver. All of these changes might catch the pilot unaware if his attention is primarily focused on the search. Previous testing of the SH-2 determined that there was no difficulty in the tail rotor's capability to produce sufficient thrust to counteract main rotor torque at steady speeds up to 35 knots in all directions. This discounted any concerns about tail rotor stall or unusual tail-rotor vortex-ring characteristics. [Ref. 12, 13]

Ms. Kelly McCool and Dr. David Haas discovered in their research [Ref. 13] that if the pilot delayed reversing the pedal position by 5 seconds (pilot distracted by search) as he went from left crosswind (90°), where much right pedal was required because of the sideslip, to downwind where left pedal was required, the result would be rapid right yawing of the helicopter. They assumed that once the pilot recognized his mistake he would move the pedals all the way to the left stop about twice as fast as required for the steady state condition. Despite the extreme, but delayed reaction, simulation by McCool and Haas showed that directional control would still be lost. The yaw rate to the right would increase from the steady 7° per second to 70° or more, and the aircraft would spin completely around more than once before stopping. Since this result agrees with the pilot reports, it seems to be a valid explanation of unanticipated right turns. It serves as a warning to pilots to understand the handling qualities of the helicopter for the wind conditions he is operating within. If the pilot had a low airspeed sensor and display, he would have benefited from wind speed and direction information and perhaps anticipated required control inputs. Omni-directional low airspeed information allows pilots to learn the sound, feel and capability of the helicopter throughout the low speed regime. This process is a learned correlation of aircraft characteristics to airspeed. This learned correlation in turn allows the pilots to augment the displayed airspeed information to that which is gained peripherally via aural, visual, and other perceptual cues. When a pilot feels a vibration or hears a sound which in turn alerts him to an unnoticed departure from their desired airspeed condition. [Ref. 12, 13, 14, 15]

1.3 VISUALIZE FLIGHT ENVELOPE FOR ENGAGEMENT OR DISENGAGEMENT OF ROTORS

Wind limits for helicopter rotor engagement and disengagement are published. There is no device onboard the helicopter which provides wind direction and velocity precisely at the helicopter. The winds measured and reported at the airfield, or onboard the ship may be radically different than those at the helicopter depending on the relative location of the wind measurement device to the helicopter. On board ship, winds are measured off a mast on the superstructure, and due to orthographic turbulence around the hangar the winds at the flight deck may be different. A low airspeed sensor would provide a method to determine precisely and in real time what the winds are at the helicopter before engagement and disengagement of the rotor system. Normally these limits are large and would be difficult to be exceeded (i.e. 45 knots from any direction for SH-60B). This large margin for error often lulls the pilot into complacency even though winds could and have exceeded these limits and resulted in damaged aircraft. With accurate wind speed and direction information at the helicopter, the helicopter crew can recommend ship course and speed changes to adjust the relative winds so they are within limits. A low airspeed sensor would help prevent the helicopter from being damaged during normally routine helicopter operations. With a digital display and separate menu, these engagement/disengagement limits could be presented on the low airspeed display for easy reference.

1.4 SHIPBOARD TAKEOFF AND LANDING

A low airspeed indicator would improve safety during shipboard take-offs and landings. During shipboard take-off winds must be within some approved operating envelope. The wind envelope for the SH-60B for a FFG-7 class ship is depicted in Figure I-9. Notice that during daytime operations up to 10 knots true tailwind are permitted.

During normal operations, relative wind speed and direction are measured by shipboard personnel from gauges indicating winds measured from a sensor on the ship's superstructure and transmitted to the pilots via radio transmission prior to take-off. Under restricted electronic emission conditions (EMCON) these limits may be given by use of a data link hard-wire to prevent the ship from revealing its position. This hardwire must be removed prior to take-off. Removing the hard-wire can takes upwards of two minutes and the wind conditions may change during that time. The shipboard operator will continue to monitor the limits, but the helicopter pilot now will be unaware of the

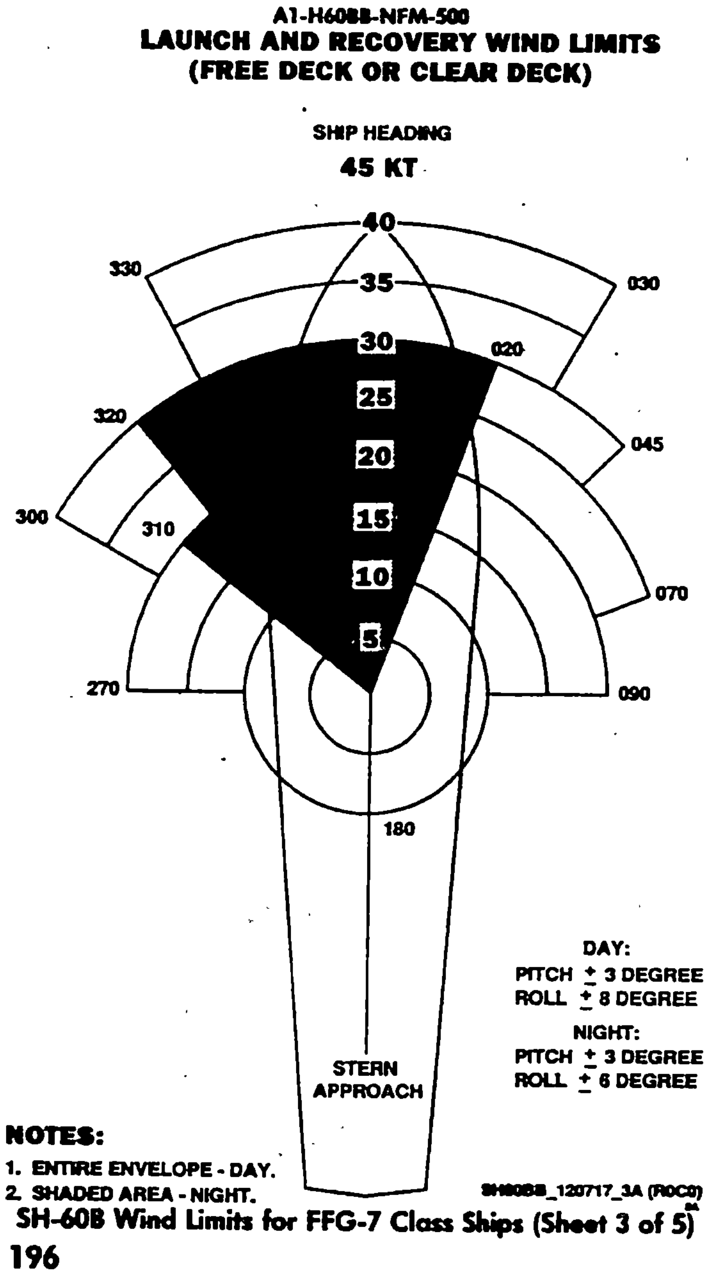


Figure I-9

SH-60B FFG-7 WIND LIMITATIONS

Source: Chief of Naval Operations, *NATOPS Pilot's Pocket Checklist, Navy Model SH-60B,* A1-H60BB-NFM-500, Change 3, 30 September 1998 change. A low airspeed indicator and display would permit a real-time indication of wind conditions at the helicopter with a display for the pilots.

During shipboard takeoff the Pitot-static indicator is unreliable until approximately 40 knots and provides no indication of relative winds. Due to a sluggish airspeed indication during take-off the pilot may over-rotate the aircraft attitude to a dangerous nose low attitude. If the pilot fixates on the airspeed indicator, he may not notice the uncommanded rate of descent due to the nose low attitude, which can result in controlled flight into the water. Controlled flight into terrain (CFIT) accidents are a reality, especially on dark nights, with no visible horizon.

If a pilot loses an engine after departing a high OGE hover to 40 knots forward flight he has no reliable source of airspeed and no source of wind data. His options at this point are to set a nose attitude (to either decrease airspeed to settle into water with level attitude) or increase airspeed through translational lift to an airspeed for minimum power required for level flight. He currently has no ability below 40 knots to determine where he is with respect to minimum airspeed. If he performed the take-off with a relative tailwind, the helicopter now must accelerate through a region of zero wind speed where there may be insufficient power to hover (single engine). The only information this pilot has with respect to winds is the last reported winds from the ship, which may no longer be accurate. If he opts to increase airspeed to an airspeed for minimum power required, he must set a nose attitude, increase power (up collective) until main rotor speed (Nr) decreases and decrease gross weight (if possible -jettison stores/fuel). He could turn into last know winds. With a low airspeed sensor he would know where the winds are and his airspeed (within the air mass) precisely to make a better decision for course of action. With integrated power management displays he would be able to better determine the appropriate strategy to safely survive a single-engine failure on take-off. [Ref. 16]

1.5 WAVE-OFF OF NIGHT APPROACH

Night shipboard approaches can result in loss of situational awareness and loss of aircraft and crew. An abort of a night approach can easily lead to this loss of situational awareness. For example, if an aircraft is executing a night recovery aboard a ship starts off too fast and high while in close to the ship, the pilot may try and correct the approach profile by rapidly pull back on the cyclic increasing nose attitude. In the resulting flare, the pilot loses visual contact with the ship and the aircraft begins to settle and may accelerate rearward due to the nose high attitude. Through noise and aircraft vibration the pilot becomes aware of the rearward flight and announces intention to abort. The pilot then applies full power (up collective), levels the wings, and levels the nose. Following the application of full power the helicopter enters climbing rearward flight. The pilot lowers the nose in an attempt to increase forward airspeed. The pilot realizes that altitude is now adequate and lowers the nose further to increase acceleration to forward airspeed. The aircraft's rearward speed decreases and as a result the aircraft begins to settle. The pilot at this point can become fixated at the airspeed indicator waiting for the indicator needle to move indicating forward flight. Nose attitude is still low and the descent rate continues to increase. If the descent rate is not abated the aircraft will fly into the water. A low airspeed indicating system would give the pilot rapid, precise airspeed information for forward and rearward flight. With a low airspeed system, the airspeed gauge would be more dynamic and rapidly give the pilot the speed reference input desired, hopefully preventing the pilot from fixating on the gauge.

1.6 INPUT FOR STRUCTURAL USAGE AND EXCEEDANCE MONITORING

The Navy and Marine Corps are in the process of acquiring a health usage monitoring system for the CH-53 and SH-60 series aircraft. The goal of the Integrated Mechanical Diagnostics (IMD) Health and Usage Monitoring (HUMS) system developed by BF Goodrich systems is to combine aircraft monitoring system requirements and capabilities for designated aircraft into a single, open architecture-type system. The IMD system will perform main and tail rotor track and balance, engine monitoring and diagnostics, rotor system monitoring, gearbox and drive train diagnostics, structural usage and exceedance monitoring. [Ref. 17]

The IMD system includes both onboard (OBS) and ground-based (GBS) subsystems. The IMD OBS will collect, analyze, and record a large number of performance measures on propulsion, drive train, and rotor system components. It will notify the aircrew of serious degradation or imminent failure of the monitored components. This subsystem will have the capability to store and download data collected in flight to a ground-based subsystem (GBS) for further analysis. The exceedance monitoring system will observe and record all NATOPS limit exceedances and their duration for more accurate maintenance troubleshooting and repair. The system will detect these exceedances and provide appropriate indications to the operator when the exceedance occurs. All exceedances detected by the IMD system will be recorded onto the Data Transfer Unit (DTU) card. [Ref. 17]

The goal of the IMD/HUMS structural usage monitoring system is to reduce time-based maintenance by measuring actual aircraft usage to determine maintenance needs. The system is designed to account for damage accumulated for all the flight regimes flown by the aircraft including, but not limited to all the flight regimes listed in the aircraft mission spectrum. To accomplish this task, the system is designed to assign appropriate life usage penalties to aircraft components based on the record of regimes flown each flight. For any time during a flight that is counted as unrecognized by the IMD system, damage accumulation equations will be used to determine life usage penalties, similar to the way life usage is accounted for now. Parameters used by the system to calculate flight regimes for structural usage are recorded normally at a low data rate (most at 1 Hz). The system will record this data at a higher rate (10 Hz) if the pilot prompts the system to record or a structural usage high data rate is breached. [Ref. 17]

The IMD/HUMS system currently lacks an accurate input for the low airspeed realm of flight. While a low airspeed source is not critical to the incorporation of the IMD/HUMS system, it would provide another data source for monitoring. A low airspeed sensor or algorithm will allow for more low airspeed limit exceedance monitoring (sideward, rearward flight) and improve structural monitoring by more exactly defining the low speed environment. The IMD/HUMS system currently incorporates all the control position and torque monitoring required for an analytical based approach. The low airspeed information derived from an analytical neural network model could be presented in a flight display for the pilots. [Ref. 17]

1.7 INPUT FOR VORTEX RING STATE WARNING SYSTEM

Vortex-ring state (VRS) is an aerodynamic phenomena of helicopters. When a helicopter begins a descent at a rate approximately equal to the hover induced velocity during low airspeed flight, a well-defined slipstream ceases to exist. The flows inside and outside the slipstream in the far wake begin to transit in opposite directions, resulting in unsteady and turbulent air. At low airspeeds when the descent rate equals the velocity of the rotor induced velocity, the rotor tip vortices cannot move away from the rotor disc and some of the air becomes trapped in a ring-shaped body enclosing the outer rim of the rotor. Tests have shown that this unsteadiness of flow starts at a vertical descent velocity of about one-quarter, peaks at about three-quarters and disappears at 1 ¼ times the hover induced velocity. [Ref. 18] The flow fluctuations in the vortex-ring state may result in changes in descent rate, thrust variations, rotor blade flapping, vibrations, and a loss of control effectiveness. Navy Pilots have termed it "power settling" based on their observation that in some cases the helicopter continues to descend even with full engine power applied. Approaches shallower than about 50°, corresponding to forward speeds of about 15 to 30 knots, will introduce enough horizontal airflow into the system to blow the tip vortices away from the rotor and free it from the vortex ring effects. [Ref. 18]

As the helicopter descends from a hovering condition, it enters the vortex-ring state and the rotor disk is now moving in the opposite direction to the thrust that it produces. In this state, the rotor is still pushing airflow downwards through the rotor disk but the free air moving upwards relative to the rotor and the air below the rotor is forced out radially. Due to this radial flow, the air from the rotor disk does not form a regular slipstream, but exists as a circulation of air in a very turbulent state. The flow is directed downwards through the rotor, then radially outward and upward outside the rotor disk. Some of the air passes upward above the rotor is again drawn inward and downward through the rotor, circulating in a manner from which this state derives its name. [Ref. 18]

During vortex ring state conditions, rotor speed (Nr) remains at 100%. In the SH-60B helicopter, the effect is measurable at descent rates above 1,000-1,250 feet per minute (fpm) and airspeeds from 0-20 ktas and is worst at descent rates of about 1,500 fpm with airspeeds of 5-10 ktas. Fully developed vortex ring state is characterized by an unstable condition where the helicopter experiences uncommanded pitch and roll oscillations, has little or no cyclic pitch authority and achieves a decent rate which may approach 6,000 fpm. A vortex ring state may also be encountered during any dynamic maneuver, which places the main rotor in a condition of high-up flow and low longitudinal airspeed. This condition is frequently seen during "quick stop" type maneuvers and during autorotative recoveries. For recovery from the onset of vortex ring state, the pilot must reduce collective and increase directional airspeed. Power should only be increased once the airspeed is above 20 knots. The only recovery from fully developed vortex ring state is to enter autorotation and once cyclic authority is regained increase forward airspeed. [Ref. 19]

The lack of a low airspeed measurement device remains one of the major obstacles in successful implementation of a device to warn pilots of impending vortex-ring state. A vortex ring state prediction algorithm was developed and incorporated into the GADGHT unit developed by the Office of Naval Research (ONR) for a project with the Naval Postgraduate School. This GADGHT unit provides an audible and visual warning to pilots when the aircraft has penetrated the Vortex Ring State (VRS) boundary as predicted by Gao and Xin Vortex Ring State Boundary theory. Because of the low airspeeds involved in defining the vortex-ring state boundaries it is crucial that the airspeed values in determining the boundary penetration are as accurate as possible. In order to produce a high degree of confidence in a vortex-ring state warning system a highly accurate (±1 knot) low airspeed sensor is required. [Ref. 19]

1.8 SYSTEM REQUIREMENTS

Helicopter flight consists of vertical take-off, transition from vertical flight to forward flight, transition from forward flight to hover, hover before landing, and vertical landing. In addition, some flight missions (such as anti-submarine warfare and airborne mine-countermeasures) require unique operations such as prolonged low-altitude loiter and hover and prolonged low speed sled-tow which impose demanding air data requirements. The air data requirements for these missions include omni-directional low airspeed, remotely sensed wind and gust conditions, vertical speed and sink rate, and low speed flow angle information in terms of angle of attack and sideslip. Power margin information is required by the pilot to assure that enough power is available to perform a successful takeoff. Power margin is the excess potential lift over the weight of the aircraft and is the function of basic air data parameters such as wind velocity, pressure altitude, and ambient air temperature. Unique effects associated with rotary wing operations include ground effect, foreign object damage, power settling, and confined-area quick turn effects. [Ref. 20]

1.9 PERFORMANCE REQUIREMENTS

No naval helicopter Operational Requirement Document (ORD) has a low airspeed sensor as a required sensor. (Ref. 1, 2, 3, 4). Further, no naval document specifies the requirements of such a low airspeed system. The following list has been derived through operational flight experience, previous low range airspeed sensor research [Ref. 20] and operational and design requirements particular for the SH-60 Seahawk helicopter. The requirements follow:

- ±1 knot longitudinal accuracy objective, (± 2 knots threshold) [Ref. 20]
- ±1 knot lateral accuracy objective, (± 2 knots threshold) [Ref. 20]
- ±5° sideslip measurement [Ref. 20]
- Dynamic response of sensor based on human factor inputs should be greater than 1 Hz. [Ref. 20]
- Valid from maximum rate of climb/to full autorotation
- Operating temperature range of -40°C (-40°F) to +60°C (+140°F)
- Operations in light to moderate icing conditions (provides for anti-icing must be included)
- Vibration tested to ± 0.40 inches per second (basic airframe vibration)
- Operates from –50 to 180 knots longitudinal airspeed
- Operates from ±50 knots sideward flight.
- Operates in salt-water sea spray environment.
- Operated in high dust environment.
- Must not interfere with normal folding and storage of main rotor blades of tail pylon
- Must not interfere with the operation of the APS-124 Search radar on the SH-60B.
- Must not interfere with the operation of the AQS-13F dipping sonar on the SH-60F.
- Must not interfere with the operation of the ALQ-142 ESM System
- Cockpit low airspeed display should be incorporated in such a manner that indicator is included into pilot's instrument scan (minimize increase in scan workload)

- No discontinuities in airspeed measurement should exist.
- Failure of system should be accurate and readily apparent to pilot.
- Cockpit display should be Night Vision Device (NVD) compatible
- System should be capable of operating in Electromagnetic environment around naval warships (not EMI susceptible)

In addition to the above requirements, the input sensor should optimally be omni-directional, lightweight and not greatly influenced by the external flow variations such as down wash and vortex shedding on the main rotor. [Ref. 20]

PART II

LOW AIRSPEED SENSORS AND SYSTEMS

2.0 GENERAL

Presently aircraft determine airspeed using Pitot-static systems. These systems measure indicated airspeed that must be corrected for both pressure and density deviations from actual ambient conditions to obtain true airspeed. A Pitot-static system does not give accurate information below about 40 knots although it is desired to have an accurate indication of airspeed down to zero airspeed. In addition to resultant airspeed, it is also desirable to determine both longitudinal, lateral and vertical components of airspeed. Airspeed systems capable of such readings are termed Omni-directional Air Data Systems (OADS).

Any low airspeed system designed for use on a helicopter must contend with the low speed inflow from the direction of flight and high-speed rotor wash. The following systems are divided into the following basic categories: Rotating Anemometers, Vortex Sensing, Swiveling Pitot-Tube Below the Rotor, Analytical Methods, and Laser Velocimeters.

2.1 ROTATING ANEMOMETERS

This type of low airspeed sensor increases the magnitude of pressure change caused by a change in airspeed when the aircraft speed is near zero. This arrangement utilizes a rotating arm with pressure ports to measure the pressure changes between the ports. This change in pressure can be used to determine lateral and longitudinal airspeed of the helicopter. A schematic representation for a rotating anemometer can be seen in Figure II-1.

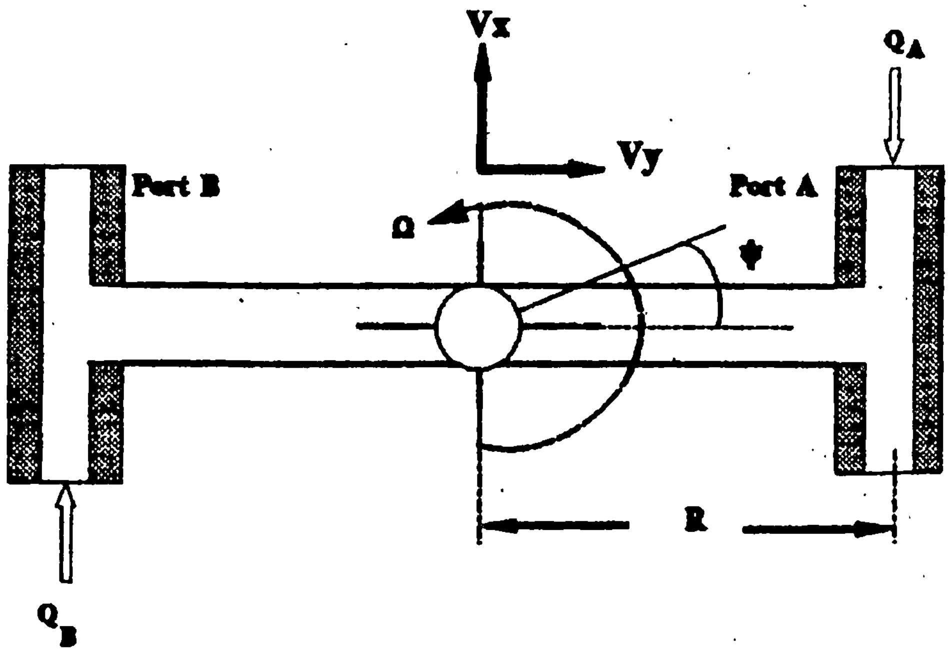


Figure II-1

ROTATING ANEMOMETER SENSOR

Source: Kayton, Myron and Walter Fried, *Avionics Navigation Systems*, 2nd Edition. John Wiley & Sons Inc. New York. April 1997.

The system measures the dynamic pressure at Ports A and B. The dynamic pressure seen at Port A can be calculated by the following equations:

$$q_A = \tfrac{1}{2} \rho (\Omega R + V_x \cos \psi - V_y \sin \psi)^2 \qquad \text{(eq.2.1)}$$

and the pressure at Port B will be:

$$q_B = \tfrac{1}{2} \rho [\Omega R + V_x \cos (\psi + \pi) - V_y \sin (\psi+\pi)]^2 \qquad \text{(eq. 2.2)}$$

$$q_B = \tfrac{1}{2} \rho [\Omega R - V_x \cos \psi + V_y \sin \psi]^2 \qquad \text{(eq. 2.3)}$$

where Ω is the rotation of sensor in radians per second

R is the radius arm length

ψ is the rotation angle of sensor with respect to the reference frame = Ωt

Solving for the difference in dynamic pressures ($q_A - q_B$):

$q_A - q_B = 2\ \rho\Omega R\ [\ V_x\cos(\Omega t) - V_y\ \sin(\Omega t)]$ (eq. 2.4)

As seen the pressure difference is proportional to the port speed ΩR of the rotating probe. To see how this amplification would work, consider a helicopter moving forward at 1.0 ft/sec longitudinally (V_x = 1.0 ft/sec) and lateral velocity is zero (V_y = 0 ft/sec). Assuming the pressure seen by the transducer is at sea level ($\rho = \rho_0$) and the Radius R=0.5 ft and the rotational speed Ω = 12 rev/sec = 24 rad/sec and V=1.0 ft/sec, then for the rotating anemometer:

$q_A - q_B = 2\ \rho_0\ \Omega\ R\ (V_x) = 2 * (2.3769*10^{-3}\ slug/ft^3)\ (24\ rad/sec)\ (3.14159)\ (0.5\ ft)\ (1.0) = 0.179\ lb/ft^2$

and for a Pitot tube under similar conditions:

$P = ½\ \rho_0\ V^2 = ½\ (2.3769*10^{-3}\ slug/ft^3)\ (1.0\ ft/sec)^2 = 1.188 * 10^{-3}\ lb/ft^2$

The amplification obtained by the rotation is 0.179/0.00119 = 150.

