

# FATIGUE ANALYSIS OF HELICOPTER LANDING PROBE BY HELICOPTER/SHIP DYNAMIC INTERFACE SIMULATION

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## ABSTRACT

The helicopter-mounted probe is a critical structure to safely secure an embarked helicopter on a rolling ship flight deck. To prevent the sudden failure of the probe, a fatigue life estimation was performed on the probe system of a helicopter for embarked operations on a new type of frigate by using a novel dynamic helicopter/ship interface simulation. The computer simulation considers all possible probe loading cases under the wide range of operating and environmental conditions of the helicopter with a six sigma (99.9999%) confidence level. The simulated time histories of all probe loads were post-processed by rainflow cycle counting method and occurrence probability of each loading case to generate the probe load spectra in the radial and vertical directions with respect to the probe assembly. The probe load spectra are then transferred to the stress spectra of the critical locations on each component of the probe assembly using the finite element method. Finally, a cumulative fatigue damage analysis was performed by monitoring the fatigue life of the critical locations using the Palmgren-Miner rule against the design life of the probe. The results indicated that the probe assembly is sufficient for the fatigue loads since approximately 5% (500 flight hours) of the fatigue life is used over the design life of the probe. This long fatigue life results from the design of the probe system being driven by the maximum securing load instead of the fatigue loads.

## INTRODUCTION

Embarked helicopters have a wide range of applications from performing ASW and other combat missions from naval ships to search and rescue operations such as medical evacuation of personnel from civilian vessels. In order to fulfill the diverse roles, shipboard helicopters must be operable in the greatest range of sea and wind conditions. Many systems have been developed to assist the safe recovery and on-deck handling of embarked helicopters in the severe sea and wind conditions. Among them, the Aircraft/Ship Integrated Securing and Traverse (ASIST) system developed by Curtiss-Wright Controls – Engineered Systems (CWC-ES) appeals most because it can safely recover, secure, and traverse shipboard aircraft without strictly requiring any personnel on the ship's flight deck. The system secures the helicopter onto the flight deck by engaging the helicopter-mounted probe, which is the only structural link between the helicopter and ship's flight deck. Depending on the sea conditions and operational factors such as ship heading and speed relative to the principal sea direction, the probe will experience cyclic securing loads over a wide range of values, which could lead to a sudden

catastrophic failure due to fatigue of the probe structure. The fatigue failure of the probe will result in the loss of the helicopter and lives of personnel on board.

Traditionally, the engineers and designers have relied on complicated statistical analysis to estimate the probe's design loads and costly physical prototype tests to determine the fatigue life of the probe. However, the design process still cannot fully evaluate the impact of the severe sea and wind conditions on the fatigue life of the probe due to safety and cost prohibitive nature of the physical prototype tests. To overcome the limitation of the traditional design process, a complete solution to accurately assess the fatigue performance of the probe as well as its individual components in one single and integrated simulation environment has been developed.

The primary task of fatigue analysis is to identify a suitable description of the expected in-service dynamic loading conditions. These loads involve time dependent securing forces in each orthogonal direction. The magnitude and characteristics of these forces depend on a description of the ship and helicopter characteristics as well as the expected operating conditions. To develop a suitable description of the dynamic loading conditions for fatigue analysis, non-linear transient dynamic computer simulations of the aircraft/ship interface were performed using CWC-ES' *Dynaface*<sup>®</sup> simulation package [1]. The simulation produces time histories of forces and displacements at the interface

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between the helicopter and ship in response to ship motion and wind of the seaway. The simulation was run for extended time periods, encompassing all the possible expected operating conditions, to obtain statistically representative securing forces. The results were analyzed to develop a complex array of loading applied to the fatigue analysis of the probe.

By combining the probe loads and load spectra derived from the dynamic helicopter/ship interface simulation, solid modeling for the virtual prototype, FE-based stress results and cyclic fatigue material parameters, the novel solution technology allows us to predict the fatigue life of the probe without physical prototype tests. It is with this in mind, that a fatigue life estimation of the probe was conducted to ensure safe operation of the embarked helicopter.

The paper is divided into several sections. Following this brief Introduction is a description of the probe structure, the fatigue analysis methodology, and the dynamic interface simulation. A description of the fatigue spectra has been provided followed by a discussion of the results and concluding remarks.

### PROBE STRUCTURE

The Curtiss-Wright Controls – Engineered Systems ASIST securing system uses a ship-mounted Rapid Securing Device (RSD) to positively engage an airborne retractable probe that extends from the bottom of the helicopter fuselage in order to secure the helicopter onto the flight deck. The system facilitates landing of helicopters with an optical ship-mounted tracking system which tracks the helicopter position during landing and provides visual cues to the pilot while the RSD simultaneously tracks the probe (fore/aft) in an expanded capture area as the helicopter lands. This allows the pilot to safely land the helicopter onto the designated landing area of the flight deck such that the probe can be captured immediately upon touchdown (within 2 seconds) by the RSD. Figure 1 shows the schematic of the ASIST system. Once landed, the powered RSD claw provides the necessary functionality to align and traverse the helicopter without the need for additional equipment or personnel on-deck.

Once initially secured, the helicopter remains secured throughout all aspects of on-deck handling operations including straightening of the helicopter and traversing it into the hangar. Once in the hangar, and depending upon the navy’s operating procedures, the probe may or may not be released from the RSD. Similarly, during launch, the helicopter remains secured from the time it leaves the hangar until the instant prior to takeoff when the probe is released from the RSD. The probe is the only structural link between the helicopter and the ship throughout all aspects of on-deck handling operations.

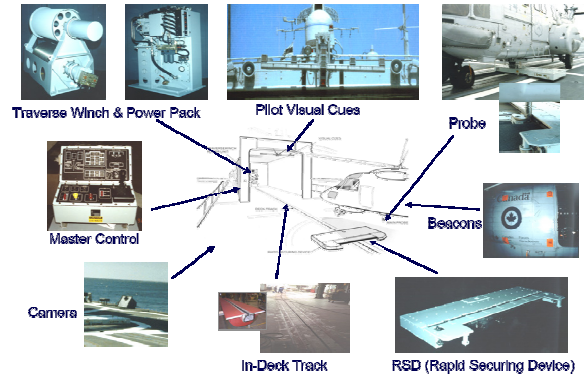


Figure 1: Schematic of components of ASIST system

The principle helicopter-mounted structure is the probe that, as considered here, is of the three-stage telescopic retractable type. It consists of three primary structural components: the shaft, the inner housing, and the outer housing as shown in the solid model in Figure 2. In the normal flight condition, the shaft and the inner housing are fully retracted into the outer housing. During the landing, traversing, launching and other on-deck operation, the shaft and the inner housing are fully extended by an embedded spring for the on-deck operations. After being secured by the RSD, the lower end of the shaft reacts to the dynamic securing loads generated from the relative motion between the helicopter and the ship due to the ship motion and the wind environment.

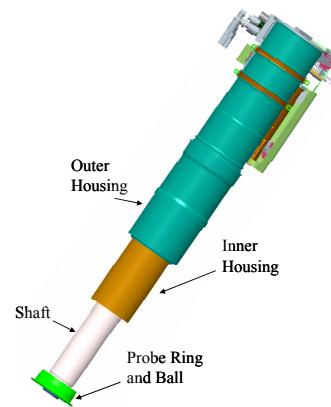


Figure 2: Structural configuration of probe assembly

Figure 3 illustrates the interface between a typical probe and the ASIST RSD. The landing gears and probe react forces that oppose sliding, yawing, and toppling of the helicopter as a result of ship motion.

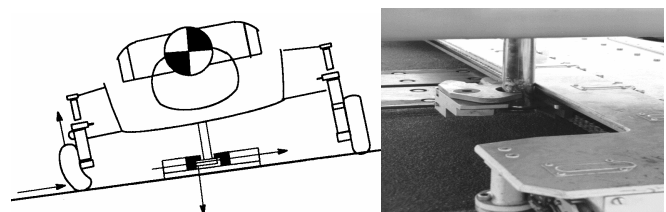


Figure 3: Schematic of securing forces (left) and pictorial view of the interface between the probe and RSD (right)

## FATIGUE ANALYSIS METHODOLOGY

The methodology for the fatigue analysis is presented by the block diagram in Figure 4. The dynamic loads are dependent on three main factors:

- i) helicopter's pertinent parameters such as geometry, inertia, stiffness and damping characteristics, etc.
- ii) sea and environmental conditions; and
- iii) operational factors such as helicopter configuration (rotor status, wheel brake status, on-deck orientation, etc.) and ship heading and speed.

Advanced nonlinear transient dynamic simulation of the helicopter/ship provides a means of exploring the full parameter space necessary to derive the securing forces. The resulting force time histories will be processed to determine i) the peak securing force for static strength design analysis and ii) a probe load spectra for the estimation of the fatigue life of the probe.

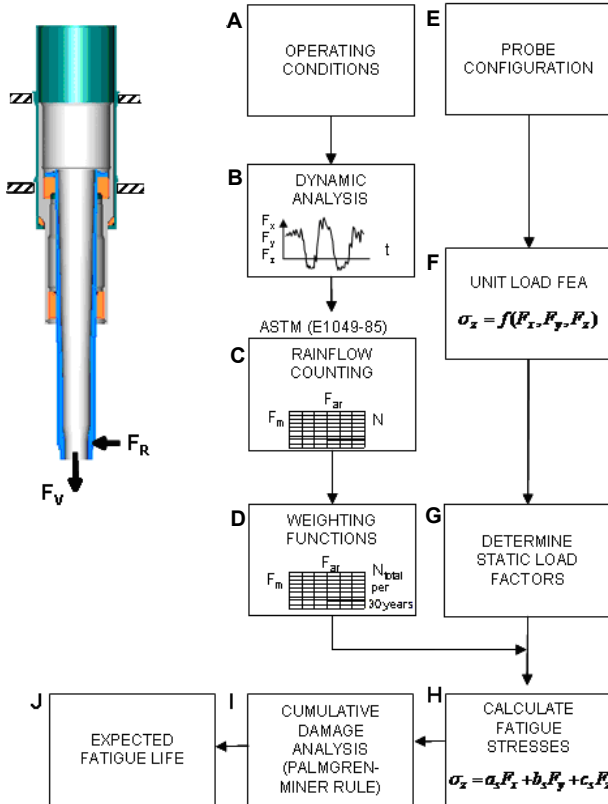


Figure 4: Fatigue analysis methodology block diagram.