In addition to obtaining improved sensitivity at low speeds, the rotating probe measures omni-directional airspeed. V_x and V_y can be extracted through calculations that permit true airspeed measurement V_t and sideslip angle β, to be obtained using the following relationships:

$V_t = (\ V_x^2 + V_y^2)^{1/2}$ (eq 2.5)

$\beta = \arctan\ (V_x/V_y)$ (eq. 2.6)

The rotation axis is assumed to be near vertical so, at large bank angles, the V_x and V_y measurements are no longer accurate, and the solution is ignored. In level flight, V_x and

V_y are used to estimate the wind vector, which is important in fire control equations. [Ref. 7]

The LORAS concept was developed at Cornell Aeronautical Laboratory under Navy funding. Pacer Systems, Inc, of Burlington, Massachusetts manufactured the LORAS II system. The system is now out of production and Titan Systems Corporation supports the systems in service by providing spare units from existing inventory. Over 1400 LORAS systems were produced and the system was tested on numerous makes and models of helicopters and it is currently used by the U.S. Coast Guard HH-65 Aerospatiale Dolphin and the AH-64A Apache.

The LORAS II system includes a sensor unit, depicted in Figure II-2, airspeed computer, control panel, and longitudinal and lateral indicator.

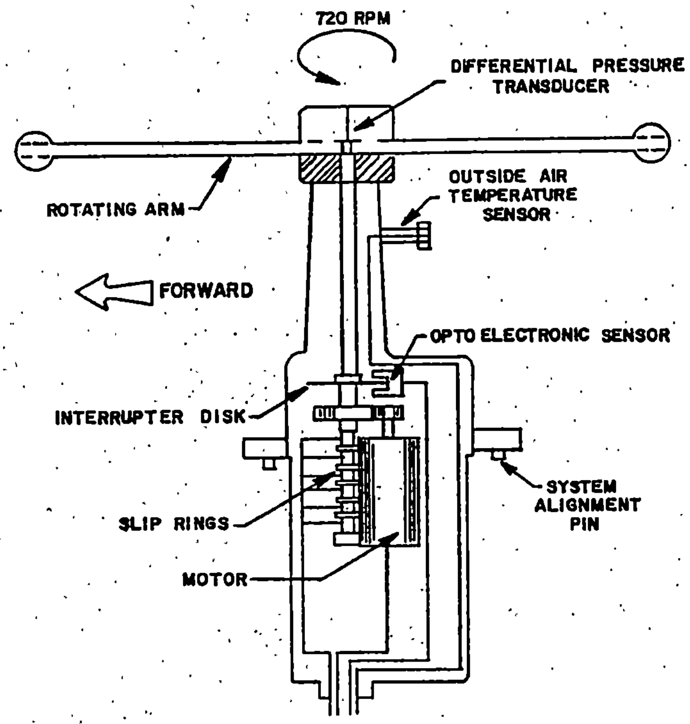


Figure II-2
PACER LORAS SENSOR

Source: McCue, JJ., *Pitot Static Systems,* US Naval Test Pilot School, Revised October 1994.

The sensor unit consists of two rotating venturi tubes oriented on opposite ends of a tubular rotor. The system is mounted directly above the rotor head on a stationary pole routed through the hollow main rotor mast.

The venturis are connected to either side of a differential pressure transducer. The rotating assembly is 13.0 inches in diameter and is driven at a constant speed of 720 rpm. The velocities at each tube (V_1 and V_2) consist of a steady component from the constant rotation ($V\omega$) and a sinusoidal component at rotational frequency from the translational velocity (V_T) in the plane of the LORAS II rotor, as shown in Figure II-3. [Ref. 21]

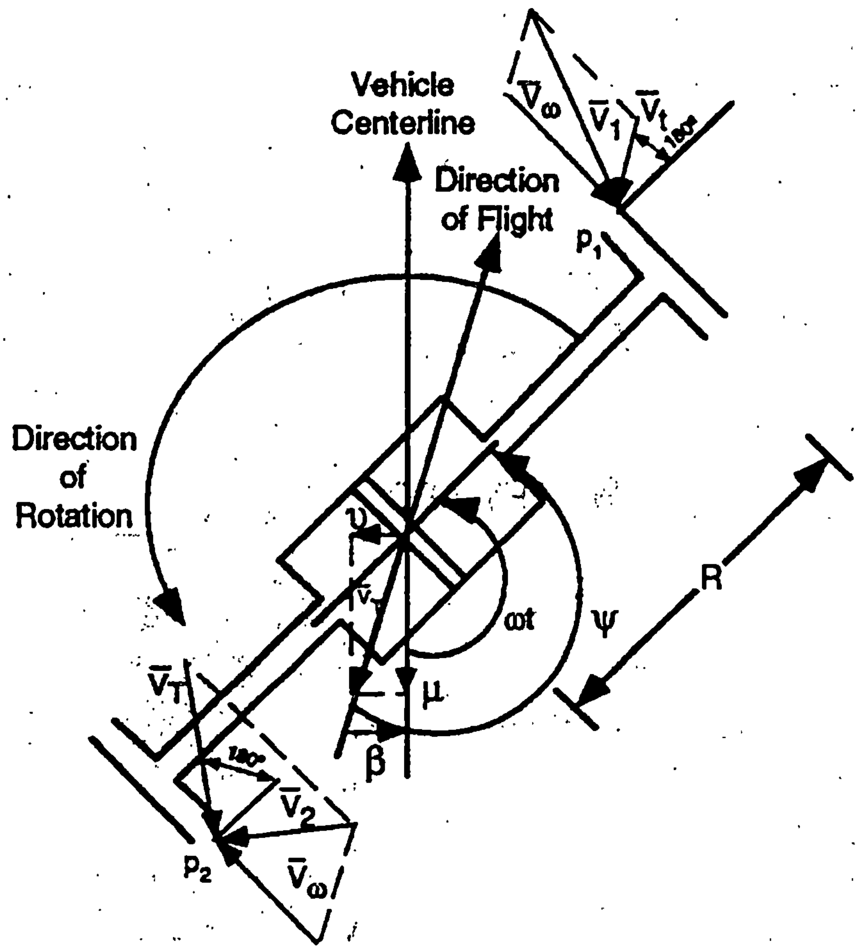


Figure II-3
LORAS VELOCITY VECTORS
Source: McCue, JJ., *Pitot Static Systems,* US Naval Test Pilot School, Revised October 1994.

The velocities at each tube (V_1 and V_2) can be calculated by the following equations:

$$V_1^2 = [\, V\omega + V_T \sin(180 - \psi)]^2 + [\, V_T \cos(180 - \psi)]^2 \qquad \text{(eq. 2.7)}$$

$$V_2^2 = [\, V\omega - V_T \sin(180 - \psi)]^2 + [\, V_T \cos(180 - \psi)]^2 \qquad \text{(eq. 2.8)}$$

The differential pressure transducer senses a modulating pressure Δp which can be expressed as:

$$\Delta p = K\,(p_1 - p_2) \qquad \text{(eq. 2.9)}$$

where K is the probe gain factor. From Bernoulli's incompressible equation:

$$\Delta p = K\, ½\, \rho\, [V_1^2 - V_2^2] \qquad \text{(eq. 2.10)}$$

Expanding the expressions for V_1^2 and V_2^2 results in:

$$V_1^2 = V_\omega^2 + 2V_\omega V_T \sin\psi + V_T^2 \sin^2\psi + V_T^2 \cos^2\psi \qquad \text{(eq. 2.11)}$$

$$V_2^2 = V_\omega^2 - 2V_\omega V_T \sin\psi + V_T^2 \sin^2\psi + V_T^2 \cos^2\psi \qquad \text{(eq. 2.12)}$$

$$[V_1^2 - V_2^2] = 4\, V_\omega\, V_T \sin\psi \qquad \text{(eq. 2.13)}$$

Letting the symbol f demote the frequency (rpm) of the rotating arm, then

$$V_\omega = 2\,\pi\, f R \qquad \text{(eq. 2.14)}$$

where R is the radius of the rotating arm. Finally, the governing expression for LORAS is:

$$\Delta p = (\, K\, 4\, \pi\, f R\, \rho\,)\, V_T \sin\psi \qquad \text{(eq. 2.15)}$$

or

$$\Delta p = (\, K\, 4\, \pi\, f R\, \rho\,)\, V_T \sin(\omega t + \beta) \qquad \text{(eq. 2.16)}$$

During no-wind operations, the flow through both Venturis is equal and the transducer is not deflected. When wind is introduced in the plane of rotation, it adds to the speed of the advancing shroud and subtracts the tip speed of the retreating shroud.

The pressure transducer deflects to the high-speed (low pressure) side and the magnitude of deflection determines wind velocity. The signal is resolved azimuthally into longitudinal (u) and lateral (v) velocity components, then filtered to remove the modulation frequency, which results in an average steady-state value. An optical total velocity output (vector sum of u and v) can be selected from the control panel. Electronic circuits provide temperature and pressure compensation so the output can be displayed as either a true or indicated airspeed. The system was designed from –50 to 200 knots longitudinal and ±50 knots laterally and to be insensitive to vertical speed. [Ref. 21, 22]

Figure II-4 and II-5 graphically depict LORAS Sensor Theory for conditions of no wind, wind parallel, perpendicular and at an angle to the motion of the helicopter.

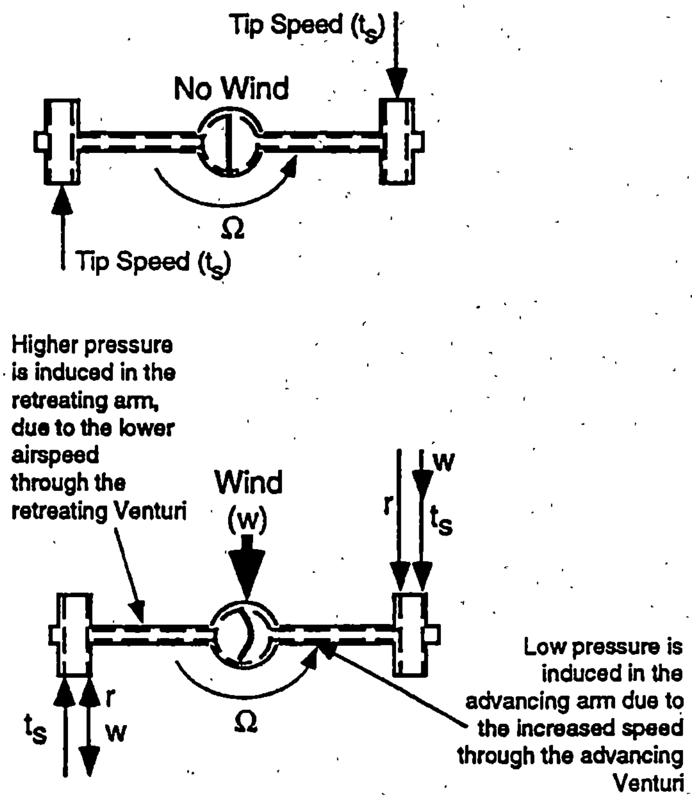


Figure II-4
LORAS SENSOR THEORY
SourceM: McCue, JJ., *Pitot Static Systems*, US Naval Test Pilot School, Revised October 1994.

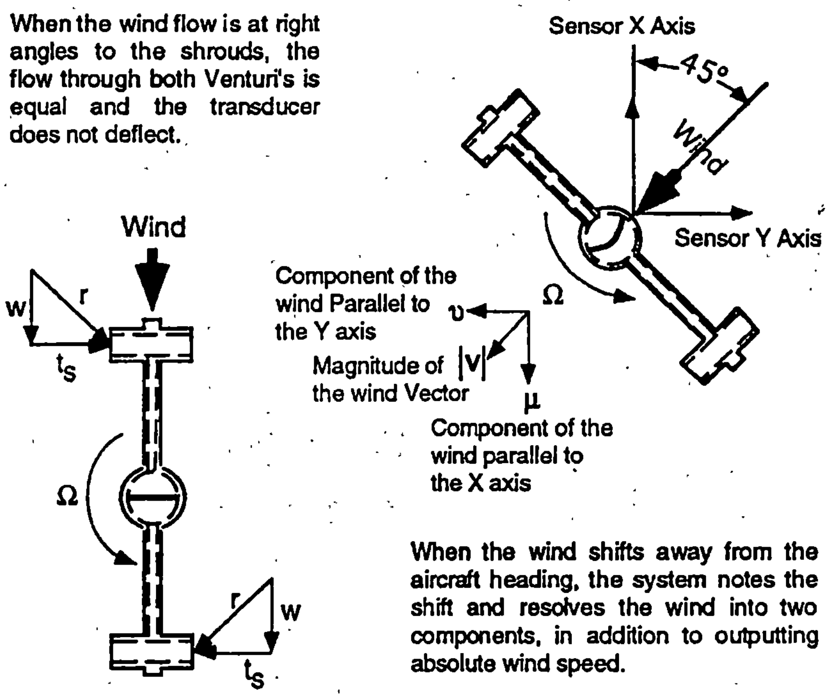


Figure II-5
LORAS SENSOR THEORY (CONTINUED)

Source: McCue, JJ., *Pitot Static Systems,* US Naval Test Pilot School, Revised October 1994.

The system weight is 2.3 lbs. for the Omni-directional Airspeed Sensor and 2.9 lbs. for the Air Data Converter. The dimensions for the system are as follows: Omni-directional Airspeed Sensor: 11 inches height, 3 inch diameter base and arm of 12.3 inches rotating diameter; Air Data Converter: Height 5.25 inches, Width 4.63 inches, and Depth 6.12 inches. The operating temperature range for the system is -40° C to + 55°C (30 minutes at +71°C). The system has been tested for Humidity, Shock (6g), Vibration, Salt Spray, Audio Frequency Conducted, Radio Frequency Susceptibility. Anti-icing is available. [Ref. 22, 23, 24]

During flight test on the CH-53E (Ref 18), the LORAS data was found to be essentially linear with maximum deviation about the regression or "truth" line of approximately ±5 kts for the airspeed range of 33 ktas rearward to 15 ktas forward. From 15 ktas to 40 ktas the output is better with only ±1 ktas about the regression line. Maximum LORAS error was found to occur during 43 ktas autorotations where there was a 13 knot error. [Ref. 23]

During operational testing on the UH-1N the LORAS system was evaluated side by side with the currently installed Pitot-static system. During this evaluation the operational test pilots conclusively determined that the inclusion of an accurate omni-directional low range airspeed sensor would dramatically enhance flight safety and would significantly enhance the potential for mission success under conditions of restricted visibility (including night operations). [Ref. 24]

During operational tests in level flight, climbs and descents at speeds above 60 KTAS, the LORAS system:

- was found to be in general agreement with the Pitot-static system
- was less subject to upset and fluctuations due to turbulence
- responded to speed changes quicker
- displayed higher apparent stability and responsiveness (useful for airspeed hold input).

During operational tests below 60 KTAS in level flight, hover, climbs and descents, the LORAS system was found to be considerably more viable speed reference than the installed Pitot-static system. [Ref. 24]

- LORAS stabilized well during climbs and descents

- Pitot-Static system did not indicate as soon (higher Cailbrated Airspeed (CAS) threshold)
- Pitot-Static system did not indicate as accurately (larger error over band of airspeeds in range)
- LORAS indicated 30-35 knots during accelerations along the ground (in ground effect) before Pitot-static airspeed indicator began its initial response.

The discrepancies found during operational testing were minor. The LORAS system did indicate a minor amount of rotor wash re-circulation during operations in very light winds, just prior to, during and just after takeoff to very low AGL hovers (less than 5 feet skid heights). The Omni-directional Airspeed Indicator (OAI) indicator bars provided a very smooth and steady indication of the local wind with the rotor system turning up to full speed, at low power settings, with winds of any magnitude, from any direction. When the wind was less than about 6 knots, and power was added for take-off, a characteristic oscillation in the LORAS OAI would develop. The maximum random motion observed about the estimated true indication was approximately ±5 knots in magnitude and totally ceased to occur as soon as the hover height increased above 10 feet from the skids at zero airspeed. The random motion was eliminated as speed was increased to about 15 knots when very low skid heights were maintained. Further, during operational tests LORAS was found to indicate very accurately during climbs, but appeared to indicate low during high rate of descents but it was determined that the errors would not impact operational suitability. [Ref. 24]

The LORAS has been installed and tested on numerous types of helicopters. Over 1400 units have been procured and it is still part of the AH-64A and HH-65 helicopters.

Since the LORAS system has already been developed, there is low technical risk associated with the system. It has already been tested and fielded on helicopters. Another advantage to the LORAS sensor is its ability to measure wind speed prior to rotor engagement. LORAS can measure wind speed as soon as power is applied to the aircraft.

The primary disadvantages of the LORAS system is the inaccuracies introduced at large bank angles. The rotation axis on LORAS is assumed to be near vertical, so at large bank angles, the $V_x$and V_y measurements are no longer accurate, and the solution is ignored. Another disadvantage is the extensive aircraft modifications required for sensor incorporation on the SH-60 helicopters.

2.2 VORTEX SENSING

This type of sensor measures vortices shed by fluid flow over an obstruction inserted into the flow. According to theory, frequency of vortices shed is proportional to the air speed. This method has been used to measure low airspeed in helicopters and in ground-vehicle fire-control systems. The theory of this vortex sensor dates back to Von Karman in 1912. The frequency F of vortex formation from each side of the obstruction is given by:

$$F = S\,(V/d) \qquad \text{(eq. 2.17)}$$

where S is the Strouhal number, V is the air velocity, and d is the width of the obstruction. The Strouhal number has been experimentally determined for a variety of obstruction widths and fluid properties. Theory and experiments have shown that the sensitivity threshold for this type of sensor is about 1.0 knot. One method of measuring vortex frequency directs an ultrasonic beam through the vortex trail. The rotational velocity of the vortices combine vectorially with the sonic ray velocity causing the sonic rays to be deflected. This causes an amplitude modulation of the received energy at the vortex frequency. To measure the horizontal velocity vector, an orthogonal sensor is required. [Ref. 7]

J-TEC Associates of Cedar Rapids, Iowa developed the True Airspeed Sensor (TAS), depicted in Figure II-6, operating using this aerodynamic phenomenon of alternating vortex shedding from a bluff body. Experimental data showed that Strouhal number is constant for Reynold's numbers ranging from about 100 to 100,000. Hence equation 2.17, shows that the vortex frequency varies linearly with velocity for a fixed rod diameter. For the J-TEC model VA-210 sensors, the Reynold's number ranges from 100 to 100,000 corresponding to an airspeed of 2 to 140 knots. In the JTEC TAS sensor, the shedding frequency is sensed as it modulates an acoustic carrier signal generated by a crystal contained in one of the struts and received by a crystal in the opposite strut. Through electronic processing of the frequency change an analog or digital signal can be supplied to an indicator for displaying True Airspeed (TAS) to the pilot. The True Airspeed Sensor was mounted on a static pole above the main rotor head where pressure fluctuations would be minimal. As of March 2001, JTEC no longer produces this type of sensor for helicopter low range airspeed operations. [Ref. 21, 25]

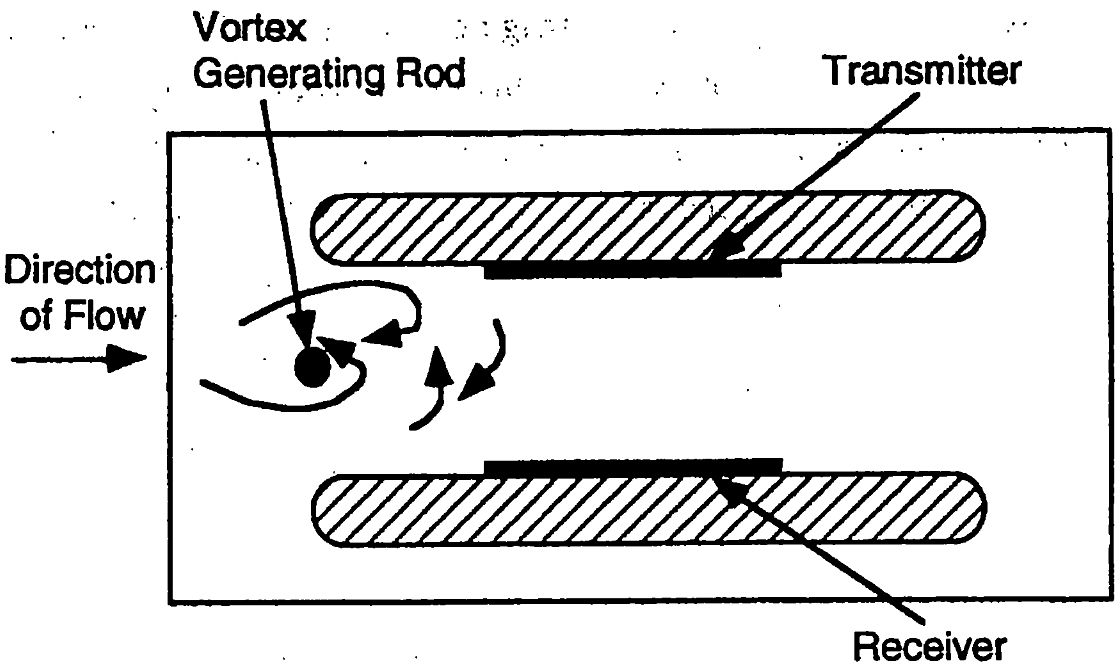


Figure II-6

J-TEC SENSOR DIAGRAM

Source: McCue, JJ., *Pitot Static Systems,* US Naval Test Pilot School, Revised October 1994.