## HELICOPTER/SHIP DYNAMIC INTERFACE SIMULATION

The helicopter/ship dynamic interface simulation is based on the model developed in Reference [1] using a generic 10 metric ton helicopter with tricycle landing gear type and a 3200 metric ton displacement frigate as shown in Figure 5 and Figure 6 respectively.

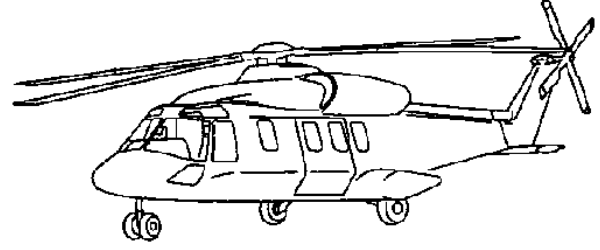


Figure 5: Typical tricycle configuration helicopter



Figure 6: Typical frigate moving through waves

Figure 7 shows a schematic of a helicopter landing on the ship deck, which includes the helicopter rigid body dynamics, aerodynamic effects of the rotors and the fuselage, landing gear dynamics, tire mechanics, and landing probe model.

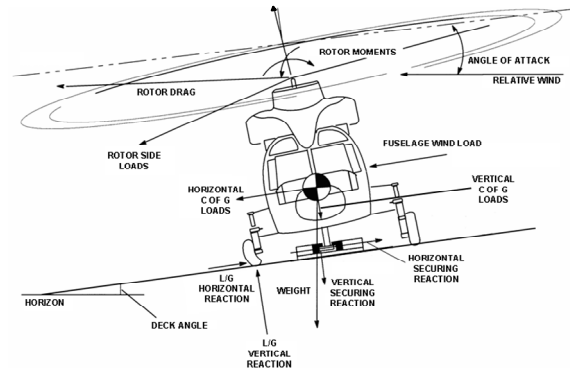


Figure 7: Identification of forces acting on a secured helicopter

The equations of the system can be expressed as:

$$m\ddot{X} = \sum F \quad (1)$$

$$I\dot{\Omega} + \Omega \times I\Omega = \sum M \quad (2)$$

$$m_g \ddot{q} = \sum F_g \quad (3)$$

$$I_g \ddot{\theta} = \sum M_g \quad (4)$$

$$K_V \delta_V = F_V \quad K_R \delta_R = F_R \quad (5)$$

where  $m$  is the mass of the helicopter,  $I$  is the mass moments of inertia tensors of the helicopter about its centre of gravity (CG),  $X$  and  $\Omega$  are the translational and rotational

displacements of the helicopter’s CG respectively,  $\Sigma F$  and  $\Sigma M$  are the external forces and moments applied to the CG,  $m_g$  is the mass of the landing gear assembly respectively,  $I_g$  is the matrix of the moment of inertia about its pivoting point,  $q$  and  $\theta$  are the extension/compression and rotation of the landing gear,  $\Sigma F_g$  and  $\Sigma M_g$  are the external forces and moments applied to the landing gear,  $K_V$  and  $K_R$  are the vertical and radial stiffness of the probe,  $\delta_V$  and  $\delta_R$  are the vertical and radial displacements of the probe with respect to the ship,  $F_V$  and  $F_R$  are the vertical and radial securing loads acting on the probe, respectively.

### FATIGUE LOAD SPECTRA OF PROBE

In order to predict the probe’s fatigue life a complete description of the operating conditions in which the helicopter probe is expected to operate throughout its service life when embarked on a frigate is required. The following sections outline the specific operating profiles and include:

- i) defining sea state conditions (i.e. significant wave height, wave modal period, wind speed and direction, and sea state probabilities);
- ii) defining ship operations (i.e. ship speed, ship heading, and probability of operation);
- iii) defining the helicopter configuration;
- iv) establishing helicopter launch and recovery times;
- v) defining dynamic analysis simulation input parameters and perform dynamic load analysis; and
- vi) generating fatigue load spectrum.

The specific characteristic and magnitude of the probe securing forces and its corresponding landing gear reaction forces vary considerably with the specific operating phase of the helicopter, the helicopter configuration, and the environmental conditions. Phases of helicopter operation include securing, straightening, traversing, and hanging. Helicopter configuration includes pertinent parameters such as helicopter mass, rotor status, alignment with respect to the ship centerline, and tire and oleo servicing factors. Environmental conditions include sea state, ship heading, ship speed, wind speed, wind direction, and geographic location. Because the ASIST system allows the helicopter to operate without imposing limitations on ship heading based on deck handling considerations, even the most severe ship headings must be considered. In fact, while in service, a helicopter/probe system will encounter loads generated by all combinations of these parameters leading to a very large number of possible operating conditions each having an associated probability of occurrence.

#### Sea and Wind Conditions

Typical government defense policy objectives include; homeland security; defense of continent; and contribute to international security. Ships can therefore be placed in a

variety of sea regions around the world. It is difficult to assess the time that a helicopter/ship combination will spend in the various sea regions throughout its design life. A conservative assessment would assume the worst case sea conditions to be expected at all times. For example, if the worst case sea conditions are within the navy’s coastal boundaries then those conditions would be conservatively applied 100% of the time. A typical distribution of sea states is summarized in Figure 8 corresponding to waters in the South-East Asian area. As most navies typically do not operate beyond sea state 5, Figure 8 shows the normalized distribution excluding sea state probabilities above sea state 5.