Tao Systems of Hampton Virginia has developed a low range airspeed sensor under a Small Business Innovative Research (SBIR) project. The Digital Electronic Low True Airspeed (DELTA) system, depicted in Figures II-7 and II-8, for helicopters also uses the phenomenon of vortex shedding. In the DELTA device, a miniature wedge instrumented with micro-thin sensors is placed inside a small venturi (Figure II-8) to create tiny vortices with clearly defined discrete frequencies for each speed. Tao system's patented constant voltage anemometer is used to operate the sensor and obtain high-quality signals whose dominant Strouhal-frequency is then extracted by a specially designed digital signal processor (DSP) output board. The frequency is then calibrated to display true airspeed. The DELTA indicator has been tested in various wind tunnels, on a truck and on a commercial helicopter (Robinson R-22). The instrument's response was

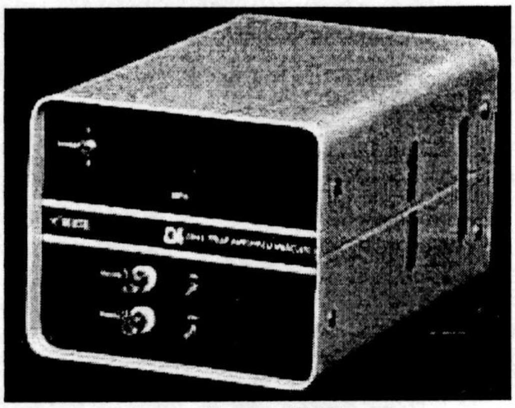


Figure II-7
DELTA AIRSPEED INDICATOR

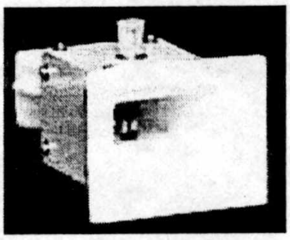


Figure II-8
DELTA SENSOR

Source for Figures II-7 & II-8: TAO Systems, DELTA Information Sheet, February 2001, Project DoD SBIR Phase II N92-156.

linear down to hover (zero airspeed) and shown by results from National Institute of Standards and Technology (NIST) 5 ft by 7 ft wind tunnel. Pitch and side-slip angles up to 45° had negligible effect on longitudinal airspeed measurement. The output was independent of altitude (temperature, pressure, and density) and relatively immune to Electro-Magnetic Interference (EMI) and Radio Frequency Interference (RFI). The dimensions for the bi-directional probe measures 10 inches (length) by 3.75 inches (width) by 3.75 inches (height) and weighs just 2 lbs. The electronics package for processing (digital display and outputs to other systems) measures 10 inches by 6 inches by 5 inches and weighs 5 lbs. TAO systems believes these dimensions can be further reduced once the specifications are finalized since the current system was developed for a one of a kind proof of concept prototype under Navy Small Business Innovative Research (SBIR) Phase II. The device was inexpensive (less $5,000), does not require extensive calibration, has no moving parts, and is easy to maintain and replace. Some other advantages as given by Tao Systems were the high resolution (0.1 knot) for the airspeed indication and lack of calibration requirements for individual probes. [Ref. 26]

TAO systems quotes the real time output from the probe at better than 100 Hz and the processing updates can be better than 20 updates per second. The probe can be heated for anti-icing without any loss of accuracy. However, the operating temperature range still needs to be established. No environmental susceptibility had been encountered to date by TAO systems, and rotor wash did not influence the sensor during flight tests on the Robinson R-22. The probe was designed to act as a filter to reduce the down wash. Further testing would need to be conducted to determine ideal location for the SH-60. The main disadvantages were that the system did not provide omni-directional speed information and the technical risk inherent with incorporating on a larger, more powerful aircraft was high. [Ref. 26]

2.3 SWIVELING PITOT-TUBE BELOW THE ROTOR

The swiveling Pitot-tube was developed in the United Kingdom; it is currently in use on the AH-1S, AH-64D, and other attack helicopters for unguided rocket delivery. It was tested extensively by the United States Army in the 1970's. A gimbaled Pitot-tube contains a vane arrangement that causes the tube to align with the airflow within the down wash field emanating from the rotor blades. Changes in the airflow field vector are correlated with changes in true airspeed. With appropriate pick-offs to measure vane orientation, the true airspeed is estimated using a calibration associated with each aircraft and its rotor system. This system is designed to utilize the rotor down wash and therefore must be mounted close up under the rotor. At speeds where the sensor is in the rotor down wash, the vector sum of horizontal airspeed and the rotor airflow is sensed. When operating in cruise flight (sensor not in down wash), the sensor acts much as a standard Pitot-static probe on a conventional aircraft. [Ref. 7]

Theory of its operation can be seen in a vector analysis (Figure II-9) for low speed, forward flight. The induced flow velocity, Vi is normal to the rotor tip path plane. Vi ($sin\ i$) is proportional to the thrust component that overcomes aircraft drag and causes a forward velocity. The vector diagram is expressed by:

$$Vi \sin (i) + V_H = V \cos \alpha \qquad \text{(eq. 2.18)}$$

The swiveling probe aligns with the resultant flow velocity **V**, sensing both its magnitude and angle α (helicopter pitch angle) and β (helicopter roll/yaw angle). The principle of the probe is that $Vi \sin i$ is a repeatable function of horizontal airspeed, independent of thrust, weight, vertical speed, center of gravity, but varies only with ground proximity.

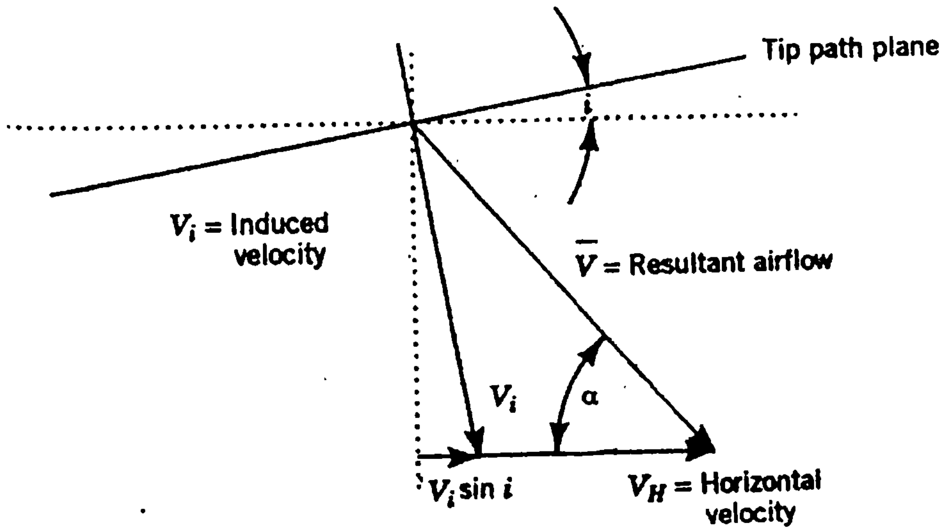


Figure II-9

SWIVELING PITOT-TUBE VECTOR ANALYSIS

Source: Kayton, Myron and Walter Fried, *Avionics Navigation Systems,* 2nd Edition. John Wiley & Sons Inc. New York. April 1997.

Hence a radar altimeter measurement is required to accommodate the ground effect. The basic sensing equations are:

$V\cos\alpha = f(V_H)$

Longitudinal True airspeed : $V_x = V_H \cos \beta$ (eq. 2.19)

Lateral True Airspeed: $V_y = V_H \sin \beta$ (eq. 2.20)

where β is the yaw angle also measured by the swiveling probe. Placing a Pitot-tube in the down wash flow field avoids the need to measure the low pressures existing near hover since the minimum down wash airflow Vi will always be greater than 15 knots. Also, aligning the Pitot-tube with the airflow eliminates alignment errors in both the Pitot and static systems. [Ref. 7, 27]

The BAE SYSTEMS Helicopter Air Data System (HADS), depicted in Figure II-10, is a swiveling Pitot system. The BAE systems concept of low airspeed measurement was first evaluated and proven in the 1960's. In the late 1970s the HADS went into production when it was selected by the U.S. Army and Bell Helicopters to provide omni-directional airspeed data to the fire control system of the AH-1S/F Cobra for unguided rockets. In addition to over 1400 air data systems supplied for the Cobra and subsequently for the Augusta A-129 helicopter, the system has been purchased by several flight test establishments for use as an airspeed reference. Using simple trigonometry and vector arithmetic the HADS can determine the indicated longitudinal and lateral velocity in addition to vertical component of velocity. Using static pressure HADS can calculate the true vertical velocity. Characterized data stored as look-up tables and matrices are used to correct for repeatable errors. [Ref. 27]

Figure II-10

HELICOPTER AIRSPEED DATA SYSTEM (HADS)

Source: Arajs, P. *Helicopter Air Data System (HADS) Advanced Digital/Optical Control System (ADOCS).* Final Report Aviation Applied Technology Directorate, US Army Aviation and Troop Command. Report No. 260/1068/5-823/VII. Nov 1983 – Nov 1986.

The HADS system was upgraded with a new Helicopter Air Data Computer (HIADC) replacing the previous Electronics Processor Unit (EPU). The HIADC incorporates solid state pressure transducers and the latest high-integration microcircuits, bringing enhanced system performance along with significant reductions in size and weight, power consumption and cost. In the mid-1990's the updated HADS was selected by Boeing as the low airspeed sensing system for the AH-64D Longbow Apache. [Ref. 27]

In the single probe system configuration, as on the Cobra and Agusta 129, the HADS consists of one Airspeed and Directional Sensor (AADS) (Figure II-11) and one miniature High Integration Air Data Computer (HIADC).

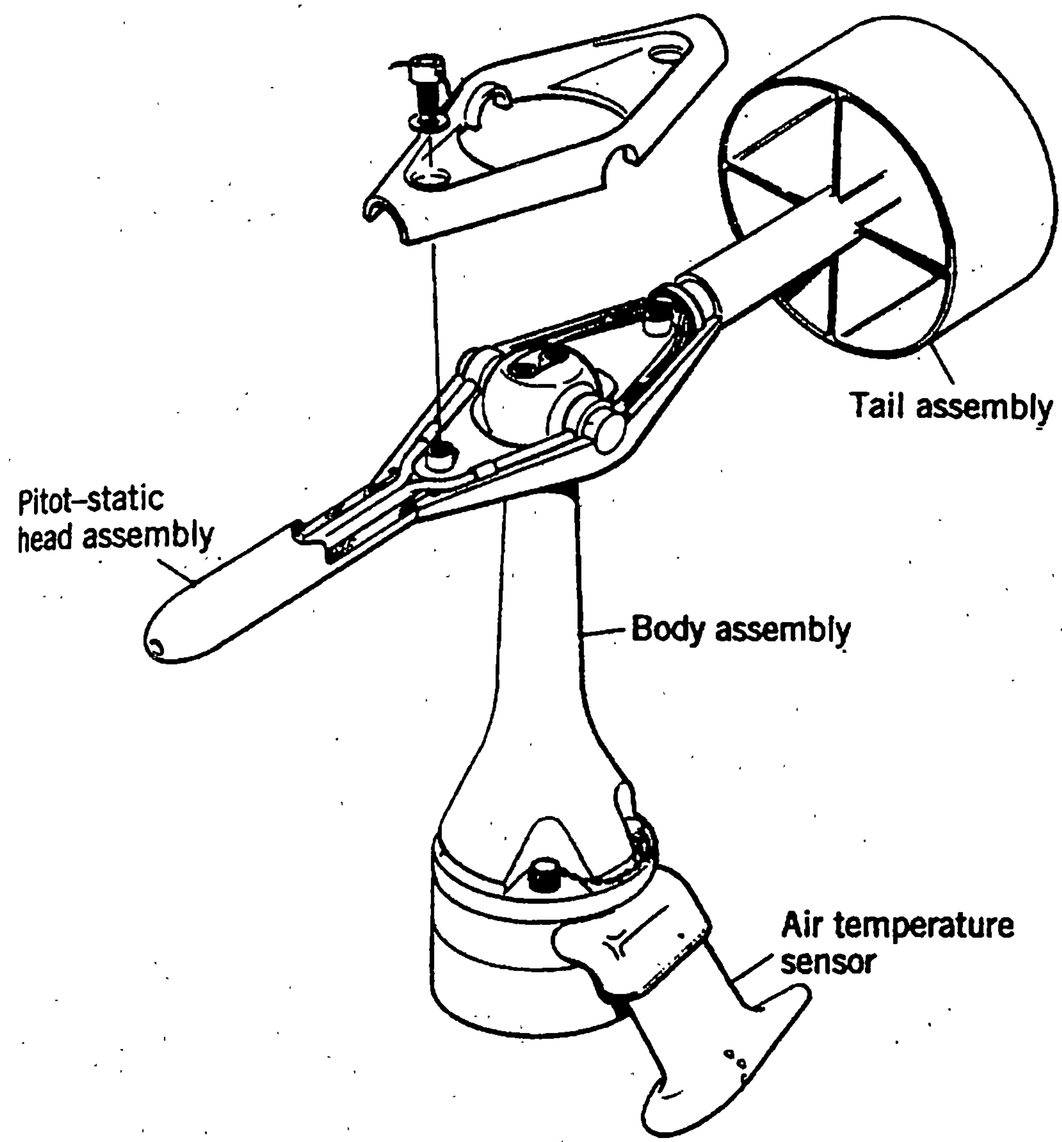


Figure II-11

HADS AIRSPEED AND DIRECTIONAL SENSOR (AADS)

Source: Arajs, P. *Helicopter Air Data System (HADS) Advanced Digital/Optical Control System (ADOCS).* Final Report Aviation Applied Technology Directorate, US Army Aviation and Troop Command. Report No. 260/1068/5-823/VII. Nov 1983 – Nov 1986.

The AADS mounts on a boom, which places it at a suitable location beneath the helicopter rotor to sense the local airflow parameters. The HIADC performs the system computing and signal interfacing functions.

The AADS provides pressure, temperature, and angular data to the HIADC and the HIADC outputs computed air data parameters on a digital bus. The AADS, illustrated in Figure II-11, consists of a Pitot-static pressure head, which is supported on a gimbal arrangement and is caused to point into the local airflow by a finned tail. Both total (Pitot) pressure and static pressure are sensed by the head, which is always aligned with the local resultant airflow and therefore does not suffer from incidence errors on either pressure. These pressures are conveyed via the axles of the gimbals and aircraft pneumatic piping to the HIADC. [Ref. 27]

Two angular resolvers sense the position of the head in pitch and yaw relative to the aircraft and transmit this information to the HIADC, where together with pressure signals, they are used to compute helicopter airspeed and direction. The gimbaled arrangement permits total angular freedom in pitch but limits to ±60 degrees in roll or yaw. In the recommended AADS location this angular movement will normally allow alignment with the local airflow angle up to the airframe limitations of forward, lateral, and vertical airspeed.

The computation of longitudinal, lateral and vertical true airspeed remains the same throughout the flight envelope, whether the AADS is within the rotor down wash or in free air at high speed. Because the AASD transitions from In Down Wash (IDW) to Out of Down Wash (ODW) conditions the HIADC must count for the discontinuity in the raw probe airspeed measurement. The discontinuity and systematic probe errors due to airframe's disturbance to the airflow, ground effect and discontinuity when the AADS transitions from the rotor wake to the free stream (usually occurs at 25 knots) are removed through a characterization process. The characterization process uses look-up tables from flight test data specific to a particular aircraft type. The data required for low speed, high speed and in-ground effect characterization can be gathered in as few as three hours of flight testing, using on-board recording equipment. It is essential that these tests are conducted in conditions of zero wind, or very steady known wind. Uncertainty in determination of ambient wind speed and direction during flight tests is a major cause of inaccuracy in the derived wind speed. [Ref. 27]

The head design is based on standard Pitot-static probe theory. The probe dimensions can be seen in Figure II-12. However in this application the head is always aligned with the airflow and is not therefore subject to incidence errors, enabling the design to be optimized for other parameters, such as the inclusion of a heating element. The thermostatically controlled heating element operating from 115VAC aircraft power is capable of providing anti-icing in a moderate airframe icing environment. [Ref. 27]

An air temperature sensor is attached to the body of the AADS at an angle such that it does not interfere with the airflow over the pressure head, or pick up heated air for the flow around the head. The AADS is always aligned with its incident airflow, ensuring that the sensed static pressure and derived pressure altitude and altitude rate are accurate and insensitive to helicopter attitude changes.

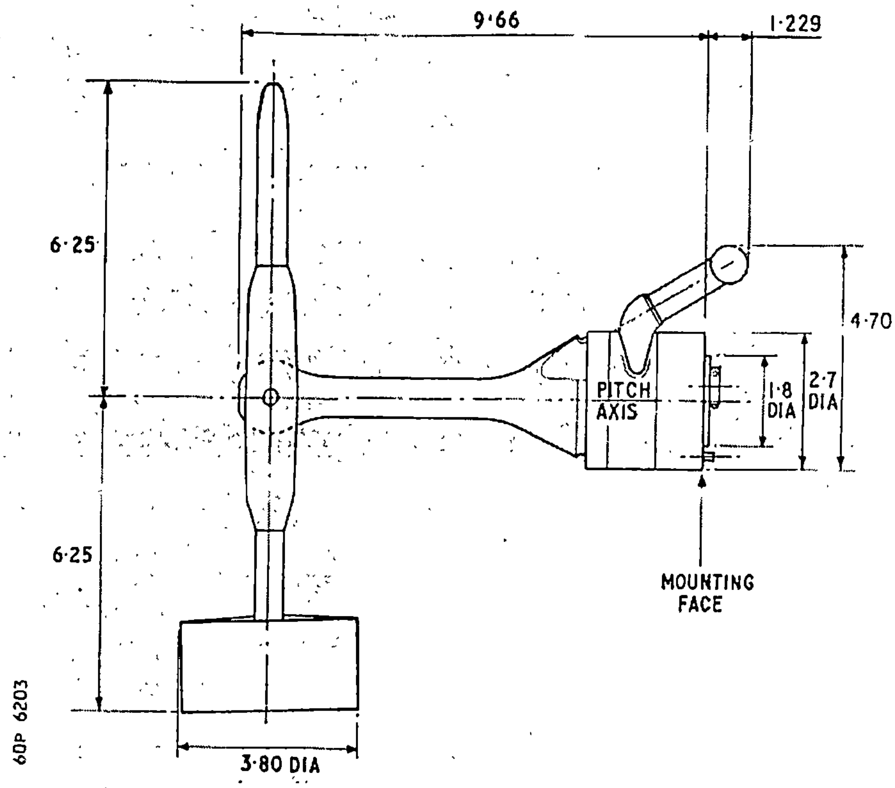


Figure II-12

HADS PROBE DIMENSIONS

Source: Arajs, P. *Helicopter Air Data System (HADS) Advanced Digital/Optical Control System (ADOCS).* Final Report Aviation Applied Technology Directorate, US Army Aviation and Troop Command. Report No. 260/1068/5-823/VII. Nov 1983 – Nov 1986.

The body has a reference mounting point spigot against which all AADS alignment is referenced and tested. The AADS is automatically aligned with the aircraft datum when this spigot is engaged in the aircraft mounting boom. The AADS is manufactured for either left or right side installation and incorporates design features to aid in draining of entrapped moisture in either orientation. [Ref. 27]

Some of the additional probe installation requirements are:

- Must be located below the rotor (ideally 15 inches below the maximum droop of the main rotor blades)
- Must remain in the down wash at speeds below 25 knots

- Must be maintained inside the fully developed portion of the rotor blade
- Ideal location is on advancing blade side (but not essential for operation)
- Must remain clear of engine inlets/exhausts and other aerodynamic effects

Some of the characteristics/design requirements for the HIADC computer are:

- Can be mounted in any orientation (prefer pressure ports down for draining)
- Pitot-static plumbing should be less than 15 feet total length (AADS sensor to HIADC)

One of the main advantages of the HADS system is the mature technology and design. The current system has been in use successfully for over 15 years. It has already been mounted and flown on a JUH-60A airframe at NASA Ames research center. One of the disadvantages is the inherent discontinuities, which must be accounted for through the characterization process. In addition, the aircraft must have minor modifications for addition of the sensor.

2.4 ANALYTICAL ESTIMATION OF TRUE AIRSPEED

A predictable airspeed results from each combination of collective, pedal, and cyclic control position, pitch, roll and yaw attitude and rates, power setting and aircraft gross weight. Methods have been developed to estimate a helicopter's airspeed vector from measurements of these quantities. Augmenting these estimates with inertial velocity accommodates dynamic, non-trim conditions. Flight tests have demonstrated accuracy of 4 knots, 2-sigma using this approach. For this type of low airspeed system, certain measurable state parameters for the helicopter (power setting, control positions, pitch/roll/yaw rates, gross weight) must be measured and input and these parameters mapped to a neural network for that state using an on-board computer system. The output of the neural network or map would be the airspeed of the helicopter within the air mass. [Ref. 28]

An analytical model for low airspeed magnitude and direction has been developed by the work of Ms. Kelly McCool, Dr. David Hass (Naval Surface Warfare Center, West Bethesda, Maryland), and Mr. Michael Morales (Computer Sciences Corporation, Falls Church VA). Their work was presented in the American Helicopter Society Paper *Neural Network Based Low Airspeed Sensor*, May 2-4, 2000 [Ref. 24]. This paper presented an investigation of neural network based low airspeed models for the SH-60 aircraft using additional flight data acquired specifically for the effort. [Ref. 28]

Dedicated low airspeed tests were conducted at the Naval Air Warfare Center in Patuxent River, MD using a SH-60F helicopter. Doppler ground speed measurement was used as the truth measurement. Since ground speed would only be accurate when the prevailing winds were low, flights were only performed when prevailing winds were less than 5 knots. The flight data was taken for several combinations of forward, rearward, left and right sideward flight, hovers, take-offs, landings and transitions between maneuvers. Data were taken for both in-ground effect and out-of-ground effect flight conditions. Flight tests were conducted at two gross weight configurations, with the auxiliary fuel tanks installed and filled with fuel and empty. [Ref. 28]

Aircraft flight data were sampled at 8 Hz with magnetic analog flight data recorder. The aircraft used for the test was instrumented to record control positions (collective, cyclic, pedal), torque left and right, yaw rate, pitch rate, and Doppler airspeed. The data was processed to remove spikes, noise and other instances of bad data prior to neural network training. The final data set consisted of 4 hours and 36 minutes of flight time. The range of airspeed magnitude and direction can be seen in Figure II-13 and the height range of test data seen in Figure II-14. [Ref. 28]

Flight data was collected from a hover to 40 kts at nominally 30° increments of sideslip.

The low airspeed sensor required the development of a single neural network. This network would predict the longitudinal (V_h) and lateral (V_d) components of the air velocity vector. Through vector addition this data can be transformed into air velocity magnitude (airspeed), and direction (sideslip). With a low airspeed display these velocity components can be presented to the helicopter pilot.

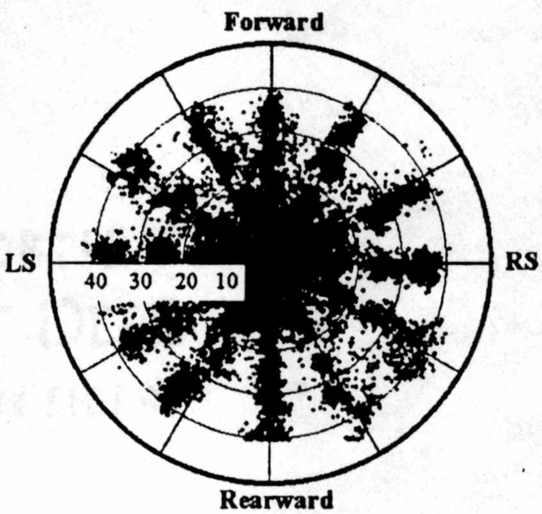


Figure II-13.

FLIGHT TEST DATA AIRSPEED RANGE (ANALYTICAL METHOD)

(1 of every 4 points plotted for clarity)

Source: McCool, Kelly, M. Morales, D.J. Haas, *Neural Network Based Low Airspeed Sensor*, Paper presented at the American Helicopter Society 56th Annual Forum, Virginia Beach, VA, May 2-4 2000.

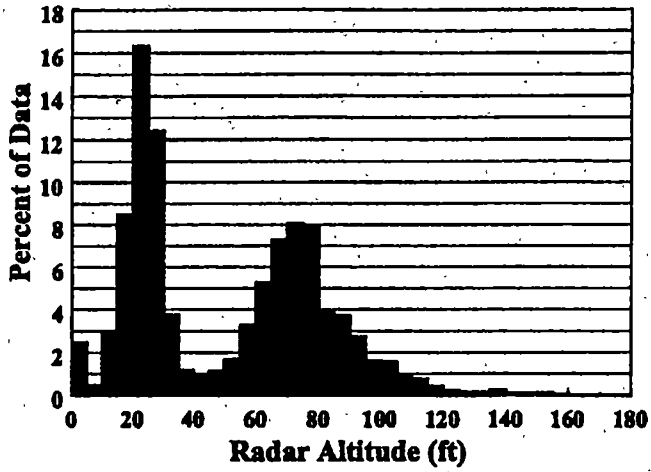


Figure II-14

TEST DATA ALTITUDE RANGE (ANALYTICAL METHOD)

Source: McCool, Kelly, M. Morales, D.J. Haas, *Neural Network Based Low Airspeed Sensor*, Paper presented at the American Helicopter Society 56th Annual Forum, Virginia Beach, VA, May 2-4 2000.

A special type of neural network map was used to train the system called a Self-Organizing Map (SOM). This type of network can map the multi-dimensional input space into a two-dimensional coordinate layer. Records from each coordinate were selected by sorting the records with a coordinate based on an influential parameter in order to guarantee its full representation. Records were selected from the center and the extremes of the sorted sequence. In this way the training set was insured of being compact yet representative. Five of these SOM's were constructed through the development of the low airspeed neural network, consisting of 4900 nodes. The following inputs were used to map out the neural network: Lateral Stick Position, Longitudinal Stick Position, Pedal Position, Engine torque (left + right /2), Yaw Rate, and Collective Stick Position. [Ref. 28]

The first advantage of this type of system is the total lack of additional moving parts. The system would rely on the position indicator measurements from another installed aircraft system. This type of approach would also free the airspeed measurements from rotor wash influence. No anti-ice capabilities are required for this system and its installation would not interfere with any previously installed weapon or sensor systems. The neural network used in the *McCool/Haas* study has a rout mean square (RMS) error of just under 3.0 knots and an RMS error for direction angle of 6.07 degrees. This level of accuracy is comparable to many of the mechanical systems currently available. An analytical low airspeed system can be deployed at low cost and with virtually no maintenance. [Ref. 28]

This type of analytical approach has not been manufactured or flight-tested in real time. The data was collected during flight on magnetic tape and analyzed post flight. With current computer processing available, the data could be analyzed and an airspeed produced at 8 Hz or better. According to Kelly McCool, a system could be produced and incorporated within the developed BF Goodrich IMD/HUMS system and use less than 2-3% of its processing capability. There is some technical risk since this method has not been flown with an indicator real time and the benefits in cost are dependent on the installation of the IMD/HUMS system. More accurate results could be obtained by developing the neural network after installing a reliable hardware system that measures low airspeed accurately. Using another low airspeed sensor would result in more accurate truth data than Doppler ground speed under low wind conditions and would improve overall accuracy of the output of the analytical approach.

2.5 LASER VELOCIMETRY

Laser Velocimetry uses non-intrusive optical methods for flow visualization. These techniques have been used as part of wind tunnel testing and since the 1970's have emerged as potential air-data systems due to the radar-observability penalty of intrusive probes (Pitot-systems) and the unsuitability of intrusive probes for hypersonic flight. In these systems optical sensors are mounted on the aircraft and measure the Doppler shift of laser energy back scattered off naturally occurring aerosol particles to determine aircraft velocity. The basic concept of the laser velocimeter is illustrated in Figure II-15, a one-dimensional view of the system geometry. [Ref. 7] In most applications, three orthogonal sensors are used in which the laser beam is split into three component beams. Each is focused at a standoff distance sufficiently removed from the aircraft to be in undisturbed flow (typically several meters away- outside the rotor down wash).

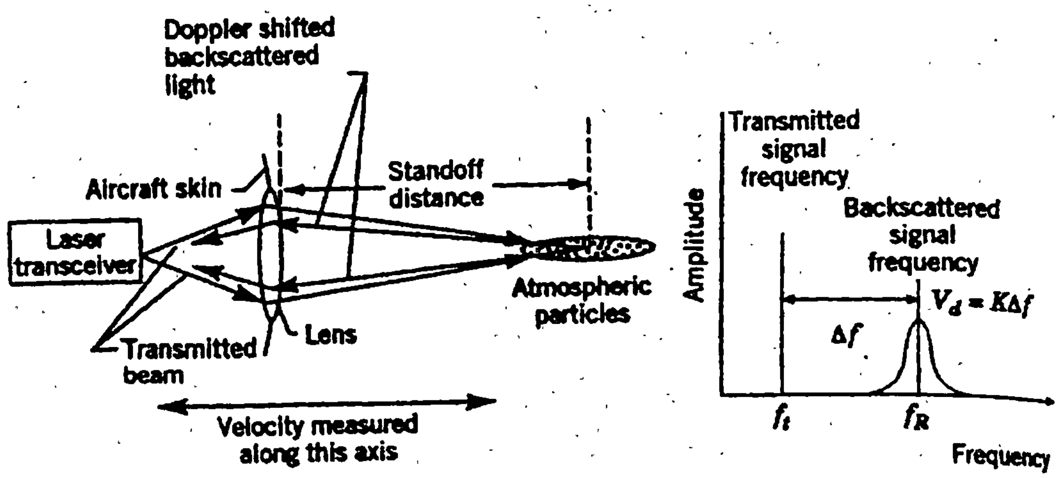


Figure II-15

TYPICAL LASER VELOCIMETER

Source: Kayton, Myron and Walter Fried, *Avionics Navigation Systems,* 2nd Edition. John Wiley & Sons Inc. New York. April 1997.

The lens configurations that converge the beams, with optimum polarization and geometric characteristics for maximizing back scatter response, are generally propriety with suppliers with such systems. [Ref. 7]

The reflected back scattered laser signal is Doppler shifted from the transmitted frequency by an amount proportional to the relative velocity between the aircraft and the undisturbed atmosphere. Back scattered signals are mixed with the transmitted signals using interferometers. Test results show accuracies of one knot or better at altitudes where particle (aerosol) density is adequate. Testing has shown that there is adequate aerosol density up to about 10,000 meters. Blending the inertial vector with an optically derived true airspeed vector allows for operations at higher altitudes. In 1996, laser velocimeters met the civil and military eye-safety standards, although there may be some question regarding the intensity at the focuses region. The trend is toward improving signal processing and lower-powered laser beams. [Ref. 7]

Honeywell Aerospace Electronics Systems, Coherent Technologies Inc. have produced the MAG-1 LIDAR for the dual purpose of Air Data Computation and Wire detection. The MAG-1 LIDAR uses the principle of laser velocimetry. In April 2000, Honeywell performed flight testing with the goal of demonstrating on a helicopter platform the capability to successfully perform wire detection measurements and perform the function of measuring relative wind and Indicated Airspeed (IAS) from the same sensor. The prototyped design interface and modifications successfully allowed a standard LIDAR wind sensing product to be used to show that this technology is a possible solution to the wire detection problem. The commercial off the shelf based signal processor was modified to display on a laptop computer the real time detection of wire within the sensor's field of view, and the relative wind and IAS regardless of aircraft heading and direction of flight. The LIDAR prototype was installed on an UH-60 helicopter. The installation was accomplished on the left side of the aircraft with the prototype system being mounted on the rear cabin floor. The MAG-1 Transceiver was pointed out through the left cargo door area with approximately a 20 degree angle to the aircraft centerline. The mounting bracket for the external stores station did partially obstruct the LIDAR Field of View (FOV). The control electronics and heat exchanger were mounted in the cargo bay on a pallet. For the UH-60 installation, a pallet was used to mount the electronic equipment on the cabin deck. Air data readouts from these initial tests were accurate but not stable due to the mounting constraints of the 20° offset and the lack of the real time aircraft attitude information. The LIDAR was mounted on the floor of the aircraft and no gyro stabilization was provided. This allowed for small aircraft attitude changes to bias the wind velocity as the LIDAR beam would move transverse through the air and create false readings. [Ref. 29]

Optical Air Data Systems, L.P. based in Manassas, Virginia is developing a laser velocimeter to accurately measure the low airspeed environment. Their patented approach uses an fiber optic source, which has the following advantages over many conventional approaches: [Ref. 30]

- OADS has reduced power consumption by using pulsed laser with optical fiber/amplifier master oscillation type configuration.
- Optical fiber eliminates mechanical laser cavities lowering size and weight and eliminating laser source susceptibility to vibration and temperature.

- Remote mounting of telescope via an optical fiber link provides for system flexibility to locate the sensor in a region with minimum impact on other systems.
- Erbium doped glass fiber laser for 1.54 μ wavelength light ensures eye safety
- High efficiency lasing, proven by the telecommunications industry, provides for an extremely low power system.
- Provides for look ahead capability – eliminates costly wind tunnel calibration of Pitot-tube installation since OADS measurement occurs in undisturbed airflow.

An all optical fiber Optical Air Data was developed and tested as part of a Phase II SBIR project. Significant improvements were made in the design and fabrication of a custom optical fiber amplifier which resulted in higher power levels and greater pumping efficiencies than previously existing technology allowed. A prototype sensor was fabricated and tested under various conditions to establish successful and accurate operation. Testing determined that a 1 μ sec long pulse was necessary to achieve 1 MHz frequency resolution to correspond for one-half knot accuracy.

The OADS measures the three dimensional relative velocity vector of the air stream with respect to the aircraft at a considerable distance (50 to 100 feet from the aircraft). These three velocity vector components are then resolved into true airspeed (TAS), angle of attack (alpha), and angle of sideslip (beta). It is important to note that the OADS measurement results in actual measurement of the True Airspeed directly, rather dynamic pressure as with a pneumatic system from which indicated airspeed must be deduced and thence True Airspeed calculated. This physical difference in the type of measurement performed results in a much greater accuracy and sensitivity of the OADS over pneumatic measurement. The OADS measurement, since it senses velocity directly, is divorced from all pressure, density, and temperature effects.

By projecting a laser beam a significant distance away from the aircraft surface, the actual air data sensing can be made to occur in relatively undisturbed airflow, as opposed to a Pitot-tube, which by its very nature cannot be made long enough to penetrate outside the flow disturbance created by the aircraft. This OADS measurement in "free stream conditions" automatically gives a significant improvement in air data accuracy. In fact, the OADS accuracy is limited only by the accuracy with which it is installed in the airframe, not by any instrument measurement accuracy. This is extremely important to the flight control designer since the availability of highly accurate data with no "Pitot lag" enables him to take full advantage of the performance envelope of the aircraft design. Further, use of an all fiber optic system allows for the remote location of almost the entire electro-optical system to a more benign, interior environment with only minimum projection on the optical sensor into the aircraft skin where space is minimum. Additionally, this probe can be mounted inside the aircraft where the sensor is protected from the effects of icing and other environmental effects [Ref. 30].

2.6 LOW AIRSPEED DISPLAYS

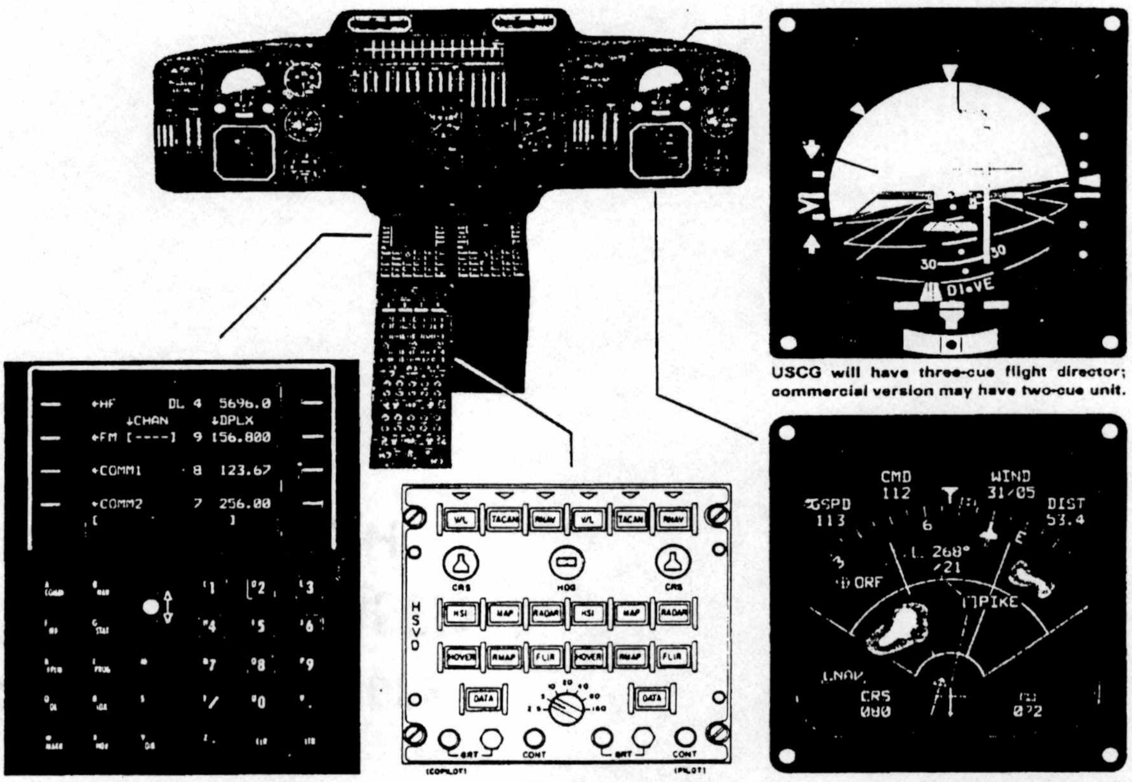
Of the low airspeed systems currently in use by helicopters, many do not have a dedicated low airspeed display.. Military attack helicopters that use low airspeed sensors for weapon systems for unguided rockets often do not incorporate a cockpit readout of the helicopter's velocity in the air mass. The lack of such a display inhibits the increase in situational awareness such a low airspeed display would provide to the helicopter pilot.

There are many different types of displays that could be used for a low airspeed system such as electromechanical, integrated, moving tape or fixed face type displays. A flexible integrated display would provide for several levels of improved situational awareness. An electromechanical display would be patterned after a standard Pitot-static airspeed indicator and driven from an electrical signal from an air data computer. This type of display would be expected to work down to the limits of the Pitot-static signal and might function adequately down to 20 knots calibrated airspeed in zero sideslip flight. Special airspeed component displays (or flexible integrated displays) would present forward/rearward airspeed on one display and sideward airspeed (sideslip) on a second display. These displays could be meter movements, tapes, or liquid crystal displays and would present resolved components of total airspeed generated by an omni-directional airspeed sensor. Electronic displays are ideal because they allow the data to be presented only when required during slow speed maneuvers. This presentation can occupy a portion of a large display or it can be one of many formats on a small multi-mode Cathode Ray Tube (CRT). Such data formats may be presented automatically once speed decreases below some value or manually selected by the pilot. This type of indicator could also be used during Instrument Meteorological Conditions (IMC) Flight in order to provide selection of sideslip and crab angles to correct/hold centerline during Instrument Flight Rules (IFR) approaches. The low airspeed indicator would decrease workload in maintaining constant airspeed during corrections to glideslope and during deceleration and acceleration on missed approaches. A low airspeed display would reduce workload during a deceleration through zero true airspeed during approaches with tail winds. It would help prevent spatial disorientation from lack of airspeed input at low airspeeds during IMC. Through use of power management techniques and a low airspeed indicator the pilot could avoid conditions with adverse power affects and take advantage of wind during One Engine Inoperative (OEI) approaches and landings. It would also allow for an accurate determination of winds at remote sites before flight.

The Pacer LORAS was the only system available with a developed Omni-directional Airspeed Indicator. Although when incorporated on the HH-65 and the AH-64A helicopters the Coast Guard and the Army did not opt to install such a display. The HH-65 uses a Horizontal Situation Display (HSI), depicted in Figure II-16, with a selectable menu for approaches to display wind conditions. [Ref. 31] The AH-64A display [not presented] only presented a vector magnitude reading of wind conditions.

The LORAS Omni-Airspeed Indicator (OAI) (Figure II-17) presents True Airspeed from zero to 150 knots, via a pointer, which moves up in the left side of the indicator. In addition, component speeds were presented up to a limit of 60 knots forward, 40 knots rearward, and 50 knots right and left. The OAI was marked in accordance with the "Airspeed Convention" as stated in Ref. 5.. That is, as the aircraft moved forward from zero airspeed the horizontal bar would move up from center. For rearward flight, the bar moved down from center. The vertical bar moved right for right sideward flight and left for left sideward components. Density altitude was presented across the bottom of the indicator from zero to 10,000 feet. This Density altitude function was designed to operate only on command. [Ref. 28, 32, 33]

This low airspeed indicator was designed in the late 1970's could be updated for the modern cockpit. For helicopters with modern glass cockpits (such as the SH-60R and MH-60S) an integrated display concept approach could be used.



USCG will have three-cue flight director; commercial version may have two-cue unit.

Aptly named, dual control-display units manage all airborne avionics functions.

Central controller feeds both horizontal-situation video displays (HSVDs) on panel.

The HSVD can show combined radar map and conventional HSI among seven modes.

Figure II-16

COAST GUARD HH-65 DOLPHIN DISPLAY

Source: Green, David L. "Thanks, Coast Guard...We needed That", <u>Rotor & Wing International</u>, June 1980.

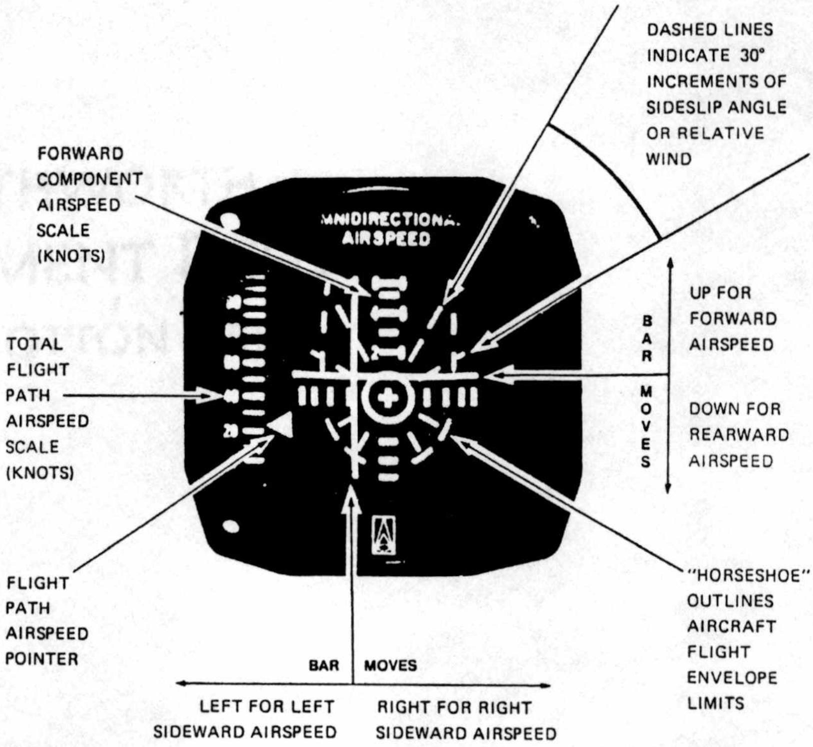


Figure II-17
LORAS LOW AIRSPEED INDICATOR

Source: Boirum, B.H, Dominick, Floyd, et al, *Flight Evaluation Pacer Systems Inc. LORAS II Low Airspeed System*, US Army Final Technical Report III, USAASTA Project No 71-30, , March 1974.

In this configuration, the low airspeed display could be selected when required through software input. When flight in the low airspeed region is anticipated (approach to landing, take-off, Coupled approached, Vertical Replenishment) the Pilot could select the low airspeed sensor as part of his critical flight parameters display. The low airspeed indicator or display would have to be integrated so it is included in the pilot's instrument scan pattern without increasing the pilot's workload for instrument flying.

For legacy aircraft such as the SH-60B/F and HH-60H incorporation of a low airspeed indicator could be accomplished through a multi-mode, dedicated display. This could be accomplished by installing it to the left of the right seat pilot's airspeed indicator on the instrument panel. This would allow for incorporation into a slightly modified instrument scan and reference by the copilot. This installation would lead to the least impact on installation. A commercial off the shelf (COTS) electronic display such as the Collins ASI-800 (Figure II-18) or a modification of the Eventide Airborne Multipurpose Display (EAMED) (Figure II-19) would be ideal. As minimum, the display should include a vertical and horizontal bars to indicate relative airspeeds. The display should have a digital readout of wind speed magnitude and direction and be marked with appropriate limits depending on selected mode of flight.

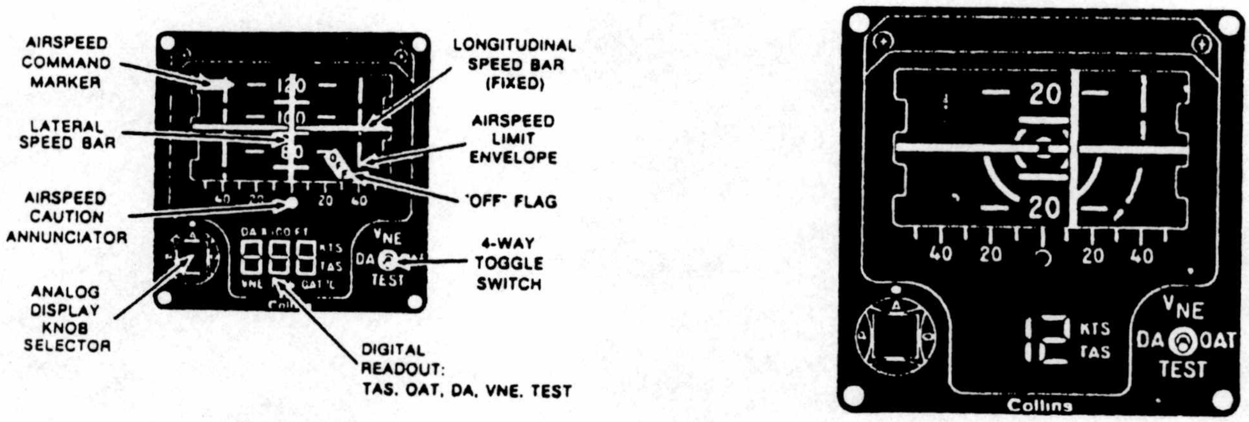


Figure II-18
COLLINS ASI-800 DISPLAY

Source: Green, David L. & Kimberlin, Ralph D, *Helicopter Unique Instrument Approaches: Trajectories, Flying Qualities, Controls and Displays,* Paper for The Engineering Society For Advancing Mobility Land, Sea Air and Space International, Aerotec '94, Los Angeles, CA October 3-6, 1994.

Figure II-19
EVENTIDE DIGITAL DISPLAY

2.7 SENSOR LOCATION

The major difficulty in developing a low range airspeed sensor is the pressure and vortex influence caused by the main rotor wash. The HADS system was designed to use the rotor wash in the determination of airspeed. The analytical method and laser velocimeter could be incorporated so that the laser looks 1-2 rotor diameters outside the rotor wash into "clean air". The best location discovered from testing of low airspeed sensors through-out the late 1970's was directly above the rotor [Ref. 35]. In this region there is a pocket of clean air where reliable airspeed information down to hover and rearward flight. This region was not totally free from vortex disturbance from the spilling of air from high to low pressure regions but it was the best location.

The choice of location was a trade-off of cost versus performance. The above the rotor location would give the best performance, but tended to cost more due to aircraft modifications to the main transmission and rotor head. The next best location is under the nose. This location has been shown to function to approximately 20 knots after which the performance is severely degraded by rotor wash. The useful range can be extended (possibly to zero) by employing calibration data (used to correct sensed data before it is presented to the pilot). If the airspeed data is extended to zero airspeed, the sensor is blanked by the fuselage during rearward and sideward flight. Therefore the useful omni-directional range for a mounting underneath the fuselage is limited. [Ref. 35]

The BAE Swiveling Pitot, Helicopter Air Data System (HADS) must be mounted in a location be influenced by the rotor wash. The HADS system was tested on the UH-60A airframe (similar to the SH-60 aircraft) and its installation point can be seen in Figure II-20.

Figure II-20
HADS INSTALLATION ON UH-60A

PART III

SH-60 AIRCRAFT AND MISSION DESCRIPTIONS

3.0 SH-60B SEAHAWK

The SH-60B, as depicted in Figures A-1/2, is a single main-rotor, twin engine helicopter manufactured by United Technology Corporation, Sikorsky Aircraft Division. The principal dimensions and turning radius can be found in Figures A-7 and A-10 respectively. The helicopter has a fully articulated four bladed main rotor, tractor type tail rotor canted 20° up from the vertical, a controllable stabilator, and an automatic flight control system (AFCS), which was designed to provide basic autopilot functions. The main rotor blades and tail pylon are designated to be foldable for storage. The SH-60B is equipped with conventional fixed landing gear, a helicopter in-flight refueling (HIFR) system, an external cargo hook, a rescue hoist, a sonobuoy launch system, and weapons rack for carrying and launching external stores. In addition the helicopter is equipped with a flight-rated auxiliary power unit (APU) an anti-ice, and blade de-ice system, and all the necessary avionics and instrumentation required for instrument flight and mission accomplishment. The helicopter is powered by two T-700-GE-401C front-drive turboshaft engines manufactured by General Electric Company which are designed to provide a maximum continuous torque of 1662 shaft horsepower (shp), intermediate rating of 1,800 shp for 30 minute duration, and a selectable contingency power rating of 1,940 shp for 2 ½ minutes duration at sea level, standard day conditions. The SH-60B was designed for a flight crew of three, two pilots (one of them is designated as the Airborne Tactics Officer (ATO) for that mission) and an enlisted aircrew Sensor Operator (SO). The aircraft's internal fuel capacity is 590 gallons. The helicopter's average gross weight without stores is 18,500 lbs. The basic structural maximum gross weight is

21, 700 lbs. with external stores. A more detailed description of the SH-60B can be found in Reference 36.