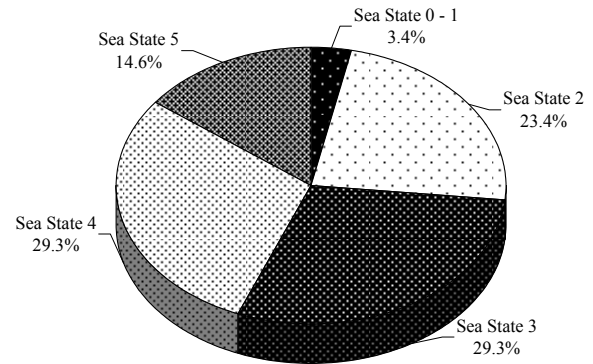


Figure 8: Normalized probability of sea states corresponding to South-East Asian waters

In order to define the sea conditions associated with a particular sea state, a description of the significant wave height (SWH) (which represents the average of top one-third wave heights), modal period, and wind speed should also be provided. Table 1 summarizes the SWH, modal period, and wind speed used for the generation of ship motion, where the SWH represent the mean of the sea state and the modal period represent the most probable value, suitable for fatigue analysis, for the sea state.

Table 1: Sea State characteristics

Sea States	SWH, m	Modal Period, s	Wind speed. kts
0-1	0.05	7.5	9.0
2	0.30	7.5	14.0
3	0.88	7.5	21.5
4	1.88	8.8	27.5
5	3.25	9.7	35.0

From experience of dynamic interface analysis, probe loads occurring in sea states less than 3 are quite low and will not significantly affect the fatigue life. Thus, only sea states 3, 4, and 5 were used to generate the fatigue load spectrum.

In the simulation, all operational cases were analyzed with the wind direction aligned with the principal sea direction, as is the case for developing seas. Sea state 5 was also

analyzed for wind directions of  $\pm 30^\circ$  relative to the sea to account for instances where the wind is not aligned with the direction of the sea. These were assumed to apply 25% of the time in each direction. The wind is assumed to be aligned with the sea direction for the remaining 50% of the time. The actual apparent wind speed and direction over the flight deck is calculated as the resultant of the wind vectors arising from the true wind speed and the ship speed.

### Ship Operation

Ship operation is specified by the wave direction relative to the ship heading and the ship speed. The ship's response to the seaway is assumed symmetrical about its longitudinal axis, as is usually the case with linear ship motion analysis. Consequently, the value at a heading of  $60^\circ$ , for example, will be the same as that at  $300^\circ$ . It is possible therefore, to choose ship headings from the range  $0^\circ$  to  $180^\circ$ . Ship headings include  $0^\circ$  through  $180^\circ$  in  $15^\circ$  increments, where  $0^\circ$  corresponds to waves approaching the bow,  $90^\circ$  corresponds to starboard beam seas, and  $180^\circ$  corresponds to wave approaching from the stern. Although only 13 ship headings were used in dynamic simulations for the fatigue analysis, the statistics for  $0^\circ$  through  $360^\circ$  in  $15^\circ$  increments were considered. The ship is assumed to spend equal time at all headings relative to the principal sea direction. This assumption is conservative regarding the fatigue life estimation as in practice the ship will likely be in more favorable headings for a larger portion of the time.

Ship speeds for a typical frigate range from 0 knots to 30 knots. The ship motion available corresponds to ship speeds in 5 knot increments. The ship's likely speed is dictated by the mission with the economical cruising speed frequently used. Very high and very low speeds are rare. Seakeeping literature provides a frequency distribution of ship speed for a typical warship and was used for the purpose of the fatigue analysis [2]. The ship motions used in the analysis corresponds to ship speeds at the end points of the ship range. It was assumed that the probabilities in Reference [2] apply to the low end of the speed range with the probability at 25 knots adjusted to be able to include the probability for a 30 knot ship speed as shown in Figure 9.

### Helicopter Operations

Typical maritime helicopters have a minimum useful life of 10,000 flight hours. For helicopters that are specifically assigned to a ship, a usage rate as a percentage of the yearly flying rate may be approximately 20% shore-based and 80% embarked. Therefore, out of the minimum useful life of 10,000 flight hours, approximately 8000 flights hours can be considered as embarked operations. Helicopter manufacturers typically include a safety factor of 1.5 cycles of probe operation per embarked flight hour. Therefore, the

minimum number of embarked cycles over the useful life of the helicopters is 12000 cycles.

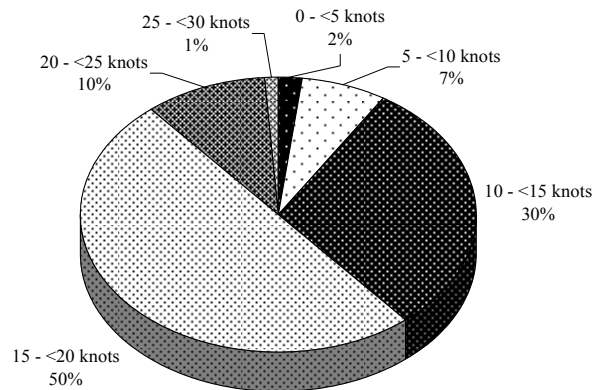


Figure 9: Frequency distribution of ship speed

The average annual flying rate is dictated by the type of missions expected from the helicopter and available funding. But for maritime helicopters, approximately 400 flight hours per year can be expected. Therefore, on an annual basis a probe will experience approximately 480 embarked cycles per year. Here an embarked cycle refers to one complete on-deck evolution of the helicopter being traversed from the hangar to the flight deck, prepared for launch, recovery of helicopter, straighten, and traverse back into hangar.

Most embarked helicopter sortie profiles typically involve the helicopter taking off at its maximum gross weight. However, upon return from a mission, the helicopter may not necessarily be at its minimum landing weight. In addition, to ensure a constant state of readiness, maritime helicopters are typically refueled prior to being traversed into the hangar. Therefore, for this analysis, the helicopter is assumed to be at the maximum weight 75% of the time and minimum landing weight 25% of the time.

The ASIST system is capable of securing a helicopter with a misalignment of up to  $30^\circ$  yaw with respect to the ship's centerline. However, experienced pilots rarely have the helicopter misaligned with the ship's centerline upon touchdown even under extreme conditions. Therefore, sea state 5 will be analyzed both with the helicopter aligned and misaligned having an assumed distribution of 80% at  $0^\circ$  alignment and 10% each for  $+30^\circ$  and  $-30^\circ$  alignment. These probabilities only occur for the recovery and straightening phases of embarked operations. For all other on-deck operations (i.e. traversing and launch) the helicopter is aligned with the ship's centerline. For sea states less than 5 the helicopter is assumed to be aligned since it will be for the majority of the time.

Once the helicopter is secured on-deck, the next step is to straighten the helicopter so that it is aligned with respect to the deck-mounted track. For a helicopter having a free

swiveling auxiliary gear, numerous gear angles are possible. As it is ultimately up to the system operator as to the sequence of maneuvers that will be required to straighten the helicopter, for the purpose of the fatigue analysis, it will be assumed that the helicopter will spend 50% of the straightening time with the auxiliary gear aligned and 50% misaligned for a given straightening evolution.

**Launch and Recovery Time Assessment**

ASIST operating cycle times are summarized in Table 2. Table 3 expands the description to include assumed estimates of the time spent with various combinations of brakes status (disengaged and engaged) and rotor status (stopped and turning). It should also be noted that helicopters fitted with a probe perform both free-deck (i.e. helicopter lands with the probe within the capture area of the RSD but is not secured by the RSD) and captured landings. Free-deck landings are typically performed in lower sea states as the ship motions are less severe. However, for the fatigue analysis it will be conservatively assumed that the probe is always secured by the RSD when the helicopter is on-deck. It is also assumed that the helicopter is stored in the hangar and lashed at all times that it is not involved in a flight cycle.

Table 2: ASIST operating cycle times

On-Deck Phase	Time
Traverse to DLA	5 minutes
Launch	5 minutes
Recovery	5 minutes
Straighten and Traverse to Hangar	5 minutes

Table 3: Rotor and brakes status for ASIST operation

On-Deck Phase	Time	Brakes	Rotor
Traverse to DLA	5 minutes	OFF	Stopped
Launch – Condition 1	2.5 minutes	ON	Stopped
Launch - Condition 2	2.5 minutes	ON	Turning
Recovery - Condition 1	2.5 minutes	ON	Turning
Recovery – Condition 2	2.5 minutes	ON	Stopped
Straighten/Traverse to Hangar	5 minutes	OFF	Stopped

The fatigue load spectra of the probe assembly can be obtained by examining all possible on-deck operations of the helicopter throughout its proposed service life by the helicopter/ship dynamic interface simulation. Table 4 shows the pertinent parameters used in dynamic simulation.

**FATIGUE LIFE ANALYSIS AND RESULTS**

All simulation cases were run for 10,000 seconds to ensure that the simulated time history of the probe loading will capture all possible probe load cases for subsequent analysis. Figure 10 shows a sample of the variation of radial and

vertical probe forces with time. Then, rainflow cycle counting [3] was performed on the time histories of probe loads to enumerate the number of fatigue cycles associated with load ranges and their mean value. Based on the knowledge of the probability of the probe assembly expected to experience for each of the operating condition analyzed, the corresponding rainflow chart of each case is weighted by an appropriate probability of occurrence for that condition.

Table 4: Pertinent dynamic simulation parameters

Parameter	Value
On-Deck Operation	Securing, Straightening, Traversing
Helicopter Weight	Maximum, Minimum landing
Rotor Status	Stopped/Turning as appropriate
Helicopter Alignment	Aligned/Misaligned as appropriate
Suspension Parameters	Nominal
Brake Status	Engaged/Disengaged as appropriate
Auxiliary Gear Rotation	Aligned/Misaligned as appropriate
Ship Speeds	0 – 30 knots in 5 knot increments
Ship Headings	0°-180° in 15° increments
Wind Speed	As per sea state
Wind Direction	Aligned/Misaligned
Sea State	3, 4, 5
Significant Wave Height	As per sea state
Sea Modal Period	As per sea state
Total Simulation Cases	21267