The SH-60B was designed to deploy from LAMPS MK III configured frigates, cruisers and destroyers. The primary missions of the LAMPS MK III helicopter are surface warfare (SUW) and Subsurface Warfare (USW). When used in the SUW mission, the aircraft provides a mobile, elevated platform for observing, identifying and localizing threat platforms beyond the parent ship's radar and/or electronic surveillance measure (ESM) horizon. When a suspected threat is detected, classification and targeting data is provided to the parent ship via the data link for surface-to-surface weapon engagement. Penguin missile equipped aircraft may coordinate independent or coordinated attack, dependent upon the threat scenario.

In the VERTREP mission, the aircraft is able to transfer material and personnel between ships or between ship and shore. In the SAR mission, the aircraft is designed to search for and locate a particular target/object/ship or plane and to rescue personnel day or night using the rescue hoist. In the MEDEVAC mission, the aircraft provides for the medical evacuation of ambulatory and litter bound patients. In the COMREL mission, the aircraft serves as the receiver and transmitter relay station for over the horizon (OTH) communication between units. In the NGFS mission, the aircraft provides the platform for spotting and controlling naval gunfire from either parent ship or units.

The missions which would directly benefit from a low airspeed sensor are Search and Rescue (SAR), Visit Board Search and Seizure (VBSS), vertical replenishment (VERTREP) and take-off and landings from air capable ships (frigates, cruisers, and destroyers). Often the majority of the SH-60B's missions are flown at night or during restricted visibility, and a low airspeed sensor would greatly aid situational awareness during these missions.

3.1 SH-60F SEAHAWK

The SH-60F, depicted in Figure A-3/4, has many of the same basic systems as the SH-60B. The principal dimensions of the SH-60F and turning radius can be found in Figures A-8 and A-11 respectively. The basic airframe layout (with the exception of main cabin), engines and flight controls are identical. The primary difference between the aircraft exists mainly in the mission systems. The SH-60F is equipped with the AN/ASQ-13F dipping sonar. The SH-60F incorporates a gravity sonobuoy launch system vice the sonobuoy rack and pneumatic launch system found on the SH-60B. The SH-60F does not include a radar, data link, or electronic surveillance measures (ESM) system similar to that on the SH-60B. The SH-60F's primary mission is anti-submarine warfare (ASW) defense of the aircraft carrier inner zone, which includes the detection, classification and destruction of hostile submarines. Secondary missions for the SH-60F are combat search and rescue (CSAR) and naval special warfare support (insertion of Navy SEAL Team members). Additional missions performed include logistics support, vertical replenishment (VERTREP), anti-surface warfare (SUW) and medical evacuation (MEDEVAC). A more detailed description of the SH-60F can be found in Reference 37.

The primary missions for which the SH-60F crew would benefit from a low airspeed sensor are Search and Rescue (SAR), Dipping Sonar operations, vertical replenishment (VERTREP), and take-off and landing from air capable ships (cruisers, frigates, and destroyers). SH-60F pilots would also benefit from the increased situational awareness a low airspeed sensor could provide during Combat Search and Rescue and

Naval special warfare missions where power management and flying quality awareness are critical.

3.2 HH-60H SEAHAWK

Combat Search and Rescue and naval special warfare support is the main mission of this version of the Seahawk. The General arrangement is depicted in Figures A-5/6. The pricipal dimensions and turning radius for the HH-60H can be found in Figures A-9 and A-11 respectively. The HH-60H cabin has a small avionics rack and has provisions for up to 10 passenger seats. The HH-60H has no anti-submarine warfare weapons or sensors. It is equipped with two M-60D/M-240 machine guns or two GAU-17A mini-guns, s stores jettison system (countermeasures), and aircraft survivability equipment. A more detailed description of the HH-60H can be found in Reference 37.

The primary missions for which the HH-60H crew would benefit from a low airspeed sensor are Combat Search and Rescue, Naval special warfare missions, Search and Rescue (SAR), vertical replenishment (VERTREP), and take-off and landing from air capable ships (cruisers, frigates, and destroyers).

3.3 MH-60S SEAHAWK

Initially developed as the direct replacement for the CH-46 Sea Knight the MH-60S will not only perform the logistics mission, but also Naval Special Warfare Support (NSW), Anti-Surface Warfare (ASUW), Combat Search and Rescue (CSAR) and Search and Rescue (SAR) missions. Secondary missions include the recovery of torpedoes, drones, Unmanned Aerial Vehicles (UAVs) and Unmanned Undersea Vehicles (UUVs); Noncombatant Evacuation Operations (NEO); aeromedical evacuations (MEDEVAC); station SAR, range support, executive transport, and humanitarian assistance and disaster relief. The MH-60S as of March 2001 are in developmental testing with an expected deployment of Summer 2002. The aircraft is designed for a maximum gross weight of 23,500 lbs. The aircraft is a new production aircraft built by Sikorsky Aircraft in Stratford CT combining Army Blackhawk (UH-60) airframe with Navy Seahawk main rotor dynamic transmission and dynamic rotor components. The cockpit is a glass cockpit developed by Lockheed Martin Federal Systems in Owego, NY which is designed to be common with the SH-60R aircraft. The MH-60S was designed to be operated with a crew of 4- 2 pilots and 2 crewman. The cabin can be configured to hold a maximum of 13 passengers or combat equipped troops. The maximum cargo hook load is limited by power maximum gross weight of aircraft to 6,716 lbs. with full internal fuel tanks and the cargo hook is limited to 9,000 lbs.

With the development of mine countermeasures capability to be resident within the Carrier Battle Group and Amphibious Ready Group, new systems will be introduced to the fleet for this mission. These systems which include the AQS-20/X Helicopter towed underwater sensor, Airborne Laser Mine Detection System (ALMDS), and Organic Surface Influence Sweep (OASIS) will be employed on the MH-60S between Fiscal Year (FY) 2005 and FY 2006.

The MH-60 crew would benefit from a low airspeed sensor during vertical replenishment missions (primarily flown in the low speed environment), Search and Rescue, Combat Search and Rescue, Naval Special Warfare Support and anti-mine operations. The MH-60S common glass cockpit is ideal for integration of a selectable low range airspeed display for operating in that environment.

3.4 SH-60R SEAHAWK

The SH-60R program began as an avionics and weapons system upgrade for the SH-60B. The acquisition program has evolved into the re-manufacturing of existing SH-60B and SH-60F into the new SH-60R (hence the "R" designation). The cockpit will be upgraded with a glass cockpit common with the MH-60S. Current plans call for the induction of existing SH-60B's and SH-60F's into a process where the tail section (aft of the fold hinge) will be saved along with the rotor system dynamic components and engines. The airframe forward of the tail will be rebuilt and make provisions for new weapons systems yielding an airframe with an increased service life from 10,000 hours to 20,000 hours. The core missions of the SH-60R will be Undersea Warfare (USW) and Anti-Surface Warfare (ASUW). The SH-60R has been designed to operate with a crew of three, two pilots, and enlisted sensor operator (SO). The new weapon and sensor systems to be incorporated in the SH-60R include a new Multi-Mode Radar (MMR) AN/APS-147 which includes Inverse Synthetic Aperture Radar modes and periscope detection, new Electronic Surveillance Measures (ESM) AN/ALQ-210, new dipping sonar AN/ASQ-22, and an Integrated Self Defense System (ISD). To be able to carry all these new systems, the maximum gross weight has been increased to 23,500.

In addition to the missions of the SH-60B and SH-60F the increased gross weight would justify the incorporation of a low airspeed sensor for improved power management situational awareness. The SH-60R will be operating a higher gross weights, with smaller power margins, which will require better power management and flying quality situational awareness by the pilots. While one type of maneuver or approach in a 21,700 lb. SH-60B might be safe, it may have greatly increased pilot workload and power required in the SH-60R. The glass cockpit common to the MH-60S would be ideal for integration of a selectable low range airspeed sensor.

3.5 INSTALLATION CHALLENGES

The primary challenge to installing a low airspeed sensor is finding a location that will be free of rotor down wash influence (or designed to operate in the rotor down wash). Previous installations of low airspeed systems on helicopters have found that directly above the rotor to be the ideal location for the sensor. All Naval models of the Seahawk incorporate an automatic blade-folding system and a hydraulic accumulator built into the top of the rotor head as seen in Figure III-1.

This hydraulic accumulator provides pressurized hydraulic fluid to each of the four main rotor dampers on the rotor head. This accumulator presents to biggest challenge to any system, which would reside on top of the rotor head. A standpipe type installation as used for previous installations would be nearly impossible to incorporate without a complete rotor head system re-design. This type of design change would be extremely expensive and difficult to justify since there other low airspeed systems which would not require such modifications.

Another challenge to the standpipe type installation would be the design of the main transmission of the Seahawk. Figures III-2 and III-3 depict the basic module and the interior of main transmission module of the Seahawk in order to appreciate the complexity of the design of the main transmission and extend to which modifications would be required to run a fixed standpipe through the transmission module to the main rotor head. [Ref. 38]

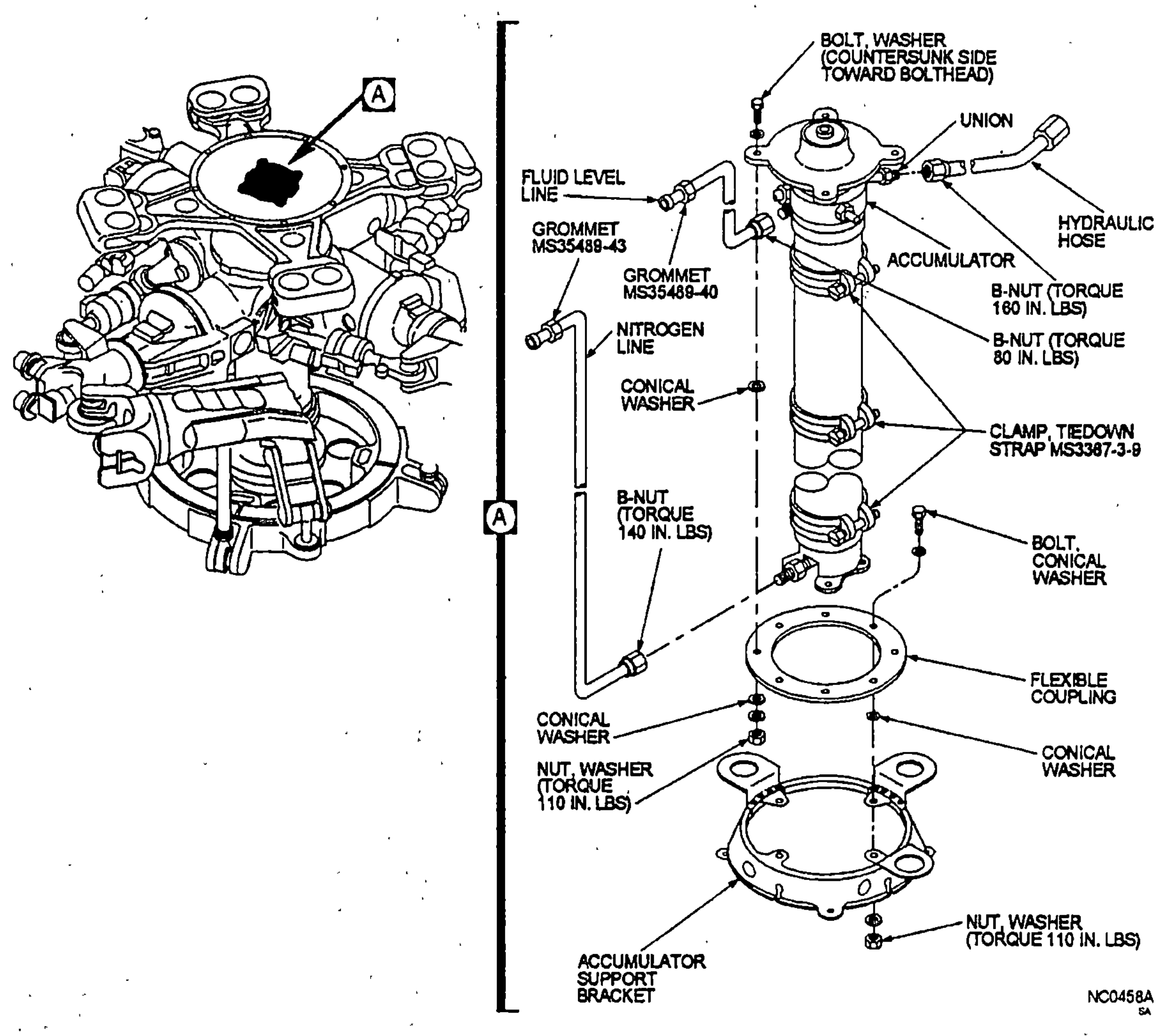


Figure III-1

MAIN ROTOR ACCUMULATOR SYSTEM

Source: Chief of Naval Operations, H-60 Depot Level Technical Manual, A1-826QA-MDB-200, Change 1, 30 September 1998

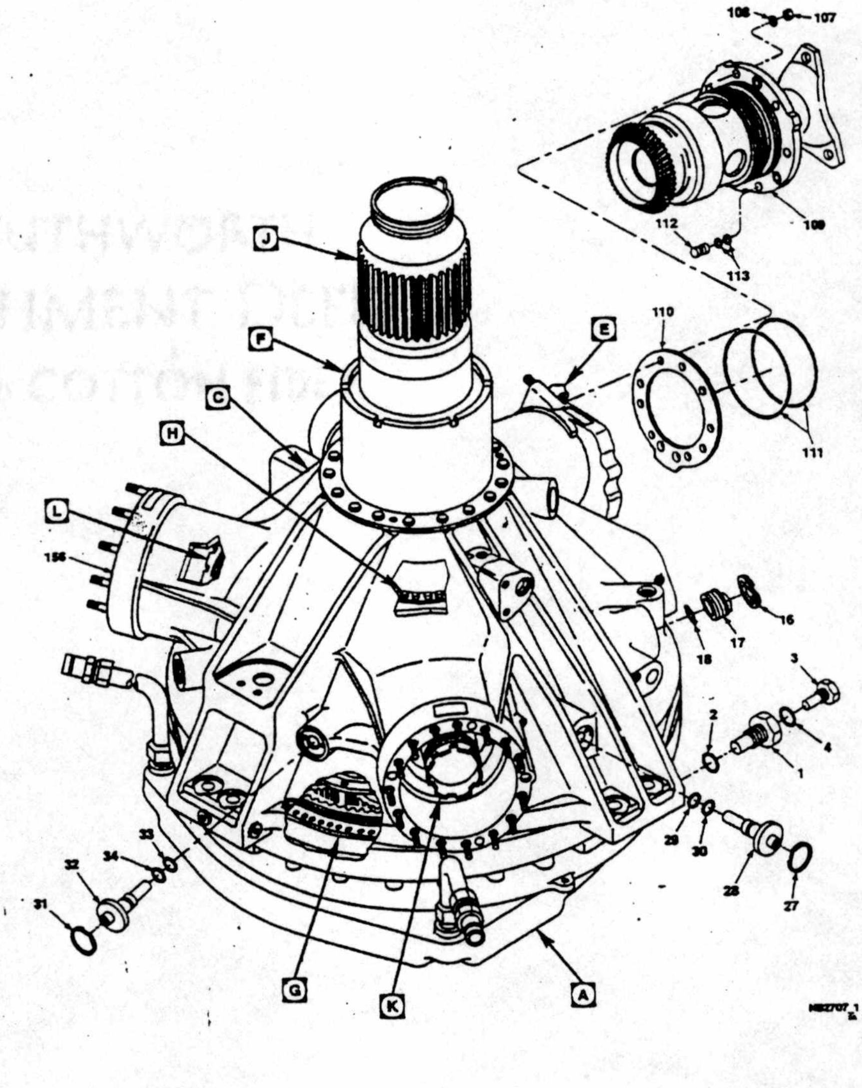


Figure III-2

MAIN TRANSMISSION MODULE

Source: Chief of Naval Operations, H-60 Depot Level Technical Manual, A1-826QA-MDB-200, Change 1, 30 September 1998

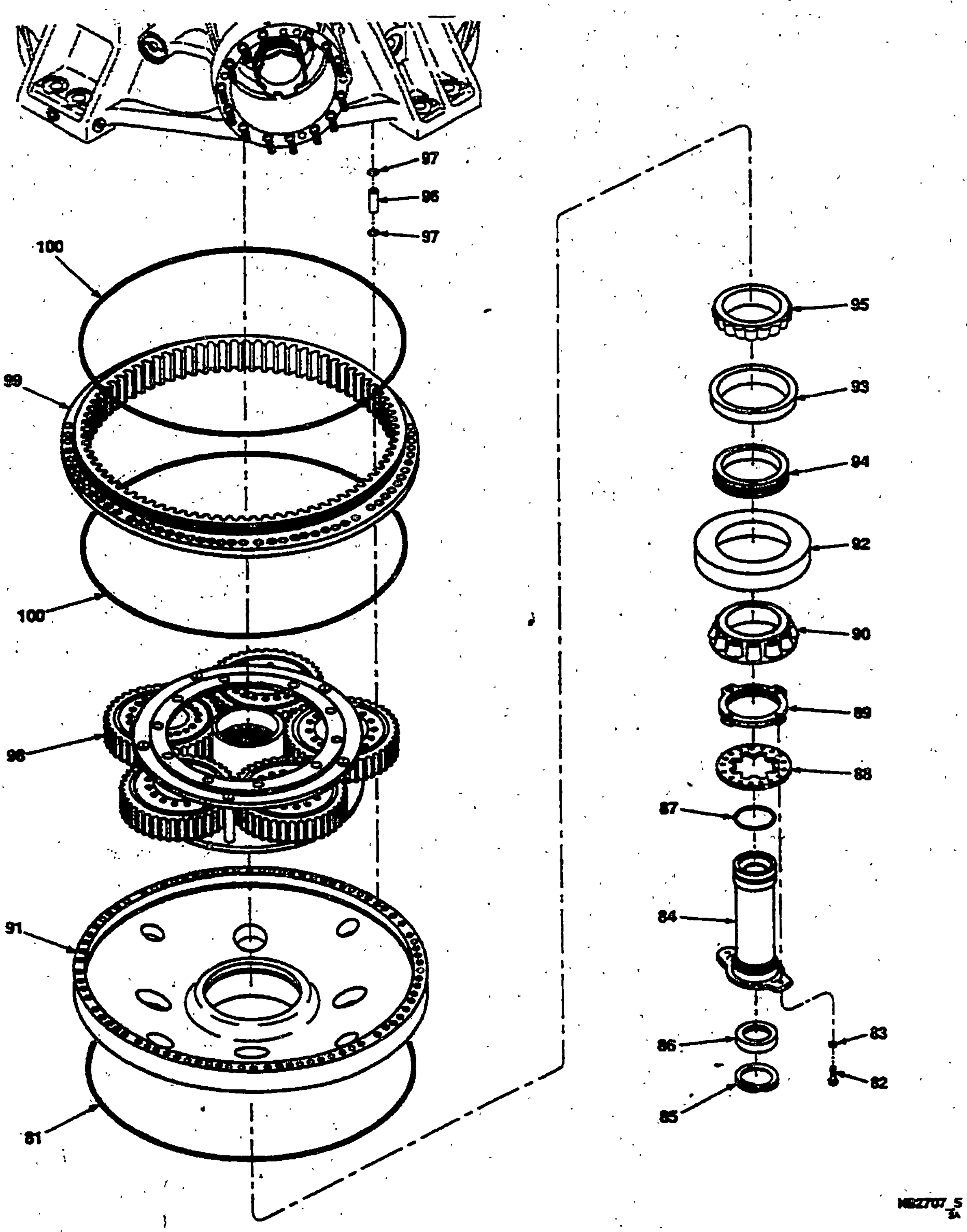


Figure III-3

INTERIOR MAIN TRASMISSION MODULE

Source: Chief of Naval Operations, H-60 Depot Level Technical Manual, A1-826QA-MDB-200, Change 1, 30 September 1998

As Figure III-3 illustrates, there is no practical method for running a standpipe through the main rotor mast and main transmission. Even though the main rotor mast is hollow, a standpipe will not fit due to the wiring bundle that currently runs through the transmission for the blade de-ice system. The junction point for the de-ice system can be seen in Figure III-4.

Slip rings are already used for the blade de-ice and blade fold systems. Additional slip rings could be incorporated and wire bundles could be added for a low airspeed system that would rotate with the rotor head. This type of system would require additional filtering due to the increase in noise in signals with a slip ring type system.

For systems which would be mounted outside the aircraft (underneath or alongside), they have to contend with the various mission systems and antennas which are on the aircraft. A system mounted underneath the SH-60B, the system would have to be designed not to interfere with the APS-124 radar, data link, ESM antennas, RAST system and Doppler antenna. On the SH-60F, low airspeed systems would have to account for the Dipping sonar.

The control boxes for any system could be installed in the avionics transition section as depicted in Figure III-5. Locating these control boxes in the avionics transition section would help save the valuable space in the inside of the aircraft cabin and would not be too far from the sensor for any of the low airspeed sensor type installations. BAE System's Helicopter Air Data System has a 15 feet of Pitot-tubing length restriction for proper system operation.

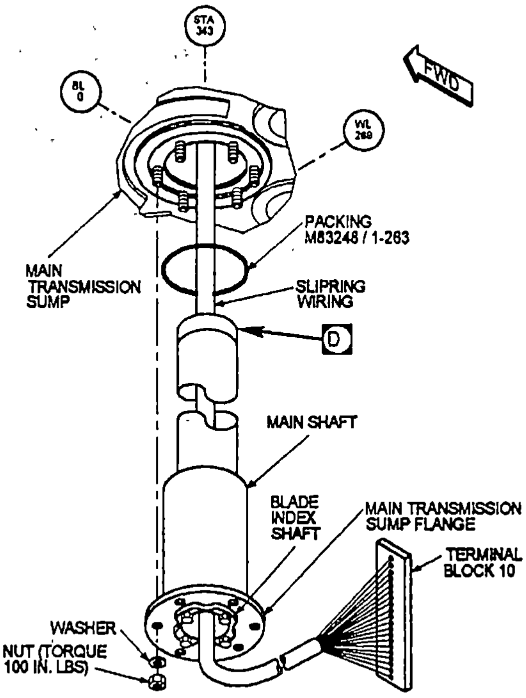


Figure III-4
MAIN ROTOR BLADE DE-ICE JUNCTION POINT
Source: Chief of Naval Operations, H-60 Depot Level Technical Manual, A1-826QA-MDB-200, Change 1, 30 September 1998

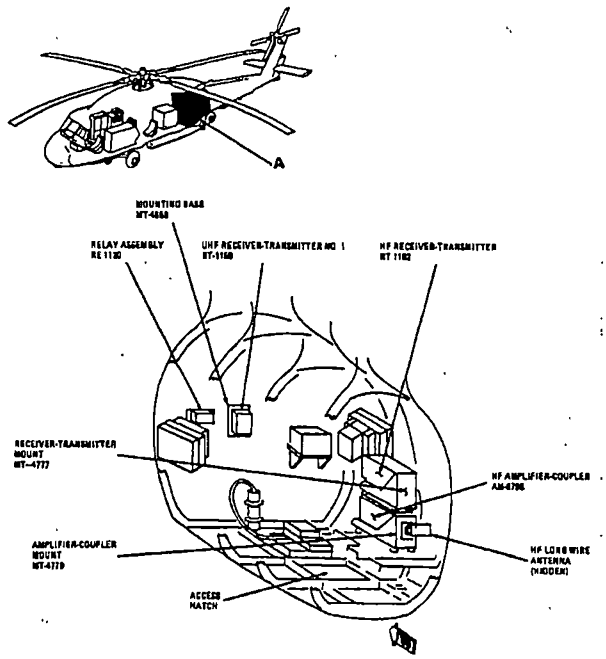


Figure III-5
SH-60B TRANSITION SECTION

3.6 LOW AIRSPEED INDICATOR LOCATION

The cockpit arrangements for the SH-60B (Figure III-6), SH-60F (Figure III-7), and HH-60H (Figure III-8) are depicted.