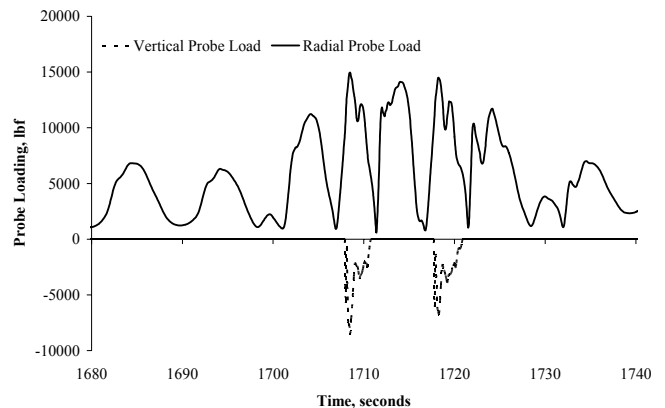


Figure 10: Sample time history of the radial and vertical probe forces corresponding to the simulation case in sea state 5 and 120° ship heading

The cumulative rainflow matrices corresponding to the radial and vertical securing load directions are converted from the expected number of load cycles per year to the total number of load cycles expected over the design life of the probe as represented by Block D in Figure 4. This provides a summary rainflow chart that is the weighted sum of the rainflow charts corresponding to each operating condition as summarized in Figure 11 and Figure 12 for radial and



vertical probe loading respectively. Note that radial load refers to the resultant of longitudinal and lateral loadings. These cycles will be further converted to equivalent fully reversed loading cycles at zero mean in order to use the S-N data which are mostly available at zero stress ratios.

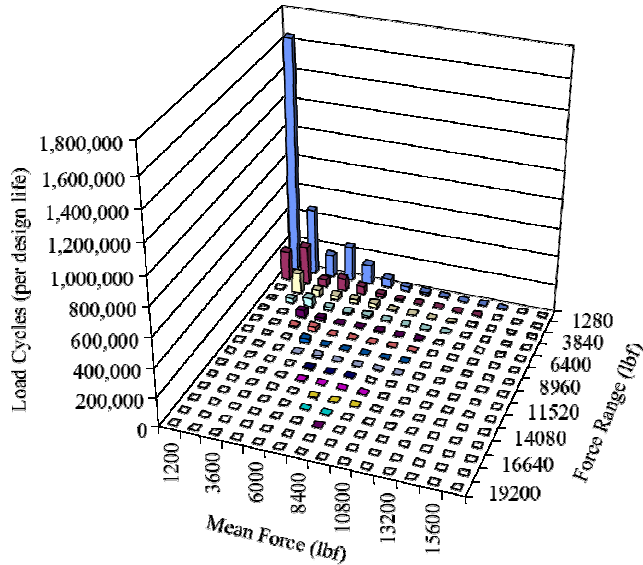


Figure 11: Rainflow cycle counting results for radial probe loading over the probe's design life

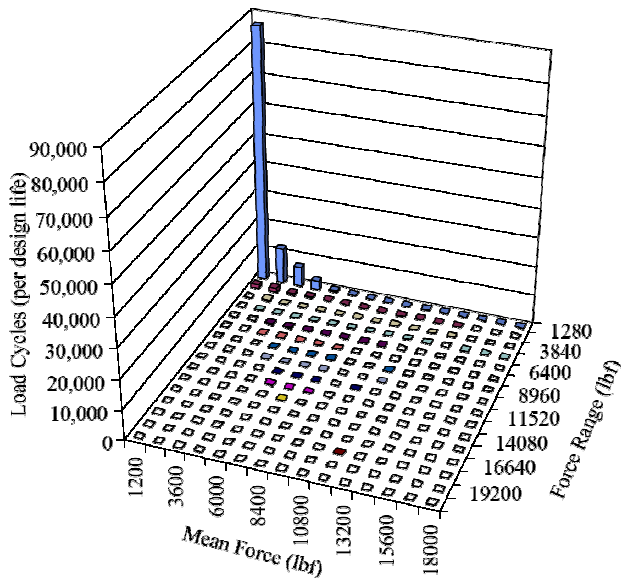


Figure 12: Rainflow cycle counting results for vertical probe loading over the probe's design life

From Figure 11 and Figure 12, it can be seen that the high number of load cycles can be expected at combinations of low force ranges and low mean values for both radial and vertical loads. While the combinations of high force ranges and corresponding mean values show very small number of load cycles, this provides an early indication that the cumulative fatigue damage may be significantly low. To

further demonstrate the characteristics of the probe load spectra, the frequency of occurrence of the radial and vertical peak load cycles were calculated and plotted in Figure 13 and Figure 14 respectively. This figure shows very low frequencies of occurrence of the peak forces. For instance, the frequency of occurrence of the maximum peak radial force is less than 1 in  $10^8$  load cycles.