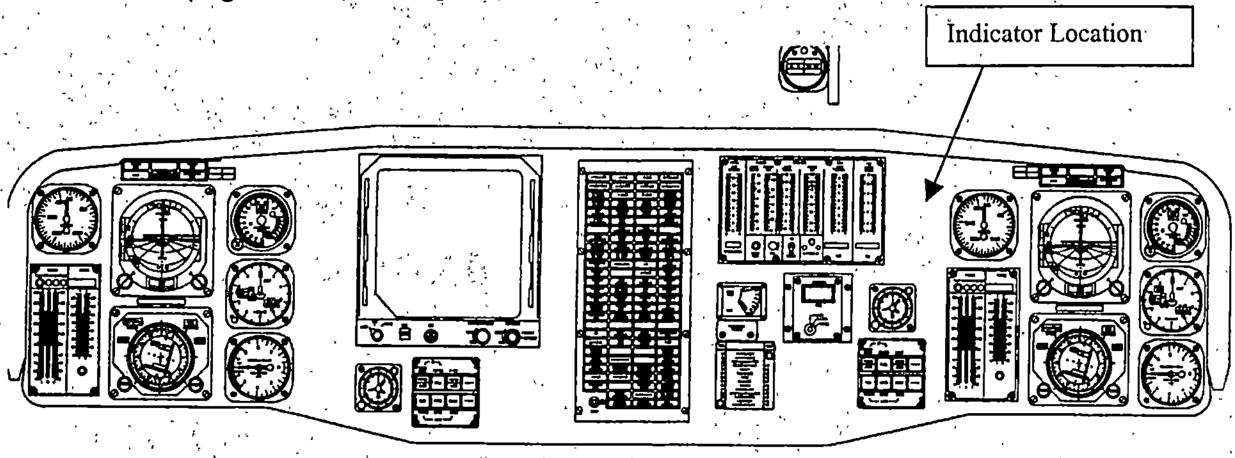


Figure III-6

SH-60B INSTRUMENT PANEL

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model SH-60B*, A1-H60BB-NFM-000, Change 1, 1 January 1998

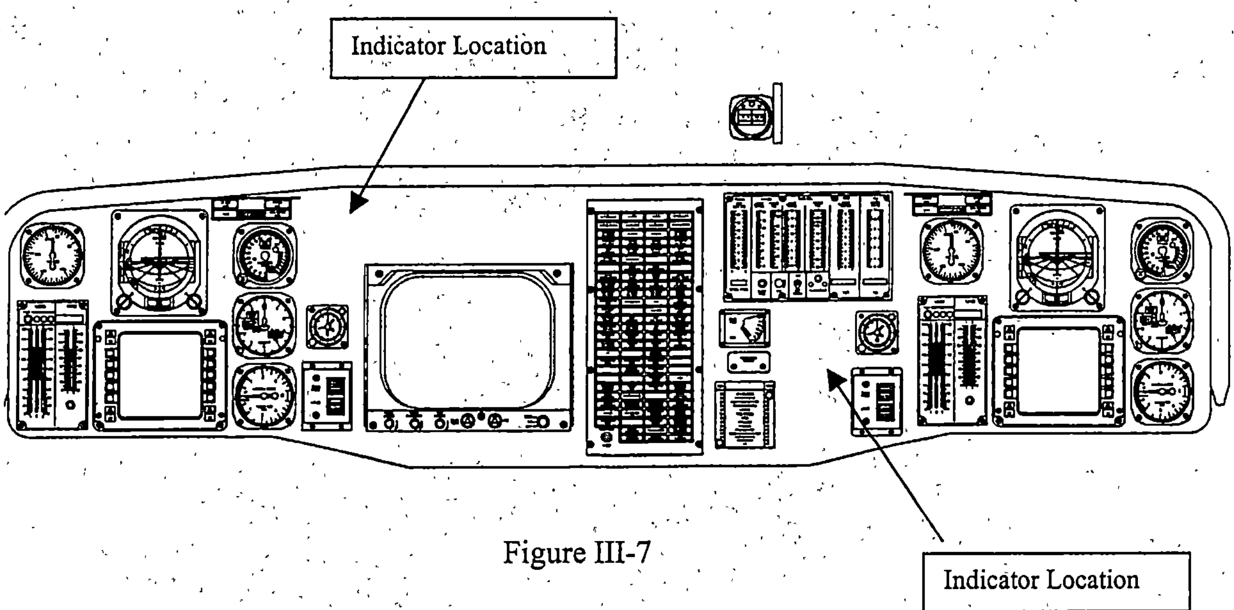


Figure III-7

SH-60F INSTRUMENT PANEL

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft*, A1-H60CA-NFM-000, Change 2, 7 March 1997.

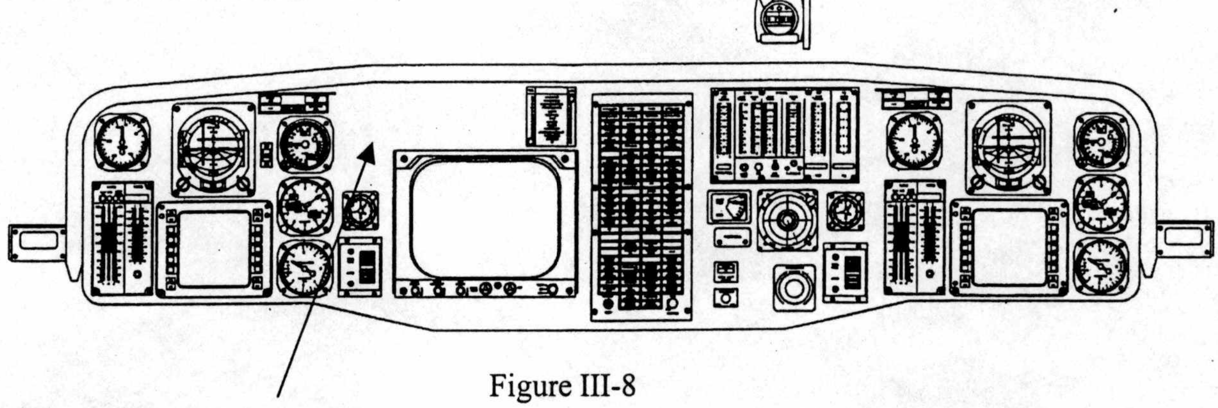


Figure III-8

HH-60H INSTRUMENT PANEL

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.

The SH-60B instrument panel (Figure III-6) gives the most room for incorporation of a low airspeed indicator to the left of the Pitot-Static airspeed indicator and the the right of the Central Display Unit (CDU) for the right seat pilot. To avoid major cockpit redesign, the best place for SH-60F (Figure III-7) is directly underneath the CDU. for the HH-60H above the Copilot's mission display. After pilots have been trained to use the Low Airspeed System, the low airspeed indicator could replace the Pitot-static airspeed indicator on the right pilot side and leave the Pitot system on the left pilot side as a backup.

The MH-60S and SH-60R could using existing Multi-function glass displays (not depicted) for incorporation of an integrated low airspeed display. This type of installation would minimize impact on the remainder of the cockpit layout.

PART IV

ANALYSIS OF SYSTEMS

4.0 ANALYSIS

In Part II, the physical description and theory of operation was presented for the various low airspeed systems in use or in development. Some advantages and disadvantages of the various systems were discussed. This section analyzes some basic characteristics of these systems for the Naval Seahawk. This analysis was very limited due to the proprietary information of many of the systems and the unknowns with many of the systems still in development. This section evaluates six systems (LORAS, HADS, DELTA, McCool's Analytical approach, Honeywell's LIDAR, and OADS laser velocimeter) against 17 characteristics that may affect the system's performance or incorporation on a naval helicopter. This list in not exclusive and many other characteristics could be evaluated prior to selecting the most beneficial system.

The cost of each low airspeed system was self-reported by each system contractor and was estimated as price per unit in a 1,000 units order. The performance of some systems was estimated based on the limited tests completed, and the lack of maturity of some systems to date. Size and weight of the system were based on currently used prototypes or manufactured systems. Vibration, environmental, and down wash susceptibility were based on flight test report data and best estimates when this information was not available. Technical risk was assessed based on the level of maturity of each system's architecture, and modifications required for use on SH-60 Seahawk. Table IV-1 provides for a comparative analysis of the six low range airspeed systems discovered during research.

Table IV-1
COMPARATIVE ANALYSIS OF LOW AIRSPEED SYSTEMS

System/ Characteristics	LORAS	HADS	DELTA	Analytical Approach	Honeywell LIDAR	OADS
Size	Medium	Medium	Medium[2]	Small[2]	Large [2]	Small[2]
Weight	Moderate	Moderate	Moderate[2]	Low[2]	Heavy [2]	Moderate[2]
Cost[3]	Moderate	Moderate	Low	Low	High	Moderate
Complexity of A/C Mod	High	Moderate	Moderate	Moderate	Moderate	Low
Longitudinal accuracy (± kts)	+/- 2	±2.5	+/- 0.1 [1]	+/- 3 [1]	±2	+/- 0.5 [1]
Lateral accuracy (± kts)	+/- 2	±6	N/A	+/- 3 [1]	±2	+/- 0.5 [1]
Sideslip accuracy (± °)	+/- 6	+/- 1	N/A	+/- 6 [1]	Unknown	Unknown
Dynamic response (Hz)	24	20	20	30	8	50
Anti-Icing provisions (Y/N/NR)	Yes	Yes	Yes	Not required.	Yes	Not Required.
Operating Temp Range (°C)	-55 to +54	-100 to +50	To be determined	-40 to +60	± 40	-40 to +60
Vibration Sensitivity	Low	Moderate	Unknown	Low	Moderate	Low
Environmental Sensitivity	Moderate	Moderate	High	Low	Moderate	Low
EMI Susceptibility	Low	Low	Low	Low	Low	Low
Influence by rotor wash	Moderate	Moderate	Moderate	Low	Low	Low
Technological risk	Low	Low	Moderate	Moderate	Moderate	Moderate

Notes:

1. Contractor assessment only. Needs to be verified through actual flight tests.
2. Based on initial prototypes/tests. Final assembly needs to be built.
3. Contractor estimate per unit cost for 1,000 units order.

The following qualitative comments are used for the ratings in Table IV-1:

Size:

Small	Volume less than 100 in^3
Medium	Volume > = 100 in^3 and < 500 in^3
Large	Volume >= 500 in^3

Weight:

Light	Weight of total system (sensor + processor) <= 2 lbs
Moderate	Weight of total system > 2lbs <= 10 lbs
Heavy	Weight of total system > 10 lbs

Cost (per system/1,000 unit order):

Low	Cost of total system < $5,000
Moderate	Cost of total system > $5,000 and <= $25,000
High	Cost of total system > $25,000

Complexity of Aircraft Modification Required for Installation of Sensor:

Low	No or minor aircraft modifications required. System can be installed by Organizational level maintenance in minimal time.
Moderate	Aircraft modifications required. These can be performed at organizational or intermediate maintenance facility or by modification team
Major	Major redesign of aircraft airframe, components, or systems. Depot level maintenance required.

Vibration Sensitivity:

Low	System not affected by aircraft vibration
Moderate	Aircraft vibration has minimal affect on system, but measures are taken so this does not affect system performance
High	Vibration adversely affects performance of system

Environmental Susceptibility:

Low	Design or location of sensor allows for no effect of sensor by rain, snow, ice, dust, salt spray, or sand
Moderate	Weather can effect system performance but there is no or limited adverse effects on system performance
High	Weather significantly impedes system performance

EMI Susceptibility:

Low	System not affected by EMI
Moderate	EMI has limited affects on system, but measures (shielding) are used in order not to affect performance
High	EMI adversely affects system performance

Influence by Rotor Wash:

Low	System not affected by rotor wash (sensor internal to aircraft or incorporated in such a way not to be influenced).
Moderate	System influenced by rotor wash, but accounts for flow and accuracy of sensor does not suffer.
High	System highly affected by rotor flow resulting in large inaccuracies or discontinuities in data

Technical Risk:

Low	System is developed, deployed and in use by helicopters
Moderate	Developed system, working prototype constructed some flight tests conducted, but tests not complete
High	Developing system, limited tests ground/flight tests, system development not complete

The LORAS and HADS systems present the most stable designs since they have both been incorporated into existing helicopter systems and have been extensively tested over the past 15 years. The least expensive approach would probably be the analytical approach, combining a low airspeed algorithm routine into the IMD/HUMS system. In the analytical approach the sensor hardware would already be installed and the neural network routine and interfaces would have to be included and flight tested. The analytical approach would however incur risk since all the data points would have to be flown which would present risk during flight test, and it would require a low airspeed sensor as truth data during development.

The DELTA system, while a unique approach, is not ideal since the system is not omni-directional. The DELTA system would also have to content with the myriad of problems of finding a suitable location on the airframe that would not be influenced by rotor wash and would not interfere with any installed mission systems or equipment.

The LIDAR systems are a cutting-edge approach to the low range airspeed problem. The problems that plagued the LIDAR development for stealth aircraft (insufficient particles above 10,000 feet pressure altitude) would have no effect on the naval helicopter which is restricted from flight above that altitude. Current lasers can be made with low power requirements, light weight, low cost, and eye-safe. The Honeywell LIDAR at the time of testing was large and very susceptible to airframe vibration [Ref. 29]. The system used optical lens to focus the laser and this critical alignment would be difficult to maintain during with the inherent vibration of the aircraft. This system would also have to be mounted outside the aircraft in such a way not to interfere with installed mission systems. The OADS system is certified eye-safe, and its fiber-optic lines would eliminate the alignment problems for conventional lens. The frequency of the laser is such that it is optimized to pass through glass, and the sensor could be placed inside the aircraft (eliminating environmental concerns and anti-icing requirements) on the windscreen where it could look 1-2 rotor diameters ahead of the aircraft into the undisturbed flow. The fiber optic cables could transmit this signal to anywhere in the aircraft where a small control box could be located. This system also is moderately priced for a low airspeed system, but has the potential for providing the most accurate airspeed reading possible.

After comparing the characteristics of the six sensors, the best approach for the SH-60 series helicopter would be the Analytical approach or the OADS LIDAR approach. While the LORAS and HADS are low technical risks due to being in productions, they have technical challenges to be overcome. For the LORAS system, a redesign of the rotor head accumulator/ main transmission or LORAS sensor would be required. The HADS system does not provide the desired accuracy, when compared with other systems. The non-linear nature of the HADS system when the sensor goes from in the rotor wash to out of the rotor wash may be confusing to pilots for use as a cockpit indication of low airspeed.

The Analytical approach presents the biggest advantage of using installed aircraft sensors and equipment with the installation of the IMD/HUMS system. This method presents some technical risks since the system is not fully developed. While some flight tests were conducted full aircraft incorporation and multiple neural networks need to be completed for various aircraft weights and aircraft configurations. Since a neural network does not extrapolate well, these flight conditions need to be tested in order to build a complete model. To make this configuration more accurate a low airspeed sensor should be used as truth data.

The OADS sensor presents advantages to accuracy, size, weight and minimizes vibration, environmental effects, vibration and rotor sensitivity. The sensor is still in development and a prototype sensor could be ready for flight test with a few months if funded.

PART V

CONCLUSIONS AND RECOMMENDATIONS

5.0 CONCLUSIONS

The SH-60 Naval Seahawk should have a low airspeed system included in the operational requirements document (ORD). The incorporation of a low airspeed sensor and display will improve situational awareness for improved power management. This improvement in situational awareness will result in fewer mishaps.

Based on the analysis in Part IV, the best approach towards incorporating a low airspeed system is an analytical type system or the fiber optic laser velocimeter produced by Optical Air Data Systems (OADS). These types of systems are the lightest, most cost-effective systems, providing the most accurate results.

If both systems are developed concurrently, the laser velocimeter could be used to as the truth data source for flight testing of the analytical approach. Both systems will require further flight testing to determine how to best incorporate on the Seahawk. Additionally, flight testing will determine with best location for the OADS sensor and test the ability of the analytical approach to process information fast enough to be useful in a flight display.

The inclusions of a low airspeed display is critical to the benefits of a low airspeed system. A selectable electronic display that displays relative airspeed information in relation to limitations for the regime of flight would be the ideal type of display.

5.1 RECOMMENDATIONS

The incorporation of a low airspeed sensor in helicopters remains a challenge particularly since many of the missions best suited for helicopters require operation at low airspeed. Further research and development of low cost, accurate sensors should be a priority for the helicopter community. Specific recommendations include:

- Flight testing of the analytical approach and OADS laser velocimeter for incorporation on the SH-60 Seahawk.
- Incorporation of a low airspeed sensor and display onto Fleet Replacement Squadron (FRS) aircraft to instruct fleet pilots on the use of such sensors and power management techniques. The installation of low airspeed sensor in FRS aircraft will generate fleet interest and help overcome the current paradigm against use development of such systems.

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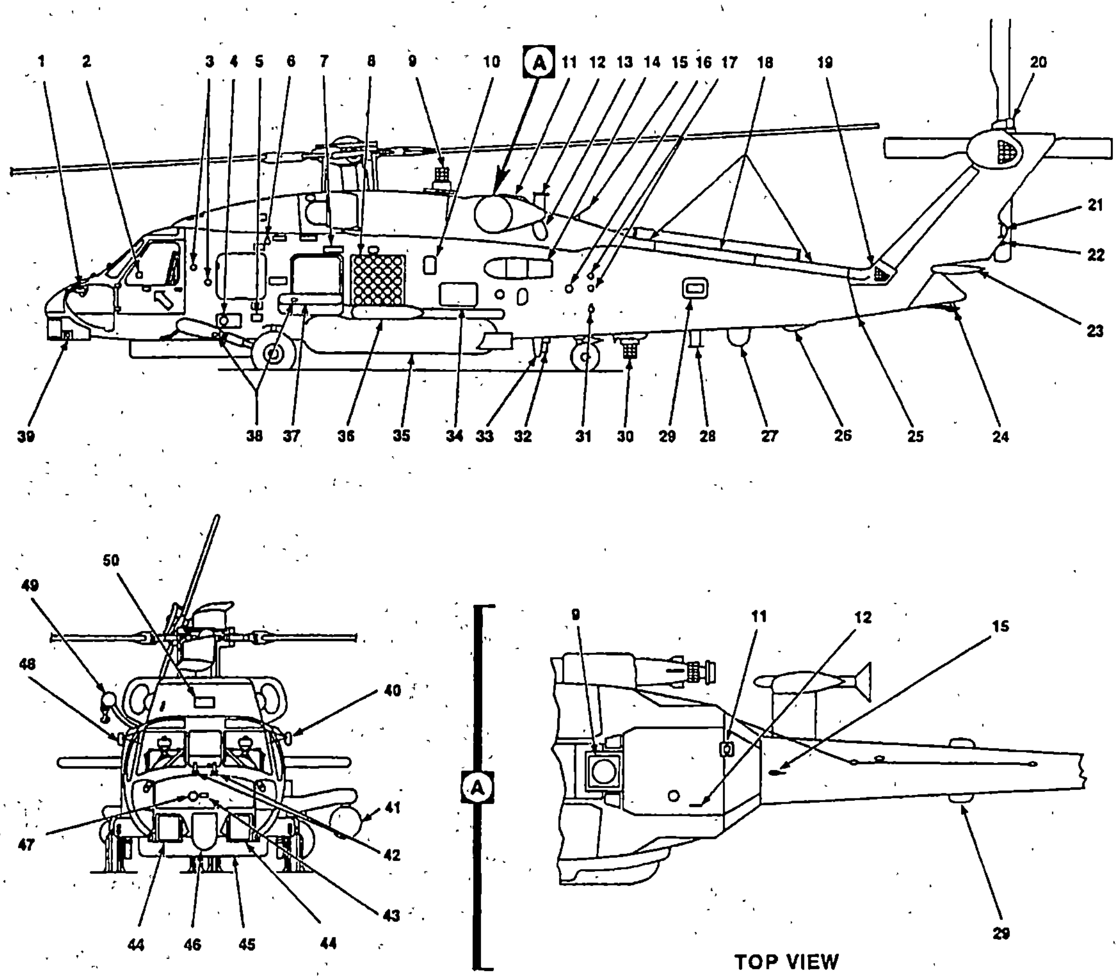
APPENDICES

APPENDIX A

HELICOPTER GENERAL ARRANGEMENTS,

PRICIPAL DIMENSIONS,

AND TURNING RADIUS



1. LEFT PITOT TUBE
2. COCKPIT WINDOW VENT
3. STATIC PORTS
4. AVIONICS COOLING EXHAUST
5. EXTERNAL ICS / ARM PANEL
6. MOORING SHACKLE
7. ENGINE WASH / SONOBUOY LAUNCHER CHARGER PANEL
8. SONOBUOY LAUNCHER
9. UPPER IRCM TRANSMITTER
10. GRAVITY REFUELING PORT
11. GPS ANTENNA
12. UPPER VHF / UHF / IFF ANTENNA
13. APU EXHAUST
14. ESM ANTENNA
15. EMERGENCY LOCATOR ANTENNA
16. FIRE EXTINGUISHER FRANGIBLE DISC
17. TAIL WHEEL STRUT INSPECTION WINDOW
18. TAIL ROTOR DRIVE SHAFT COVER
19. INTERMEDIATE GEAR BOX
20. UPPER ANTICOLLISION LIGHT
21. AFT MISSILE DETECTION SENSOR
22. TAIL POSITION LIGHT
23. STABILATOR
24. TAIL BUMPER
25. PYLON FOLD ASSIST CONNECTOR
26. REMOTE COMPASS
27. AFT DATA LINK ANTENNA
28. LOWER VHF / UHF / TACAN ANTENNA
29. CHAFF / FLARE DISPENSER
30. LOWER IRCM TRANSMITTER
31. MOORING SHACKLE
32. LOWER ANTICOLLISION LIGHT
33. SONOBUOY ANTENNA
34. PRESSURE REFUELING PORT
35. EXTERNAL FUEL TANK
36. INBOARD LEFT PYLON
37. OUTBOARD LEFT PYLON
38. POSITION LIGHT
39. FORWARD MISSILE DETECTION SENSOR
40. ATO'S REAR VIEW MIRROR
41. PENGUIN MISSILE
42. OUTSIDE AIR TEMPERATURE SENSOR
43. AVIONICS COMPARTMENT COOLING DAMPER DOOR
44. FORWARD ESM ANTENNA
45. SEARCH RADAR ANTENNA
46. FORWARD DATA LINK ANTENNA
47. TACAN ANTENNA
48. PILOT'S REAR VIEW MIRROR
49. RESCUE HOIST
50. HYDRAULICS BAY COOLING INLET