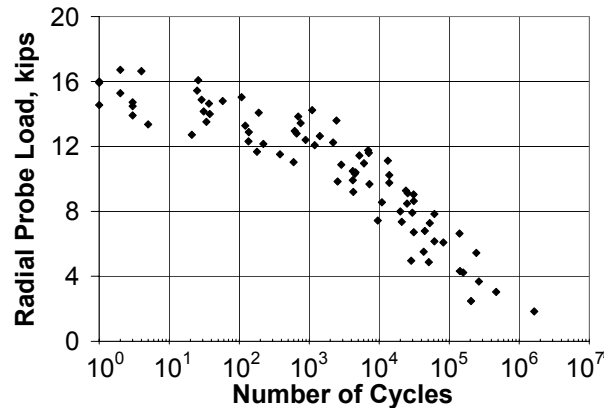


Figure 13: Load cycle occurrences of peak radial probe forces over design life

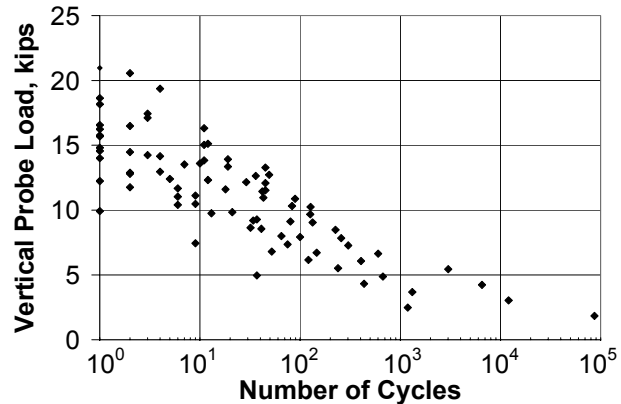


Figure 14: Load cycle occurrences of peak vertical probe forces over design life

### Critical Locations in Probe Components

The fatigue life of the probe assembly is estimated by monitoring the fatigue life at various critical locations (hotspots) of each component of the probe. The landing probe assembly was first modeled using solid modeling technology and then input into a FE program for static analysis using contact algorithm. By applying the vertical and radial probe loads separately, the static analysis determined:

- 1) critical highly stressed locations (hotspots) in the probe assembly, and
- 2) load factors relating the hotspot stresses to the external loads.

The most critical points in each probe component are shown in Figure 15. The true stress at the critical locations can be calculated from:

$$\sigma = a_s F_r + b_s F_v \quad (6)$$

where  $a_s$  and  $b_s$  are the load factors in the radial and vertical directions, and  $F_r$  and  $F_v$  are the radial and vertical probe components, respectively.

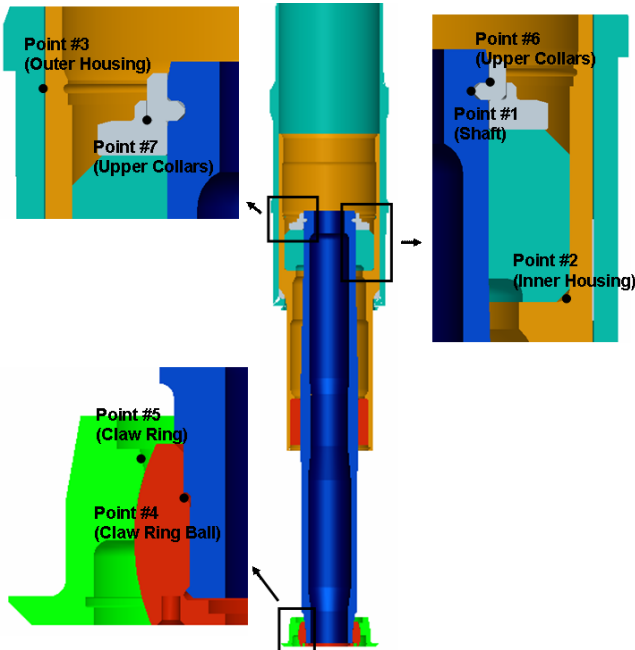


Figure 15: Critical locations in probe components

There are several fatigue failure criteria described in the literature that can be used such as: the Soderberg method; the modified Goodman method; the Gerber method; and the ASME/Gough Ellipse. Among them, the Soderberg criterion is the only method guarding against yielding and is adopted for fatigue analysis here.

The Soderberg equation written in terms of mean and alternating stresses is:

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_y} = 1 \quad \text{or} \quad \sigma_e = \frac{\sigma_a}{1 - \frac{\sigma_m}{\sigma_y}} \quad (7)$$

where  $\sigma_a$  and  $\sigma_m$  are the stress amplitude and mean stress, and  $\sigma_e$  and  $\sigma_y$  are the equivalent fully reversed stress amplitude and yield strength of the material, respectively.

The equivalent fatigue stresses at the critical locations were calculated by using the load spectra from Figure 11 and Figure 12 and Equations 6 and 7. The expected fatigue life of the probe components were then determined using the Palmgren-Miner cumulative damage analysis [4]. The Palmgren-Miner rule states that the cumulative total fatigue

damage  $D_t$  is comprised of damage contributions  $D_i$  arising from load cycles occurring at each stress level and can be written as:

$$D_t = \sum_{i=1}^m \frac{n_i}{N_i} \quad (8)$$

where  $m$  is the number of distinct stress levels. Each contribution to the fatigue damage is defined as the ratio of the number of cycles expected during the design life  $n$  to the number of cycles that would cause crack initiation under the same loading  $N$ , based on available S-N data [5]. For a fatigue damage  $D_t$  calculated as indicated by Equation 8, the expected fatigue life is given by:

$$\text{Fatigue life} = \text{Design life} / D_t \quad (9)$$

Therefore, value of  $D_t$  less than unity indicates acceptable fatigue design ignoring factors of safety on fatigue.

### Fatigue Flaw Tolerance

The S-N curves found in literature typically are the expected results of smooth-specimen tests conducted in the laboratory and are not necessarily reflective of the actual components being designed to and are referred to the “as manufactured” mean curves. As a result, these curves need to be adjusted to yield a degraded S-N curve that reflects the actual in-service condition of the probe; in essence reducing the fatigue life of the material to account for various flaws. In addition, the degraded S-N curves are further modified to include a life reduction factor applied to cycles less than  $10^4$ . This yields a working S-N curve for estimating the fatigue life of the probe containing some initial flaws. Figure 16 shows a generalized fatigue strength versus life curves.