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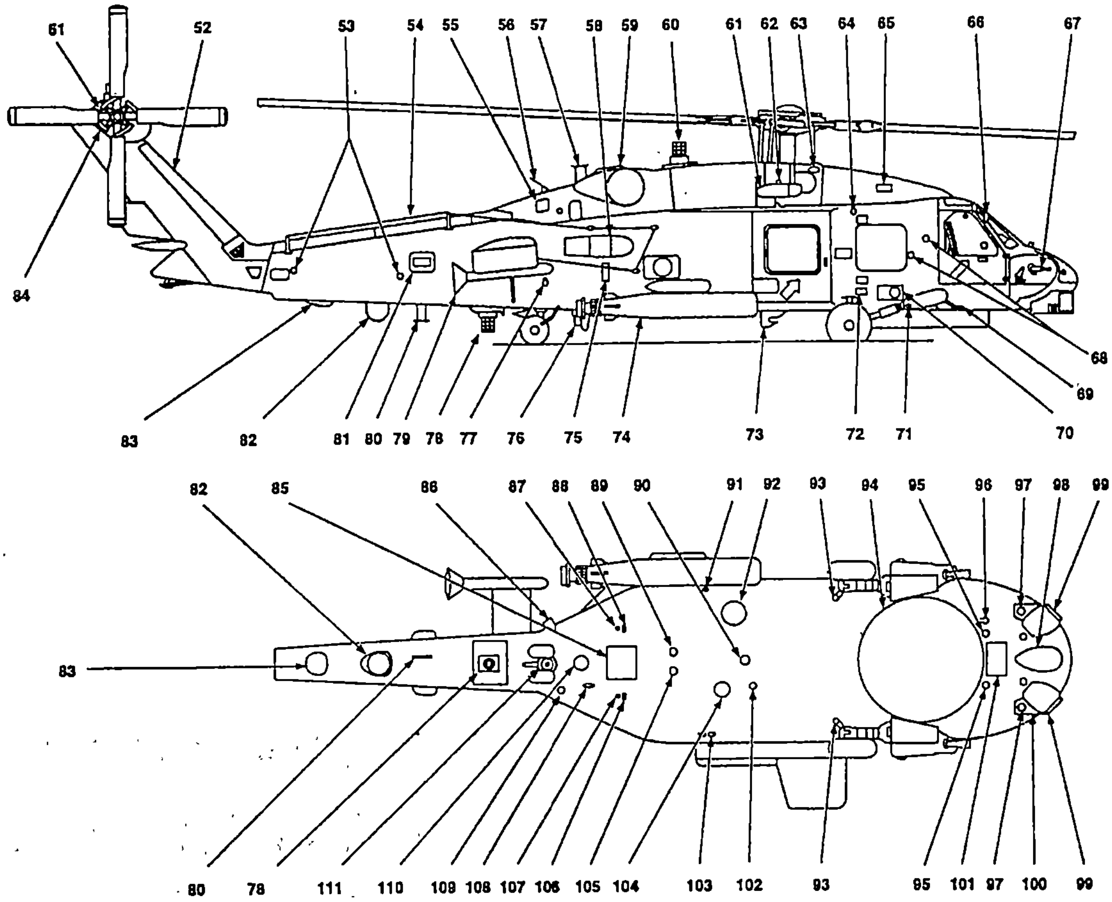
Figure A-1
SH-60B GENERAL ARRANGEMENT

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model SH-60B,* A1-H60BB-NFM-000, Change 1, 1 January 1998

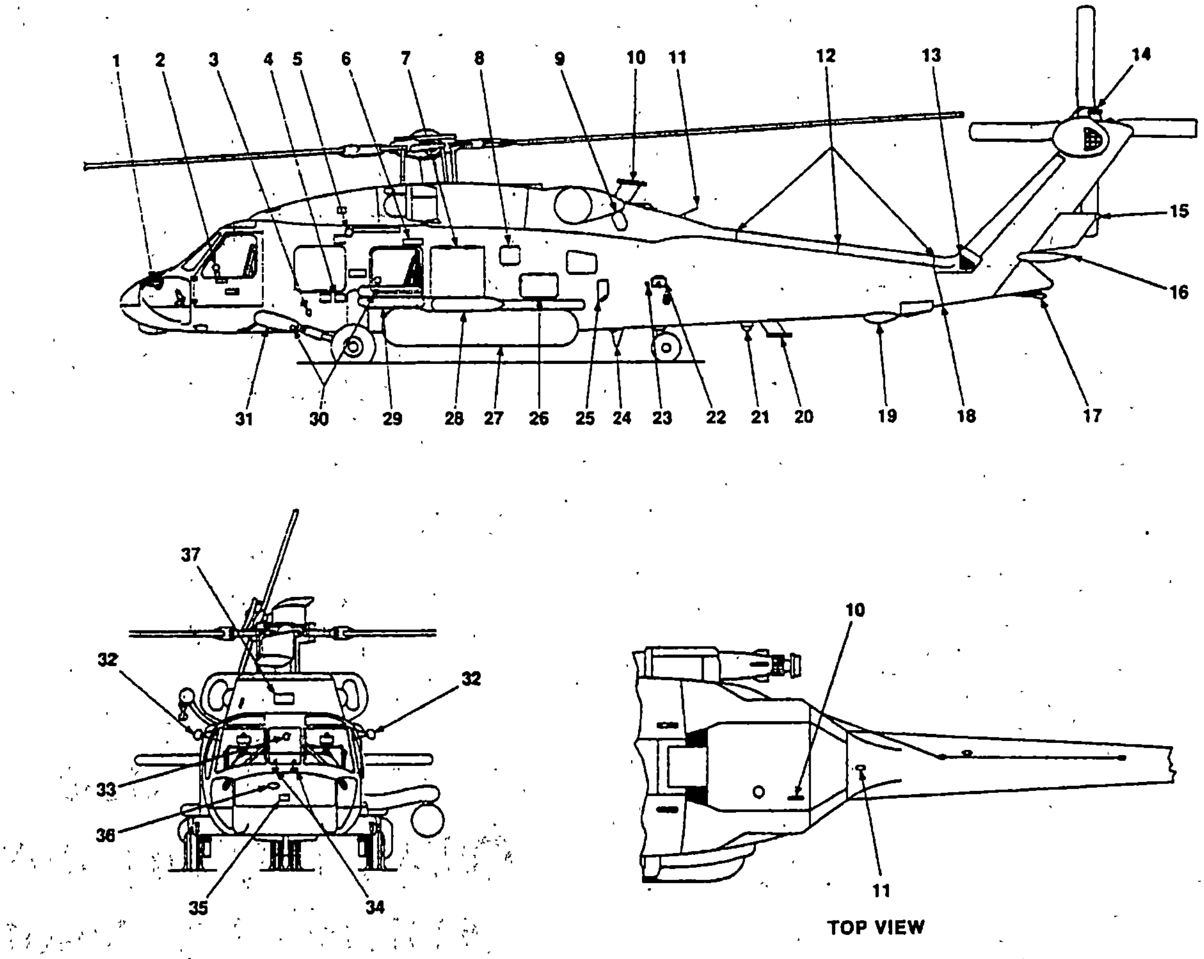


51. TAIL ROTOR
52. PYLON DRIVE SHAFT
53. BLADE STOWAGE SUPPORT
54. HF ANTENNA
55. ECS EXHAUST
56. EMERGENCY LOCATOR ANTENNA
57. UPPER VHF / UHF / IFF ANTENNA
58. ESM ANTENNA
59. GPS ANTENNA
60. UPPER IRCM TRANSMITTER
61. RESCUE HOIST
62. ICE DETECTOR
63. ROTOR HEAD LIGHT
64. MOORING SHACKLE
65. AVIONICS COOLING INTAKE
66. REAR VIEW MIRROR
67. RIGHT PITOT TUBE
68. STATIC PORT
69. COCKPIT STEP (BOTH SIDES)
70. AVIONICS COOLING EXHAUST
71. POSITION LIGHT
72. EXTERNAL POWER CONNECTOR
73. CARGO HOOK
74. TORPEDO (BOTH SIDES)
75. ECS AIR INLET
76. LOWER ANTICOLLISION LIGHT
77. MOORING SHACKLE
78. LOWER IRCM TRANSMITTER
79. MAD AND REELING MACHINE
80. LOWER VHF / UHF / TACAN ANTENNA
81. RIGHT CHAFF / FLARE DISPENSER
82. AFT DATA LINK ANTENNA
83. REMOTE COMPASS
84. TAIL GEAR BOX
85. DOPPLER ANTENNA
86. FUEL DUMP PORT
87. NO. 1 FUEL CELL VENT
88. NO. 2 ENGINE OVERBOARD DRAIN
89. RIGHT FUEL TANK SUMP DRAIN
90. MAIN RAST PROBE
91. TRANSMISSION DRIP PAN DRAIN
92. ADF ANTENNA
93. HYDRAULIC SYSTEM OVERBOARD DRAIN
94. SEARCH RADAR ANTENNA
95. LAND / HOVER LIGHT
96. SEARCH LIGHT
97. RADAR ALTIMETER
98. FORWARD DATA LINK ANTENNA
99. FORWARD ESM ANTENNA
100. FORWARD MISSILE DETECTION SENSOR
101. FLOTATION BOTTLE ACCESS PANEL
102. MAIN RAST PROBE LIGHT
103. TRANSMISSION DRIP PAN DRAIN
104. LOWER IFF ANTENNA
105. LEFT FUEL TANK SUMP DRAIN
106. NO. 1 ENGINE AND APU OVERBOARD DRAIN
107. NO. 2 FUEL TANK VENT
108. SONOBUOY RECEIVING ANTENNA
109. TAIL PROBE LIGHT
110. LOWER ANTICOLLISION LIGHT
111. TAIL PROBE

NB1654_2C

Figure A-2
SH-60B GENERAL ARRANGEMENT (continued)

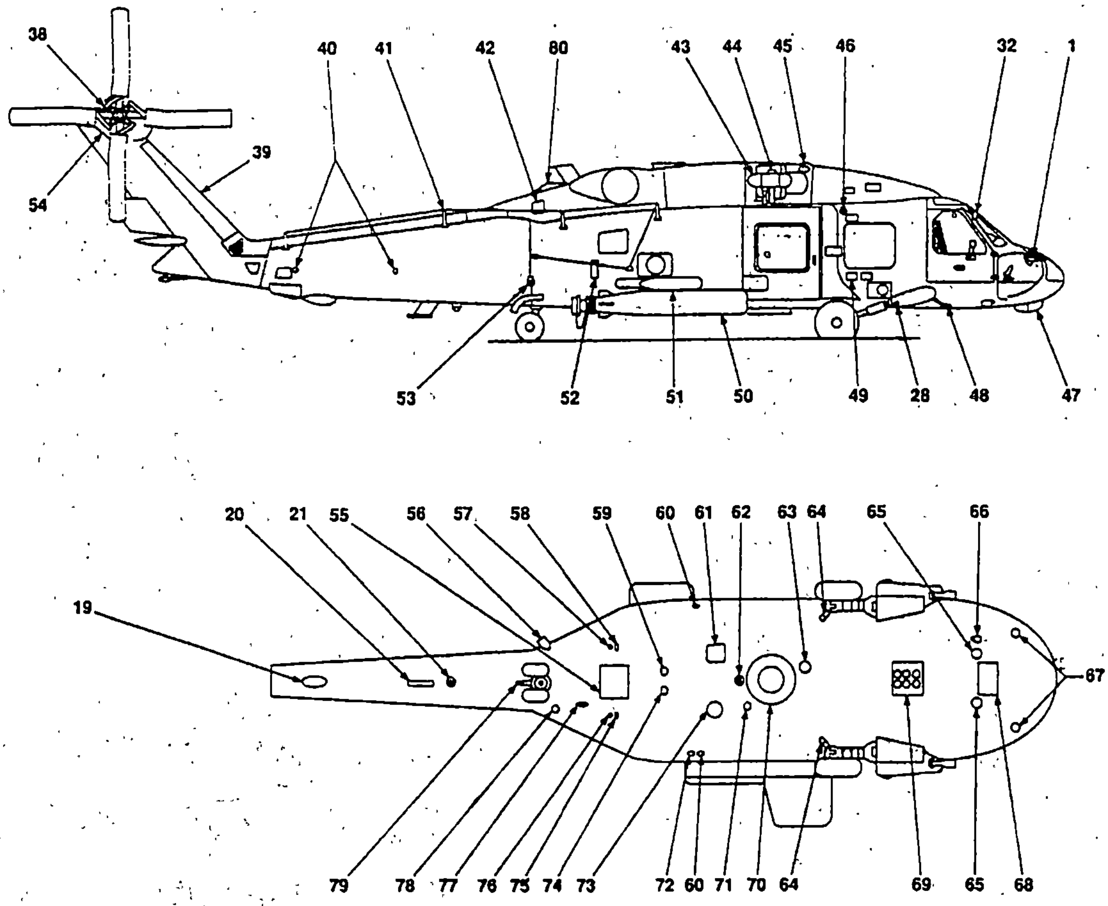
Source: Chief of Naval Operations, *NATOPS Manual, Navy Model SH-60B,* A1-H60BB-NFM-000, Change 1, 1 January 1998



1. PITOT TUBE
2. COCKPIT WINDOW POPOUT VENT
3. INTERNAL AUXILIARY FUEL TANK VENT
4. EXTERNAL ICS / ARM PANEL
5. MOORING SHACKLE
6. ENGINE WASH PANEL
7. AVIONICS ACCESS DOOR
8. GRAVITY REFUEL PANEL
9. APU EXHAUST
10. UPPER V / UHF ANTENNA / IFF TRANSMITTER
11. EMERGENCY LOCATOR ANTENNA
12. TAIL ROTOR DRIVE COVER
13. INTERMEDIATE GEAR BOX
14. UPPER ANTICOLLISION LIGHT
15. TAIL POSITION LIGHT
16. STABILATOR
17. TAIL BUMPER
18. PYLON FOLD ASSIST CONNECTOR
19. REMOTE COMPASS
20. LOWER V / UHF AND TACAN ANTENNA
21. LOWER ANTICOLLISION LIGHT
22. TAILWHEEL SERVICING PORT
23. FIRE EXTINGUISHER THERMAL DISCHARGE DISK
24. SONOBUOY ANTENNA
25. PNEUMATIC GROUND START PORT
26. PRESSURE REFUELING PANEL
27. EXTERNAL FUEL TANK
28. INBOARD LEFT PYLON
29. OUTBOARD LEFT PYLON
30. POSITION LIGHT
31. LEFT FLOTATION
32. REARVIEW MIRROR
33. OAT GAUGE
34. OUTSIDE AIR TEMPERATURE SENSOR
35. AVIONICS COMPARTMENT EMERGENCY COOLING VENT
36. UPPER TACAN ANTENNA
37. HYDRAULIC BAY COOLING INLET

Figure A-3
SH-60F GENERAL ARRANGEMENT

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.



38. TAIL ROTOR
39. PYLON DRIVE SHAFT COVER
40. BLADE STOWAGE SUPPORTS
41. HF ANTENNA
42. ECS EXHAUST
43. RESCUE HOIST
44. ICE DETECTOR
45. ROTOR HEAD LIGHT
46. MOORING SHACKLE
47. RADAR ALTIMETER ANTENNA
48. COCKPIT STEP
49. EXTERNAL POWER CONNECTION
50. TORPEDO
51. RIGHT PYLON
52. ECS AIR INLET
53. MOORING SHACKLE
54. TAIL GEAR BOX
55. DOPPLER ANTENNA
56. FUEL DUMP PORT
57. NO. 1 FUEL TANK VENT
58. NO. 2 ENGINE OVERBOARD FUEL DRAIN
59. RIGHT FUEL TANK SUMP DRAIN
60. TRANSMISSION DRIP PAN DRAIN
61. OTPI / DFG ANTENNA
62. MAIN RAST PROBE
63. RESCUE LIGHT
64. HYDRAULIC SYSTEM OVERBOARD DRAIN
65. LAND / HOVER LIGHT
66. SEARCHLIGHT
67. RADAR ALTIMETER ANTENNA
68. FLOTATION BOTTLE ACCESS PANEL
69. SONOBUOY LAUNCHER
70. SONAR FUNNEL
71. MAIN RAST PROBE LIGHT
72. AUXILIARY INTERNAL FUEL TANK DRAIN
73. IFF ANTENNA
74. LEFT FUEL TANK SUMP DRAIN
75. NO. 1 ENGINE AND APU OVERBOARD FUEL DRAIN
76. NO. 2 FUEL TANK VENT
77. SONOBUOY RECEIVING ANTENNA
78. TAIL RAST PROBE LIGHT
79. TAIL RAST PROBE
80. GPS ANTENNA

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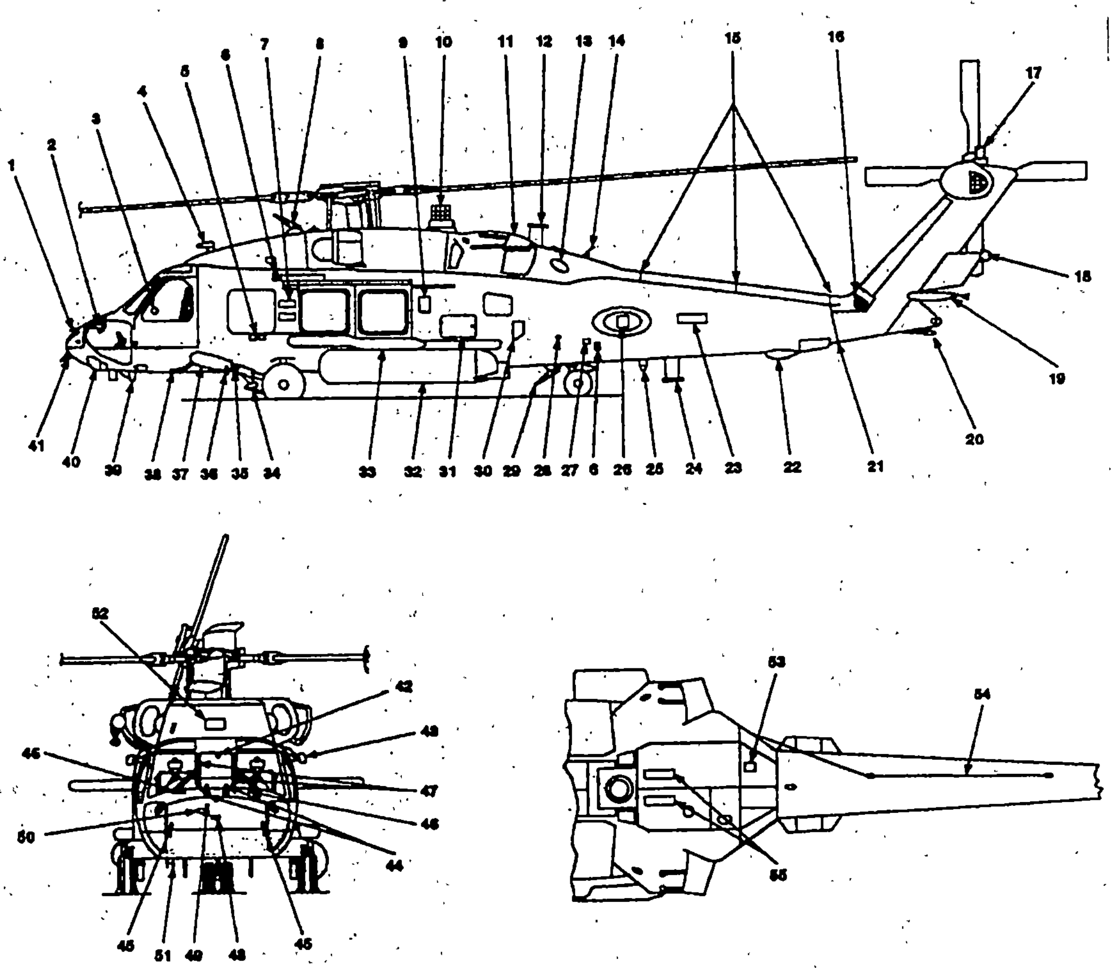
Figure A-4
SH-60F GENERAL ARRANGEMENT (continued)

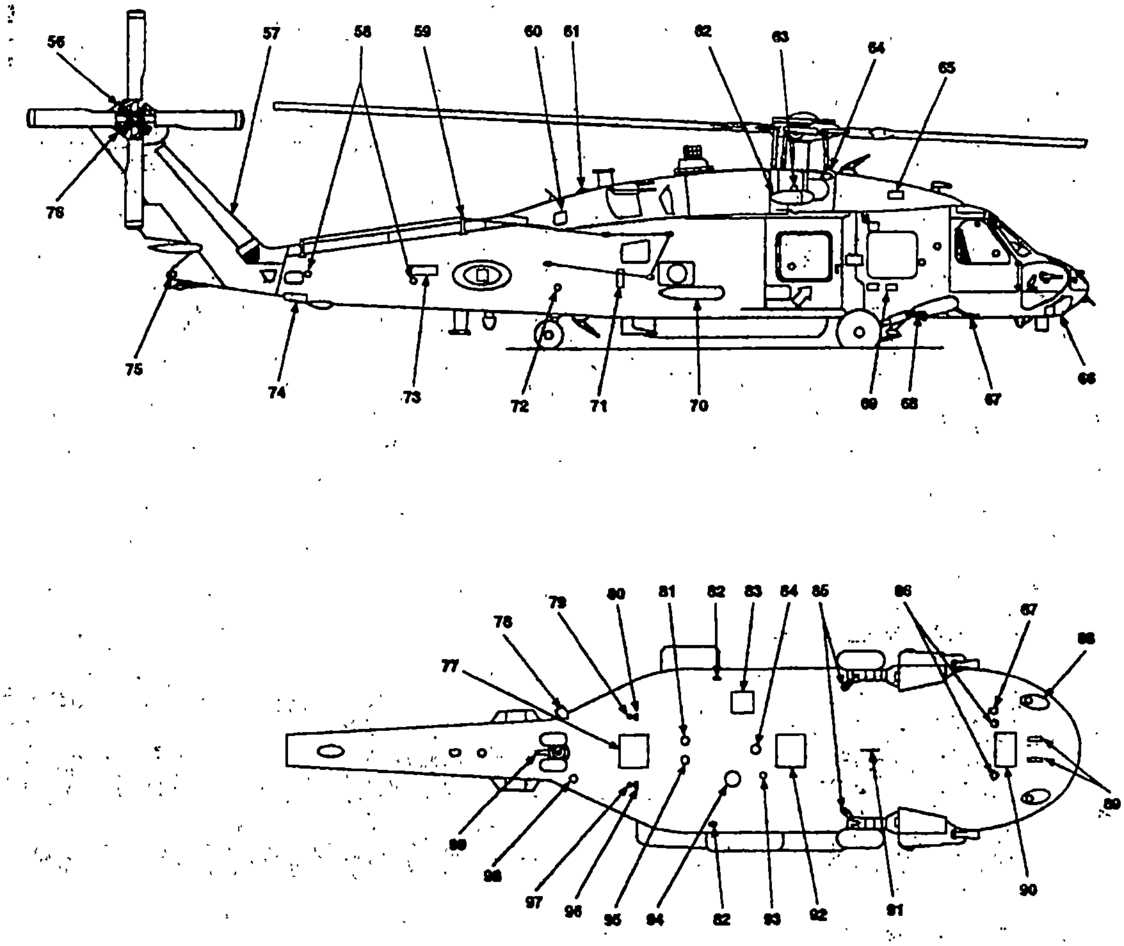
Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.



1. PITOT CUTTER
2. PITOT TUBE
3. COCKPIT WINDOW POPOUT VENT
4. COWLING CUTTER
5. EXTERNAL ICS / ARM PANEL
6. MOORING SHACKLE
7. ENGINE WASH PANEL
8. UPPER CUTTER
9. GRAVITY REFUEL PANEL
10. INFRARED COUNTERMEASURE TRANSMITTER
11. HOVER INFRARED SUPPRESSION SYSTEM
12. UPPER VHF / UHF / IFF ANTENNA
13. APU EXHAUST
14. EMERGENCY LOCATOR TRANSMITTER ANTENNA
15. TAIL ROTOR DRIVE COVERS
16. INTERMEDIATE GEAR BOX
17. UPPER ANTICOLLISION LIGHT
18. TAIL POSITION LIGHT
19. STABILATOR
20. TAIL BUMPER
21. PYLON FOLD ASSIST CONNECTOR
22. REMOTE COMPASS
23. FUSELAGE FORMATION LIGHT
24. LOWER VHF / UHF / TACAN
25. LOWER ANTICOLLISION LIGHT
26. CHAFF / FLARE DISPENSER
27. TAILWHEEL SERVICING DOOR
28. FIRE EXTINGUISHER THERMAL DISCHARGE DISK
29. TAIL LANDING GEAR CUTTER
30. PNEUMATIC GROUND START PORT
31. PRESSURE REFUEL PORT
32. EXTERNAL FUEL TANK
33. LEFT PYLON
34. MAIN LANDING GEAR CUTTERS
35. LEFT POSITION LIGHT
36. MAIN LANDING GEAR JOINT DEFLECTORS
37. LEFT FLOTATION
38. STEP DEFLECTOR
39. ANTENNA DEFLECTOR
40. LEFT RADAR ALTIMETER
41. LASER SENSOR CUTTERS
42. OUTSIDE AIR TEMPERATURE GAUGE
43. REAR VIEW MIRROR
44. OUTSIDE AIR TEMPERATURE SENSORS
45. RADAR WARNING ANTENNA
46. WIPER POST DEFLECTORS
47. WINDSHIELD DEFLECTORS
48. AVIONICS COMPARTMENT EMERGENCY COOLING VENT
49. HINGE DEFLECTOR
50. UPPER TACAN ANTENNA
51. SEARCH LIGHT DEFLECTORS
52. HYDRAULIC BAY COOLING INLET
53. GPS ANTENNA
54. HF ANTENNA
55. UPPER FORMATION LIGHT

Figure A-5
HH-60H GENERAL ARRANGEMENT

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.



56. TAIL ROTOR
57. PYLON DRIVE SHAFT COVER
58. BLADE STOWAGE SUPPORTS
59. HF ANTENNA
60. ECS EXHAUST
61. GPS ANTENNA
62. RESCUE HOIST
63. ICE DETECTOR
64. ROTOR HEAD LIGHT
65. AVIONICS COOLING INTAKE
66. RIGHT RADAR ALTIMETER ANTENNA
67. COCKPIT STEP
68. RIGHT POSITION LIGHT
69. EXTERNAL POWER CONNECTION
70. RIGHT PYLON
71. ECS AIR INLET
72. MOORING SHACKLE
73. FUSELAGE FORMATION LIGHT
74. REMOTE COMPASS ACCESS PANEL
75. RADAR WARNING ANTENNA
76. TAIL ROTOR GEARBOX
77. DOPPLER ANTENNA
78. FUEL DUMP PORT
79. NO. 1 FUEL TANK VENT
80. NO. 2 ENGINE OVERBOARD FUEL DRAIN
81. RIGHT FUEL TANK SUMP DRAIN
82. TRANSMISSION DRIP PAN DRAIN
83. ADF ANTENNA
84. MAIN RAST PROBE (IF INSTALLED)
85. HYDRAULIC SYSTEM OVERBOARD DRAIN
86. LAND / HOVER LIGHT
87. SEARCH LIGHT
88. RADAR ALTIMETERS ANTENNAS
89. DOWNED AIRCREW LOCATOR SYSTEM ANTENNA
90. FLOTATION BOTTLE ACCESS PANELS
91. RADAR WARNING BLADE ANTENNA
92. CARGO HOOK BAY
93. MAIN RAST PROBE LIGHT
94. IFF ANTENNA
95. LEFT FUEL TANK SUMP DRAIN
96. NO. 1 ENGINE AND APU OVERBOARD FUEL DRAIN
97. NO. 2 FUEL TANK VENT
98. TAIL RAST PROBE LIGHT
99. TAIL RAST PROBE (IF INSTALLED)

Figure A-6
HH-60H GENERAL ARRANGEMENT (continued)

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.

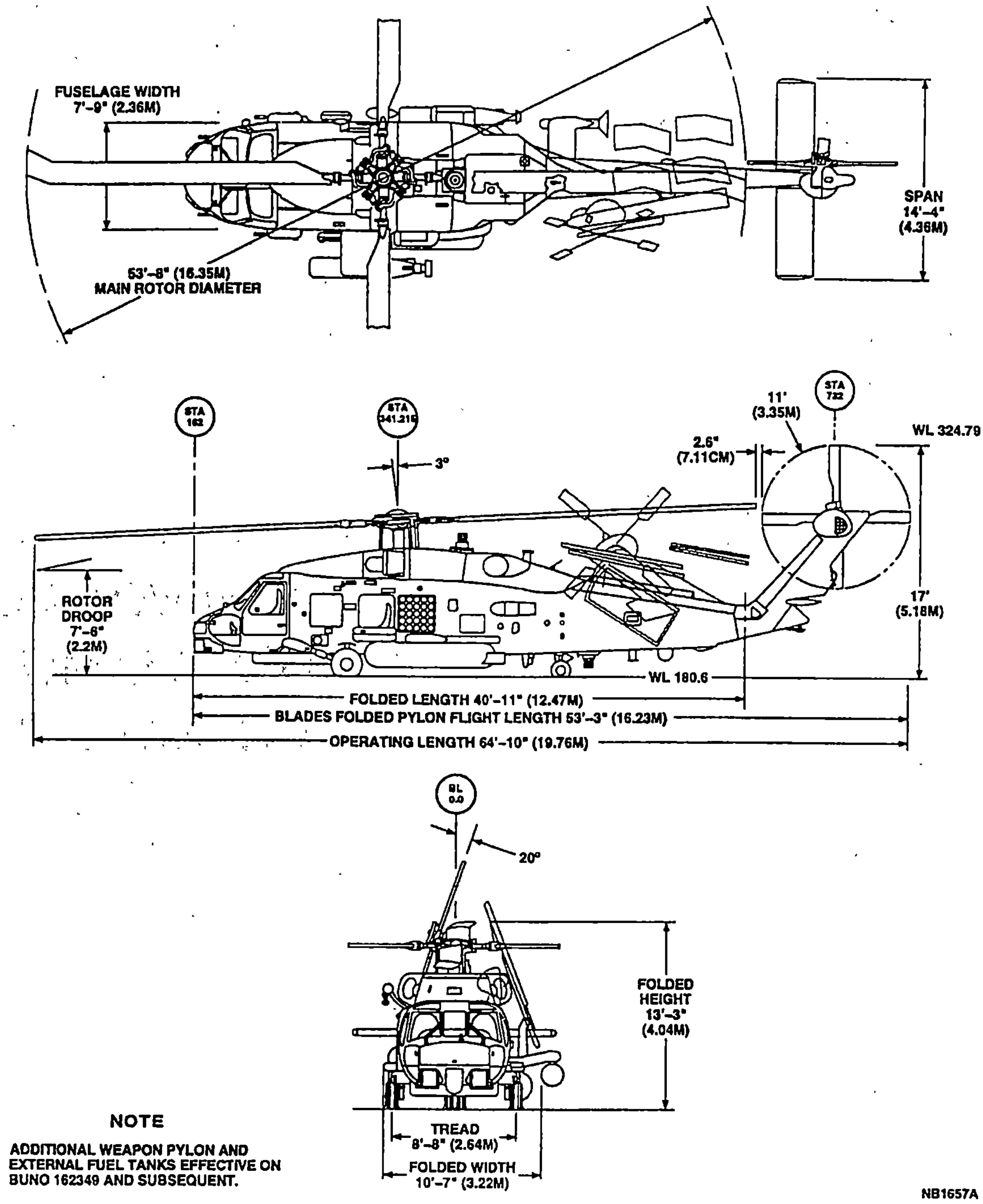


Figure A-7
SH-60B PRINCIPAL DIMENSIONS

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model SH-60B,* A1-H60BB-NFM-000, Change 1, 1 January 1998

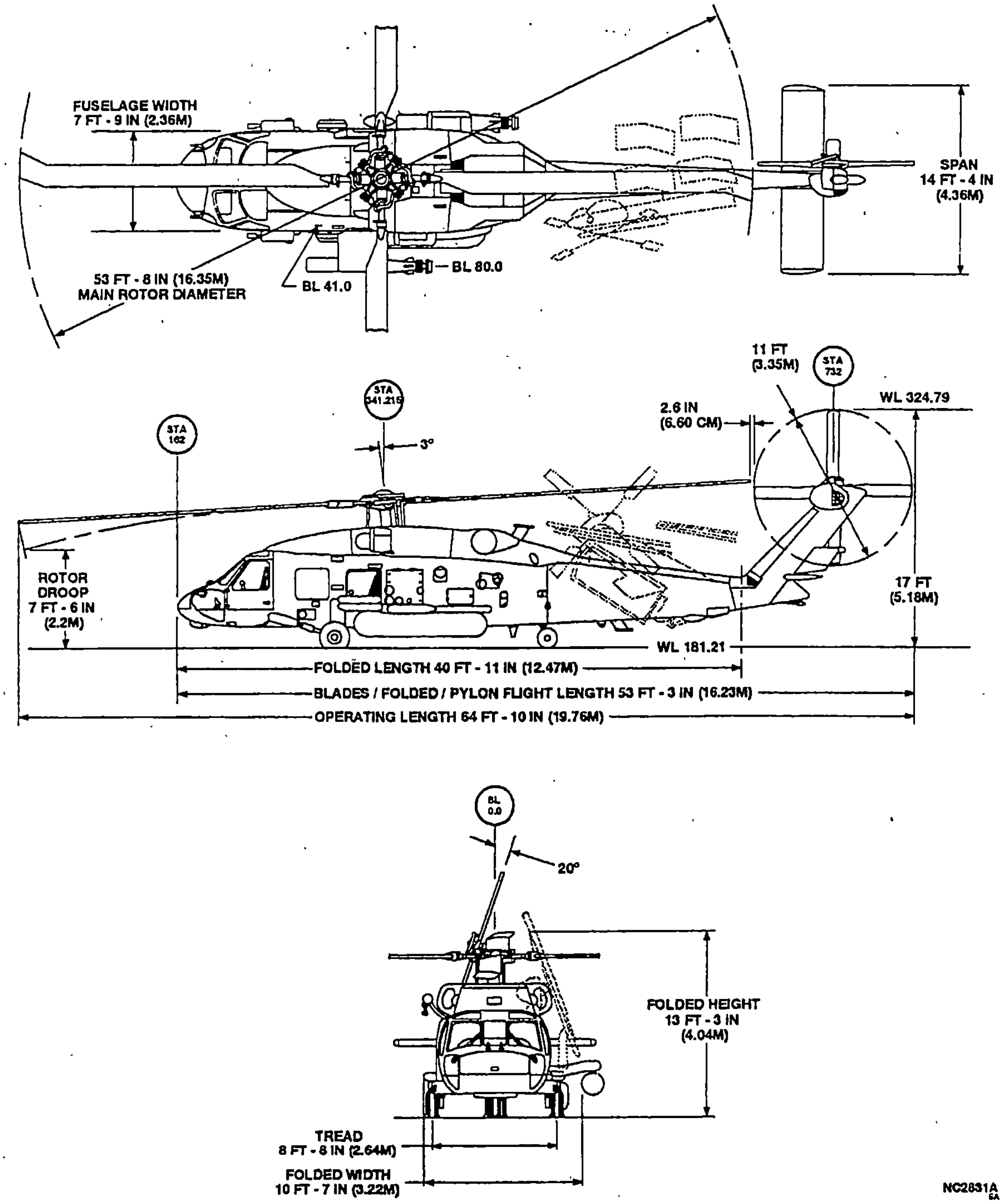


Figure A-8
SH-60F PRINCIPAL DIMENSIONS

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.

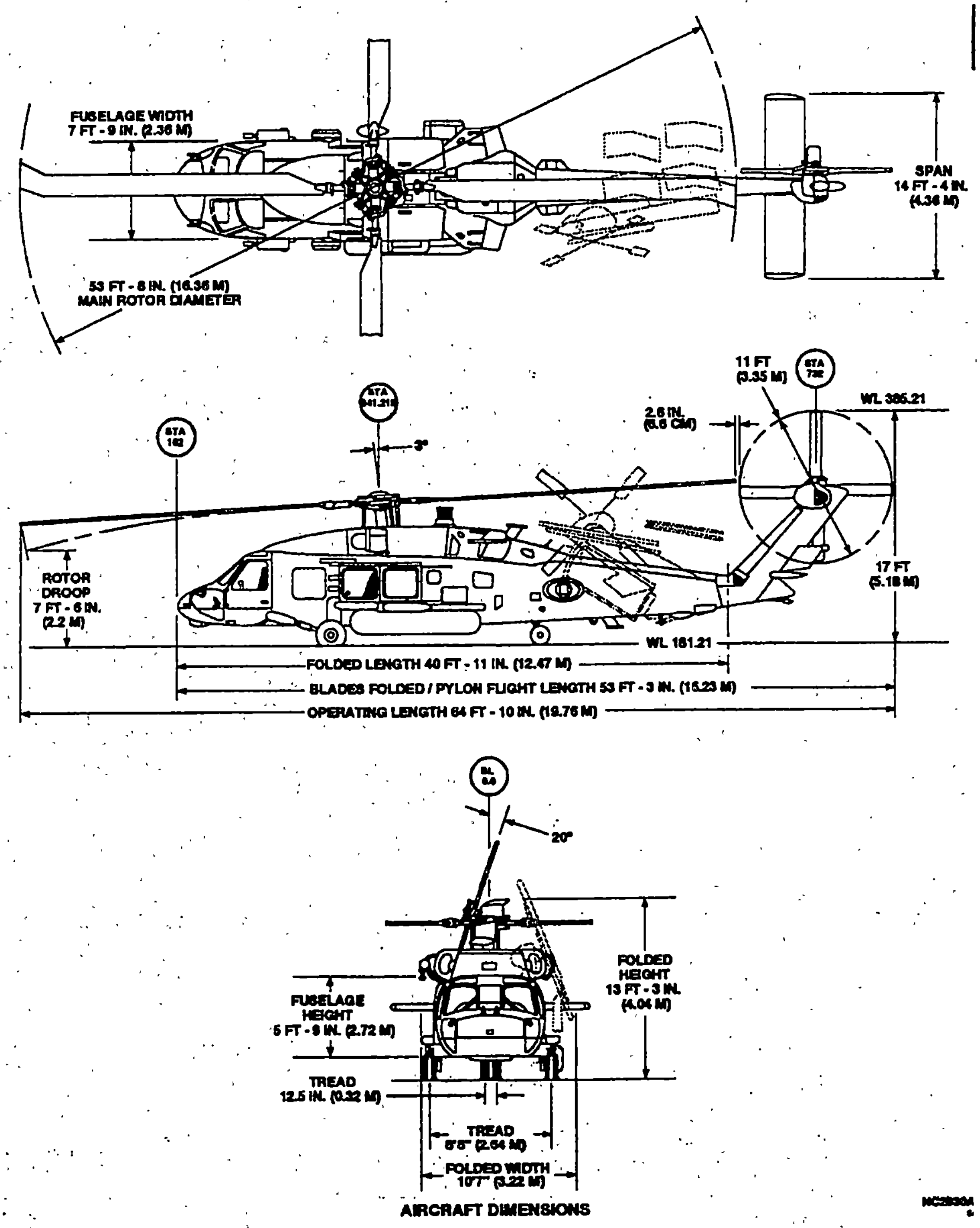


Figure A-9

HH-60H PRINCIPAL DIMENSIONS

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.

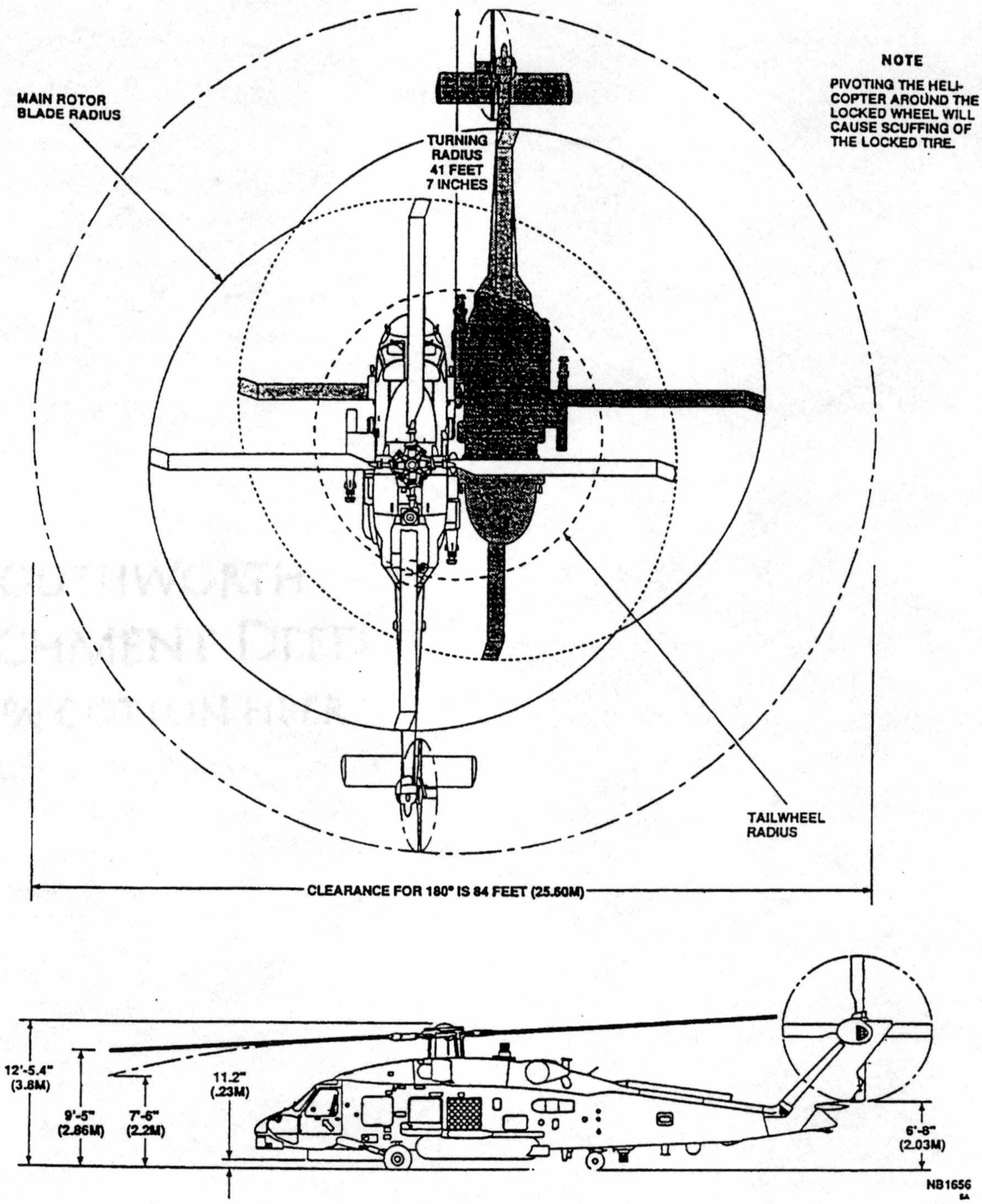


Figure A-10
SH-60B CLEARING RADIUS

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model SH-60B,* A1-H60BB-NFM-000, Change 1, 1 January 1998

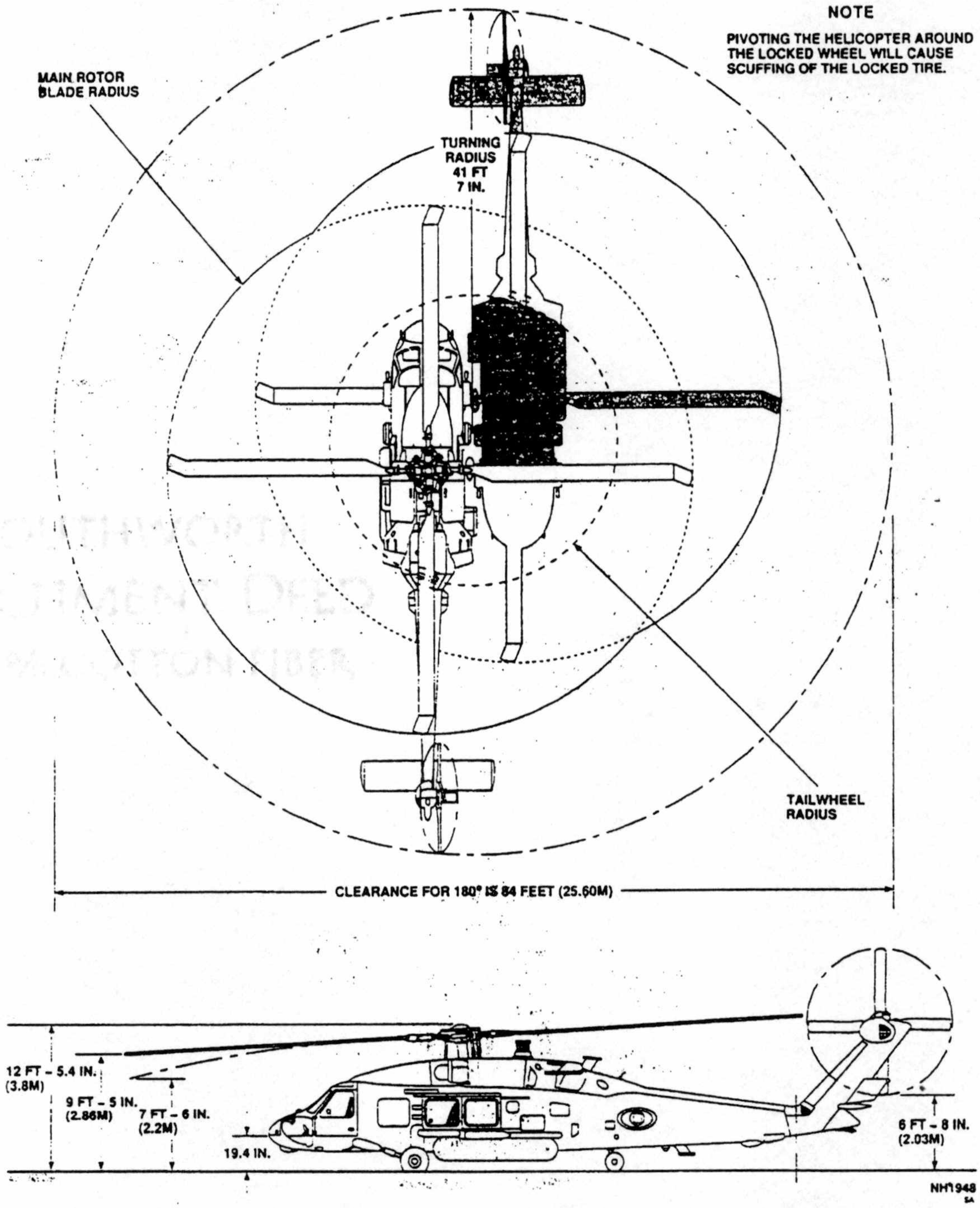


Figure A-11
SH-60F/H CLEARING RADIUS

Source: Chief of Naval Operations, *NATOPS Manual, Navy Model H-60F/H Aircraft,* A1-H60CA-NFM-000, Change 2, 7 March 1997.

VITA

James Joseph Maune was born in Mineola, New York on November 23, 1970. He received his private Pilot's license in April 1992. He attended Rensselaer Polytechnic Institute under a full NROTC scholarship where he graduated with a Bachelor of Science Degree in Physics in May 1992.

He received a commission in the United States Naval Service and after two years of flight training, earned his "wings of gold" as an unrestricted Naval Aviator in July 1994. He completed the Fleet Replacement Squadron for the SH-60B Seahawk, HSL-41, in October 1995 and transferred to his first squadron tour with Helicopter Anti-Submarine Squadron Light Thirty-Seven (HSL-37). There he qualified as Helicopter Aircraft Commander and Functional Check Pilot for the SH-60B. He was assigned as the Maintenance Officer for a two-helicopter detachment and made two deployments to the Western/Pacific and Arabian Gulf on board the *USS CROMMELIN (FFG-37)* and *USS PORT ROYAL (CG-73)*. After completing his first tour he transferred to Air Test Evaluation Squadron One (VX-1) in Patuxent River MD where he qualified as Aircraft Commander in the SH-60B/F and HH-60H. While assigned at VX-1 he was selected to attend US Naval Test Pilot School as part of Class 117.

Presently LT Maune is assigned as the Aide to Program Executive Officer for Air ASW, Assault and Special Mission Programs. He has qualified for Level 1 Acquisition Professional certification. He has logged over 2000 total flight hours, 1800 in helicopters. He has flown more than 12 different fixed wing and rotary wing aircraft. He has completed over 1,000 small deck landings on 7 different classes of naval vessels.