The modifying factors that have been taken into consideration include the following: surface finish condition of the parts; size effect of the parts; impact factor; reliability factor; temperature factor; corrosion factor; and life reduction factor.

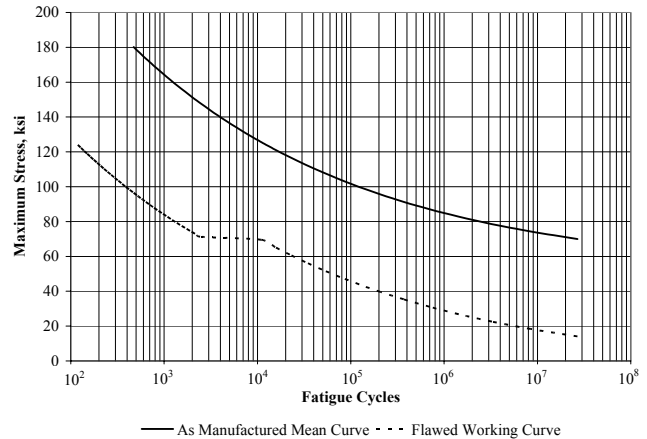


Figure 16: Generalized stress versus cycles curves



From the predicted load spectra in Figure 11 and Figure 12, the equivalent fatigue stresses at the critical locations in each of the probe components were calculated by Equation 7. As a result, the stresses and its cycles at each critical point can be compared with the working S-N curve to determine the fatigue cumulative damage using the Palmgren-Miner rule. Among all the structural components of the probe assembly, the fatigue stress levels at the critical points were below the material endurance limits except the outer housing and the claw ring ball. Figure 17 shows the fatigue stress levels and cycle numbers at the critical points for the outer housing and the claw ring ball.

This indicates that the other components will theoretically have an infinite fatigue life, except the outer housing and the claw ring ball, where there are small numbers of stress cycles that exceed the endurance limits given for the materials used. However, the number of cycles corresponding to these high stresses is very small, so that their effects over the design life of the probe are insignificant to the fatigue damage. Using the Palmgren-Miner's rule, the cumulative fatigue damage amounts to approximately 5% or 500 flight hours over the design life of the probe.

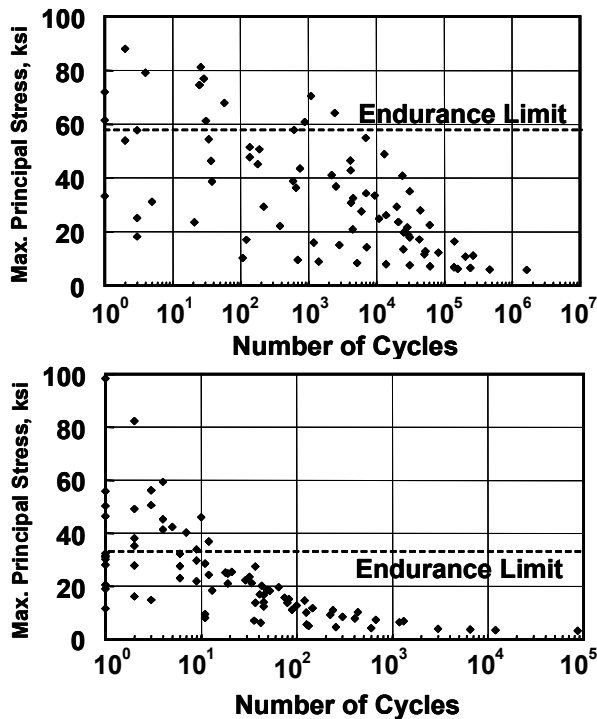


Figure 17: Fatigue stress cycles at critical points: outer housing, point no.3 (top), claw ring ball, point no.4 (bottom)

### CONCLUSIONS

A novel design procedure that integrates advanced dynamic simulation, virtual prototyping and fatigue analysis has been developed for the design of the helicopter probe assembly

for embarked operations on a new frigate type. The fatigue life estimation of the probe assembly consists of two sub-tasks; 1) the dynamic helicopter/ship interface simulation to generate the probe load spectra, and 2) the cumulative fatigue damage analysis of the probe assembly. The dynamic helicopter/ship interface simulation calculated the time histories of the probe loads with a six sigma (99.9999%) confidence level effectively capturing all possible probe load cases that can be expected over the design life of the probe. Secondly, the simulated time histories of the probe loads were post-processed using the rainflow cycle counting method to characterize the probe force cycles at all combinations of force ranges and mean force values in the radial and vertical directions with respect to the probe assembly. Finally, the resulting rainflow cycle charts of each load case were combined into a single load cycle matrix with the weighting functions representing the probability of occurrence of each operating condition over the probe's design life. The cumulative fatigue damage analysis was conducted by monitoring the fatigue life of the critical locations on each component of the probe assembly subjected to the probe load spectra. The results indicated that approximately 5% (or 500 flight hours) of the total fatigue life is used over the design life of the probe. This long fatigue life results from the probe system design being driven by the maximum securing loads and not by the fatigue loads.

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